The Design of the NetBSD I/O Subsystems

SungWon Chung

Pusan National University

This book is dedicated to the open-source code developers in the NetBSD community. The original copy of this publication is available in an electronic form and it can be downloaded for free from http://arXiv.org.

Copyright (c) 2002 by SungWon Chung.

For non-commercial and personal use, this publication may be reproduced, stored in a retrieval system, or transmitted in any form by any means, electronic, mechanical, photocopying, recording or otherwise. For commercial use, no part of this publication can be reproduced by any means without the prior written permission of the author.

NetBSD is the registered trademark of The NetBSD Foundation, Inc.

Contents

Pı	reface	9	14
Ι	Ba	sics to Learn Filesystem	15
1	Wel	come to the World of Kernel!	17
	1.1	How Does a System Call Dive into Kernel from User Program?	17
		1.1.1 Example: write system call	17
		1.1.2 Ultra SPARC 0x7c CPU Trap	18
		1.1.3 Jump to the File Descriptor Layer	24
		1.1.4 Arriving at Virtual Filesystem Operations	28
	1.2	General Data Structures in Kernel such as List, Hash, Queue, \dots	30
		1.2.1 Linked-Lists	30
		1.2.2 Tail Queues	34
		1.2.3 Hash	38
	1.3	Waiting and Sleeping in Kernel	39
	1.4	Kernel Lock Manager	39
		1.4.1 simplelock and lock	39
		1.4.2 Simplelock Interfaces	40
		1.4.3 Lock Interfaces	40
	1.5	Kernel Memory Allocation	43
	1.6	Resource Pool Manager	43
		1.6.1 Design of Resource-Pool Manager	44
		1.6.2 Initializing a pool	44
		1.6.3 Destroying a Pool	45
		1.6.4 Allocating Items from a Pool	45
		1.6.5 Returning Items to a Pool	45
		1.6.6 Using Cache to Speed Up	45
		1.6.7 Other Resource-Pool Manager API	46
2	I/O	System	47
	2.1	I/O Mapping from User to Device	47
		2.1.1 Device Drivers	47
		2.1.2 I/O Queueing	47
		2.1.3 Interrupt Handling	48
	2.2	Block Devices	48
		2.2.1 Entry Points for Block-Device Drivers	48
		2.2.2 Disk Labels	48
	2.3	Character Devices	49
		2.3.1 Raw Devices and Physical I/O	49
		2.3.2 Entry Points for Character-Device Drivers	54
	2.4	Descriptor Management	54

		2.4.1	File Descriptor, Descriptor Table, and File Entry	
		2.4.2	What does the File Entry Points?	55
		2.4.3	Movement of Data Inside the Kernel: uiomove function	55
3	Virt		le System	5 9
	3.1	Archit	ecture of Virtual File System	
		3.1.1	Why VFS is needed?	
		3.1.2	What Is in the Vnode?	. 59
		3.1.3	How to Call Vnode Operations?	61
	3.2	Virtua	ll Filesystem Initialization	65
		3.2.1	Initializing the namei pathname buffer pool	66
		3.2.2	Initializing the vnode table	67
		3.2.3	Initializing the Name Cache Buffer	
		3.2.4	Initialize the Special Vnode Operations	68
	3.3	Attach	ning Available Static File System	. 73
		3.3.1	Set vnode attribute to empty	. 73
		3.3.2	How is vfs_list_initial initialized?	. 74
		3.3.3	Establish a filesystem and initialize it	. 77
		3.3.4	Fast Filesystem Initialization	. 78
		3.3.5	Soft Dependency Module Initialization	
		3.3.6	UFS Initialization	. 82
	3.4	Virtua	l Filesystem Operations	. 84
	3.5	Refere	nces to Source Code	. 86
		3.5.1	kern/vfs_init.c - 334 lines, 7 functions	86
4	Buf	fer Ca	che	87
	4.1	Buffer	Cache Header	. 87
	4.2	Buffer	Cache Contents	. 89
		4.2.1	Allocation Virtual Memory to Buffer Cache	. 89
		4.2.2	Identifying Buffer	. 90
	4.3	Buffer	$\operatorname{Hash} \ \dots $. 90
	4.4	Buffer	Cache Free Lists	90
		4.4.1	LOCKED List	. 91
		4.4.2	LRU List	. 91
		4.4.3	AGE List	
		4.4.4	EMPTY List	. 92
	4.5	Buffer	Cache Initialization	92
		4.5.1	Physical Memory Allocation	. 92
		4.5.2	Initialization of Hash and Free List	98
	4.6	Buffer	Cache Operation	102
		4.6.1	Finding a Buffer Cache from Hash: incore function	103
	4.7	Manag	ging Buffer Cache Free Lists	103
		4.7.1	Reusing Old Buffer: bremfree function	
		4.7.2	Allocating a New Buffer: getnewbuf function	106
		4.7.3	Adjusting Buffer Size: allocbuf function	108
		4.7.4	Getting a Buffer: getblk function	
	4.8	Alloca	ting and Reading Filesystem with Buffer Cache	116
		4.8.1	Just Read: bread function	
		4.8.2	Read Ahead Multiple Buffers: breadn function	121
		4.8.3	Read Ahead a Single Buffer: breada function	122
	4.9	Releas	ing Buffer Cache	122
		4.9.1	Just Release: brelse function	123
		4.9.2	Delayed Write: bdwrite function	
		4.9.3	Asynchronous Write: bawrite function	129

		4.9.4	Synchronous Write: bwrite function
	4.10	Referen	nces to Source Code
		4.10.1	kern/vfs_bio.c - 334 lines, 21 functions
5	V_{no}		135
	5.1	Introdu	action
	5.2	Vnode	Management Function
		5.2.1	Vnode Flag
		5.2.2	Reference Counts
		5.2.3	Vnode Identifier
		5.2.4	Links to Virtual File System Information
		5.2.5	Vnode Cache
		5.2.6	Type of Object
		5.2.7	Vnode Lock
		5.2.8	Private Area
		5.2.9	Other Vnode-Manipulating Functions
	5.3	Vnode	Attributes
	5.4		Operation about Filesystem Hierarchy
		5.4.1	Overview
		5.4.2	componentname structure
		5.4.3	Pathname Searching
		5.4.4	Name Creation
		5.4.5	Name Change/Deletion
		5.4.6	Attribute Manipulation
		5.4.7	Object Interpretation
		5.4.8	Process Control
		5.4.9	Object Management
	5.5	Vnode	Operation about Storage
		5.5.1	Object Creation and Deletion
		5.5.2	Attribute Update
		5.5.3	Object Read and Write
		5.5.4	Change in Space Allocation
	5.6	High-L	evel Vnode Convenient Function
		5.6.1	Filesystem Hierarchy
		5.6.2	General File I/O
		5.6.3	Advanced I/O
	5.7	Referen	nces to Source Code
		5.7.1	vfs_subr.c - 2846 lines, 57 functions
		5.7.2	vfs_vnops.c - 808 lines, 19 functions
		5.7.3	vfs_syscalls.c - 3116 lines, 65 functions
6	$\mathbf{U}\mathbf{V}$		157
	6.1		action
	6.2		Overview
		6.2.1	Virtual Memory Space
		6.2.2	Memory Map
		6.2.3	Memory Object
		6.2.4	Pager
		6.2.5	Page
	6.3		External Interface
	6.4		ry Mapping Files and Devices
		6.4.1	Attaching a Memory Object to Vnode: uvn_attach 164
		6.4.2	Setting Vnode Size: uvn_vnp_setsize
		n 4 3	Clearing a Vnode: uvn vnp zerorange 166

	6.5	Management of Physical Memory
7	UB	C 17:
	7.1	Introduction
	7.2	Traditional Accesses to File
		7.2.1 I/O Subsystem: read() and write()
		7.2.2 Virtual Memory Subsystem: mmap()
	7.3	File Access with Unified Buffer Cache
	7.4	VFS Support for UVM
		7.4.1 VOP_GETPAGES Operation
		7.4.2 VOP_PUTPAGES Operation
	7.5	UVM Support for I/O
	1.0	7.5.1 ubc_alloc Function
		7.5.2 ubc_release Function
	7.6	Example
	1.0	7.6.1 Reading from Disk to Buffer with UBC
		7.6.2 Writing from Buffer to Disk with UBC
		1.0.2 Williams from Build to Blok with OBO
II	\mathbf{A}	nalyzing Fast Filesystem 181
8	Nan	ning 18
•	8.1	Directories
	0.1	8.1.1 Chunk
		8.1.2 Modification of Directory
	8.2	Finding of Names in Directories
	٠ 	8.2.1 Match Algorithm
		8.2.2 Search Performance Improvement
	8.3	Pathname Translation
	8.4	The Name Cache
	0.1	8.4.1 Vnode's Capability
		8.4.2 Negative Caching
		8.4.3 Special Device Handling
	8.5	Links
	0.0	8.5.1 Hard Links
		8.5.2 Soft Links
		8.5.3 The Differences
	8.6	References to Source Code
	0.0	8.6.1 vfs_cache.c - 537 lines, 17 functions
		8.6.2 vfs_lookup.c - 777 lines, 4 functions
		•
9	Inoc	
	9.1	The Structures of an Inode
		9.1.1 File Flags
		9.1.2 Inode Flags
	0.0	9.1.3 Inode for Root Directory
	9.2	Inode Management
		9.2.1 Opening a File
		9.2.2 Closing a File
	9.3	Quotas

	9.3.1	Soft and Hard Quota		195
	9.3.2	Quota Imposing Mechanism		195
	9.3.3	Quota Records		195
	9.3.4	Active Quota Entry: dquot		
	9.3.5	Consistency Maintenance		
9.4	Refere	nces to Source Code		197
-	9.4.1	ufs_bmap.c - 325 lines, 3 functions		
	9.4.2	ufs_ihash.c - 194 lines, 7 functions		
	9.4.3	ufs_inode.c - 268 lines, 3 functions		
	9.4.4	ufs_lookup.c - 1216 lines, 9 functions		
	9.4.5	ufs_quota.c - 960 lines, 20 functions		
	9.4.6	ufs_readwrite.c - 481 lines, 4 functions		
	9.4.0 $9.4.7$			
		ufs_vfsops.c - 262 lines, 8 functions		
	9.4.8	ufs_vnops.c - 2074 lines, 30 functions	•	199
10 Bor	kolov I	Fast File System		201
	-	ore Services		
10.1		Allocating and Freeing Objects		
		Updating Inode Attribute		
		Manipulating Existing Objects		
		Changing in Space Allocation		
		Virtual Memory System Support		
10.2		ization of the FFS		
		Superblock		
		Cylinder Group		
		Fragment		
10.3	Readir	ng a File		211
	10.3.1	Regular File Reading Algorithm: using UBC		211
	10.3.2	Non-regular File Reading Algorithm: without UBC		211
	10.3.3	Implementation		212
10.4	Writin	g a File		214
	10.4.1	Regular File Writing Algorithm		214
		Non-regular File Writing Algorithm		
		Implementation		
10.5		t Policies		
		Inode Layout Policy		
		Data Block Layout Policy		
10.6		Block Allocation Mechanisms		
10.0		Work Flow		
		Main Function that Does Allocation: ffs_balloc		
		Cylinder Overflow Algorithm: ffs_hashalloc		
		Global Policy 1 - Extending an Fragment: ffs_reallocgg.		
		Global Policy 2 - Get a New Block: ffs_alloc		
		Local Policy - Allocate a Block or Fragment: ffs_alloccg		
		Searching Fragment Descriptor Table: ffs_mapsearch		228
40 -		Rotational Layout Table		231
10.7		Allocation Mechanism		231
		Global Policy: ffs_valloc		
		Local Policy 1: ffs_dirpref		
		Local Policy 2: ffs_nodealloccg		
		ronous Operations		
10.9		stem Semantics		
	10.9.1	Large File Sizes		233
10.10	Refere	nces to Source Code		233

		10.10.1fs.h - 574 lines	. 233
		10.10.2ffs_vfsops.c - 1518 lines, 18 functions	. 235
		10.10.3ffs_vnops.c - 580 lines, 6 functions	. 235
		10.10.4ffs_alloc.c - 1895 lines, 18 functions	. 236
		10.10.5ffs_balloc.c - 552 lines, 2 functions	. 236
		10.10.6ffs_inode.c - 582 lines, 3 functions	. 237
		10.10.7ffs_subr.c - 295 lines, 7 functions	. 237
		10.10.8ffs_tables.c - 147 lines, 0 functions	. 237
		10.10.9ffs_swap.c - 158 lines, 3 functions	. 237
11 ľ	Mot	inting Root File System	239
1	1.1	System Bootstrapping	. 239
		Before Mounting	
		11.2.1 Creating stopped init process	
		11.2.2 Finding Where is the Root File System	
		11.2.3 Executing Root Mount Hook	
1	1.3	Let's Mount the Root File System!	
		11.3.1 Telling the VFS to Mount the Root Filesystem	
		11.3.2 Getting Vnode for Root Device	
		11.3.3 Allocating Mount Structure	
		11.3.4 Reading Superblock	
		11.3.5 Mount!	
1	1.4	What Must Be Done after Mount?	
		11.4.1 Find vnode for '/' — root directory	
		11.4.2 Set current working directory of init process	
		11.4.3 Check File System Time	
		11.4.4 Create Kernel Threads about File System	
		11.4.5 Start Up init processor	
III	\mathbf{S}	Storage Systems	25 9
12 5	Stor	rage Device	261
		Generic Disk Framework	. 261
		12.1.1 disk Structure	. 261
		12.1.2 Disk Interfaces	
		12.1.3 Using the Framework	
1	2.2	Disk Label	
		12.2.1 What does it have?	. 267
		12.2.2 disklabel structure	
		12.2.3 Where is the Disk Label?	. 270
		12.2.4 General Disk Label Interfaces	
		12.2.5 Reading Diak Label: DIOCGDINFO	. 271
		12.2.6 Writing In-Core Disk Label: DIOCSDINFO	
		12.2.7 Writing On-Disk Disk Label: DIOCWDINFO	
		12.2.8 Restrictions of Disk Label in sparc64	
1	2.3	Concatenated Disk Driver	
		12.3.1 Streture	
		12.3.2 Gloval Variables	. 276
		12.3.3 Functions	

13 Logical Volume Manager 2			
13.1 RAID	${ m frame}$	279	
13.1.1	Introduction	279	
13.1.2	Component Labels	280	
13.1.3	Hot Spares	280	
13.1.4	Hierarchical Organization	280	
13.1.5	Kernel Configuration	281	
13.2 VERI	ΓAS Volume Manager	282	
13.2.1	Introduction	282	
13.2.2	Volume Manager Overview	282	
13.2.3	Physical Objects	283	
13.2.4	Volumes and Virtual Objects	283	
Appendix		285	
A. NetBSD	Kernel Sources	285	
Bibliography		287	

Influenced by the documentation of Fast File System (FFS) in NetBSD Operating System Release 1.6, which is a derivative of 4.4BSD-Lite [1], this book aims to provide necessary information to design and implement a new filesystem by describing the implementation of the NetBSD FFS while trying to answer the following questions. This work contains many direct excerpts from the books and papers listed in bibliography section as well as text manual entries from the NetBSD operation system. What I did is merely connecting the concepts in books, papers, and manuals, to the assembly and C source code of the NetBSD Operating System on 64-bit UltraSPARC platform.

- How the root filesystem is mounted?
- How the system call request by application program is executed by the virtual filesystem layer?
- How can we add a new filesystem as another virtual filesystem layer?
- How the UFS integrates FFS as a virtual filesystem layer?
- How the buffer cache of the kernel works with the filesystem ?
- How the UVM works with the filesystem?
- How to replace buffer cache?

I am debted to my project team members, Young-Jin Shin and Woo-Young Park who generously have offered insightful comments and spiritual encouragement towards the completion of our project. I am grateful to the USENIX Association for financial support through the USENIX Student Research Grant program in 2002. I sincerely wish to thank my project team advisor, Professor Sang-Hwa Chung at the Division of Electrical and Computer Engineering in Pusan National University.

SungWon Chung
Busan, Korea
27 November 2002
sungwon@ieee.org

A note added in 2016 when archiving this publication to arXiv.org: Since many part of this book need clarification and correction, the readers' generous understanding will be greatly appreciated until a second edition is available in the future. This archival version is the same as the initial 2002 release of this publication except few typo corrections and updates here in the preface. During the past 14 years, I had switched my main field of interests from operating system software to integrated circuits design while my two project members Young-Jin Shin and Woo-Young Park have kept their endeavors and have had successful careers as well-known technical writers, entrepreneurs, and software engineers. For the second edition, we are planning to include a simple example of new virtual filesystem development. Your comments on any other suggestions will be extremely valuable to us.

Source Code Copyright

The NetBSD Foundation

The NetBSD specific code contains the following copyright notice.

```
* Copyright (c) 1998, 2000 The NetBSD Foundation, Inc.
* All rights reserved.
* This code is derived from software contributed to The NetBSD Foundation
* by Jason R. Thorpe of the Numerical Aerospace Simulation Facility,
* NASA Ames Research Center.
* Redistribution and use in source and binary forms, with or without
* modification, are permitted provided that the following conditions
* are met:
st 1. Redistributions of source code must retain the above copyright
    notice, this list of conditions and the following disclaimer.
* 2. Redistributions in binary form must reproduce the above copyright
    notice, this list of conditions and the following disclaimer in the
     documentation and/or other materials provided with the distribution.
* 3. All advertising materials mentioning features or use of this software
     must display the following acknowledgement:
      This product includes software developed by the NetBSD
      Foundation, Inc. and its contributors.
* 4. Neither the name of The NetBSD Foundation nor the names of its
     contributors may be used to endorse or promote products derived
     from this software without specific prior written permission.
* THIS SOFTWARE IS PROVIDED BY THE NETBSD FOUNDATION, INC. AND CONTRIBUTORS
* ''AS IS'' AND ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED
* TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR
* PURPOSE ARE DISCLAIMED. IN NO EVENT SHALL THE FOUNDATION OR CONTRIBUTORS
* BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR
* CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF
* SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS
* INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN
* CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE)
* ARISING IN ANY WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE
* POSSIBILITY OF SUCH DAMAGE.
*/
```

University of California at Berkeley

All the source code in this book that is taken from the 4.4BSD-Lite release contains the following copyright notice.

```
* Copyright (c) 1989, 1993
* The Regents of the University of California. All rights reserved.
*
* This code is derived from software contributed
* to Berkeley by John Heidemann of the UCLA Ficus project.
*
```

* Source: * @(#)i405_init.c 2.10 92/04/27 UCLA Ficus project

```
* Redistribution and use in source and binary forms, with or without
* modification, are permitted provided that the following conditions
* are met:
* 1. Redistributions of source code must retain the above copyright
    notice, this list of conditions and the following disclaimer.
* 2. Redistributions in binary form must reproduce the above copyright
    notice, this list of conditions and the following disclaimer in the
    documentation and/or other materials provided with the distribution.
* 3. All advertising materials mentioning features or use of this software
    must display the following acknowledgement:
       This product includes software developed by the University of
       California, Berkeley and its contributors.
* 4. Neither the name of the University nor the names of its contributors
    may be used to endorse or promote products derived from this software
     without specific prior written permission.
* THIS SOFTWARE IS PROVIDED BY THE REGENTS AND CONTRIBUTORS ''AS IS'' AND
* ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE
* IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE
* ARE DISCLAIMED. IN NO EVENT SHALL THE REGENTS OR CONTRIBUTORS BE LIABLE
* FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL
* DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF SUBSTITUTE GOODS
* OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION)
* HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT
* LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY
* OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF
* SUCH DAMAGE.
       @(#)vfs_init.c 8.5 (Berkeley) 5/11/95
*/
```

Washington University

/*

UVM code contains the following copyright notice.

```
* Copyright (c) 1997 Charles D. Cranor and Washington University.
* All rights reserved.
* Redistribution and use in source and binary forms, with or without
* modification, are permitted provided that the following conditions
* are met:
* 1. Redistributions of source code must retain the above copyright
    notice, this list of conditions and the following disclaimer.
* 2. Redistributions in binary form must reproduce the above copyright
    notice, this list of conditions and the following disclaimer in the
     documentation and/or other materials provided with the distribution.
* 3. All advertising materials mentioning features or use of this software
    must display the following acknowledgement:
      This product includes software developed by Charles D. Cranor and
      Washington University.
```

* 4. The name of the author may not be used to endorse or promote products * derived from this software without specific prior written permission.

*

- * THIS SOFTWARE IS PROVIDED BY THE AUTHOR ''AS IS'' AND ANY EXPRESS OR
- * IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES
- * OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE DISCLAIMED.
- * IN NO EVENT SHALL THE AUTHOR BE LIABLE FOR ANY DIRECT, INDIRECT,
- * INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT
- * NOT LIMITED TO, PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE,
- * DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY
- * THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT
- * (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF
- * THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.

*/

Part I Basics to Learn Filesystem

Chapter 1

Welcome to the World of Kernel!

In this chapter, the procedure involved in mounting root filesystem is described.

1.1 How Does a System Call Dive into Kernel from User Program?

In this section, we present how a system call works with an example using a filesystem related system call.

1.1.1 Example: write system call

Let's see how a system call such as write, used in the below user application program, is processed.

	neno.c
main()) {
cl	har *string = "Hello World ?";
	rite(0, string, strlen(string));
}	
	——————————————————————————————————————
	function is defined in libc library of GNU C compiler. For sparc64 he source code of write function in libc library is shown below.
	src/lib/libc/obj/write.S
1 #:	include "SYS.h"
2 R	SYSCALL(write)
	src/lib/libc/obj/write.S

 ${\tt RSYSCALL\ macro\ used\ in\ the\ above\ platform-independent\ write.S\ code\ is\ defined} in\ a\ machine\ independent\ way\ in\ {\tt libc\ library\ source,\ src/lib/libc/arch/sparc64/SYS.h.}$

Thus, write system call used in hello.c executes assembly code of line 93 where argument x is replaced with write. As a result, system call number is stored g1 register, and Ultra SPARC CPU Trap is occured by t instruction.

1.1.2 Ultra SPARC 0x7c CPU Trap

Ultra SPARC CPU trap number, ST_SYSCALL is defined as

How Ultra SPARC CPU trap is processed is determined by CPU initialization stage during bootstrap, according to arch/sparc64/sparc64/locore.s. This part of the kernel source code is listed below.

```
- arch/sparc64/include/trap.h
 636 #define SYSCALL
                             VTRAP(0x100, syscall_setup)
             .globl _C_LABEL(trapbase)
805
806 _C_LABEL(trapbase):
                                     ! 000 = reserved -- Use it to boot
 807
             b dostart; nop; TA8
             /* We should not get the next 5 traps */
 808
 809
             UTRAP(0x001)
                                    ! 001 = POR Reset -- ROM should get this
             UTRAP(0x002)
                                     ! 002 = WDR -- ROM should get this
 810
             UTRAP(0x003)
                                     ! 003 = XIR -- ROM should get this
 811
             UTRAP(0x0fc); TA32
                                     ! 0x0fc fill_7_other
1010
1011 TABLE(syscall):
1012
             SYSCALL
                                     ! 0x100 = sun syscall
                                        - arch/sparc64/sparc64/locore.s
```

Remember that write function defined in libc library requests CPU Trap, ST_SYSCALL that is defined as 0x7c. So, according to line 1012 of arch/sparc64/include/trap.h, jump to syscall_setup label is made.

Source code from the syscall_setup is shown below.

```
-- arch/sparc64/sparc64/locore.s
3905 /*
3906 * syscall_setup() builds a trap frame and calls syscall().
3907 * sun_syscall is same but delivers sun system call number
3908 * XXX should not have to save&reload ALL the registers just for
3909 * ptrace...
3910 */
3911 syscall_setup:
3912 #ifdef TRAPS_USE_IG
                %g0, PSTATE_KERN|PSTATE_IG, %pstate ! DEBUG
3913
       wrpr
3914 #endif
3915
        TRAP_SETUP(-CC64FSZ-TF_SIZE)
3916
3917 #ifdef DEBUG
3918
        rdpr
               %tt, %o1
                            ! debug
        sth %o1, [%sp + CC64FSZ + STKB + TF_TT]! debug
3920 #endif
3921
              %g0, PSTATE_KERN, %pstate ! Get back to normal globals
3922
        stx \%g1, [\%sp + CC64FSZ + STKB + TF_G + (1*8)]
3923
3924
        mov %g1, %o1 ! code
3925
               %tpc, %o2
        rdpr
                                   ! (pc)
        stx %g2, [%sp + CC64FSZ + STKB + TF_G + ( 2*8)]
3926
               %tstate, %g1
3927
        rdpr
3928
        stx \%g3, [\%sp + CC64FSZ + STKB + TF_G + (3*8)]
3929
               %tnpc, %o3
        rdpr
3930
        stx \%g4, [%sp + CC64FSZ + STKB + TF_G + (4*8)]
3931
        rd %y, %o4
3932
        stx %g5, [%sp + CC64FSZ + STKB + TF_G + (5*8)]
        stx %g6, [%sp + CC64FSZ + STKB + TF_G + ( 6*8)]
3933
3934
        CHKPT(%g5,%g6,0x31)
3935
        wrpr %g0, 0, %tl
                                   ! return to tl=0
        stx \%g7, [%sp + CC64FSZ + STKB + TF_G + ( 7*8)]
3936
        add %sp, CC64FSZ + STKB, %o0
3937
                                      ! (&tf)
3938
3939
        stx %g1, [%sp + CC64FSZ + STKB + TF_TSTATE]
3940
        stx %o2, [%sp + CC64FSZ + STKB + TF_PC]
3941
        stx %o3, [%sp + CC64FSZ + STKB + TF_NPC]
3942
        st %o4, [%sp + CC64FSZ + STKB + TF_Y]
3943
3944
        rdpr
                %pil, %g5
        stb %g5, [%sp + CC64FSZ + STKB + TF_PIL]
3945
3946
        stb %g5, [%sp + CC64FSZ + STKB + TF_OLDPIL]
3947
3948
        !! In the EMBEDANY memory model %g4 points to the start of the data segment.
3949
        !! In our case we need to clear it before calling any C-code
3950
        clr %g4
        wr %g0, ASI_PRIMARY_NOFAULT, %asi ! Restore default ASI
3951
3952
3953
        call
                _C_LABEL(syscall) ! syscall(&tf, code, pc)
                %g0, PSTATE_INTR, %pstate ! turn on interrupts
3954
         wrpr
3955
```

/* see 'proc_trampoline' for the reason for this label */

3956

```
3957 return_from_syscall:
                  %gO, PSTATE_KERN, %pstate
3958
         wrpr
                                                ! Disable intterrupts
         CHKPT(%o1,%o2,0x32)
3959
3960
         wrpr
                  %g0, 0, %tl
                                       ! Return to tl==0
3961
         CHKPT(\%01,\%02,4)
3962
         ba,a,pt %icc, return_from_trap
3963
          nop
         NOTREACHED
3964
                                          -- arch/sparc64/sparc64/locore.s
```

Notice that in **line 3953**, jump to syscall function defined in arch/sparc64/sparc64/trap.c. trap.c is somewhat complex since it supports system call emulation such as Solaris or Ultra Linux. Critical part of trap.c managing NetBSD specific system call is shown below.

```
- arch/sparc64/sparc64/trap.s
1721 void
1722 syscall(tf, code, pc)
1723
         register_t code;
1724
         struct trapframe64 *tf;
1725
         register_t pc;
1726 {
1727
         int i, nsys, nap;
1728
         int64_t *ap;
1729
         const struct sysent *callp;
1730
         struct proc *p;
         int error = 0, new;
1731
1732
         union args {
1733
             register32_t i[8];
1734
             register64_t 1[8];
1735
         } args;
         p = curproc;
1766
1780
         callp = p->p_emul->e_sysent;
1781
         nsys = p->p_emul->e_nsysent;
1851
             callp += code;
                 error = copyin((caddr_t)(u_long)tf->tf_out[6] + BIAS +
1876
1877
                             offsetof(struct frame64, fr_argx),
1878
                             &args.l[nap],
1879
                             (i - nap) * sizeof(register64_t));
1997
         error = (*callp->sy_call)(p, &args, rval);
                                          - arch/sparc64/sparc64/trap.s
```

By line 1997, a function pointed by a function pointer is called. The function pointer is set by line 1780 and line 1851. To explain what this function pointer means, kernel structure for a process should briefly described.

Kernel structure to describe a process is struct proc and it contains so called per-process emulation information in const struct emul *p_emul structure.

```
sys/proc.h

149 struct proc {
...

173     pid_t     p_pid;     /* Process identifier */
...

218     const struct emul *p_emul;     /* Emulation information */
219     void     *p_emuldata;     /*
...

264 };
```

This member is used to run a SUN Solaris or Linux binary on NetBSD/sparc64. However, for native NetBSD/sparc64 binary, this member is initialized by kern/init_main.c to point a const struct emul emul_netbsd structure defined in kern/kern_exec.c. The source for this initialization is

```
- sys/proc.h
165 /*
166 * System startup; initialize the world, create process 0, mount root
167 * filesystem, and fork to create init and pagedaemon. Most of the
168 * hard work is done in the lower-level initialization routines including
169 * startup(), which does memory initialization and autoconfiguration.
170 */
171 void
172 main(void)
173 {
174
            struct proc *p;
188
            /*
189
             * Initialize the current process pointer (curproc) before
190
             * any possible traps/probes to simplify trap processing.
191
            simple_lock_init(&proc0.p_raslock);
192
            p = &proc0;
193
194
            curproc = p;
            p->p_emul = &emul_netbsd;
274
545
             * Okay, now we can let init(8) exec! It's off to userland!
546
547
             */
548
            start_init_exec = 1;
549
            wakeup((void *)&start_init_exec);
550
551
            /* The scheduler is an infinite loop. */
552
            uvm_scheduler();
553
            /* NOTREACHED */
554 }
                                                         sys/proc.h
```

and,

kern/kern_exec.h

```
128 const struct emul emul_netbsd = {
    129
                "netbsd",
                                /* emulation path */
    130
                NULL,
    131 #ifndef __HAVE_MINIMAL_EMUL
                EMUL_HAS_SYS___syscall,
    132
    133
                NULL,
    134
                SYS_syscall,
                SYS_NSYSENT,
    135
    136 #endif
    137
                sysent,
    138 #ifdef SYSCALL_DEBUG
    139
                syscallnames,
    140 #else
    141
                NULL,
    142 #endif
    143
                sendsig,
    144
                trapsignal,
    145
                sigcode,
    146
                esigcode,
    147
                setregs,
    148
                NULL,
    149
                NULL,
                NULL,
    150
    151 #ifdef __HAVE_SYSCALL_INTERN
                syscall_intern,
    153 #else
    154
                syscall,
    155 #endif
    156
                NULL,
                NULL.
    157
    158 };
                                                       - kern/kern_exec.h
where the definition of struct emul structure is
                                                       - kern/kern_exec.h
     94 struct emul {
                                                 /* Symbolic name */
               const char
                                 *e_name;
                                                 /* Extra emulation path (NULL if none)*/
     96
                const char
                                 *e_path;
     97 #ifndef __HAVE_MINIMAL_EMUL
     98
                int
                                                 /* Miscellaneous flags, see above */
                                 e_flags;
     99
                                                 /* Syscall handling function */
                                                 /* Errno array */
    100
                const int
                                 *e_errno;
    101
                int
                                 e_nosys;
                                                 /* Offset of the nosys() syscall */
    102
                int
                                 e_nsysent;
                                                 /* Number of system call entries */
    103 #endif
                const struct sysent *e_sysent; /* System call array */
    104
                const char * const *e_syscallnames; /* System call name array */
    105
    106
                                                 /* Signal sending function */
    107
                void
                                 (*e_sendsig) __P((int, sigset_t *, u_long));
                                 (*e_trapsignal) __P((struct proc *, int, u_long));
    108
                void
```

1.1. HOW DOES A SYSTEM CALL DIVE INTO KERNEL FROM USER PROGRAM ?23

```
/* Start of sigcode */
109
            char
                             *e_sigcode;
                                              /* End of sigcode */
110
            char
                             *e_esigcode;
                                              /* Set registers before execution */
111
                             (*e_setregs) __P((struct proc *, struct exec_package *,
112
            void
113
                                       u_long));
114
115
                                              /* Per-process hooks */
                             (*e_proc_exec) __P((struct proc *,
            void
116
117
                                                  struct exec_package *));
                             (*e_proc_fork) __P((struct proc *p,
118
            void
119
                                                  struct proc *parent));
120
                             (*e_proc_exit) __P((struct proc *));
            void
121
122 #ifdef __HAVE_SYSCALL_INTERN
                             (*e_syscall_intern) __P((struct proc *));
123
            void
124 #else
125
            void
                             (*e_syscall) __P((void));
126 #endif
127
                                              /* Emulation specific sysctl */
128
            int
                             (*e_sysctl) __P((int *, u_int , void *, size_t *,
129
                                     void *, size_t, struct proc *p));
130
                             (*e_fault) __P((struct proc *, vaddr_t, int, int));
            int.
131 };
                                                     kern/kern_exec.h
```

The emul_netbsd structure has a member whose definition is const struct sysent *e_sysent and this member points, by the initialization of kern/kern_exec.c, to struct sysent sysent[] array of structure which is defined in init_sysent.c as

```
kern/init_sysent.h
 71 struct sysent sysent[] = {
             { 0, 0, 0,
 73
                                                        /* 0 = syscall (indir) */
                  sys_nosys },
 74
             { 1, s(struct sys_exit_args), 0,
                                                        /* 1 = exit */
 75
                  sys_exit },
 76
             { 0, 0, 0,
 77
                  sys_fork },
                                                        /* 2 = fork */
 78
             { 3, s(struct sys_read_args), 0,
 79
                  sys_read },
                                                        /* 3 = read */
             { 3, s(struct sys_write_args), 0,
 80
                  sys_write },
                                                        /* 4 = write */
 81
             { 3, s(struct sys_open_args), 0,
 82
 83
                  sys_open },
                                                        /* 5 = open */
1227
                                                        /* 511 = filler */
                  sys_nosys },
1228 };
                                                      kern/init_sysent.h
```

where struct sysent is defined as

— kern/init_sysent.h

```
/* system call table */
131 extern struct sysent {
                                     /* number of args */
132
            short
                    sy_narg;
                                     /* total size of arguments */
133
            short
                    sy_argsize;
134
            int
                     sy_flags;
                                     /* flags. see below */
135
            sy_call_t *sy_call;
                                     /* implementing function */
136 } sysent[];
                                                   - kern/init_sysent.h
```

Now, based on the description up to now, we can exactly understand what the **line 1997** means. Actually, It means that jump to the **sys_write** function.

1.1.3 Jump to the File Descriptor Layer

sys_write function is defined in sys_generic.c as

```
kern/sys_generic.c
278 /*
279 * Write system call
280 */
281 int
282 sys_write(struct proc *p, void *v, register_t *retval)
283 {
284
            struct sys_write_args /* {
285
                    syscallarg(int)
                                                      fd;
286
                    syscallarg(const void *)
                                                      buf;
287
                    syscallarg(size_t)
                                                      nbyte;
288
            } */ *uap = v;
289
            int
                             fd;
290
            struct file
                             *fp;
291
            struct filedesc *fdp;
292
293
            fd = SCARG(uap, fd);
294
            fdp = p->p_fd;
295
296
            if ((fp = fd_getfile(fdp, fd)) == NULL)
297
                    return (EBADF);
298
299
            if ((fp->f_flag & FWRITE) == 0)
300
                    return (EBADF);
301
            FILE_USE(fp);
302
303
304
            /* dofilewrite() will unuse the descriptor for us */
            return (dofilewrite(p, fd, fp, SCARG(uap, buf), SCARG(uap, nbyte),
305
                &fp->f_offset, FOF_UPDATE_OFFSET, retval));
306
307 }
308
309 int
310 dofilewrite(struct proc *p, int fd, struct file *fp, const void *buf,
            size_t nbyte, off_t *offset, int flags, register_t *retval)
311
312 {
313
            struct uio
                             auio;
314
            struct iovec
                            aiov;
```

```
315
            size_t
                          cnt;
316
           int
                           error;
317 #ifdef KTRACE
318
           struct iovec
                           ktriov;
319 #endif
320
321
            error = 0;
322
            aiov.iov_base = (caddr_t)buf;
                                                /* XXX kills const */
323
            aiov.iov_len = nbyte;
324
            auio.uio_iov = &aiov;
325
            auio.uio_iovcnt = 1;
326
            auio.uio_resid = nbyte;
327
            auio.uio_rw = UIO_WRITE;
328
           auio.uio_segflg = UIO_USERSPACE;
329
           auio.uio_procp = p;
330
331
           /*
332
            * Writes return ssize_t because -1 is returned on error. Therefore
333
             * we must restrict the length to SSIZE_MAX to avoid garbage return
334
            * values.
335
            */
336
            if (auio.uio_resid > SSIZE_MAX) {
337
                   error = EINVAL;
338
                    goto out;
339
340
341 #ifdef KTRACE
342
343
            * if tracing, save a copy of iovec
344
            */
345
            if (KTRPOINT(p, KTR_GENIO))
346
                   ktriov = aiov;
347 #endif
348
           cnt = auio.uio_resid;
349
            error = (*fp->f_ops->fo_write)(fp, offset, &auio, fp->f_cred, flags);
350
            if (error) {
351
                    if (auio.uio_resid != cnt && (error == ERESTART ||
352
                       error == EINTR || error == EWOULDBLOCK))
353
                           error = 0;
354
                    if (error == EPIPE)
355
                            psignal(p, SIGPIPE);
356
            cnt -= auio.uio_resid;
357
358 #ifdef KTRACE
359
            if (KTRPOINT(p, KTR_GENIO) && error == 0)
                   ktrgenio(p, fd, UIO_WRITE, &ktriov, cnt, error);
360
361 #endif
362
           *retval = cnt;
363 out:
            FILE_UNUSE(fp, p);
364
365
            return (error);
366 }
```

kern/sys_generic.c

Do you think it is the whole kernel source code to process write system call? Unfortunately, there remains somewhat long way for us to walk before we reach the realm of the fast filesystem code. /:)

See the line 349 of kern/sys/generic.c. You may wonder how the f_ops member of fp structure is set. It is initialized when open system call is executed as,

— kern/vfs_syscalls.c

```
986 /*
 987 * Check permissions, allocate an open file structure,
 988 * and call the device open routine if any.
 989 */
 990 int
 991 sys_open(p, v, retval)
 992
             struct proc *p;
 993
             void *v;
 994
             register_t *retval;
 995 {
 996
             struct sys_open_args /* {
 997
                     syscallarg(const char *) path;
 998
                     syscallarg(int) flags;
999
                     syscallarg(int) mode;
             } */ *uap = v;
1000
             struct cwdinfo *cwdi = p->p_cwdi;
1001
1002
             struct filedesc *fdp = p->p_fd;
             struct file *fp;
1003
1004
             struct vnode *vp;
1005
             int flags, cmode;
1006
             int type, indx, error;
1007
             struct flock lf;
1008
             struct nameidata nd;
1009
             flags = FFLAGS(SCARG(uap, flags));
1010
             if ((flags & (FREAD | FWRITE)) == 0)
1011
1012
                     return (EINVAL);
1013
             /* falloc() will use the file descriptor for us */
1014
             if ((error = falloc(p, &fp, &indx)) != 0)
1015
                     return (error);
1016
             cmode = ((SCARG(uap, mode) & cwdi->cwdi_cmask) & ALLPERMS) & S_ISTXT;
             NDINIT(&nd, LOOKUP, FOLLOW, UIO_USERSPACE, SCARG(uap, path), p);
1017
1018
             p \rightarrow p_dupfd = -indx - 1;
                                                      /* XXX check for fdopen */
             if ((error = vn_open(&nd, flags, cmode)) != 0) {
1019
                     FILE_UNUSE(fp, p);
1020
1021
                     ffree(fp);
1022
                     if ((error == ENODEV || error == ENXIO) &&
1023
                         p->p_dupfd >= 0 &&
                                                               /* XXX from fdopen */
1024
                         (error =
1025
                              dupfdopen(p, indx, p->p_dupfd, flags, error)) == 0) {
                              *retval = indx;
1026
1027
                             return (0);
1028
1029
                     if (error == ERESTART)
1030
                             error = EINTR;
```

```
1031
                     fdremove(fdp, indx);
1032
                     return (error);
1033
             }
1034
             p->p_dupfd = 0;
1035
             vp = nd.ni_vp;
1036
             fp->f_flag = flags & FMASK;
1037
             fp->f_type = DTYPE_VNODE;
             fp->f_ops = &vnops;
1038
1039
             fp->f_data = (caddr_t)vp;
             if (flags & (0_EXLOCK | 0_SHLOCK)) {
1040
1041
                     lf.l_whence = SEEK_SET;
                     lf.l_start = 0;
1042
1043
                     lf.l_len = 0;
1044
                     if (flags & O_EXLOCK)
1045
                              lf.l_type = F_WRLCK;
1046
                     else
1047
                              lf.l_type = F_RDLCK;
1048
                     type = F_FLOCK;
                     if ((flags & FNONBLOCK) == 0)
1049
1050
                              type |= F_WAIT;
                     VOP_UNLOCK(vp, 0);
1051
1052
                     error = VOP_ADVLOCK(vp, (caddr_t)fp, F_SETLK, &lf, type);
                     if (error) {
1053
                              (void) vn_close(vp, fp->f_flag, fp->f_cred, p);
1054
                              FILE_UNUSE(fp, p);
1055
1056
                              ffree(fp);
                              fdremove(fdp, indx);
1057
1058
                              return (error);
1059
1060
                     vn_lock(vp, LK_EXCLUSIVE | LK_RETRY);
1061
                     fp->f_flag |= FHASLOCK;
1062
             }
             VOP_UNLOCK(vp, 0);
1063
             *retval = indx;
1064
             FILE_SET_MATURE(fp);
1065
1066
             FILE_UNUSE(fp, p);
1067
             return (0);
1068 }
```

You can check that this code segment is described by the page 205-207 of a book titled as 'the design and implementation of the 4.4BSD operating system'

kern/vfs_syscalls.c

For more important, see 1038 of vfs_syscalls.c. Did you have a sense what this means? By this code line, the f_ops member of fp structure in line 349 of kern/sys_generic.c points vnops global variable which is defined as,

where the definition of struct fileops is embedded in the definition of file structure as,

```
sys/file.h
53 /*
54 * Kernel descriptor table.
* One entry for each open kernel vnode and socket.
56 */
57 struct file {
           LIST_ENTRY(file) f_list;
                                            /* list of active files */
58
                                            /* see fcntl.h */
59
                           f_flag;
           int
                           f_iflags;
                                            /* internal flags */
61 #define DTYPE_VNODE
                                            /* file */
                           1
62 #define DTYPE_SOCKET
                                            /* communications endpoint */
                           2
63 #define DTYPE_PIPE
                                            /* pipe */
                           3
64 #define DTYPE_KQUEUE
                           4
                                            /* event queue */
65 #define DTYPE_MISC
                           5
                                            /* misc file descriptor type */
                                            /* descriptor type */
66
           int
                           f_type;
67
           u_int
                           f_count;
                                            /* reference count */
                                            /* references from message queue */
68
           u_int
                           f_msgcount;
                                            /* number active users */
69
           int
                           f_usecount;
                           *f_cred;
70
                                            /* creds associated with descriptor */
           struct ucred
71
           struct fileops {
72
                            (*fo_read)
                                            (struct file *fp, off_t *offset,
                   int
73
                                                struct uio *uio,
74
                                                struct ucred *cred, int flags);
75
                   int
                            (*fo_write)
                                            (struct file *fp, off_t *offset,
76
                                                struct uio *uio,
77
                                                struct ucred *cred, int flags);
                            (*fo_ioctl)
78
                                            (struct file *fp, u_long com,
                   int
79
                                                caddr_t data, struct proc *p);
                            (*fo_fcntl)
80
                   int
                                            (struct file *fp, u_int com,
                                                caddr_t data, struct proc *p);
81
                            (*fo_poll)
                                            (struct file *fp, int events,
82
                   int
83
                                                struct proc *p);
84
                   int
                            (*fo_stat)
                                            (struct file *fp, struct stat *sp,
85
                                                struct proc *p);
86
                   int
                            (*fo_close)
                                            (struct file *fp, struct proc *p);
87
                            (*fo_kqfilter)
                                            (struct file *fp, struct knote *kn);
88
           } *f_ops;
89
                            f_offset;
           off_t
90
           caddr_t
                           f_data;
                                            /* descriptor data, e.g. vnode/socket */
91 };
```

sys/file.h

Based on the above code, **line 349** of kern_sysgeneric.c makes a jump to vn_write.

1.1.4 Arriving at Virtual Filesystem Operations

The vn_write function is defined in vfs_vnops.c as,

kern/	vfs_vno	ps.c
ICI II /	V 10 _ V 11 O	00.0

```
526 /*
527 * File table vnode write routine.
528 */
529 static int
530 vn_write(fp, offset, uio, cred, flags)
            struct file *fp;
532
            off_t *offset;
            struct uio *uio;
533
534
            struct ucred *cred;
535
            int flags;
536 {
537
            struct vnode *vp = (struct vnode *)fp->f_data;
538
            int count, error, ioflag = IO_UNIT;
539
540
            if (vp->v_type == VREG && (fp->f_flag & O_APPEND))
541
                    ioflag |= IO_APPEND;
542
            if (fp->f_flag & FNONBLOCK)
543
                    ioflag |= IO_NDELAY;
            if (fp->f_flag & FFSYNC ||
544
545
                (vp->v_mount && (vp->v_mount->mnt_flag & MNT_SYNCHRONOUS)))
546
                    ioflag |= IO_SYNC;
            else if (fp->f_flag & FDSYNC)
547
                    ioflag |= IO_DSYNC;
548
549
            if (fp->f_flag & FALTIO)
                    ioflag |= IO_ALTSEMANTICS;
550
551
            VOP_LEASE(vp, uio->uio_procp, cred, LEASE_WRITE);
            vn_lock(vp, LK_EXCLUSIVE | LK_RETRY);
552
553
            uio->uio_offset = *offset;
554
            count = uio->uio_resid;
            error = VOP_WRITE(vp, uio, ioflag, cred);
555
556
            if (flags & FOF_UPDATE_OFFSET) {
557
                    if (ioflag & IO_APPEND)
558
                             *offset = uio->uio_offset;
559
                    else
560
                             *offset += count - uio->uio_resid;
561
562
            VOP_UNLOCK(vp, 0);
            return (error);
563
564 }
```

kern/vfs_vnops.c

By the functions used in line line 551, 555 — VOP_LEASE, VOP_WRITE — are calls to virtual filesystem operations. Before describing the jump to virtual file system code by this function, we should explain architecture and source code for virtual filesystem layer in NetBSD/sparc64. Therefore, we postpone further description to the next chapter telling about virtual filesystem layer implementation.

Starting from write system call in hello.c, we arrived just before the filesystem code. Isn't it interesting?

1.2 General Data Structures in Kernel such as List, Hash, Queue, ...

In NetBSD, general data structure manipulation macros are provided. Conceptually, they are equivalent to templates of C++ language. To use these macro, the only thing to do is including sys/queue.h header file.

Those built-in macros in NetBSD supports five types of data structures: singly-linked lists, linked-lists, simple queues, tail queues, and circular queues. They are used by the various parts of kernel. For example, *buffer cache* uses lists and tail queues.

All five data structures support the following four functionality:

- Insertion of a new entry at the head of the list
- Insertion of a new entry before or after any element in the list
- Removal of any entry in the list
- Forward traversal through the list

All doubly linked types of data structures (lists, tail queues, and circle queues) additionally allow:

- Insertion of a new entry before any element in the list.
- \bullet O(1) removal of any entry in the list.

However, code size and execution time of operations (except for removal) is about twice that of the singly-linked data structures.

1.2.1 Linked-Lists

Linked lists are the simplest of the doubly linked data structures. Here is an example using linked lists.

An Example

```
LIST_HEAD(listhead, entry) head;
struct listhead *headp;
                                 /* List head. */
struct entry {
        LIST_ENTRY(entry) entries;
                                        /* List. */
} *n1, *n2, *np;
LIST_INIT(&head);
                                         /* Initialize the list. */
n1 = malloc(sizeof(struct entry));
                                         /* Insert at the head. */
LIST_INSERT_HEAD(&head, n1, entries);
                                         /* Insert after. */
n2 = malloc(sizeof(struct entry));
LIST_INSERT_AFTER(n1, n2, entries);
n2 = malloc(sizeof(struct entry));
                                         /* Insert before. */
LIST_INSERT_BEFORE(n1, n2, entries);
                                         /* Forward traversal. */
```

From now on, with this example, we will describe how to use built-in macros about linked-lists.

List Definition

A list is headed by a structure defined by the LIST_HEAD macro. This macro is defined in sys/queue.h as,

– sys/queue.h

This structure contains a single pointer to the first element on the list. The elements are doubly linked so that an arbitrary element can be removed without traversing the list. New elements can be added to the list after an existing element, before an existing element, or at the head of the list. A LIST_HEAD structure is declared as follows:

```
LIST_HEAD(HEADNAME, TYPE) head;
```

where HEADNAME is the name of the structure to be defined, and TYPE is the type of the elements to be linked into the list. A pointer to the head of the list can later be declared as:

```
struct HEADNAME *headp;
```

(The names head and headp are user selectable.)

Declaring Entry

The macro LIST_ENTRY declares a structure that connects the elements in the list. This macro is defined in sys/queue.h as,

List Initialization

The macro LIST_INIT initializes the list referenced by head. This marco is defined as,

Entry Insertion

LIST_INSERT_HEAD macro inserts the new element elm at the head of

LIST_INSERT_AFTER inserts the new element elm after the element listelm.

LIST_INSERT_BEFORE inserts the new element elm before the element listelm.

Those macros are defined in sys/queue.h as,

```
– sys/queue.h
132 #define LIST_INSERT_AFTER(listelm, elm, field) do {
            QUEUEDEBUG_LIST_OP((listelm), field)
133
            if (((elm)->field.le_next = (listelm)->field.le_next) != NULL)
134
                    (listelm)->field.le_next->field.le_prev =
135
136
                        &(elm)->field.le_next;
137
            (listelm)->field.le_next = (elm);
            (elm)->field.le_prev = &(listelm)->field.le_next;
138
139 } while (/*CONSTCOND*/0)
140
141 #define LIST_INSERT_BEFORE(listelm, elm, field) do {
142
            QUEUEDEBUG_LIST_OP((listelm), field)
            (elm)->field.le_prev = (listelm)->field.le_prev;
143
            (elm)->field.le_next = (listelm);
144
145
            *(listelm)->field.le_prev = (elm);
            (listelm)->field.le_prev = &(elm)->field.le_next;
147 } while (/*CONSTCOND*/0)
148
```

```
149 #define LIST_INSERT_HEAD(head, elm, field) do {
                QUEUEDEBUG_LIST_INSERT_HEAD((head), (elm), field)
    150
    151
                if (((elm)->field.le_next = (head)->lh_first) != NULL)
    152
                         (head)->lh_first->field.le_prev = &(elm)->field.le_next;\
    153
                (head)->lh_first = (elm);
    154
                (elm)->field.le_prev = &(head)->lh_first;
    155 } while (/*CONSTCOND*/0)
                                                             sys/queue.h
From the definition, macros beginning with QUEUEDEBUG is assertion macros. They
are meaningful only if QUEUEDEBUG macro is defined. These macros are defined as
                                                            - sys/queue.h
    107 #if defined(_KERNEL) && defined(QUEUEDEBUG)
    108 #define QUEUEDEBUG_LIST_INSERT_HEAD(head, elm, field)
    109
                if ((head)->lh_first &&
                     (head)->lh_first->field.le_prev != &(head)->lh_first)
    110
    111
                         panic("LIST_INSERT_HEAD %p %s:%d", (head), __FILE__, __LINE__);
    112 #define QUEUEDEBUG_LIST_OP(elm, field)
    113
                if ((elm)->field.le_next &&
    114
                    (elm)->field.le_next->field.le_prev !=
    115
                    &(elm)->field.le_next)
    116
                         panic("LIST_* forw %p %s:%d", (elm), __FILE__, __LINE__);\
                if (*(elm)->field.le_prev != (elm))
    117
                         panic("LIST_* back %p %s:%d", (elm), __FILE__, __LINE__);
    118
    119 #define QUEUEDEBUG_LIST_POSTREMOVE(elm, field)
    120
                (elm)->field.le_next = (void *)1L;
    121
                (elm)->field.le_prev = (void *)1L;
    122 #else
    123 #define QUEUEDEBUG_LIST_INSERT_HEAD(head, elm, field)
    124 #define QUEUEDEBUG_LIST_OP(elm, field)
    125 #define QUEUEDEBUG_LIST_POSTREMOVE(elm, field)
    126 #endif
                                                             sys/queue.h
Entry Removal
The macro LIST_REMOVE removes the element elm from the list.
  This marco is defined as
                                                            - sys/queue.h
```

```
157 #define LIST_REMOVE(elm, field) do {
158
            QUEUEDEBUG_LIST_OP((elm), field)
159
            if ((elm)->field.le_next != NULL)
160
                    (elm)->field.le_next->field.le_prev =
161
                        (elm)->field.le_prev;
            *(elm)->field.le_prev = (elm)->field.le_next;
162
            QUEUEDEBUG_LIST_POSTREMOVE((elm), field)
163
164 } while (/*CONSTCOND*/0)
```

sys/queue.h

List Access

LIST_EMPTY macro return true if the list head has no elements.

LIST_FIRST macro returns the first element of the list head.

LIST_FOREACH macro traverses the list referenced by head in the forward direction, assigning each element in turn to var.

LIST_NEXT macro returns the element after the element elm.

Those macros are defined as

```
- sys/queue.h
166 #define LIST_FOREACH(var, head, field)
            for ((var) = ((head)->lh_first);
167
168
                    (var);
                    (var) = ((var)->field.le_next))
169
170
171 /*
172 * List access methods.
173 */
174 #define LIST_EMPTY(head)
                                             ((head)->lh_first == NULL)
175 #define LIST_FIRST(head)
                                             ((head)->lh_first)
176 #define LIST_NEXT(elm, field)
                                             ((elm)->field.le_next)
                                                        - sys/queue.h
```

Now, if you see again the previous example, you would fully understand how it works !

1.2.2 Tail Queues

Tail queues add the following one additional functionality:

• Entries can be added at the end of a list.

However,

- All list insertions and removals, except insertion before another element, must specify the head of the list.
- Code size is about 15 slower than linked-lists.

An Example

```
TAILQ_INSERT_HEAD(&head, n1, entries);
n1 = malloc(sizeof(struct entry));
                                        /* Insert at the tail. */
TAILQ_INSERT_TAIL(&head, n1, entries);
n2 = malloc(sizeof(struct entry));
                                        /* Insert after. */
TAILQ_INSERT_AFTER(&head, n1, n2, entries);
n2 = malloc(sizeof(struct entry));
                                        /* Insert before. */
TAILQ_INSERT_BEFORE(n1, n2, entries);
                                        /* Forward traversal. */
TAILQ_FOREACH(np, &head, entries)
        np-> ...
                                         /* Reverse traversal. */
TAILQ_FOREACH_REVERSE(np, &head, tailhead, entries)
        np-> ...
                                        /* Delete. */
while (TAILQ_FIRST(&head) != NULL)
        TAILQ_REMOVE(&head, TAILQ_FIRST(&head), entries);
if (TAILQ_EMPTY(&head))
                                        /* Test for emptiness. */
        printf("nothing to do\n");
```

If you read the previous subsection about linked-list, you will not have any problem in understanding the above example. Therefore, instead of describing usages for each macro, we show the definition of those macros.

```
sys/queue.h
310 /*
311 * Tail queue definitions.
312 */
313 #define TAILQ_HEAD(name, type)
314 struct name {
            struct type *tqh_first; /* first element */
315
316
            struct type **tqh_last; /* addr of last next element */
317 }
318
319 #define TAILQ_HEAD_INITIALIZER(head)
            { NULL, &(head).tqh_first }
321
322 #define TAILQ_ENTRY(type)
323 struct {
324
            struct type *tqe_next; /* next element */
325
            struct type **tqe_prev; /* address of previous next element */
326 }
327
328 /*
329 * Tail queue functions.
330 */
331 #if defined(_KERNEL) && defined(QUEUEDEBUG)
332 #define QUEUEDEBUG_TAILQ_INSERT_HEAD(head, elm, field)
333
            if ((head)->tqh_first &&
                (head)->tqh_first->field.tqe_prev != &(head)->tqh_first)
334
```

```
panic("TAILQ_INSERT_HEAD %p %s:%d", (head), __FILE__, __LINE__);
335
336 #define QUEUEDEBUG_TAILQ_INSERT_TAIL(head, elm, field)
337
            if (*(head)->tqh_last != NULL)
338
                    panic("TAILQ_INSERT_TAIL %p %s:%d", (head), __FILE__, __LINE__);
339 #define QUEUEDEBUG_TAILQ_OP(elm, field)
340
            if ((elm)->field.tqe_next &&
                (elm)->field.tqe_next->field.tqe_prev !=
341
                &(elm)->field.tge_next)
342
                    panic("TAILQ_* forw %p %s:%d", (elm), __FILE__, __LINE__);\
343
344
            if (*(elm)->field.tqe_prev != (elm))
                    panic("TAILQ_* back %p %s:%d", (elm), __FILE__, __LINE__);
345
346 #define QUEUEDEBUG_TAILQ_PREREMOVE(head, elm, field)
            if ((elm)->field.tqe_next == NULL &&
347
348
                (head)->tqh_last != &(elm)->field.tqe_next)
349
                    panic("TAILQ_PREREMOVE head %p elm %p %s:%d",
350
                          (head), (elm), __FILE__, __LINE__);
351 #define QUEUEDEBUG_TAILQ_POSTREMOVE(elm, field)
            (elm)->field.tqe_next = (void *)1L;
352
353
            (elm)->field.tqe_prev = (void *)1L;
354 #else
355 #define QUEUEDEBUG_TAILQ_INSERT_HEAD(head, elm, field)
356 #define QUEUEDEBUG_TAILQ_INSERT_TAIL(head, elm, field)
357 #define QUEUEDEBUG_TAILQ_OP(elm, field)
358 #define QUEUEDEBUG_TAILQ_PREREMOVE(head, elm, field)
359 #define QUEUEDEBUG_TAILQ_POSTREMOVE(elm, field)
360 #endif
361
362 #define TAILQ_INIT(head) do {
363
            (head)->tqh_first = NULL;
364
            (head)->tqh_last = &(head)->tqh_first;
365 } while (/*CONSTCOND*/0)
366
367 #define TAILQ_INSERT_HEAD(head, elm, field) do {
            QUEUEDEBUG_TAILQ_INSERT_HEAD((head), (elm), field)
368
369
            if (((elm)->field.tqe_next = (head)->tqh_first) != NULL)
                    (head)->tqh_first->field.tqe_prev =
370
371
                        &(elm)->field.tqe_next;
372
            else
                    (head)->tqh_last = &(elm)->field.tqe_next;
373
            (head)->tqh_first = (elm);
374
            (elm)->field.tqe_prev = &(head)->tqh_first;
376 } while (/*CONSTCOND*/0)
377
378 #define TAILQ_INSERT_TAIL(head, elm, field) do {
            QUEUEDEBUG_TAILQ_INSERT_TAIL((head), (elm), field)
379
380
            (elm)->field.tqe_next = NULL;
381
            (elm)->field.tqe_prev = (head)->tqh_last;
382
            *(head)->tqh_last = (elm);
383
            (head)->tqh_last = &(elm)->field.tqe_next;
384 } while (/*CONSTCOND*/0)
385
386 #define TAILQ_INSERT_AFTER(head, listelm, elm, field) do {
387
            QUEUEDEBUG_TAILQ_OP((listelm), field)
388
            if (((elm)->field.tqe_next = (listelm)->field.tqe_next) != NULL)\
```

```
389
                    (elm)->field.tqe_next->field.tqe_prev =
390
                        &(elm)->field.tqe_next;
391
            else
392
                    (head)->tqh_last = &(elm)->field.tqe_next;
393
            (listelm)->field.tqe_next = (elm);
394
            (elm)->field.tqe_prev = &(listelm)->field.tqe_next;
395 } while (/*CONSTCOND*/0)
396
397 #define TAILQ_INSERT_BEFORE(listelm, elm, field) do {
            QUEUEDEBUG_TAILQ_OP((listelm), field)
399
            (elm)->field.tqe_prev = (listelm)->field.tqe_prev;
400
            (elm)->field.tqe_next = (listelm);
401
            *(listelm)->field.tqe_prev = (elm);
402
            (listelm)->field.tqe_prev = &(elm)->field.tqe_next;
403 } while (/*CONSTCOND*/0)
404
405 #define TAILQ_REMOVE(head, elm, field) do {
406
            QUEUEDEBUG_TAILQ_PREREMOVE((head), (elm), field)
            QUEUEDEBUG_TAILQ_OP((elm), field)
407
408
            if (((elm)->field.tqe_next) != NULL)
409
                    (elm)->field.tqe_next->field.tqe_prev =
410
                        (elm)->field.tqe_prev;
411
            else
412
                    (head)->tqh_last = (elm)->field.tqe_prev;
            *(elm)->field.tqe_prev = (elm)->field.tqe_next;
413
            QUEUEDEBUG_TAILQ_POSTREMOVE((elm), field);
415 } while (/*CONSTCOND*/0)
416
417 /*
418 * Tail queue access methods.
419 */
420 #define TAILQ_EMPTY(head)
                                             ((head)->tqh_first == NULL)
421 #define TAILQ_FIRST(head)
                                             ((head)->tqh_first)
422 #define TAILQ_NEXT(elm, field)
                                             ((elm)->field.tqe_next)
423
424 #define TAILQ_LAST(head, headname) \
            (*(((struct headname *)((head)->tqh_last))->tqh_last))
426 #define TAILQ_PREV(elm, headname, field) \
427
            (*(((struct headname *)((elm)->field.tqe_prev))->tqh_last))
429 #define TAILQ_FOREACH(var, head, field)
                                                                             ١
            for ((var) = ((head)->tqh_first);
430
431
                    (var);
432
                    (var) = ((var)->field.tqe_next))
433
434 #define TAILQ_FOREACH_REVERSE(var, head, headname, field)
            for ((var) = (*(((struct headname *)((head)->tqh_last))->tqh_last));
436
                    (var);
437
                    (var) = (*(((struct headname *)((var)->field.tqe_prev))->tqh_last)))
```

1.2.3 Hash

360

case HASH_TAILQ:

The hash implementation in NerBSD kernel is so simple that it has only two functions: hashinit, hashfree. Only just read the source code will be adequate description for how to use hash in kernel.

```
- kern/kern_subr.c
314 /*
315 * General routine to allocate a hash table.
316 * Allocate enough memory to hold at least 'elements' list-head pointers.
317 * Return a pointer to the allocated space and set *hashmask to a pattern
318 * suitable for masking a value to use as an index into the returned array.
319 */
320 void *
321 hashinit(elements, htype, mtype, mflags, hashmask)
322
            u_int elements;
323
            enum hashtype htype;
324
            int mtype, mflags;
            u_long *hashmask;
325
326 {
327
            u_long hashsize, i;
328
            LIST_HEAD(, generic) *hashtbl_list;
329
            TAILQ_HEAD(, generic) *hashtbl_tailq;
330
            size_t esize;
            void *p;
331
332
333
            if (elements == 0)
334
                    panic("hashinit: bad cnt");
335
            for (hashsize = 1; hashsize < elements; hashsize <<= 1)</pre>
336
                    continue;
337
338
            switch (htype) {
339
            case HASH_LIST:
340
                     esize = sizeof(*hashtbl_list);
341
                    break;
342
            case HASH_TAILQ:
343
                    esize = sizeof(*hashtbl_tailq);
344
                    break;
345 #ifdef DIAGNOSTIC
346
            default:
                    panic("hashinit: invalid table type");
347
348 #endif
349
            }
350
351
            if ((p = malloc(hashsize * esize, mtype, mflags)) == NULL)
352
                    return (NULL);
353
354
            switch (htype) {
            case HASH_LIST:
355
356
                    hashtbl_list = p;
                     for (i = 0; i < hashsize; i++)
357
358
                             LIST_INIT(&hashtbl_list[i]);
359
                    break;
```

kern/kern_subr.c

```
361
                     hashtbl_tailq = p;
362
                     for (i = 0; i < hashsize; i++)</pre>
363
                             TAILQ_INIT(&hashtbl_tailq[i]);
364
                     break;
365
366
            *hashmask = hashsize - 1;
367
            return (p);
368 }
369
370 /*
371 * Free memory from hash table previously allocated via hashinit().
372 */
373 void
374 hashdone(hashtbl, mtype)
375
            void *hashtbl;
376
            int mtype;
377 {
378
379
            free(hashtbl, mtype);
380 }
```

1.3 Waiting and Sleeping in Kernel

1.4 Kernel Lock Manager

The lock functions provide synchronisation in the kernel by preventing multiple threads from simultaneously executing critical sections of code accessing shared data. A number of different locks are available:

1.4.1 simplelock and lock

struct simplelock

Provides a simple spinning mutex. A processor will busy-wait while trying to acquire a simplelock. The simplelock operations are implemented with machine-dependent locking primitives.

Simplelocks are usually used only by the high-level lock manager and to protect short, critical sections of code. Simplelocks are the only locks that can be be used inside an interrupt handler. For a simplelock to be used in an interrupt handler, care must be taken to disable the interrupt, acquire the lock, do any processing, release the simplelock and re-enable the interrupt. This procedure is necessary to avoid deadlock between the interrupt handler and other threads executing on the same processor.

struct lock

Provides a high-level lock supporting sleeping/spinning until the lock can be acquired. The lock manager supplies both exclusive-access and shared-access locks, with recursive exclusive-access locks within a single thread. It also allows upgrading a shared-access lock to an exclusive-access lock, as well as down-

grading an exclusive-access lock to a shared-access lock.

If the kernel option LOCKDEBUG is enabled, additional facilities are provided to record additional lock information. These facilities are provided to assist in determining deadlock occurrences.

1.4.2 Simplelock Interfaces

simple_lock_init(slock)

The simplelock slock is initialised to the unlocked state. A statically allocated simplelock also can be initialised with the macro SIMPLELOCK_INITIALIZER. The effect is the same as the dynamic initialisation by a call to simple_lock_init. For example,

struct simplelock slock = SIMPLELOCK_INITIALIZER;

simple_lock(slock)

The simplelock slock is locked. If the simplelock is held then execution will spin until the simplelock is acquired. Care must be taken that the calling thread does not already hold the simplelock. In this case, the simplelock can never be acquired. If kernel option LOCKDEBUG is enabled, a "locking against myself" panic will occur.

simple_lock_try(slock)

Try to acquire the simplelock slock without spinning. If the simplelock is held by another thread then the return value is 0. If the simplelock was acquired successfully then the return value is 1.

simple_lock_unlock(slock)

The simplelock slock is unlocked. The simplelock must be locked and the calling thread must be the one that last acquired the simplelock. If the calling thread does not hold the simplelock, the simplelock will be released but the kernel behaviour is undefined.

simple_lock_freecheck(start, end)

Check that all simplelocks in the address range start to end are not held. If a simplelock within the range is found, the kernel enters the debugger. This function is available only with kernel option LOCKDEBUG. It provides a mechanism for basic simplelock consistency checks.

simple_lock_dump(void)

Dump the state of all simplelocks in the kernel. This function is available only with kernel option LOCKDEBUG.

1.4.3 Lock Interfaces

lockinit(lock, prio, wmesg, timo, flags)

The lock lock is initialised according to the parameters provided. Arguments are as follows:

lock The lock.

prio The thread priority when it is woken up after sleeping on the lock.

wmesg A sleep message used when a thread goes to sleep waiting for the lock, so that the exact reason it is sleeping can easily be identified.

timo The maximum sleep time. Used by tsleep(9).

flags Flags to specify the lock behaviour permanently over the lifetime of the lock. Valid lock flags are:

LK_NOWAIT

Threads should not sleep when attempting to acquire the lock.

LK_SLEEPFAIL

Threads should sleep, then return failure when acquiring the lock.

LK_CANRECURSE

Threads can acquire the lock recursively.

lockmgr(lock, flags, slock)

Set, change or release a lock according to the parameters provided. Arguments are as follows:

lock The lock.

slock Simplelock interlock. If the flag LK_INTERLOCK is set in flags, slock is a simplelock held by the caller. When the lock lock is acquired, the simplelock is released. If the flag LK_INTERLOCK is not set, slock is ignored.

flags Flags to specify the lock request type. In addition to
 the flags specified above, the following flags are
 valid:

LK_SHARED

Get one of many possible shared-access locks. If a thread holding an exclusive-access lock requests a shared-access lock, the exclusive-access lock is downgraded to a shared-access lock.

LK_EXCLUSIVE

Stop further shared-access locks, when they are cleared, grant a pending upgrade if it exists, then grant an exclusive-access lock.

Only one exclusive-access lock may exist at a

time, except that a thread holding an exclusive-access lock may get additional exclusive-access locks if it explicitly sets the LK_CAN-RECURSE flag in the lock request, or if the LK_CANRECURSE flag was set when the lock was initialised.

LK_UPGRADE

The thread must hold a shared-access lock that it wants to have upgraded to an exclusive-access lock. Other threads may get exclusive access to the protected resource between the time that the upgrade is requested and the time that it is granted.

LK_EXCLUPGRADE

The thread must hold a shared-access lock that it wants to have upgraded to an exclusive-access lock. If the request succeeds, no other threads will have acquired exclusive access to the protected resource between the time that the upgrade is requested and the time that it is granted. However, if another thread has already requested an upgrade, the request will fail.

LK_DOWNGRADE

The thread must hold an exclusive-access lock that it wants to have downgraded to a shared-access lock. If the thread holds multiple (recursive) exclusive-access locks, they will all be downgraded to shared-access locks.

LK_RELEASE

Release one instance of a lock.

LK_DRAIN

Wait for all activity on the lock to end, then mark it decommissioned. This feature is used before freeing a lock that is part of a piece of memory that is about to be freed.

LK_REENABLE

Lock is to be re-enabled after drain. The LK_REENABLE flag may be set only at the release of a lock obtained by a drain.

LK_SETRECURSE

Other locks while we have it OK.

LK_RECURSEFAIL

Attempt at recursive lock fails.

LK_SPIN Lock spins instead of sleeping.

LK_INTERLOCK

Unlock the simplelock slock when the lock is acquired.

lockstatus(lock)

Determine the status of lock lock. Returns LK_EXCLUSIVE or LK_SHARED for exclusive-access and shared-access locks respectively.

lockmgr_printinfo(lock)

Print out information about state of lock lock.

spinlockinit(lock, wmesg, flags)

The lock lock is initialised as a spinlock according to the parameters provided. Arguments are as follows:

lock The lock.

wmesg This is a simple name for lock.

flags Flags to specify the lock behaviour. Valid lock flags are the same as outlined above.

spinlockmgr(lock, flags, slock)

Set, change or release a lock according to the parameters provided. Arguments are as follows:

lock The spin lock.

flags to specify the lock request type. Valid lock flags are the same as outlined above.

slock Simplelock interlock. The simplelock slock is set by the caller. When the lock lock is acquired, the simplelock is released.

1.5 Kernel Memory Allocation

1.6 Resource Pool Manager

Before describing virtual filesystem initialization, there needs to be brief mention of resource-pool manager which is used as base library in implementating (1) namei pathname buffers, (2) vnode management data structures, (3) file structures, (4) current working directory structures, (5) file descriptor structures, and so forth.

resource-pool manager is implemented in kern/subr_pool.c. Instead of investigating details of this code, we present the API of pool allocator defined in sys/pool.h to minimize the basic knowledge to access to the essentials of fast filesystem code.

Theses utility routines provide management of pools of fixed-sized areas of memory. Resource pool set aside an amount of memory for exclusive use by the resource pool owner.

1.6.1 Design of Resource-Pool Manager

Memory is allocated in pages which are split into pieces according to the pool item size. Each page is kept on a list headed by 'pr_pagelist' in the pool structure. The individual pool items are on a linked list headed by 'ph_itemlist' in each page header.

```
pool_init(struct pool *, size_t, u_int, u_int,
208 void
209
                        int, const char *, struct pool_allocator *);
210 void
                    pool_destroy(struct pool *);
211
212 void
                    pool_set_drain_hook(struct pool *,
213
                        void (*)(void *, int), void *);
214
                    *pool_get(struct pool *, int);
215 void
216 void
                    pool_put(struct pool *, void *);
217 int
                    pool_reclaim(struct pool *);
218
231 int
                    pool_prime(struct pool *, int);
232 void
                    pool_setlowat(struct pool *, int);
233 void
                    pool_sethiwat(struct pool *, int);
234 void
                    pool_sethardlimit(struct pool *, int, const char *, int);
235 void
                    pool_drain(void *);
236
237 /*
238 * Debugging and diagnostic aides.
239 */
240 void
                    pool_print(struct pool *, const char *);
241 void
                    pool_printit(struct pool *, const char *,
242
                        void (*)(const char *, ...));
243 int
                    pool_chk(struct pool *, const char *);
244
245 /*
246 * Pool cache routines.
247 */
248 void
                    pool_cache_init(struct pool_cache *, struct pool *,
249
                        int (*ctor)(void *, void *, int),
250
                        void (*dtor)(void *, void *),
251
                        void *);
252 void
                    pool_cache_destroy(struct pool_cache *);
253 void
                    *pool_cache_get(struct pool_cache *, int);
254 void
                    pool_cache_put(struct pool_cache *, void *);
255 void
                    pool_cache_destruct_object(struct pool_cache *, void *);
256 void
                    pool_cache_invalidate(struct pool_cache *);
```

1.6.2 Initializing a pool

The pool_init function declared in line 208 initializes a resource pool. This function allow other kernel parts to declare static pools that must be initialized before malloc kernel function is available.

sys/pool.h

The arguments are, in order,

struct pool *pp is the handle identifying the pool resource instance
size_t size specifies the size of the memory items managed by the pool

u_int align specifies the memory address alignment of the items returned by pool_get function. This argument must be a power of two. If zero, the alignment defaults to a architecture specific natural alignment.

u_int ioff

int flags

const char *wchan set the wait channel passed on to tsleep function, a kernel function similar to sleep in C library, if pool_get must wait for items to be returned to the pool. If you run top program, you may see this string in the state field.

struct pool_allocator *palloc is called to add additional memory if the pool is depleted.

1.6.3 Destroying a Pool

pool_destroy function declared in line 210 destroys a resource pool. It takes a single argument identifying the pool resource instance.

1.6.4 Allocating Items from a Pool

pool_get function allocates an item from the pool and returns a pointer to it. The arguments are, in order,

struct pool *pp is the handle identifying the pool resource instance

int flags defines behavior in case the pooled resources are depleted. If no resources are available and PR_WAITOK is given, this function will wait until items are returned to the pool. If both PR_LIMITFAIL and PR_WAITOK is specified, and the pool has reached its hard limit, pool_get function will return NULL without waiting, allowing the caller to do its own garbage collection.

1.6.5 Returning Items to a Pool

pool_put function declared in line 216 returns the pool item to the resource pool. If the number of available items in the pool exceeds the maximum pool size set by pool_sethiwat function and there are no outstanding requests for pool items, the excess items will be returned to the system.

The arguments are, in order,

struct pool *pp is the handle identifying the pool resource instance.
void *item is a pointer to a pool item previously obtained by pool_get
function.

1.6.6 Using Cache to Speed Up

Pool caches provide a way for constructed objects to be cached. This can lead to performance improvements by avoiding needless object construction/destruction that is deferred until absolutely necessary.

Caches are grouped into cache groups. Each cache group references up to 16 constructed objects. The pool cache is initialized by pool_cache_init function.

When a cache allocates an object from the pool, it calls the object's constructor and places it into a cache group. When a cache group frees an object back to the pool, it first calls the object's destructor. This allows the object to persist in constructed form while freed to the cache.

Though pool_cache is initialized by virtual filesystem, it is not used.

1.6.7 Other Resource-Pool Manager API

There are some resource-pool manager API that is not described such as pool_prime, pool_sethiwat, pool_setlowat, pool_set_drain_hook, pool_reclaim, pool_drain, pool_sethardlimit, and so forth.

Although this API is designed and implemented by the resource-pool manager designer, it is not used in filesystem code.

Chapter 2

I/O System

2.1 I/O Mapping from User to Device

There are four main kinds of I/O in 4.4BSD.

- filesystem
- character-device interface
- block-device interface
- socket interface

The character device interface provides unstructured access to the underlying hardware, whereas the block device provides structured acess to the underlying hardware.

All I/O executed by block-device interface is done to or from I/O buffers that resides in the kernel's address space, the buffer cache. This approach requires at least one memory-to-memory copy operation to satisfy a user request.

For character-device interface, I/O operations do not go through the buffer cache; instead, they are made directly between the device and buffers in the application's virtual address space.

2.1.1 Device Drivers

A device driver is divided into three main sections:

- 1. Autoconfiguration and initialization routines
- 2. The top half: routines for servicing I/O requests
- 3. The bottom half: interrupt service routines

2.1.2 I/O Queueing

Queue Processing Procedure

The I/O queues are the primary means of communication bewteen the top and bottom halves of a device dirver. When an input or output request is received by the top half of the driver,

1. it is recorded in a data structure that is placed on per-device queue for processing.

- 2. When an input or output operation completes, the device dirver receives an interrupt from the controller.
- 3. The interrupt service routine removes the appropriate request from the device's queue,
- 4. notifies the requester that the command has completed, and then
- 5. starts the next request from the queue.

Maintaing Queue Consistency

Because I/O queues are shared among asynchronous routines, access to the queues must be synchronized. Routine that make up the top half of a device driver must raise the processor priority level using splbio(), spltty(), etc. to prevent the bottom half from being entered as a result of an interrupt while a top-half routine is manipulating an I/O queue.

2.1.3 Interrupt Handling

The system arranges for the unit-number parameter to be passed to the interrupt service routine for each device by installing the address of an auxiliary glue routine in the interrupt-vector table. This glue routine, rather than the actual interrupt service routine, is invoked to service the interrupt.

2.2 Block Devices

The task of the block-device interface is to convert from the user abstraction of a disk as an array of bytes to the structure imposed by the underlying physical medium. This operation of converting random access to an array of bytes to reads and writes of disk serctors is known as $block\ I/O$.

2.2.1 Entry Points for Block-Device Drivers

open commonly verify the integrity of the associated medium. open entry point will be called for each open or mount system call on a block special device file.

strategy start a read or write operation, and return immediately. Block I/O routines such as bread or bwrite routines call the device's strategy routine to read or write data not in the buffer cache. If the request is synchronous, the caller must sleep until I/O completes.

close Disk devices have nothing to do when a device is closed.

dump write all physical memory to the device.

psize returns the size of a disk-drive partition. This entry point is used during the bootstrap procedure to calculate the location at which a crash dump should be placed and to determine the sizes of the swap devices.

2.2.2 Disk Labels

What is in it?

Disk label contains the information about the geometry of the disk and about the layout of he partitions.

How is it used?

When the machine is powered up or the reset button is pressed, the CPU executes the hardware bootstrap code from the ROM. The hardware bootstrap code typically reads the first few sectors on the disk into the main memory, then branches to the address of the first location that it read. The program stored in these first few sectors is the second-level bootstrap. Having the disk label stored in the part of the disk read as part of the hardware bootstrap allows the second-level bootstrap to have the disk-label information. This information gives it the ability to find the root filesystem and hence the files, such as kernel, needed to bring up 4.4BSD.

Format of Disk Label

The size and location of the second-level bootstrap are dependent on the requirements of the hardware bootstrap code. Since there is no standard for disk-label formats and the hardware bootstrap code usually understands only the vendor lavel, it is often necessary to support both the vendor and the 4.4BSD disk labels. Here, the vendor label must be placed where the hardware bootstrap ROM code expects it; the 4.4BSD label must be placed out of the way of the vendor label but within the are that is read in by the hardware bootstrap code, so that it will be available to the second-level bootstrap.

2.3 Character Devices

A character device ususally maps the hardware interface into a byte stream. The character interface for disks and tapes is also called the *raw device interface*. Its primary task is to arrange for direct I/O to and from the device. It also handles the asynchronous nature of I/O by maintaing and ordering an active queue of pending transfers.

2.3.1 Raw Devices and Physical I/O

Most raw devices differ from block devices only in the way that they do I/O. Whereas block devices read and write to and from the system buffer cache, raw device bypasses the buffer cache. This eliminates the memory-to-memory copy, but denies the benefits of data caching. To preserve consistency between data in the buffer cache and data written directly to the device via character-device interface, the raw device should be used only when the block device is idle.

Buffers for Character-Device Interface

Because raw devices bypass the buffer cache, they are responsible for managing their own buffer structures. The read and write entry points for raw device driver uses physio function to start a raw I/O operatin. The strategy funtion manages buffers to map the user data buffer. This buffer is completely different and separated from buffer cache used by block-device driver.

The strategy function of kern/kern_physio.c is shown below. You may understand details after you read chapters about UVM and buffer cache. Now, just see the algorithm described in comments!

kern/kern_physio.c

^{69 /*}

^{70 *} Do "physical I/O" on behalf of a user. "Physical I/O" is I/O directly

^{71 *} from the raw device to user buffers, and bypasses the buffer cache.

```
72 *
 73 * Comments in brackets are from Leffler, et al.'s pseudo-code implementation.
 74 */
 75 int
 76 physio(strategy, bp, dev, flags, minphys, uio)
            void (*strategy) __P((struct buf *));
 78
            struct buf *bp;
            dev_t dev;
 79
 80
            int flags;
            void (*minphys) __P((struct buf *));
 81
 82
            struct uio *uio;
 83 {
 84
            struct iovec *iovp;
 85
            struct proc *p = curproc;
 86
            int error, done, i, nobuf, s;
 87
            long todo;
 88
 89
            error = 0;
            flags &= B_READ | B_WRITE;
 90
 91
 92
            /* Make sure we have a buffer, creating one if necessary. */
 93
            if ((nobuf = (bp == NULL)) != 0) {
 94
 95
                    bp = getphysbuf();
 96
                    /* bp was just malloc'd so can't already be busy */
 97
                    bp->b_flags |= B_BUSY;
 98
            } else {
99
100
101
                    /* [raise the processor priority level to splbio;] */
102
                    s = splbio();
103
104
                    /* [while the buffer is marked busy] */
105
                    while (bp->b_flags & B_BUSY) {
106
                            /* [mark the buffer wanted] */
107
                            bp->b_flags |= B_WANTED;
108
                            /* [wait until the buffer is available] */
109
                            tsleep((caddr_t)bp, PRIBIO+1, "physbuf", 0);
                    }
110
111
                    /* Mark it busy, so nobody else will use it. */
112
                    bp->b_flags |= B_BUSY;
113
114
115
                    /* [lower the priority level] */
116
                    splx(s);
            }
117
118
119
            /* [set up the fixed part of the buffer for a transfer] */
120
            bp->b_dev = dev;
121
            bp->b_error = 0;
122
            bp->b_proc = p;
123
            LIST_INIT(&bp->b_dep);
124
125
            /*
```

```
126
             * [while there are data to transfer and no I/O error]
127
             * Note that I/O errors are handled with a 'goto' at the bottom
128
             * of the 'while' loop.
             */
129
130
            for (i = 0; i < uio->uio_iovcnt; i++) {
131
                    iovp = &uio->uio_iov[i];
132
                    while (iovp->iov_len > 0) {
133
134
                              * [mark the buffer busy for physical I/0]
135
136
                              * (i.e. set B_PHYS (because it's an I/O to user
137
                              * memory, and B_RAW, because B_RAW is to be
138
                              * "Set by physio for raw transfers.", in addition
139
                              * to the "busy" and read/write flag.)
140
                              */
141
                             bp->b_flags = B_BUSY | B_PHYS | B_RAW | flags;
142
143
                             /* [set up the buffer for a maximum-sized transfer] */
144
                             bp->b_blkno = btodb(uio->uio_offset);
145
                             bp->b_bcount = iovp->iov_len;
146
                             bp->b_data = iovp->iov_base;
147
                             /*
148
149
                              * [call minphys to bound the transfer size]
                              * and remember the amount of data to transfer,
150
151
                              * for later comparison.
152
                              */
153
                             (*minphys)(bp);
                             todo = bp->b_bcount;
154
155 #ifdef DIAGNOSTIC
                             if (todo <= 0)
156
157
                                     panic("todo(%ld) <= 0; minphys broken", todo);</pre>
158
                             if (todo > MAXPHYS)
159
                                     panic("todo(%ld) > MAXPHYS; minphys broken",
160
                                           todo);
161 #endif
162
163
                             /*
                              * [lock the part of the user address space involved
164
165
                                   in the transfer]
                              * Beware vmapbuf(); it clobbers b_data and
166
                              * saves it in b_saveaddr. However, vunmapbuf()
167
                              * restores it.
168
169
                              */
170
                            PHOLD(p);
171
                             error = uvm_vslock(p, bp->b_data, todo,
172
                                                 (flags & B_READ) ?
173
                                                VM_PROT_WRITE : VM_PROT_READ);
174
                             if (error) {
175
                                     bp->b_flags |= B_ERROR;
176
                                     bp->b_error = error;
177
                                     goto after_vsunlock;
178
179
                             vmapbuf(bp, todo);
```

```
180
181
                             /* [call strategy to start the transfer] */
182
                             (*strategy)(bp);
183
184
185
                              * Note that the raise/wait/lower/get error
186
                              * steps below would be done by biowait(), but
187
                              * we want to unlock the address space before
188
                              * we lower the priority.
189
190
                              * [raise the priority level to splbio]
191
192
                             s = splbio();
193
194
                             /* [wait for the transfer to complete] */
195
                             while ((bp->b_flags & B_DONE) == 0)
196
                                     tsleep((caddr_t) bp, PRIBIO + 1, "physio", 0);
197
                             /* Mark it busy again, so nobody else will use it. */
198
                             bp->b_flags |= B_BUSY;
199
200
201
                             /* [lower the priority level] */
202
                             splx(s);
203
204
205
                              * [unlock the part of the address space previously
206
                                   locked]
207
                              */
                             vunmapbuf(bp, todo);
208
209
                             uvm_vsunlock(p, bp->b_data, todo);
210 after_vsunlock:
211
                             PRELE(p);
212
213
                             /* remember error value (save a splbio/splx pair) */
214
                             if (bp->b_flags & B_ERROR)
215
                                     error = (bp->b_error ? bp->b_error : EIO);
216
217
                              * [deduct the transfer size from the total number
218
219
                                   of data to transfer]
                              */
220
221
                             done = bp->b_bcount - bp->b_resid;
222
                             KASSERT(done >= 0);
223
                             KASSERT(done <= todo);</pre>
224
225
                             iovp->iov_len -= done;
226
                             iovp->iov_base = (caddr_t)iovp->iov_base + done;
227
                             uio->uio_offset += done;
228
                             uio->uio_resid -= done;
229
230
231
                              * Now, check for an error.
232
                              * Also, handle weird end-of-disk semantics.
233
                              */
```

```
if (error || done < todo)
234
235
                                    goto done;
236
                    }
            }
237
238
239 done:
240
            /*
             * [clean up the state of the buffer]
241
242
             * Remember if somebody wants it, so we can wake them up below.
             * Also, if we had to steal it, give it back.
243
244
             */
245
            s = splbio();
            bp->b_flags &= ~(B_BUSY | B_PHYS | B_RAW);
246
247
            if (nobuf)
248
                    putphysbuf(bp);
249
            else {
250
                     * [if another process is waiting for the raw I/O buffer,
251
252
                          wake up processes waiting to do physical I/O;
253
254
                    if (bp->b_flags & B_WANTED) {
255
                            bp->b_flags &= ~B_WANTED;
256
                            wakeup(bp);
257
                    }
258
259
            splx(s);
260
261
            return (error);
262 }
263
264 /*
265 * allocate a buffer structure for use in physical I/O.
266 */
267 struct buf *
268 getphysbuf()
269 {
270
            struct buf *bp;
271
            int s;
272
            s = splbio();
273
            bp = pool_get(&bufpool, PR_WAITOK);
274
            splx(s);
275
276
            memset(bp, 0, sizeof(*bp));
277
            return(bp);
278 }
279
280 /*
281 * get rid of a swap buffer structure which has been used in physical I/O.
282 */
283 void
284 putphysbuf(bp)
285
           struct buf *bp;
286 {
287
            int s;
```

```
288
            if (__predict_false(bp->b_flags & B_WANTED))
289
290
                    panic("putphysbuf: private buf B_WANTED");
291
            s = splbio();
292
            pool_put(&bufpool, bp);
293
            splx(s);
294 }
295
296 /*
297 * Leffler, et al., says on p. 231:
298 * "The minphys() routine is called by physio() to adjust the
299 * size of each I/O transfer before the latter is passed to
300 * the strategy routine..."
301
302 * so, just adjust the buffer's count accounting to MAXPHYS here,
303 * and return the new count;
304 */
305 void
306 minphys(bp)
307
            struct buf *bp;
308 {
309
            if (bp->b_bcount > MAXPHYS)
310
311
                    bp->b_bcount = MAXPHYS;
312 }
                                                  kern/kern_physio.c
```

2.3.2 Entry Points for Character-Device Drivers

open clode ioctl

mmap Map a device offset into a memory address. This entry point is called by the virtual-memory system to convert a logical mapping to a physical address.

read
reset
select
stop
write

2.4 Descriptor Management

2.4.1 File Descriptor, Descriptor Table, and File Entry

For user process, all I/O is done through *file descriptors*. System calls that refer to open files take a file descriptor as an argument to specify the file. The file descriptor is used by the kernel to index into the *descriptor table* for the current process to locate a *file entry*.

2.4.2 What does the File Entry Points?

File entry can point to *vnode* structure or *socket*.

vnode The *file entry* provides a file type and a pointer to an underlying object for the descriptor. For data files, the file entry points to a vnode structure.

Special files do not have data blocks allocated on the disk; they are handled by the special-device filesystem that calls appropriate drivers to haldle I/O for them.

The virtual-memory system supports the mapping of files into a process's address space. Here, the file descriptor must reference a vnode that will be partially or completely mapped into the user's address space.

socket The file entry may also reference a socket. The Sockets have a different file type, and the file entry points to a system block that is used in doing interprocess communication.

2.4.3 Movement of Data Inside the Kernel: uiomove function

Within the kernel, I/O data are described by an array of vectors. Each I/O vector or iovec has a base address and a length. The kernel maintains another structure, called a uio structure. All I/O within the kernel is described with iovec and uio structures. Movement of data is processed as following steps.

- 1. System calls such as read and write that are not passed an iovec create a uio to describe their arguemnts.
- 2. The uio structure reaches the part of the kernel responsible for moving the data to or from the process address space: the filesystem, the network, or a device driver.
- 3. In general, these parts of the kernel arrange a kernel buffer to hold the data, then use uiomove function to copy the data to or from the buffer or buffers describved by the uio structure.
- 4. uiomove function is called with a pointer to kernel data area, a data count, and a uio structure. As it moves data, it updates the counters and pointers of the iovec and uio structures by a corresponding amount.
- 5. If the kernel buffer is not as large as the area described by the uio structure, the uio structure will point to the part of the process address space just beyond the location completed most recently. Thus, while servicing a request, the kernel may call uiomove function multiple times, each time giving a pointer to a new kernel buffer for the next block of data.

The source for the definition of iovec, uio structure is

```
sys/uio.h

54 struct iovec {
55    void *iov_base; /* Base address. */
56    size_t iov_len; /* Length. */
57 };
58

59 #if !defined(_POSIX_C_SOURCE) && !defined(_XOPEN_SOURCE)
```

- kern/kern_subr.c

```
60 #include <sys/ansi.h>
62 #ifndef off_t
63 typedef __off_t
                    off_t; /* file offset */
64 #define off_t
                      __off_t
65 #endif
66
67 enum uio_rw { UIO_READ, UIO_WRITE };
69 /* Segment flag values. */
70 enum uio_seg {
      UIO_USERSPACE,
                         /* from user data space */
71
                         /* from system space */
72
      UIO_SYSSPACE
73 };
74
75 struct uio {
      struct iovec *uio_iov; /* pointer to array of iovecs */
      int uio_iovcnt; /* number of iovecs in array */
77
      off_t uio_offset; /* offset into file this uio corresponds to */
78
      size_t uio_resid; /* residual i/o count */
79
      enum uio_seg uio_segflg; /* see above */
      enum uio_rw uio_rw; /* see above */
81
      struct proc *uio_procp;/* process if UIO_USERSPACE */
82
83 };
                                                      - sys/uio.h
```

The source for uiomove function is

140 int 141 uiomove(buf, n, uio) 142 void *buf; 143 size_t n; 144 struct uio *uio; 145 { 146 struct iovec *iov; 147 u_int cnt; int error = 0; 148 149 char *cp = buf; struct proc *p = uio->uio_procp; 150 151 152 #ifdef DIAGNOSTIC 153 if (uio->uio_rw != UIO_READ && uio->uio_rw != UIO_WRITE) 154 panic("uiomove: mode"); 155 #endif 156 while (n > 0 && uio->uio_resid) { 157 iov = uio->uio_iov; 158 cnt = iov->iov_len; 159 if (cnt == 0) { uio->uio_iov++; 160 161 uio->uio_iovcnt--; 162 continue; 163 }

```
if (cnt > n)
164
165
                cnt = n;
166
            switch (uio->uio_segflg) {
167
168
            case UIO_USERSPACE:
169
                if (curproc->p_cpu->ci_schedstate.spc_flags &
170
                    SPCF_SHOULDYIELD)
171
                    preempt(NULL);
172
                if (__predict_true(p == curproc)) {
                    if (uio->uio_rw == UIO_READ)
173
174
                         error = copyout(cp, iov->iov_base, cnt);
175
                    else
176
                        error = copyin(iov->iov_base, cp, cnt);
177
                } else {
178
                    if (uio->uio_rw == UIO_READ)
179
                         error = copyout_proc(p, cp,
180
                             iov->iov_base, cnt);
181
                    else
182
                         error = copyin_proc(p, iov->iov_base,
183
                             cp, cnt);
184
185
                if (error)
186
                    return (error);
187
                break;
188
189
            case UIO_SYSSPACE:
190
                if (uio->uio_rw == UIO_READ)
191
                    error = kcopy(cp, iov->iov_base, cnt);
192
                else
193
                    error = kcopy(iov->iov_base, cp, cnt);
194
                if (error)
195
                    return (error);
196
                break;
197
            }
198
            iov->iov_base = (caddr_t)iov->iov_base + cnt;
199
            iov->iov_len -= cnt;
200
            uio->uio_resid -= cnt;
201
            uio->uio_offset += cnt;
202
            cp += cnt;
203
            KDASSERT(cnt <= n);</pre>
204
            n -= cnt:
205
        }
206
        return (error);
207 }
                                                   - kern/kern_subr.c
```

where

```
int
copyin(const void *uaddr, void *kaddr, size_t len);
```

Copies len bytes of data from the user-space address uaddr to the kernel-space address kaddr. $\,$

```
int
copyout(const void *kaddr, void *uaddr, size_t len);
```

Copies len bytes of data from the kernel-space address kaddr to the user-space address uaddr.

Character device drivers that do not copy data from the process generally do not interpret the uio structure. Instead, there is one low-level kernel routine that arranges a direct transfer to or from the address space of the process. Here, a separate I/O operation is done for each iovec element.

Block device drivers does not use $\verb"uio"$ structures. User operations on block devies are done through the buffer cache.

Chapter 3

Virtual File System

The virtual filesystem, VFS, is the kernel interface to filesystems. The interface specifies the calls for the kernel to access filesystems. It also specifies the core functionality that a filesystem must provide to the kernel. The focus of VFS activity is the vnode and is discussed in the other chapter.

3.1 Architecture of Virtual File System

3.1.1 Why VFS is needed?

In earlier BSD, the file entries directly referenced the local filesystem *inode*. An inode is a data structure that describes the contents of a file. However, with the advent of multiple filesystem types, the architecture had to be generalized. Thus, it was easier and more logical to add a new layer to the system below the file entry and above the inode. This new layer was first implemented by Sun Microsystems, which called it the virtual-node, or *vnode*, later. A vnode used by a local filesystem would refer to an inode. A vnode used by a remote filesystem would refer to a protocol control block that described the location and naming information necessary to access the remote file.

3.1.2 What Is in the Vnode?

The vnode is an extensible object-oriented interface. It contains information that is generically useful independent of the underlying filesystem object that it represents. vnode structure is defined as,

```
sys/vnode.h
86 struct vnode {
       struct uvm_object v_uobj;
                                             /* the VM object
                                                                             */
88 #define v_usecount
                           v_uobj.uo_refs
89 #define v_interlock
                           v_uobj.vmobjlock
90
       voff_t
                           v_size;
                                             /* size of file
91
       int
                           v_flag;
                                             /* flags
                                                                             */
                                             /* number of pending writes
92
                                                                             */
       int
                           v_numoutput;
93
                                             /* reference count of writers */
       long
                           v_writecount;
94
       long
                           v_holdcnt;
                                             /* page & buffer references
                                                                             */
95
       u_long
                           v_id;
                                             /* capability identifier
                                                                             */
96
       struct mount
                          *v_mount;
                                             /* ptr to vfs we are in
                                                                             */
                (**v_op) __P((void *));
                                             /* vnode operations vector
97
       int
                                                                             */
```

sys/vnode.h

```
98
        TAILQ_ENTRY(vnode) v_freelist;
                                              /* vnode freelist
                                                                             */
99
        LIST_ENTRY(vnode) v_mntvnodes;
                                              /* vnodes for mount point
                                                                             */
100
                            v_cleanblkhd;
                                             /* clean blocklist head
                                                                             */
        struct buflists
101
        struct buflists
                            v_dirtyblkhd;
                                              /* dirty blocklist head
                                                                             */
102
        LIST_ENTRY(vnode) v_synclist;
                                              /* vnodes with dirty buffers
                                                                             */
103
        union {
104
          struct mount
                           *vu_mountedhere; /* ptr to mounted vfs (VDIR)
                                                                             */
                           *vu_socket;
                                             /* unix ipc (VSOCK)
105
          struct socket
                                                                             */
          struct specinfo *vu_specinfo;
                                             /* device (VCHR, VBLK)
106
                                                                             */
                                             /* fifo (VFIFO)
107
          struct fifoinfo *vu_fifoinfo;
                                                                             */
108
        }
                            v_un;
                                             /* Soft reference to lease
109
        struct nqlease
                           *v_lease;
                                                                             */
                                              /* vnode type
110
        enum vtype
                            v_type;
                                                                             */
111
        enum vtagtype
                                              /* type of underlying data
                            v_tag;
                                                                             */
112
        struct lock
                            v_lock;
                                              /* lock for this vnode
                                                                             */
113
        struct lock
                           *v_vnlock;
                                              /* pointer to lock
                                                                             */
                                              /* private data for fs
                                                                             */
114
        void
                           *v_data;
                            v_klist;
                                             /* knotes attached to vnode
115
        struct klist
                                                                             */
116 #ifdef VERIFIED_EXEC
117
        char
                            fp_status;
                                              /* fingerprint status
118
                                                 (see below)
                                                                             */
119 #endif
120 };
121 #define v_mountedhere v_un.vu_mountedhere
122 #define v_socket
                            v_un.vu_socket
123 #define v_specinfo
                            v_un.vu_specinfo
124 #define v_fifoinfo
                            v_un.vu_fifoinfo
```

The information stored in a vnode includes the following:

v_usecount is the number of file entries that are open for reading and/or writing that reference the vnode.

v_numoutput is the number of buffer write operations in progress. To speed the flushing of dirty data, the kernel does this operation by doing asynchronous writes on all the dirty buffers at once. For local filesystem, this simultaneous push causes all the buffers to be put into the disk queue, so that they can be sorted into an optimal order to minimize seeking. System calls that return until the data are on stable store, such as **fsync** system call, can sleep on the count of pending output operations, waiting for the count to reach zero.

v_writecount is the number of file entries that are open for writing that reference the vnode.

v_holdcnt is the number of pages and buffers that are associated with the vnode.

v_mount describes the filesystem that contains the object represented by the vnode.

v_op is a pointer to the set of vnode operations defined for the object.

v_freelist is a list linking together all the vnodes in the system that are not being used actively. The free list is used when a filesystem needs to allocate a new vnode.

- v_mntvnodes is a list linking together all the vnodes associated with a specific mount point. Thus, when sync system call is executed for a filesystem, the kernel can traverse this list to visit all the files active within that filesystem.
- v_cleanblkhd is the header of vnode clean-buffer list. This list stores all the buffers, about the vnode, that have not been modified, or have been written back since they were last modified.

This list is used to free buffers when a file is deleted. Since the file is never be read again, the kernel can immediately calcel any pending I/O on its dirty buffers, and reclaim all its clean and dirty buffers and place them at the head of the buffer free list, ready for immediate reuse.

- v_dirtyblkhd is the header of vnode dirty-buffer list. This list stores all the buffers, about the vnode, that have been modified, but not yet been written back.
- v_un is a reference to state about special devices, sockets, and FIFOs.
- v_lease is used with NFS. So you need not regard it if you are only interested in local filesystem code.
- v_type is the type of the underlying object such as regular file, directory, character device, and etc. This type information is not strictly necessary, since a vnode client could always call a vnode operation to get the type of the underlying object. However, because the type often is needed, the type of underlying objects does not change, and it takes time to call through the vnode interface, the object type is cached in the vnode.

This field has a value among VNON, VREG, VDIR, VBLK, VCHR, VLNK, VSOCK, VFIFO, VBAD.

- v_lock is used for locking the vnode.
- **v_data** is a pointer to private information needed for the underlying object. For the local filesystem, this pointer will reference an inode.

3.1.3 How to Call Vnode Operations?

Kernel manipulates vnode by passing requests to the underlying object through a set of defined operations.

As part of the booting process, each filesystem registers the set of vnode operations that is able to support. The kernel then builds a table that lists the union of all operations supported by any filesystem.

Supported operations are filled in with the entry point registered by the filesystem. Filesystems amy opt to have unsupported operations filled in with either a default routine, or a routine that returns the characteristic error.

When a filesystem is mounted on a directory, the previous contents of the directory are hidden; only the contents of the root of the newly mounted filesystem are visible. The mount command pushes a new layer onto a vnode stack; an unmount command removes a layer.

When a file access such as open, read, stat, or close occurs to a vnode in the stack, that vnode has several options as

- Do the requested operation and resutn a result
- Pass the operation without change to the next-lower vnode on the satck.

• Modify the operations provided with the request, then pass it to the next-lower vnode. When the operation returns from the lower vnode, it may modify the results, or simply return them.

If an operation is passed to the bottom of the stack without any layer taking action on it, then the interface will return the error "operation not supported."

To make pass-operation efficient, the kernel places the vnode operation name and its arguments into an argument structure. This structure is then passed as a single parameter to the vnode operation. Thus all call on a vnode operation will always have exactly one parameter, which is the pointer to the argument structure.

Let's see how this design policy is implemented in NetBSD. When user level write system call is executed, kernel executes vn_write function of kern/vfs_syscalls.c as we have read in the previous chapter. The code of vn_write function is again listed here for easy reference.

```
kern/vfs_init.c
526 /*
527
    * File table vnode write routine.
528 */
529 static int
530 vn_write(fp, offset, uio, cred, flags)
            struct file *fp;
531
            off_t *offset;
532
533
            struct uio *uio;
534
            struct ucred *cred;
535
            int flags;
536 {
537
            struct vnode *vp = (struct vnode *)fp->f_data;
            int count, error, ioflag = IO_UNIT;
538
539
540
            if (vp->v_type == VREG && (fp->f_flag & O_APPEND))
541
                     ioflag |= IO_APPEND;
            if (fp->f_flag & FNONBLOCK)
542
                     ioflag |= IO_NDELAY;
543
            if (fp->f_flag & FFSYNC ||
544
545
                 (vp->v_mount && (vp->v_mount->mnt_flag & MNT_SYNCHRONOUS)))
546
                     ioflag |= IO_SYNC;
            else if (fp->f_flag & FDSYNC)
547
                     ioflag |= IO_DSYNC;
548
549
            if (fp->f_flag & FALTIO)
550
                     ioflag |= IO_ALTSEMANTICS;
551
            VOP_LEASE(vp, uio->uio_procp, cred, LEASE_WRITE);
552
            vn_lock(vp, LK_EXCLUSIVE | LK_RETRY);
            uio->uio_offset = *offset;
553
554
            count = uio->uio_resid;
555
            error = VOP_WRITE(vp, uio, ioflag, cred);
556
            if (flags & FOF_UPDATE_OFFSET) {
557
                     if (ioflag & IO_APPEND)
                             *offset = uio->uio_offset;
558
559
                     else
560
                             *offset += count - uio->uio_resid;
561
562
            VOP_UNLOCK(vp, 0);
            return (error);
563
```

```
564 } ______ kern/vfs_init.c
```

The second virtual file system operation in this function is VOP_WRITE.

VOP_WRITE(vp, uio, ioflag, cred) write to a file. The argument vp is the vnode of the file to write to, uio is the location of the data to write, ioflag is a set of flags and cred are the credentials of the calling process.

The ioflag argument is used to give directives and hints to the file system. The low 16 bits are a bit mask which can contain the same flags as VOP_READ().

Zero is returned on success, otherwise an error is returned. The vnode should be locked on entry and remains locked on exit.

This function is defined in kern/vnode_if.c ans kern/vnode_if.h twice! In one way, it is defined as an inline function, equivalent to macro. And the other way, it is defined as a general function. Loadable Kernel Module (LKM) used general function, and normal kernel uses a fast inline function. The code list shown below is inline function version.

```
- sys/vnode_if.h
    374 static __inline int VOP_WRITE(vp, uio, ioflag, cred)
    375
                struct vnode *vp;
    376
                struct uio *uio;
    377
                int ioflag;
    378
                struct ucred *cred;
    379 {
    380
                struct vop_write_args a;
    381
                a.a_desc = VDESC(vop_write);
                a.a_vp = vp;
    382
    383
                a.a_uio = uio;
    384
                a.a_ioflag = ioflag;
    385
                a.a_cred = cred;
    386
                return (VCALL(vp, VOFFSET(vop_write), &a));
    387 }
                                                            sys/vnode_if.h
VCALL and VOFFSET macros are defined as,
    469 /*
```

```
469 /*

470 * VOCALL calls an op given an ops vector. We break it out because BSD's

471 * vclean changes the ops vector and then wants to call ops with the old

472 * vector.

473 */

474 /*

475 * actually, vclean doesn't use it anymore, but nfs does,

476 * for device specials and fifos.

477 */

478 #define VOCALL(OPSV,OFF,AP) ((*(OPSV)[(OFF)])) (AP))

479
```

```
480 /*
   481 * This call works for vnodes in the kernel.
   483 #define VCALL(VP,OFF,AP) VOCALL((VP)->v_op,(OFF),(AP))
   484 #define VDESC(OP) (& __CONCAT(OP,_desc))
   485 #define VOFFSET(OP) (VDESC(OP)->vdesc_offset)
                                                       sys/cdefs.h
VOFFSET macro used in line 1476 of sys/vnode_if.h is expanded as,
             VOFFSET(vop_write)
           (VDESC(vop_write)->vdesc_offset)
       -->
           ((& __CONCAT(vop_write))->vdesc_offset,_desc)
             (vop_write_desc->vdesc_offset)
Therefore VCALL macro used in line 1476 is expanded as,
             VCALL(vp, VOFFSET(vop_write), &a))
       --> VCALL(vp, vop_write_desc->vdesc_offset, &a)
       --> VOCALL((vp)->v_op,(vop_write_desc->vdesc_offset),(&a))
            (( *(((vp)->v_op)[((vop_write_desc->vdesc_offset))])) (&a))
Thus line 1476 is equivalent to
  1476
           return (VCALL(vp, VOFFSET(vop_write), &a));
          return ( *( (vp->v_op) [vop_write_desc->vdesc_offset] ) ) (&a);
  <===>
                 1 1
                  +----+
  vop_write_desc is defined in kern/vnode_if.c as,
                                         ------kern/vnode_if.h
   109 const struct vnodeop_desc vop_bwrite_desc = {
          2,
   110
              "vop_bwrite",
   111
   112
              vop_bwrite_vp_offsets,
   113
   114
              VDESC_NO_OFFSET,
             VDESC_NO_OFFSET,
   115
             VDESC_NO_OFFSET,
   116
             VDESC_NO_OFFSET,
   117
   118
              NULL,
   119 };
                                         -----kern/vnode_if.h
where the struct vnodeop_desc is defined in sys/vnode.h as,
                                                     - \text{sys/vnode.h}
```

```
389 /*
  390 * This structure describes the vnode operation taking place.
 391 */
 392 struct vnodeop_desc {
 393
             int
                              vdesc_offset;
                                             /* offset in vector--first for speed */
  394
             const char
                              *vdesc_name;
                                             /* a readable name for debugging */
                                              /* VDESC_* flags */
 395
             int
                              vdesc_flags;
 396
 397
 398
               * These ops are used by bypass routines to map and locate arguments.
 399
               * Creds and procs are not needed in bypass routines, but sometimes
               * they are useful to (for example) transport layers.
  400
  401
               * Nameidata is useful because it has a cred in it.
 402
              */
                                                      /* list ended by VDESC_NO_OFFSET */
 403
             const int
                              *vdesc_vp_offsets;
 404
             int
                              vdesc_vpp_offset;
                                                      /* return vpp location */
 405
                              vdesc_cred_offset;
                                                      /* cred location, if any */
             int
 406
                              vdesc_proc_offset;
                                                      /* proc location, if any */
             int
 407
                              vdesc_componentname_offset; /* if any */
             int
  408
              * Finally, we've got a list of private data (about each operation)
 409
               * for each transport layer. (Support to manage this list is not
 410
 411
               * yet part of BSD.)
 412
               */
 413
             caddr_t
                              *vdesc_transports;
 414 };
                                                         sys/vnode.h
Therefore line 1476 is equivalent to
         return ( *( (vp->v_op) [vop_lease_desc->vdesc_offset] ) ) (&a);
<====>
         return ( *( (vp->v_op) [2] ) ) (&a);
<====>
<===>
         return ffs_write (&a);
```

In the next section, we will explain how the vp->v_op pointer is initialized.

3.2 Virtual Filesystem Initialization

Virtual filesystem initialization is initiated in main function of kern/init_main.c which is practically the first function executed after machine bootstrap. At there, vfsinit function of kern/vfs_init.c is called.

That function calls vfsinit function of kern/vfs_init.c

```
329
            /*
330
             * Initialize the namei pathname buffer pool and cache.
331
            pool_init(&pnbuf_pool, MAXPATHLEN, 0, 0, 0, "pnbufpl",
332
333
                  &pool_allocator_nointr);
334
            pool_cache_init(&pnbuf_cache, &pnbuf_pool, NULL, NULL, NULL);
335
336
337
             * Initialize the vnode table
338
             */
            vntblinit();
339
340
341
342
             * Initialize the vnode name cache
343
             */
344
            nchinit();
345
346 #ifdef DEBUG
347
            /*
             * Check the list of vnode operations.
348
349
350
            vfs_op_check();
351 #endif
352
353
             * Initialize the special vnode operations.
354
355
356
            vfs_opv_init(vfs_special_vnodeopv_descs);
357
            /*
358
359
             * Establish each file system which was statically
360
             * included in the kernel.
             */
361
362
            vattr_null(&va_null);
            for (i = 0; vfs_list_initial[i] != NULL; i++) {
363
364
                     if (vfs_attach(vfs_list_initial[i])) {
                             printf("multiple '%s' file systems",
365
                                 vfs_list_initial[i]->vfs_name);
366
                             panic("vfsinit");
367
368
                     }
            }
369
370 }
                                                       kern/vfs_init.c
```

Now, we describes each portion of vfsinit function with related source codes.

3.2.1 Initializing the namei pathname buffer pool

At line 332, vfsinit function initializes the name pathname buffer pool. MAXPATHLEN specifies the size of the memory items managed by the pool and is defined to 1024 at sys/param.h and sys/syslimits.h. The next three zero parameter means there is no alignment constraint in initializing pool and logging facility is not used. When the top program executes, we will see "pnbufpl" in the state field when kernel is waiting for allocation of item for pool.

At line 334, vfsinit function initializes the pool cache for namei pathname buffer pool. This cache, however, is not used anywhere; It is only executed here, but it may be useful for future release of NetBSD operating system.

3.2.2 Initializing the vnode table

Vnode table is initialized by calling vntblinit function, at line 339 of vfs_subr.c.

```
kern/vfs_subr.c
190 void
191 vntblinit()
192 {
193
            pool_init(&vnode_pool, sizeof(struct vnode), 0, 0, 0, "vnodepl",
194
195
                 &pool_allocator_nointr);
196
197
              * Initialize the filesystem syncer.
198
199
             */
200
            vn_initialize_syncerd();
201 }
                                                       - kern/vfs_subr.c
```

Just the same way as namei buffer cache pool is initialized, at **line 194** of vfs_subr.c, pool for vnode management data structures is initialized.

At line 200, vn_initialize_syncerd function calls filesystem syncer that flushes cached data to disk at regular intervals.

Surpringly, filesystem syncer daemon uses a special kind of virtual filesystem called as <code>syncfs</code> filesystem! Syncfs virtual filesystem is implemented in <code>miscfs/syncfs</code> directory. When a filesystem is mounted, syncfs is installed, as a virtual filesystem layer, on top of the filesystem by creating a new filesystem syncer vnode for the specified mount point by calling <code>vfs_allocate_syncvnode</code> function of <code>miscfs/syncfs/sync_vnops.c.</code>

Source code of ${\tt vn_initialize_syncerd}$ function is

70 void 71 vn_initialize_syncerd() 72 { 73 int i; 74 75 syncer_last = SYNCER_MAXDELAY + 2; 76 77 syncer_workitem_pending = malloc(syncer_last * sizeof (struct synclist), 78 M_VNODE, M_WAITOK); 79 80 for (i = 0; i < syncer_last; i++)</pre> 81 LIST_INIT(&syncer_workitem_pending[i]); 82 83 lockinit(&syncer_lock, PVFS, "synclk", 0, 0); 84 }

miscfs/syncfs_subr.c

miscfs/syncfs_subr.c

line 75 SYNCER_MAXDELAY is maximum delay interval between syncer daemon works and it is defined to 32 seconds by default.

3.2.3 Initializing the Name Cache Buffer

```
- kern/vfs_cache.c
401 void
402 nchinit(void)
403 {
404
405
        TAILQ_INIT(&nclruhead);
406
        nchashtbl =
407
            hashinit(desiredvnodes, HASH_LIST, M_CACHE, M_WAITOK, &nchash);
408
        ncvhashtbl =
409 #ifdef NAMECACHE_ENTER_REVERSE
410
            hashinit(desiredvnodes, HASH_LIST, M_CACHE, M_WAITOK, &ncvhash);
411 #else
            hashinit(desiredvnodes/8, HASH_LIST, M_CACHE, M_WAITOK, &ncvhash);
412
413 #endif
        pool_init(&namecache_pool, sizeof(struct namecache), 0, 0, 0,
414
415
                  "ncachepl", &pool_allocator_nointr);
416 }
                                                    kern/vfs_cache.c
```

3.2.4 Initialize the Special Vnode Operations

This initialization process is started by **line 356** of kern/vfs_init.c that we have already listed. We list here again for easy reference.

```
kern/vfs_init.c

vfs_opv_init(vfs_special_vnodeopv_descs);

kern/vfs_init.c
```

The vfs_special_vnodeopv_descs argument used in line 356 of kern/vfs_init.c is defined in kern/vfs_init.c as

sys/vnode.h

```
449 struct vnodeopv_desc {
                              /* ptr to the ptr to the vector where op should go */
   450
   451
               int (***opv_desc_vector_p)(void *);
   452
               const struct vnodeopv_entry_desc *opv_desc_ops; /* null terminated list */
   453 };
                                                       - sys/vnode.h
  For example, the one of the four members contained in vfs_special_vnodeopv_descs
array, sync_vnodeop_opv_desc is defined in miscfs/syncfs/sync_vnops.c as
                                        — miscfs/syncfs/sync_vnops.c
    47 int (**sync_vnodeop_p) __P((void *));
    48 const struct vnodeopv_entry_desc sync_vnodeop_entries[] = {
               { &vop_default_desc, vn_default_error },
    49
    50
               { &vop_close_desc, sync_close },
                                                            /* close */
    51
              { &vop_fsync_desc, sync_fsync },
                                                            /* fsync */
    52
              { &vop_inactive_desc, sync_inactive },
                                                           /* inactive */
              { &vop_reclaim_desc, sync_reclaim },
                                                            /* reclaim */
    53
              { &vop_lock_desc, sync_lock },
                                                            /* lock */
    54
                                                            /* unlock */
              { &vop_unlock_desc, sync_unlock },
    55
              { &vop_print_desc, sync_print },
    56
                                                            /* print */
    57
              { &vop_islocked_desc, sync_islocked },
                                                            /* islocked */
              { &vop_putpages_desc, sync_putpages },
    58
                                                            /* islocked */
              { NULL, NULL }
    59
    60 };
    61
    62 const struct vnodeopv_desc sync_vnodeop_opv_desc =
               { &sync_vnodeop_p, sync_vnodeop_entries };
                                          miscfs/syncfs/sync_vnops.c
where struct vnodeopv_entry_desc is defined in sys/vnode.h as,
                                                   ----- sys/vnode.h
   445 struct vnodeopv_entry_desc {
             const struct vnodeop_desc *opve_op;
                                                   /* which operation this is */
   446
               447
   448 };
                                                       - sys/vnode.h
where struct vnodeop_desc is defined in sys/vnode.h and we showed this code
in the previous section.
  To prevent your confusion, we summarized the relation between vnodeopv_desc,
vnodeopv_entry_desc, vnodeop_desc structures.
    // Vnode Operation Vector Description Table (vfs_init.c)
    //
    const struct vnodeopv_desc vfs_special_vnodeopv_descs[] = {
            &sync_vnodeop_opv_desc,
```

```
};
// Vnode Operation Vector Description (miscfs/syncfs/sync_vnops.c)
int (**sync_vnodeop_p) __P((void *));
const struct vnodeopv_desc sync_vnodeop_opv_desc = {
      &sync_vnodeop_p, sync_vnodeop_entries
};
// Vnode Operation Vector Entry Description Table (misc/syncfs/sync_vnops.c)
//
const struct vnodeopv_entry_desc sync_vnodeop_entries[] = {
      { &vop_fsync_desc, sync_fsync },
                                          /* fsync */
      { NULL, NULL }
};
// Vnode Operation Vector Entry Description (kern/vnode_if.c)
const int vop_fsync_vp_offsets[] = {
      VOPARG_OFFSETOF(struct vop_fsync_args,a_vp),
      VDESC_NO_OFFSET
};
const struct vnodeop_desc vop_fsync_desc = {
      19,
      "vop_fsync",
      0,
      vop_fsync_vp_offsets,
      VDESC_NO_OFFSET,
      VOPARG_OFFSETOF(struct vop_fsync_args, a_cred),
      VOPARG_OFFSETOF(struct vop_fsync_args, a_p),
      VDESC_NO_OFFSET,
      NULL,
};
// Vnode Operation (misc/syncfs/sync_vnops.c)
//
int
sync_fsync(v)
      void *v;
{
      . . .
}
```

Before going on reading this book, you should clearly understand the relation between vnode operation vector description table, vnode operation vector entry description, vnode operation vector entry description, and vnode operation, from the above summary. Only when if you know the

relation without confusion, you can clearly understand how vfs_opv_init function work.

vfs_opv_init function is defined in kern/vfs_init.c as,

```
kern/vfs_init.c
240 void
241 vfs_opv_init(vopvdpp)
242
        const struct vnodeopv_desc * const *vopvdpp;
243 {
244
        int (**opv_desc_vector) __P((void *));
245
        int i;
246
247
        /*
         * Allocate the vectors.
248
249
         */
        for (i = 0; vopvdpp[i] != NULL; i++) {
250
251
                /* XXX - shouldn't be M_VNODE */
252
                opv_desc_vector =
253
                   malloc(VNODE_OPS_COUNT * sizeof(PFI), M_VNODE, M_WAITOK);
254
                memset(opv_desc_vector, 0, VNODE_OPS_COUNT * sizeof(PFI));
255
                *(vopvdpp[i]->opv_desc_vector_p) = opv_desc_vector;
                DODEBUG(printf("vector at %p allocated\n",
256
257
                    opv_desc_vector_p));
        }
258
259
260
         * ...and fill them in.
261
262
        for (i = 0; vopvdpp[i] != NULL; i++)
263
264
                vfs_opv_init_explicit(vopvdpp[i]);
265
266
267
         * Finally, go back and replace unfilled routines
268
         * with their default.
269
         */
270
        for (i = 0; vopvdpp[i] != NULL; i++)
                vfs_opv_init_default(vopvdpp[i]);
271
272 }
                                                      - kern/vfs_init.c
```

for loop used in line 250-258 executes 4 times with vopvdpp variable set respectively to dead_vnodeop_opv_desc, fifo_vnodeop_opv_desc, spec_vnodeop_opv_desc, and sync_vnodeop_opv_desc. line 252-255 makes room for storing array of function pointer indicating each available vnode operation function.

VNODE_OPS_COUNT and PFI are defined as,

```
kern/vfs_init.c

1640 #define VNODE_OPS_COUNT 50

kern/vfs_init.c
```

and

```
kern/vfs_init.c

127 /*

128 * This code doesn't work if the defn is **vnodop_defns with cc.

129 * The problem is because of the compiler sometimes putting in an

130 * extra level of indirection for arrays. It's an interesting

131 * "feature" of C.

132 */

133 typedef int (*PFI) __P((void *));

kern/vfs_init.c
```

After completion of this loop, for example, the value of sync_vnodeop_p used in line 63 of miscfs/syncfs/sync_vnops.c changes from NULL to a allocated memory by line 252-253 of kern/vfs_init.c

Now, we will analyze vfs_init_explicit and vfs_init_default functions which fill the allocated array with function pointers pointing to vnode operation functions. The code for this function is,

}

209

```
kern/vfs_init.c
176 vfs_opv_init_explicit(vfs_opv_desc)
177
            const struct vnodeopv_desc *vfs_opv_desc;
178 {
            int (**opv_desc_vector) __P((void *));
179
180
            const struct vnodeopv_entry_desc *opve_descp;
181
            opv_desc_vector = *(vfs_opv_desc->opv_desc_vector_p);
182
183
184
            for (opve_descp = vfs_opv_desc->opv_desc_ops;
185
                 opve_descp->opve_op;
186
                 opve_descp++) {
187
                    /*
188
                     * Sanity check: is this operation listed
                     * in the list of operations? We check this
189
                     * by seeing if its offest is zero. Since
190
191
                     * the default routine should always be listed
192
                     * first, it should be the only one with a zero
                     * offset. Any other operation with a zero
193
194
                     * offset is probably not listed in
195
                     * vfs_op_descs, and so is probably an error.
196
197
                     * A panic here means the layer programmer
198
                     * has committed the all-too common bug
199
                     * of adding a new operation to the layer's
200
                     * list of vnode operations but
201
                     * not adding the operation to the system-wide
202
                     * list of supported operations.
203
                     */
                    if (opve_descp->opve_op->vdesc_offset == 0 &&
204
                        opve_descp->opve_op->vdesc_offset != VOFFSET(vop_default)) {
205
206
                            printf("operation %s not listed in %s.\n",
207
                                 opve_descp->opve_op->vdesc_name, "vfs_op_descs");
208
                            panic ("vfs_opv_init: bad operation");
```

```
210
211
212
                      * Fill in this entry.
213
214
                     opv_desc_vector[opve_descp->opve_op->vdesc_offset] =
215
                         opve_descp->opve_impl;
216
            }
217 }
218
219 static void
220 vfs_opv_init_default(vfs_opv_desc)
221
            const struct vnodeopv_desc *vfs_opv_desc;
222 {
            int j;
223
            int (**opv_desc_vector) __P((void *));
224
225
226
            opv_desc_vector = *(vfs_opv_desc->opv_desc_vector_p);
227
228
            /*
229
             * Force every operations vector to have a default routine.
230
             */
            if (opv_desc_vector[VOFFSET(vop_default)] == NULL)
231
                     panic("vfs_opv_init: operation vector without default routine.");
232
233
            for (j = 0; j < VNODE_OPS_COUNT; j++)</pre>
234
235
                     if (opv_desc_vector[j] == NULL)
236
                             opv_desc_vector[j] =
237
                                  opv_desc_vector[VOFFSET(vop_default)];
238 }
                                                       - kern/vfs_init.c
```

If you keep in mind the summary about structures related with vnode operation, only reading the source code would be sufficient to understand how vfs_opv_init_explicit and vfs_opv_init_default function initialize opv_desc_vector_p member in vnode operation vector description structure.

3.3 Attaching Available Static File System

line 362-369 of kern/vfs_init.c attaches available static filesystem.

3.3.1 Set vnode attribute to empty

line 362 of kern/vfs_init.c creates va_null global variable, defined in kern/vfs_init.c,
as a null vnode.

```
kern/vfs_init.c
318 struct vattr va_null;
kern/vfs_init.c
```

This variable is not directly used, but used with VATTR_NULL macro used to clear a vnode. This macro is defined in sys/vnode.h as,

```
kern/vfs_init.c

281 #define VATTR_NULL(vap) (*(vap) = va_null) /* initialize a vattr */

kern/vfs_init.c
```

Now we list the source code for vattr_null function which creates a null vnode. The reason why kernel source uses VATTR_NULL macro instead of directly calling vattr_null function, is simple since the later is faster.

```
- kern/vfs_subr.c
372 void
373 vattr_null(vap)
374
            struct vattr *vap;
375 {
376
            vap->va_type = VNON;
377
378
379
380
             * Assign individually so that it is safe even if size and
381
             * sign of each member are varied.
382
            vap->va_mode = VNOVAL;
383
384
            vap->va_nlink = VNOVAL;
            vap->va_uid = VNOVAL;
385
386
            vap->va_gid = VNOVAL;
387
            vap->va_fsid = VNOVAL;
388
            vap->va_fileid = VNOVAL;
389
            vap->va_size = VNOVAL;
390
            vap->va_blocksize = VNOVAL;
391
            vap->va_atime.tv_sec =
392
                vap->va_mtime.tv_sec =
393
                vap->va_ctime.tv_sec = VNOVAL;
394
            vap->va_atime.tv_nsec =
395
                vap->va_mtime.tv_nsec =
396
                vap->va_ctime.tv_nsec = VNOVAL;
397
            vap->va_gen = VNOVAL;
398
            vap->va_flags = VNOVAL;
399
            vap->va_rdev = VNOVAL;
400
            vap->va_bytes = VNOVAL;
401
            vap->va_vaflags = 0;
402 }
```

- kern/vfs_subr.c

3.3.2 How is vfs_list_initial initialized?

vfs_list_initial is array of pointer to virtual filesystem operation. The source code for initializing this variable is not included in the kernel source: the needed code is generated automatically when we compile kernel.

Berfore compiling kernel, we executes config program. For example, we generates new kenel as

```
# cd /usr/src/syssrc/sys/arch/sparc64/conf
# config MY_KERNEL
# cd ../compile/MY_KERNEL
# make depend; make
```

In the above sample session, config program generates Makefile, and many header files under ../compile/MY_KERNEL directory. There is, however, only four C source code is generated: devsw.c, ioconf.c, param.c, swapnetbsd.c, vers.c

From these automatically generated C source files by config program, ioconf.c contains the definition of vfs_list_initial variable.

For instance, if kernel configuration file contains,

```
152 ## File systems. You probably need at least one of FFS or NFS.
                                   # Berkeley Fast Filesystem
153 file-system
154 file-system
                   NFS
                                   # Sun NFS-compatible filesystem client
                                   # kernel data-structure filesystem
155 file-system
                   KERNFS
156 file-system
                   NULLFS
                                  # NULL layered filesystem
157 file-system
                   OVERLAY
                                  # overlay file system
158 file-system
                   MFS
                                  # memory-based filesystem
159 file-system
                   FDESC
                                 # user file descriptor filesystem
160 file-system
                   UMAPFS
                                 # uid/gid remapping filesystem
161 file-system
                   LFS
                                 # Log-based filesystem (still experimental)
                                 # portal filesystem (still experimental)
162 file-system
                   PORTAL
163 file-system
                   PROCFS
                                  # /proc
164 file-system
                   CD9660
                                  # ISO 9660 + Rock Ridge file system
165 file-system
                   UNION
                                  # union file system
                   MSDOSFS
                                  # MS-DOS FAT filesystem(s).
166 file-system
                                   -- arch/sparc64/conf/GENERIC32
```

then, ioconf.c would contain

- arch/sparc64/compile/MY_KERNEL/ioconf.c

```
1643 struct vfsops * const vfs_list_initial[] = {
1644
           &ffs_vfsops,
1645
             &nfs_vfsops,
1646
             &kernfs_vfsops,
             &nullfs_vfsops,
1647
1648
             &overlay_vfsops,
1649
             &mfs_vfsops,
1650
             &fdesc_vfsops,
             &umapfs_vfsops,
1651
1652
             &lfs_vfsops,
             &portal_vfsops,
1653
1654
             &procfs_vfsops,
1655
             &cd9660_vfsops,
1656
             &union_vfsops,
             &msdosfs_vfsops,
1657
1658
             NULL,
1659 };
```

where struct vfsops is defined in sys/mount.h as,

```
sys/mount.h
344 struct vfsops {
345
            const char *vfs_name;
346
            int
                    (*vfs_mount)
                                     __P((struct mount *mp, const char *path,
347
                                         void *data, struct nameidata *ndp,
                                         struct proc *p));
348
349
            int
                     (*vfs_start)
                                     __P((struct mount *mp, int flags,
350
                                         struct proc *p));
351
            int
                     (*vfs_unmount)
                                     __P((struct mount *mp, int mntflags,
352
                                         struct proc *p));
353
            int
                     (*vfs_root)
                                     __P((struct mount *mp, struct vnode **vpp));
354
            int
                     (*vfs_quotactl) __P((struct mount *mp, int cmds, uid_t uid,
355
                                         caddr_t arg, struct proc *p));
356
            int
                     (*vfs_statfs)
                                     __P((struct mount *mp, struct statfs *sbp,
357
                                         struct proc *p));
358
                    (*vfs_sync)
            int
                                     __P((struct mount *mp, int waitfor,
359
                                         struct ucred *cred, struct proc *p));
                    (*vfs_vget)
360
            int
                                     __P((struct mount *mp, ino_t ino,
                                         struct vnode **vpp));
361
362
                     (*vfs_fhtovp)
                                     __P((struct mount *mp, struct fid *fhp,
            int
363
                                         struct vnode **vpp));
                                     __P((struct vnode *vp, struct fid *fhp));
364
            int
                    (*vfs_vptofh)
365
                    (*vfs_init)
                                     __P((void));
            void
366
                    (*vfs_reinit)
            void
                                     __P((void));
367
            void
                    (*vfs_done)
                                     __P((void));
368
            int
                     (*vfs_sysctl)
                                     __P((int *, u_int, void *, size_t *, void *,
369
                                         size_t, struct proc *));
370
                     (*vfs_mountroot) __P((void));
            int
371
                     (*vfs_checkexp) __P((struct mount *mp, struct mbuf *nam,
            int
372
                                         int *extflagsp, struct ucred **credanonp));
373
            const struct vnodeopv_desc * const *vfs_opv_descs;
374
                    vfs_refcount;
            LIST_ENTRY(vfsops) vfs_list;
375
376 };
```

For example, ffs_vfsops variable appeared in line 1644 of arch/sparc64/compile/MY_KERNEL/ioconf.c is initialized in ufs/ffs_vfsops.c as

sys/mount.h

```
ufs/ffs/ffs_vfsops.c
97 struct vfsops ffs_vfsops = {
98
            MOUNT_FFS,
99
            ffs_mount,
100
            ufs_start,
101
            ffs_unmount,
102
            ufs_root,
            ufs_quotactl,
103
104
            ffs_statfs,
            ffs_sync,
105
```

```
106
             ffs_vget,
107
             ffs_fhtovp,
             ffs_vptofh,
108
109
             ffs_init,
110
             ffs_reinit,
111
             ffs_done,
             ffs_sysctl,
112
             ffs_mountroot,
113
114
             ufs_check_export,
115
             ffs_vnodeopv_descs,
116 };
                                                      ufs/ffs/ffs_vfsops.c
```

You may wonder how Makefile for kernel compile know where the filesystem related files are. Makefile in ufs directory specifies the location of filesystem related kernel sources recursively with the help of system-wide makefile script, /usr/share/mk/bsd.kinc.mk.

With this information, we can plant our own file system with a different name onto NetBSD kernel !

3.3.3 Establish a filesystem and initialize it

line 363-369 of vfs_init.c attaches and initializes all available virtual filesystem layers such as FFS, NFS and LFS, by calling vfs_attach function.

```
kern/vfs_subr.c
2634 int
2635 vfs_attach(vfs)
2636
             struct vfsops *vfs;
2637 {
2638
             struct vfsops *v;
2639
             int error = 0;
2640
2641
2642
             /*
2643
              * Make sure this file system doesn't already exist.
2644
              */
             LIST_FOREACH(v, &vfs_list, vfs_list) {
2645
2646
                      if (strcmp(vfs->vfs_name, v->vfs_name) == 0) {
                              error = EEXIST;
2647
2648
                              goto out;
                      }
2649
2650
             }
2651
2652
2653
              * Initialize the vnode operations for this file system.
2654
2655
             vfs_opv_init(vfs->vfs_opv_descs);
2656
2657
2658
              * Now initialize the file system itself.
2659
              */
2660
             (*vfs->vfs_init)();
```

```
2661
2662
2663
                ...and link it into the kernel's list.
2664
2665
             LIST_INSERT_HEAD(&vfs_list, vfs, vfs_list);
2666
2667
              * Sanity: make sure the reference count is 0.
2668
2669
              */
2670
             vfs->vfs_refcount = 0;
2671
2672
     out:
2673
             return (error);
2674 }
                                                       kern/vfs_subr.c
```

In the case of FFS, line 2660 of kern/vfs_subr.c calls ffs_init function, since ffs_vfsops variable used in line 1644 of arch/sparc64/compile/MY_KERNEL/ioconf.c is initialized so that its vfs_init member is set to ffs_init by line 97-116 of ufs/ffs/vfs_ffsops.c.

3.3.4 Fast Filesystem Initialization

Fast Filesystem as a virtual filesystem layer is initialized by ffs_init function. This ffs_init function called by vfs_attach function that we just described is shown below.

```
kern/vfs_subr.c
1368 void
1369 ffs_init()
1370 {
1371
             if (ffs_initcount++ > 0)
1372
                      return;
1373
             softdep_initialize();
1374
1375
             ufs_init();
1376
             pool_init(&ffs_inode_pool, sizeof(struct inode), 0, 0, 0, "ffsinopl",
1377
1378
                  &pool_allocator_nointr);
1379 }
1380
1381 void
1382 ffs_reinit()
1383 {
1384
         softdep_reinitialize();
1385
         ufs_reinit();
1386 }
                                                       - kern/vfs_subr.c
```

3.3.5 Soft Dependency Module Initialization

To use soft dependency support, 14 additional caches for meta data structure is needed. It is only 5 caches, however, when Fast File System(FFS) without soft de-

ufs/ffs/ffs_softdep.c

pendency support is considered. For simplicity, we do not consider caches for soft dependency. For not to use soft dependency support in NetBSD Sparc64, it is sufficient for you to remove a line saying "options SOFTDEP" in arch/sparc64/sparc64/conf/GENERIC32 kernel configuration file.

Be sure to know that even if you turn off the switch, 14 additional caches for soft dependency support is initialized, but they are never used, since every call to soft dependency related functions are avoided by checking mnt_flag in structure mount. Soft dependency module initialization function, softdep_initalize is shown below.

```
1050 /*
1051 * Executed during filesystem system initialization before
1052 * mounting any file systems.
1053 */
1054 void
1055 softdep_initialize()
1056 {
1057
             int i;
1058
1059
             LIST_INIT(&mkdirlisthd);
             LIST_INIT(&softdep_workitem_pending);
1060
             max_softdeps = desiredvnodes * 4;
1061
             pagedep_hashtbl = hashinit(desiredvnodes / 5, HASH_LIST, M_PAGEDEP,
1062
1063
                 M_WAITOK, &pagedep_hash);
             sema_init(&pagedep_in_progress, "pagedep", PRIBIO, 0);
1064
1065
             inodedep_hashtbl = hashinit(desiredvnodes, HASH_LIST, M_INODEDEP,
1066
                 M_WAITOK, &inodedep_hash);
             sema_init(&inodedep_in_progress, "inodedep", PRIBIO, 0);
1067
1068
             newblk_hashtbl = hashinit(64, HASH_LIST, M_NEWBLK, M_WAITOK,
1069
                 &newblk_hash);
             sema_init(&newblk_in_progress, "newblk", PRIBIO, 0);
1070
             pool_init(&sdpcpool, sizeof(struct buf), 0, 0, 0, "sdpcpool",
1071
1072
                 &pool_allocator_nointr);
1073
             for (i = 0; i < PCBPHASHSIZE; i++) {</pre>
1074
                     LIST_INIT(&pcbphashhead[i]);
1075
1076
1077
             pool_init(&pagedep_pool, sizeof(struct pagedep), 0, 0, 0,
1078
                 "pagedeppl", &pool_allocator_nointr);
1079
             pool_init(&inodedep_pool, sizeof(struct inodedep), 0, 0, 0,
                 "inodedeppl", &pool_allocator_nointr);
1080
             pool_init(&newblk_pool, sizeof(struct newblk), 0, 0, 0,
1081
                 "newblkpl", &pool_allocator_nointr);
1082
1083
             pool_init(&bmsafemap_pool, sizeof(struct bmsafemap), 0, 0, 0,
1084
                 "bmsafemappl", &pool_allocator_nointr);
1085
             pool_init(&allocdirect_pool, sizeof(struct allocdirect), 0, 0, 0,
                 "allocdirectpl", &pool_allocator_nointr);
1086
             pool_init(&indirdep_pool, sizeof(struct indirdep), 0, 0, 0,
1087
1088
                 "indirdeppl", &pool_allocator_nointr);
             pool_init(&allocindir_pool, sizeof(struct allocindir), 0, 0, 0,
1089
1090
                 "allocindirpl", &pool_allocator_nointr);
1091
             pool_init(&freefrag_pool, sizeof(struct freefrag), 0, 0, 0,
```

```
1092
                 "freefragpl", &pool_allocator_nointr);
1093
             pool_init(&freeblks_pool, sizeof(struct freeblks), 0, 0, 0,
                 "freeblkspl", &pool_allocator_nointr);
1094
1095
             pool_init(&freefile_pool, sizeof(struct freefile), 0, 0, 0,
1096
                 "freefilepl", &pool_allocator_nointr);
1097
             pool_init(&diradd_pool, sizeof(struct diradd), 0, 0, 0,
                 "diraddpl", &pool_allocator_nointr);
1098
             pool_init(&mkdir_pool, sizeof(struct mkdir), 0, 0, 0,
1099
                 "mkdirpl", &pool_allocator_nointr);
1100
1101
             pool_init(&dirrem_pool, sizeof(struct dirrem), 0, 0, 0,
                 "dirrempl", &pool_allocator_nointr);
1102
             pool_init(&newdirblk_pool, sizeof (struct newdirblk), 0, 0, 0,
1103
1104
                 "newdirblkpl", &pool_allocator_nointr);
1105 }
```

ufs/ffs/ffs_softdep.c

All jumps to the soft dependency code, lives in ffs_mount, ffs_reload, ffs_mountfs, ffs_unmount, ffs_vget functions of ufs/ffs_vfsops.c.

ffs_mount and ffs_unmount functions are called respectively when the mount and umount system call is executed. ffs_mountfs is subroutine of ffs_mount function and is also used for ffs_mountroot function. ffs_reload function reloads all incore data for a filesystem after running fsck on the root filesystem and finding things to fix. ffs_vget function is called to look up a FFS dinode number to find its incore vnode.

These code are shown in the following list. You do not need to understand it all, since the point is soft dependency functions are not called when kernel configuration is set up so.

```
ufs/ffs/ffs_vfsops.c
177 int
178 ffs_mount(mp, path, data, ndp, p)
179
        struct mount *mp;
180
        const char *path;
181
        void *data;
182
        struct nameidata *ndp;
183
        struct proc *p;
184 {
307
                if (mp->mnt_flag & MNT_SOFTDEP)
308
                     error = softdep_flushfiles(mp, flags, p);
309
                else
                     error = ffs_flushfiles(mp, flags, p);
310
338
            if ((fs->fs_flags & FS_DOSOFTDEP) &&
                 !(mp->mnt_flag & MNT_SOFTDEP) && fs->fs_ronly == 0) {
339
340 #ifdef notyet
341
                flags = WRITECLOSE;
                if (mp->mnt_flag & MNT_FORCE)
342
                     flags |= FORCECLOSE;
343
344
                error = softdep_flushfiles(mp, flags, p);
                if (error == 0 && ffs_cgupdate(ump, MNT_WAIT) == 0)
345
346
                    fs->fs_flags &= ~FS_DOSOFTDEP;
                     (void) ffs_sbupdate(ump, MNT_WAIT);
347
```

```
348 #elif defined(SOFTDEP)
                    mp->mnt_flag |= MNT_SOFTDEP;
   350 #endif
                }
   351
   382
                    if ((fs->fs_flags & FS_DOSOFTDEP)) {
   383
                        error = softdep_mount(devvp, mp, fs,
   384
                            p->p_ucred);
   385
                        if (error)
   386
                            return (error);
   387
                    }
   427 }
   442 int
   443 ffs_reload(mountp, cred, p)
          struct mount *mountp;
   445
           struct ucred *cred;
   446
           struct proc *p;
   447 {
            if ((fs->fs_flags & FS_DOSOFTDEP))
   586
   587
                softdep_mount(devvp, mountp, fs, cred);
   646 }
. . .
. . .
   651 int
   652 ffs_mountfs(devvp, mp, p)
           struct vnode *devvp;
   654
           struct mount *mp;
   655
           struct proc *p;
   656 {
   894
            if (ronly == 0 && (fs->fs_flags & FS_DOSOFTDEP)) {
   895
                error = softdep_mount(devvp, mp, fs, cred);
   896
                if (error) {
   897
                    free(fs->fs_csp, M_UFSMNT);
   898
                    goto out;
   899
                }
            }
   900
   916 }
. . .
   950 int
   951 ffs_unmount(mp, mntflags, p)
   952
         struct mount *mp;
   953
           int mntflags;
   954
           struct proc *p;
```

```
955 {
            if (mp->mnt_flag & MNT_SOFTDEP) {
   964
   965
                if ((error = softdep_flushfiles(mp, flags, p)) != 0)
   966
                    return (error);
    967
            } else {
   968
                if ((error = ffs_flushfiles(mp, flags, p)) != 0)
   969
                    return (error);
   970
            }
   1006 }
. . .
  1191 int
  1192 ffs_vget(mp, ino, vpp)
            struct mount *mp;
  1193
  1194
            ino_t ino;
  1195
            struct vnode **vpp;
  1196 {
  1286
            if (DOINGSOFTDEP(vp))
                softdep_load_inodeblock(ip);
  1287
  1288
                ip->i_ffs_effnlink = ip->i_ffs_nlink;
  1289
  1290
            brelse(bp);
  1319 }
                                                       ufs/ffs/ffs_vfsops.c
```

The DOINGSOFTDEP() macro used in the above list is defined in ufs/inode.h as

```
#define DOINGSOFTDEP(vp) ((vp)->v_mount->mnt_flag & MNT_SOFTDEP)
```

As you have seen the codes, there is no need to worry about the operation of soft dependency facility if you removed the kernel option from kernel configuration file, although 14 caches for soft dependency is initialized.

3.3.6 UFS Initialization

In line 1375 of ufs/ffs/ffs_vfsops.c, ffs_init function calls ufs_init, UFS initialization function that is defined as,

```
ufs/ufs/ufs_vfsops.c

225 /*

226 * Initialize UFS filesystems, done only once.

227 */

228 void

229 ufs_init()

230 {

231     if (ufs_initcount++ > 0)

232         return;

233
```

```
234
                ufs_ihashinit();
    235 #ifdef QUOTA
   236
                dqinit();
    237 #endif
    238 }
                                                   ufs/ufs/ufs_vfsops.c
where ufs_ihashint function that initializes inode hash table is shown below.
                                                    — ufs/ufs/ufs_ihash.c
    61 /*
    62 * Initialize inode hash table.
    63 */
    64 void
    65 ufs_ihashinit()
    66 {
                lockinit(&ufs_hashlock, PINOD, "ufs_hashlock", 0, 0);
    67
    68
                ihashtbl =
    69
                    hashinit(desiredvnodes, HASH_LIST, M_UFSMNT, M_WAITOK, &ihash);
    70
               simple_lock_init(&ufs_ihash_slock);
    71 }
                                                    ufs/ufs/ufs_ihash.c
Note the line 69 which creates hash table that can store 'desiredvnodes' elements.
desiredvnodes global variable is also defined by param.c — autogenerated source
code by config program.
                          —— arch/sparc64/compile/MY_KERNEL/param.c
   107 int
              hz = HZ;
    108 int
              tick = 1000000 / HZ;
              tickadj = 240000 / (60 * HZ); /* can adjust 240ms in 60s */
   109 int
              rtc_offset = RTC_OFFSET;
   110 int
              maxproc = NPROC;
   111 int
   112 int
              desiredvnodes = NVNODE;
   113 int
              maxfiles = MAXFILES;
   114 int
              ncallout = 16 + NPROC; /* size of callwheel (rounded to ^2) */
    115 u_long sb_max = SB_MAX;
                                        /* maximum socket buffer size */
    116 int fscale = FSCALE;
                                        /* kernel uses 'FSCALE', user uses 'fscale' */
                             - arch/sparc64/compile/MY_KERNEL/param.c
where the NVNODE macro is defined in sys/param.h as,
                                                   —- kern/sys/param.h
    128 #ifndef NPROC
    129 #define NPROC
                        (20 + 16 * MAXUSERS)
    130 #endif
    131 #ifndef NTEXT
    132 #define NTEXT
                        (80 + NPROC / 8)
                                                       /* actually the object cache */
    133 #endif
    134 #ifndef NVNODE
    135 #define NVNODE (NPROC + NTEXT + 100)
    136 #define NVNODE_IMPLICIT
    137 #endif
```

where the **line 134** means NVNODE parameter can be tuned in *kernel configuration* file using option command. Since default MAXUSERS is 64 unless tuned by kernel configuration file,

```
NPROC = 20 + 16 * MAXUSERS

= 20 + 16 * 64

= 1044

NTEXT = 80 + NPROC / 8

= 80 + 1044 / 8

= 210

NVNODE = NPROC + NTEXT + 100

= 1044 + 210 + 100

= 1354
```

So, if you want to change the default value of desiredvnodes other than 1354, you can change by tuning MAXUSERS parameter in kernel configuration file using option command.

Up to now, we showed how virtual file system layer is initialized. In the next chapter, we will describe a file system is mounted, with exploring the mount process of root file system!

3.4 Virtual Filesystem Operations

In a similar fashion to the vnode interface, all operations that are done on a file system are conducted through a single interface that allows the system to carry out operations on a file system without knowing its construction or type.

As we had described earlier, all supported file systems in the kernel have an entry in the vfs_list_initial table. This table is generated by config program and is a NULL-terminated list of vfsops structures. The vfsops structure describes the operations that can be done to a specific file system type. The vfsops structure is shown below.

```
344 struct vfsops {
345
            const char *vfs_name;
346
                     (*vfs_mount)
                                      __P((struct mount *mp, const char *path,
            int
347
                                          void *data, struct nameidata *ndp,
348
                                          struct proc *p));
                     (*vfs_start)
                                      __P((struct mount *mp, int flags,
349
            int
350
                                          struct proc *p));
351
                     (*vfs_unmount)
                                      __P((struct mount *mp, int mntflags,
            int.
352
                                          struct proc *p));
353
            int
                     (*vfs_root)
                                      __P((struct mount *mp, struct vnode **vpp));
354
            int
                     (*vfs_quotactl) __P((struct mount *mp, int cmds, uid_t uid,
                                          caddr_t arg, struct proc *p));
355
356
            int
                     (*vfs_statfs)
                                     __P((struct mount *mp, struct statfs *sbp,
357
                                          struct proc *p));
358
                     (*vfs_sync)
            int
                                      __P((struct mount *mp, int waitfor,
                                          struct ucred *cred, struct proc *p));
359
360
                     (*vfs_vget)
                                      __P((struct mount *mp, ino_t ino,
            int
```

sys/mount.h

sys/mount.h

```
361
                                          struct vnode **vpp));
362
            int
                     (*vfs_fhtovp)
                                      __P((struct mount *mp, struct fid *fhp,
363
                                          struct vnode **vpp));
364
            int
                     (*vfs_vptofh)
                                      __P((struct vnode *vp, struct fid *fhp));
365
            void
                     (*vfs_init)
                                      __P((void));
366
            void
                     (*vfs_reinit)
                                      __P((void));
                                      __P((void));
            void
                     (*vfs_done)
367
                     (*vfs_sysctl)
                                      _{-}P((int *, u_int, void *, size_t *, void *,
368
            int
                                          size_t, struct proc *));
369
370
            int
                     (*vfs_mountroot) __P((void));
371
                     (*vfs_checkexp) __P((struct mount *mp, struct mbuf *nam,
            int.
372
                                          int *extflagsp, struct ucred **credanonp));
373
            const struct vnodeopv_desc * const *vfs_opv_descs;
374
                     vfs_refcount;
375
            LIST_ENTRY(vfsops) vfs_list;
376 };
```

The following table list the elements of the vfsops vector, the corresponding invocation macro, and a description of the element.

```
Vector element
                                       Description
                         Macro
int.
     (*vfs_mount)()
                         VFS_MOUNT
                                       Mount a file system
int
     (*vfs_start)()
                         VFS_START
                                       Make operational
int
     (*vfs_unmount)()
                         VFS_UMOUNT
                                       Unmount a file system
     (*vfs_root)()
                         VFS_ROOT
                                       Get the file system root vnode
int
int
     (*vfs_quotactl)()
                        VFS_QUOTACTL
                                       Query/modify space quotas
     (*vfs_statfs)()
                         VFS_STATFS
                                       Get file system statistics
     (*vfs_sync)()
                         VFS_SYNC
                                       Flush file system buffers
int.
     (*vfs_vget)()
                         VFS_VGET
                                       Get vnode from file ID
int
int
     (*vfs_fhtovp)()
                         VFS_FHTOVP
                                       NFS file handle to vnode lookup
     (*vfs_vptofh)()
                         VFS_VPTOFH
                                       Vnode to NFS file handle lookup
void (*vfs_init)()
                                       Initialise file system
void (*vfs_reinit)()
                                       Reinitialise file system
void (*vfs_done)()
                                       Cleanup unmounted file system
     (*vfs_sysctl)()
                                       Query/modify kernel state
int
     (*vfs_mountroot)() -
int
                                       Mount the root file system
     (*vfs_checkexp)() VFS_CHECKEXP
                                       Check if fs is exported
```

Some additional non-function members of the vfsops structure are the file system name vfs_name and a reference count vfs_refcount. It is not mandatory for a filesystem type to support a particular operation, but it must assign each member function pointer to a suitable function to do the minimum required of it. In most cases, such functions either do nothing or return an error value to the effect that it is not supported.

At system boot, each filesystem with an entry in vfs_list_initial is established and initialised. Each initialised file system is recorded by the kernel in the list vfs_list and the file system specific initialisation function vfs_init in its vfsops vector is invoked. When the filesystem is not longer needed vfs_done is invoked to run file system specific cleanups and the file system is removed from the kernel list.

At system boot, the root filesystem is mounted by invoking the file system type specific vfs_mountroot function in the vfsops vector. All filesystems that can be mounted as a root file system must define this function. It is responsible for initialising to list of mount structures for all future mounted file systems.

Kernel state which affects a specific filesystem type can be queried and modified using the sysctl interface. The vfs_sysctl member of the vfsops structure is invoked by filesystem independent code.

3.5 References to Source Code

3.5.1 kern/vfs_init.c - 334 lines, 7 functions

Gloval Variables

```
const struct vnodeopv_desc * const vfs_special_vnodeopv_descs[] = {
          &dead_vnodeop_opv_desc,
          &fifo_vnodeop_opv_desc,
          &spec_vnodeop_opv_desc,
          &sync_vnodeop_opv_desc,
          NULL,
};
struct vattr va_null;
```

Functions

```
vn_default_error()
vfs_opv_init_explicit()
vfs_opv_init_default()
vfs_opv_init()
vfs_opv_free()
vfs_op_check()
vfsinit()
```

Chapter 4

Buffer Cache

Buffer cache manages the memory that buffers data being transferred to and from the network or disk, and act as a cache of recently used blocks.

Since we are planning to replace buffer cache, it is essential for us to know the details of buffer cache, and the interaction between vnode operations and buffer cache

The architecture of buffer cache is best described by [1]. But the details about how the buffer cache is implemented is best described by [2].

The buffer cache is composed of two parts. The first part is the buffer header and the second part is the actual buffer contents.

4.1 Buffer Cache Header

The Buffer header of NetBSD release 1.6 is defined in sys/buf.h as,

```
sys/buf.h
151 /*
152 * The buffer header describes an I/O operation in the kernel.
153 */
154 struct buf {
155
            LIST_ENTRY(buf) b_hash;
                                             /* Hash chain. */
156
            LIST_ENTRY(buf) b_vnbufs;
                                             /* Buffer's associated vnode. */
                                             /* Free list position if not active. */
            TAILQ_ENTRY(buf) b_freelist;
157
158
            TAILQ_ENTRY(buf) b_actq;
                                             /* Device driver queue when active. */
            struct proc *b_proc;
                                             /* Associated proc if B_PHYS set. */
159
            volatile long
                            b_flags;
                                             /* B_* flags. */
160
                                             /* Errno value. */
161
            int
                    b_error;
                                             /* Allocated buffer size. */
162
            long
                    b_bufsize;
                                             /* Valid bytes in buffer. */
163
            long
                    b_bcount;
                                             /* Remaining I/O. */
164
            long
                    b_resid;
165
            dev_t
                    b_dev;
                                             /* Device associated with buffer. */
166
            struct {
167
                    caddr_t b_addr;
                                             /* Memory, superblocks, indirect etc. */
            } b_un;
168
                                             /* Original b_addr for physio. */
                    *b_saveaddr;
169
            void
            daddr_t b_lblkno;
170
                                             /* Logical block number. */
171
            daddr_t b_blkno;
                                             /* Underlying physical block number
172
                                                (partition relative) */
                                             /* Raw underlying physical block
173
            daddr_t b_rawblkno;
```

sys/buf.h

```
174
                                                number (not partition relative) */
                                             /* Function to call upon completion. */
175
176
                    (*b_iodone) __P((struct buf *));
            void
177
            struct vnode *b_vp;
                                            /* File vnode. */
178
            void
                    *b_private;
                                            /* Private data for owner */
179
            off_t
                    b_dcookie;
                                            /* Offset cookie if dir block */
                                            /* List of filesystem dependencies. */
180
            struct workhead b_dep;
181 };
```

where

b_vnbufs is a pointer to the vnode whose data the buffer holds.

b_flags tracks status information about the buffer, such as whether the buffer contains useful data, whether the buffer is in use, and whether the data must be written back to the file before the buffer can be reused.

b_bufsize indicates the size of allocated buffer contents, without regard to the validity of the data contained.

b_bcount contains the number of valid bytes contained in the buffer.

The possible values of b_flags variable are,

```
sys/buf.h
192 /*
193 * These flags are kept in b_flags.
194 */
195 #define B_AGE
                        0x00000001 /* Move to age queue when I/O done. */
196 #define B_NEEDCOMMIT 0x00000002 /* Needs committing to stable storage */
197 #define B_ASYNC
                        0x00000004 /* Start I/O, do not wait. */
                        0x00000008 /* Bad block revectoring in progress. */
198 #define B_BAD
199 #define B_BUSY
                        0x00000010 /* I/O in progress. */
200 #define B_SCANNED
                        0x00000020 /* Block already pushed during sync */
201 #define B_CALL
                        0x00000040 /* Call b_iodone from biodone. */
202 #define B_DELWRI
                        0x00000080 /* Delay I/O until buffer reused. */
203 #define B_DIRTY
                        0x00000100 /* Dirty page to be pushed out async. */
204 #define B_DONE
                        0x00000200 /* I/O completed. */
205 #define B_EINTR
                        0x00000400 /* I/O was interrupted */
                        0x00000800 /* I/O error occurred. */
206 #define B ERROR
                        0x00001000 /* LFS: already in a segment. */
207 #define B_GATHERED
208 #define B_INVAL
                        0x00002000 /* Does not contain valid info. */
209 #define B_LOCKED
                        0x00004000 /* Locked in core (not reusable). */
210 #define B_NOCACHE
                        0x00008000 /* Do not cache block after use. */
                        0x00020000 /* Bread found us in the cache. */
211 #define B_CACHE
212 #define B_PHYS
                        0x00040000 /* I/O to user memory. */
213 #define B_RAW
                        0x00080000 /* Set by physio for raw transfers. */
214 #define B_READ
                        0x00100000 /* Read buffer. */
                        0x00200000 /* Magnetic tape I/O. */
215 #define B_TAPE
216 #define B_WANTED
                        0x00800000 /* Process wants this buffer. */
217 #define B_WRITE
                        0x00000000 /* Write buffer (pseudo flag). */
                        0x02000000 /* Debugging flag. */
218 #define B_XXX
                        0x04000000 /* Buffer is being synced. */
219 #define B_VFLUSH
```

```
_______sys/buf.h
To set and test these flags, convevient macros are provided as,
________kern/vfs_bio.c

70 /* Macros to clear/set/test flags. */
71 #define SET(t, f) (t) |= (f)
72 #define CLR(t, f) (t) &= ~(f)
73 #define ISSET(t, f) ((t) & (f))
_______kern/vfs_bio.c
```

As we analyze buffer cache, we will gradually know every meaning of these flags.

4.2 Buffer Cache Contents

Buffer contents are maintaained separately from the header to allow easy manipulation of buffer sizes via the page-mapping hardware.

4.2.1 Allocation Virtual Memory to Buffer Cache

Kernel allocates to each buffer MAXBSIZE bytes of virtual memory, but the address space is not fully populated with physical memory. Initially, each buffer is assigned 4096 bytes of physical memory. As smaller buffers are allocated, they give up their unused physical memory to buffers that need to hold more than 4096 bytes.

MAXSIZE is machine-dependent since it is defined by

```
sys/param.h
   211 /*
    212 * File system parameters and macros.
    213 *
    214 * The file system is made out of blocks of at most MAXBSIZE units, with
    215
        * smaller units (fragments) only in the last direct block. MAXBSIZE
    216 * primarily determines the size of buffers in the buffer pool. It may be
    217 * made larger without any effect on existing file systems; however making
    218 * it smaller may make some file systems unmountable.
    219 */
    220 #ifndef MAXBSIZE
                                                        /* XXX */
    221 #define MAXBSIZE
                                MAXPHYS
    222 #endif
    223 #define MAXFRAG
                                                           sys/param.h
and
                                           arch/sparc64/include/param.h
    128 #define DEV_BSIZE
                                512
    129 #define DEV_BSHIFT
                                9
                                                /* log2(DEV_BSIZE) */
    130 #define BLKDEV IOSIZE
                                2048
    131 #define MAXPHYS
                                (64 * 1024)
```

arch/sparc64/include/param.h

4.2.2 Identifying Buffer

How can we identify buffer? Is there unique ID?

4.4BSD identify buffers by their logical block number within filesystem by blblkno member in buffer header.

Since it is difficult to detect aliases for a block belonging to a local file and the same block accessed through the block device disk, kernel prevents this case from occuring: The kernel does not allow the block device from a partition to be opened while that partition is mounted. Nor does the kernel allow a partition to be mounted if the block device from the partition is already open.

4.3 Buffer Hash

A buffer with valid contents is contained on exactly one bufhash hash chain. The kernel uses the hash chains to determine quickly whether a block is in the buffer pool, and if it is, to locate it.

A buffer is removed from the *buffer hash* only when its contents become invalid or it is reused for different data. Thus, even if the buffer is in use by one process, it can still be found by another process, although B_BUSY flag will be set so that it will not be used until the buffer is released.

The buffer hash is defined in kern/vfs_bio.c as,

If you as unfamilar with the LIST_HEAD macro, review a section describing kernel list data structures in chapter 1. If you know how to use linked list macros, then you would know the above definition of line 80 is equal to

```
struct bufhashhdr {
    struct buf *lh_first; /* first element */
} *bufhashtbl, invalhash;
```

bufhashtbl points to a hash table composed of an array of linked-lists. However, invalhash is simply a linked-list, not an array.

4.4 Buffer Cache Free Lists

In addition to appearing on the hash list, each unlocked byffer appears on exactly one free list. There are four kinds of free list. They are defined in vfs_bio.c as,

_____ kern/vfs_bio.c

```
92 /*
93 * Definitions for the buffer free lists.
94 */
95 #define BQUEUES
                                             /* number of free buffer queues */
96
97 #define BQ_LOCKED
                            0
                                             /* super-blocks &c */
98 #define BQ_LRU
                                             /* lru, useful buffers */
                            1
                            2
                                             /* rubbish */
99 #define BQ_AGE
100 #define BQ_EMPTY
                            3
                                             /* buffer headers with no memory */
102 TAILQ_HEAD(bqueues, buf) bufqueues[BQUEUES];
103 int needbuffer;
                                                      kern/vfs_bio.c
```

If you as unfamilar with the TAILQ_HEAD macro, review a section describing kernel list data structures in chapter 1.

If you had read the section, you would know line 102 means that four tail queues are defined, and these tail queues contain elements whose type is struct buf. Also, you would know these definition is exactly equivalent to

```
struct bqueues {
        struct buf *tqh_first; /* first element */
        struct buf **tqh_first; /* addr of last next element */
} bufqueues [BQUEUES];
```

4.4.1 LOCKED List

Buffers on this list cannot be flushed from the cache.

4.4.2 LRU List

After a buffer is used, the buffer is then returned to the end of the LRU list. When new buffers are needed, they are taken from the front of the LRU list. As its name suggests, this list implements a least recently used (LRU) algorithm.

4.4.3 AGE List

AGE list holds two kinds of buffers. They are the buffers which are,

Blocks of unlinked file: These buffers are not likely to be reused. The buffers are placed at the front of the AGE list where they will be reclaimed quickly.

Read-ahead block: These buffers are not proben their usefulness. The buffers are placed at the end of the AGE list where they will might remain long enough to be used again.

AGE list is used for two purposes. First, if a block is requested and it is found on a buffer cache that lives in the AGE list, the buffer is returned to the end of the LRU list, not the AGE list, because it has proved its usefulness. Second, when a new buffer is needed, the front of the AGE list is searched first; only when the AGE list is empty, the LRU list is used.

- arch/sparc64/sparc64/machdep.c

4.4.4 EMPTY List

The EMPTY list contains buffers that have no physical memory. They are held on this list waiting for another buffer to be reused for a smaller block and thus give up its extra physical memory.

4.5 Buffer Cache Initialization

Buffer cache is initialized in the beginning stage of the system bootstrap. Initialization process consists of two stages.

At first, cpu_startup function does machine dependent memory allocation. At Second, bufinit function called by cpu_startup function initializes buffer cache hash and free lists using the memory allocated by previous machine dependent initialization stage.

4.5.1 Physical Memory Allocation

main function of kern/init_main.c is machine independent bootstrap routine, and
it calls machine dependent startup routine cpu_startup function of arch/sparc64/sparc64/machdep.c
defined as

166 /* 167 * Machine-dependent startup code 168 */ 169 void 170 cpu_startup() 171 { caddr_t v; 172 173 long sz; 174 u_int i, base, residual; 175 #ifdef DEBUG 176 extern int pmapdebug; 177 int opmapdebug = pmapdebug; 178 #endif 179 vaddr_t minaddr, maxaddr; 180 vsize_t size; extern struct user *proc0paddr; 181 182 char pbuf[9]; 183 184 #ifdef DEBUG 185 pmapdebug = 0; 186 #endif 187 proc0.p_addr = proc0paddr; 188 189 190 * Good {morning,afternoon,evening,night}. 191 */ 192 193 printf(version); 194 /*identifycpu();*/ 195 format_bytes(pbuf, sizeof(pbuf), ctob((u_int64_t)physmem)); 196 printf("total memory = %s\n", pbuf);

```
197
198
            /*
199
             * Find out how much space we need, allocate it,
200
             * and then give everything true virtual addresses.
201
202
            sz = (long)allocsys(NULL, NULL);
203
            if ((v = (caddr_t)uvm_km_alloc(kernel_map, round_page(sz))) == 0)
204
                    panic("startup: no room for %lx bytes of tables", sz);
205
            if (allocsys(v, NULL) - v != sz)
206
                    panic("startup: table size inconsistency");
207
208
             * allocate virtual and physical memory for the buffers.
209
210
             */
            size = MAXBSIZE * nbuf;
211
                                             /* # bytes for buffers */
212
213
            /* allocate VM for buffers... area is not managed by VM system */
214
            if (uvm_map(kernel_map, (vaddr_t *) &buffers, round_page(size),
                        NULL, UVM_UNKNOWN_OFFSET, O,
215
                        UVM_MAPFLAG(UVM_PROT_NONE, UVM_PROT_NONE, UVM_INH_NONE,
216
217
                                    UVM_ADV_NORMAL, 0)) != 0)
218
                    panic("cpu_startup: cannot allocate VM for buffers");
219
220
            minaddr = (vaddr_t) buffers;
            if ((bufpages / nbuf) >= btoc(MAXBSIZE)) {
221
222
                    bufpages = btoc(MAXBSIZE) * nbuf; /* do not overallocate RAM */
223
224
            base = bufpages / nbuf;
225
            residual = bufpages % nbuf;
226
227
            /* now allocate RAM for buffers */
228
            for (i = 0 ; i < nbuf ; i++) {
229
                    vaddr_t curbuf;
230
                    vsize_t curbufsize;
231
                    struct vm_page *pg;
232
233
                    /*
234
                     * each buffer has MAXBSIZE bytes of VM space allocated. of
235
                     * that MAXBSIZE space we allocate and map (base+1) pages
236
                     * for the first "residual" buffers, and then we allocate
237
                     * "base" pages for the rest.
238
                     */
239
                    curbuf = (vaddr_t) buffers + (i * MAXBSIZE);
240
                    curbufsize = NBPG * ((i < residual) ? (base+1) : base);</pre>
241
242
                    while (curbufsize) {
243
                            pg = uvm_pagealloc(NULL, 0, NULL, 0);
                            if (pg == NULL)
244
245
                                    panic("cpu_startup: "
                                         "not enough RAM for buffer cache");
246
247
                            pmap_kenter_pa(curbuf, VM_PAGE_TO_PHYS(pg),
248
                                VM_PROT_READ | VM_PROT_WRITE);
249
                            curbuf += PAGE_SIZE;
250
                            curbufsize -= PAGE_SIZE;
```

```
}
251
252
            }
253
            pmap_update(kernel_map->pmap);
254
255
256
             * Allocate a submap for exec arguments. This map effectively
             * limits the number of processes exec'ing at any time.
257
258
259
            exec_map = uvm_km_suballoc(kernel_map, &minaddr, &maxaddr,
                                      16*NCARGS, VM_MAP_PAGEABLE, FALSE, NULL);
260
261
262
             * Finally, allocate mbuf cluster submap.
263
264
265
            mb_map = uvm_km_suballoc(kernel_map, &minaddr, &maxaddr,
266
                nmbclusters * mclbytes, VM_MAP_INTRSAFE, FALSE, NULL);
267
268 #ifdef DEBUG
269
            pmapdebug = opmapdebug;
270 #endif
271
            format_bytes(pbuf, sizeof(pbuf), ptoa(uvmexp.free));
272
            printf("avail memory = %s\n", pbuf);
            format_bytes(pbuf, sizeof(pbuf), bufpages * NBPG);
273
            printf("using %u buffers containing %s of memory\n", nbuf, pbuf);
274
275
276
277
             * Set up buffers, so they can be used to read disk labels.
278
             */
279
            bufinit();
280
281 #if 0
282
            pmap_redzone();
283 #endif
284 }
```

From the above function, buffers global variable is defined, in automatically

as

arch/sparc64/compile/MY_KERNEL/param.c

compile-time generated code by config program, arch/sparc64/compile/MY_KERNEL/param.c,

```
194 /*

195 * These have to be allocated somewhere; allocating

196 * them here forces loader errors if this file is omitted

197 * (if they've been externed everywhere else; hah!).

198 */

199 struct buf *buf;

200 char *buffers;
```

- arch/sparc64/compile/MY_KERNEL/param.c

-- arch/sparc64/sparc64/machdep.c

and NBPG macro is defined, in machine dependent source code, arch/sparc64/include/param.h, as

```
- arch/sparc64/include/param.h

298 #define PGSHIFT 13 /* log2(NBPG) */
299 #define NBPG (1<<PGSHIFT) /* bytes/page */
300 #define PGOFSET (NBPG-1) /* byte offset into page */
- arch/sparc64/include/param.h
```

Global variables used in cpu_startup function, such as nbuf, bufpages, bufcache is defined in kern_kern_allocsys.c as

```
—- arch/sparc64/include/param.h
94 /*
95 * Declare these as initialized data so we can patch them.
96 */
97 #ifndef NBUF
98 # define NBUF 0
99 #endif
100
101 #ifndef BUFPAGES
102 # define BUFPAGES 0
103 #endif
104
105 #ifdef BUFCACHE
106 # if (BUFCACHE < 5) || (BUFCACHE > 95)
107 # error BUFCACHE is not between 5 and 95
108 # endif
109 #else
    /* Default to 10% of first 2MB and 5% of remaining. */
110
111 # define BUFCACHE 0
112 #endif
113
114 u_int
           nbuf = NBUF;
115 u_int
          nswbuf = 0;
116 u_int bufpages = BUFPAGES;
                                    /* optional hardwired count */
                                    /* % of RAM to use for buffer cache */
117 u_int bufcache = BUFCACHE;
                                      - arch/sparc64/include/param.h
```

If you specifies NBUF, or BUFPAGES macro in your kernel configuration file, then the kernel come to have fixed amount of buffer cache. However, by default, current NetBSD releases automatically calculates the amount of memory allocated for buffer cache by setting the value of NBUF, and BUFPAGES to zero! Automatically calculated amount of memory allocated for buffer cache is 0.2 MB of the first system memory plus 5 percent of the remaining system memory.

You can change the 5 percent by setting BUFCACHE macro in your kernel configuration file using option command.

This calculation is done by allocsys function called from line 202-206 of cpu_startup function. The source code of allocsys function is in the kern/kern_allocsys.c as

```
kern/kern_allocsys.c

119 /*

120 * Allocate space for system data structures. We are given
```

```
121 * a starting virtual address and we return a final virtual
122 * address; along the way we set each data structure pointer.
123 *
124 * We call allocsys() with 0 to find out how much space we want,
125 * allocate that much and fill it with zeroes, and then call
126 * allocsys() again with the correct base virtual address.
127 *
128 */
129
130 caddr t
131 allocsys(caddr_t v, caddr_t (*mdcallback)(caddr_t))
132 {
133
134
            /* Calculate the number of callwheels if necessary. */
            if (callwheelsize == 0)
135
136
                    callout_setsize();
137
138
            ALLOCSYS(v, callwheel, struct callout_queue, callwheelsize);
139 #ifdef CALLWHEEL_STATS
140
            ALLOCSYS(v, callwheel_sizes, int, callwheelsize);
141 #endif
142 #ifdef SYSVSHM
            ALLOCSYS(v, shmsegs, struct shmid_ds, shminfo.shmmni);
144 #endif
145 #ifdef SYSVSEM
146
            ALLOCSYS(v, sema, struct semid_ds, seminfo.semmni);
147
            ALLOCSYS(v, sem, struct __sem, seminfo.semmns);
148
            /* This is pretty disgusting! */
            ALLOCSYS(v, semu, int, (seminfo.semmnu * seminfo.semusz) / sizeof(int));
149
150 #endif
151 #ifdef SYSVMSG
152
            ALLOCSYS(v, msgpool, char, msginfo.msgmax);
153
            ALLOCSYS(v, msgmaps, struct msgmap, msginfo.msgseg);
154
            ALLOCSYS(v, msghdrs, struct __msg, msginfo.msgtql);
155
            ALLOCSYS(v, msqids, struct msqid_ds, msginfo.msgmni);
156 #endif
157
            /*
158
             * Determine how many buffers to allocate.
159
160
                    - If bufcache is specified, use that % of memory
161
                      for the buffer cache.
162
163
164
                    - Otherwise, we default to the traditional BSD
165
                      formula of 10% of the first 2MB and 5% of
166
                      the remaining.
167
             */
168
            if (bufpages == 0) {
                    if (bufcache != 0) {
169
170
                            if (bufcache < 5 || bufcache > 95)
171
                                    panic("bufcache is out of range (%d)",
172
                                        bufcache);
173
                            bufpages = physmem / 100 * bufcache;
174
                    } else {
```

```
if (physmem < btoc(2 * 1024 * 1024))
175
176
                                     bufpages = physmem / 10;
177
                            else
178
                                     bufpages = (btoc(2 * 1024 * 1024) + physmem) /
179
180
                    }
181
            }
182
183 #ifdef DIAGNOSTIC
            if (bufpages == 0)
184
185
                    panic("bufpages = 0");
186 #endif
187
188
189
             * Call the mdcallback now; it may need to adjust bufpages.
190
            */
191
            if (mdcallback != NULL)
192
                    v = mdcallback(v);
193
194
            /*
195
             * Ensure a minimum of 16 buffers.
196
             */
            if (nbuf == 0) {
197
                    nbuf = bufpages;
198
199
                    if (nbuf < 16)
200
                            nbuf = 16;
201
            }
202
203 #ifdef VM_MAX_KERNEL_BUF
204
            /*
205
             * XXX stopgap measure to prevent wasting too much KVM on
206
             * the sparsely filled buffer cache.
207
208
            if (nbuf > VM_MAX_KERNEL_BUF / MAXBSIZE)
                    nbuf = VM_MAX_KERNEL_BUF / MAXBSIZE;
209
210 #endif
211
212
             * We allocate 1/2 as many swap buffer headers as file I/O buffers.
213
214
             */
            if (nswbuf == 0) {
215
                    nswbuf = (nbuf / 2) &^{-}1;
                                                   /* force even */
216
217
                    if (nswbuf > 256)
                                                    /* sanity */
218
                            nswbuf = 256;
219
220
            ALLOCSYS(v, buf, struct buf, nbuf);
221
222
            return (v);
223 }
```

where the ALLOCSYS macro is defined in ${\tt sys/systm.h}$ as

sys/systm.h

kern/kern_allocsys.c

where the ALIGN macro is defined in machine dependent source, arch/sparc64/include/param.h as

```
-- arch/sparc64/include/param.h
 95 /*
 96 * Round p (pointer or byte index) up to a correctly-aligned value for
 97 * the machine's strictest data type. The result is u_int and must be
98 * cast to any desired pointer type.
99 *
100 * ALIGNED_POINTER is a boolean macro that checks whether an address
101 * is valid to fetch data elements of type t from on this architecture.
102 * This does not reflect the optimal alignment, just the possibility
103 * (within reasonable limits).
104 *
105 */
106 #define ALIGNBYTES32
                                    0x7
107 #define ALIGNBYTES64
                                    0xf
108 #ifdef __arch64__
109 #define ALIGNBYTES
                                    ALIGNBYTES64
110 #else
111 #define ALIGNBYTES
                                    ALIGNBYTES32
112 #endif
113 #define ALIGN(p)
                                    (((u_long)(p) + ALIGNBYTES) & ~ALIGNBYTES)
                                    (((u_long)(p) + ALIGNBYTES32) & ~ALIGNBYTES32)
114 #define ALIGN32(p)
115 #define ALIGNED_POINTER(p,t)
                                    ((((u_long)(p)) & (sizeof(t)-1)) == 0)
                                      -- arch/sparc64/include/param.h
```

Exactly saying, you may not fully understand cpu_start function, until we describe UVM memory management system. Thing worthy of being remembered is that now you know

- How the physical memory for buffer cache is allocated?
- How can I change the amount of buffer cache?
- After machine dependent, physical memory allocation for buffer cache, nbuf, bufpages variables are set to relevant values on the basis of BUFCACHE that is representing how much portion of the available physical system memory should be allocated for buffer cache.
- buffer global variable is a pointer to virtual memory chunk allocated by UVM for the whole buffer cache.

4.5.2 Initialization of Hash and Free List

bufinit function is called from line 279 of cpu_startup machine dependent function. The bufinit function initalizes buffer cache hash and its four free lists.

kern/vfs_bio.c

```
146 /*
147 * Initialize buffers and hash links for buffers.
148 */
149 void
150 bufinit()
151 {
152
            struct buf *bp;
153
            struct bqueues *dp;
            u_int i, base, residual;
154
155
            /*
156
             * Initialize the buffer pool. This pool is used for buffers
157
158
             * which are strictly I/O control blocks, not buffer cache
159
             * buffers.
160
             */
161
            pool_init(&bufpool, sizeof(struct buf), 0, 0, 0, "bufpl", NULL);
162
163
            for (dp = bufqueues; dp < &bufqueues[BQUEUES]; dp++)</pre>
164
                    TAILQ_INIT(dp);
            bufhashtbl = hashinit(nbuf, HASH_LIST, M_CACHE, M_WAITOK, &bufhash);
165
166
            base = bufpages / nbuf;
            residual = bufpages % nbuf;
167
            for (i = 0; i < nbuf; i++) {
168
169
                    bp = \&buf[i];
                    memset((char *)bp, 0, sizeof(*bp));
170
171
                    bp->b_dev = NODEV;
                    bp->b_vnbufs.le_next = NOLIST;
172
173
                    LIST_INIT(&bp->b_dep);
174
                    bp->b_data = buffers + i * MAXBSIZE;
                    if (i < residual)
175
                             bp->b_bufsize = (base + 1) * PAGE_SIZE;
176
177
                    else
                             bp->b_bufsize = base * PAGE_SIZE;
178
                    bp->b_flags = B_INVAL;
179
                    dp = bp->b_bufsize ? &bufqueues[BQ_AGE] : &bufqueues[BQ_EMPTY];
180
181
                    binsheadfree(bp, dp);
182
                    binshash(bp, &invalhash);
            }
183
184 }
```

line 161 initialize the buffer pool. Notice that this buffer pool is completely different thing from buffer cache. Buffer cache holds data block specified by logical file block. Buffer pool, however, is used to transfer data between raw device and user buffers, and bypass the buffer cache.

Buffer pool is used by physical I/O by device driver layers such as SCSI controller. When we describe ccd device driver in other chapter, we will explain how the buffer pool is used.

line 164 Did you review chapter 1 about using linked-list and tail queues? Then your will know the line is equivalent to

```
dp->tqh_first = NULL;
dp->tqh_last = &dp->tqh_first;
```

This code initializes four buffer cache free lists: LOCKED, LRU, AGE, EMPTY lists.

- line 165 initializes buffer cache hash and receives mask value in bufhash variable.

 If are not certain what this line do, review a subsection about description of kernel hash implementatin, in chapter 1.
- line 166-167 nbuf is the number of all buffer cache. bufpages is the number of all physical memory pages that is available for buffer cache. nbuf is equal to bufpages unless NBUF kernel configuration variable is explicitly set. Therefore, by default, these two line is equivalent to

```
base = 1;
residual = 0;
```

line 168 Remember that nbuf is the total number of buffer cache in kernel. This number is displayed in kernel bootstrap message such as

```
console is keyboard/display
Copyright (c) 1996, 1997, 1998, 1999, 2000, 2001, 2002
    The NetBSD Foundation, Inc. All rights reserved.
Copyright (c) 1982, 1986, 1989, 1991, 1993
    The Regents of the University of California. All rights reserved.

NetBSD 1.6K (KERNEL) #0: Sat Nov 9 22:09:36 KST 2002
    cimon@ultra1:/usr/src/syssrc/sys/arch/sparc64/compile/KERNEL
total memory = 128 MB
avail memory = 108 MB
using 832 buffers containing 6656 KB of memory
otpath: /sbus@1f,0/SUNW,fas@e,8800000/sd@0,0
mainbusO (root): SUNW,Ultra-1
cpuO at mainbusO: SUNW,UltraSPARC @ 170 MHz, version 0 FPU
cpuO: 32K instruction (32 b/1), 16K data (32 b/1), 512K external (64 b/1)
```

The nbuf variable is set to 832, for a system having the above bootstrap message.

line 169 Do you remember where buf variable appeared? We described, in this section, that buf appears in arch/sparc64/compile/MY_KERNEL/param.c as

line 170 clears i-th buffer cache header in the system.

```
- arch/sparc64/compile/MY_KERNEL/param.c

199 struct buf *buf;
200 char *buffers;

- arch/sparc64/compile/MY_KERNEL/param.c
```

buf global variables the whole memory chunk that can hold all the buffer cache header.

This is initialized in **line 220** of kern/kern_allocsys.c. The line is equivalent to

```
ALLOCSYS(v, buf, struct buf, nbuf);
====> buf = (struct buf *) v;
    v = (caddr_t) ALIGN (buf + nbuf);
```

Therefore, buf points to a memory chunk that can hold all available buffer cache header in system. Ok? If you are not certain, review this section. And then you are still not certain, please ask me.

buffers global variables the whole memory chunk that can hold all the buffer cache contents. We already explained, in the previous subsection, how buffers is initialized.

line 171 Since the buffer pointed by bp is just initialized and empty, this buffer is not associated with any other physical storage device. Therefore set b_dev member of the buffer cache header to NODEV.

We showed the whole source code of buffer cache header in a previous section. And the definition of NODEV macro is in sys/param.h as

```
- sys/param.h

203 #define NODEV (dev_t)(-1) /* non-existent device */
- sys/param.h
```

line 172 This is some kinds of ad-hoc approach or hacking to make common linkedlist header. b_vnbufs member is a link to a linked-list that holds the vnode
for the buffer cache. However, the head for the linked-list is not defined.
Therefore, instead of using LIST_INIT macro requiring head node, this line
initializes the virtual link-list!

line 173 You may disregard it, since it is only used by Soft Dependency facilities.

line 174 set the b_data member of buffser cache to point the virtual memory chunk
 whose size is MAXBSIZE.

line 175-178 by default, only line 178 is effective.

line 179 set the status of buffer cache. Because buffer cache is not associated with any *vnode* or valid data, the status is set to B_INVAL.

line 180-181 by default, these two lines are equivalent to

```
binheadfree(bp, &bufqueues[BQ_AGE]);
```

meaning that a buffer cache pointed by bp variable is inserted in the head of AGE list, since the binheadfree is a macro defined as,

- kern/vfs_bio.c

kern/vfs_bio.c

line 182 places a buffer cache pointed by bp into invalid hash list. It is natural that the buffer cache does not go to hash list since it does not contain any contents.

```
kern/vfs_bio.c

86 /*

87 * Insq/Remq for the buffer hash lists.

88 */

89 #define binshash(bp, dp) LIST_INSERT_HEAD(dp, bp, b_hash)

90 #define bremhash(bp) LIST_REMOVE(bp, b_hash)

kern/vfs_bio.c
```

4.6 Buffer Cache Operation

In this section, we shows list of buffer cache operations that are used by filesystem. Buffer cache operations are defined in kern/vfs_bio.c and declared in sys/buf.h as,

```
sys/buf.h
260 void
            allocbuf __P((struct buf *, int));
261 void
            bawrite __P((struct buf *));
262 void
            bdirty __P((struct buf *));
263 void
            bdwrite __P((struct buf *));
            biodone __P((struct buf *));
264 void
265 int
            biowait __P((struct buf *));
266 int
            bread __P((struct vnode *, daddr_t, int,
267
                       struct ucred *, struct buf **));
            breada __P((struct vnode *, daddr_t, int, daddr_t, int,
268 int
                        struct ucred *, struct buf **));
269
            breadn __P((struct vnode *, daddr_t, int, daddr_t *, int *, int,
270 int
271
                        struct ucred *, struct buf **));
            brelse __P((struct buf *));
272 void
273 void
            bremfree __P((struct buf *));
274 void
            bufinit __P((void));
275 int
            bwrite __P((struct buf *));
276 void
            cluster_callback __P((struct buf *));
277 int
            cluster_read __P((struct vnode *, u_quad_t, daddr_t, long,
                              struct ucred *, struct buf **));
278
279 void
            cluster_write __P((struct buf *, u_quad_t));
280 struct buf *getblk __P((struct vnode *, daddr_t, int, int, int));
281 struct buf *geteblk __P((int));
282 struct buf *getnewbuf __P((int slpflag, int slptimeo));
283 struct buf *incore __P((struct vnode *, daddr_t));
284
285 void
            minphys __P((struct buf *bp));
            physio __P((void (*strategy)(struct buf *), struct buf *bp, dev_t dev,
286 int
287
                        int flags, void (*minphys)(struct buf *), struct uio *uio));
288
```

4.6.1 Finding a Buffer Cache from Hash: incore function

The following incore function is used to find a buffer cache related with a vnode that has specific logical file block number. (note that line **596-597**)

```
kern/vfs_bio.c
580 /*
581 * Determine if a block is in the cache.
582 * Just look on what would be its hash chain. If it's there, return
583 * a pointer to it, unless it's marked invalid. If it's marked invalid,
584 * we normally don't return the buffer, unless the caller explicitly
585 * wants us to.
586 */
587 struct buf *
588 incore(vp, blkno)
589
            struct vnode *vp;
590
            daddr_t blkno;
591 {
592
            struct buf *bp;
593
594
            /* Search hash chain */
595
            LIST_FOREACH(bp, BUFHASH(vp, blkno), b_hash) {
                    if (bp->b_lblkno == blkno && bp->b_vp == vp &&
596
597
                         !ISSET(bp->b_flags, B_INVAL))
598
                    return (bp);
599
            }
600
601
            return (NULL);
602 }
                                                       kern/vfs_bio.c
```

line 595 since buffer cache hash is actually an array of linked-lists, this access is logical. BUFHASH chooses an linked-list from the array. If you are not certain this operation, review a section describing usage of data structure in kernel, in chapter 1.

line 596 shows that buffer cache is identified with its associated vnode and logical $file\ block\ number$.

From the following sections, we will explain what the functions in the above list do.

4.7 Managing Buffer Cache Free Lists

4.7.1 Reusing Old Buffer: bremfree function

The bremfree function is used to remove a buffer cache from a free list.

kern/vfs_b

. . .

```
120 void
121 bremfree(bp)
122
            struct buf *bp;
123 {
124
            int s = splbio();
125
            struct bqueues *dp = NULL;
126
127
128
129
             * We only calculate the head of the freelist when removing
130
             * the last element of the list as that is the only time that
131
             * it is needed (e.g. to reset the tail pointer).
132
             \ast NB: This makes an assumption about how tailq's are implemented.
133
134
             */
135
            if (TAILQ_NEXT(bp, b_freelist) == NULL) {
136
                    for (dp = bufqueues; dp < &bufqueues[BQUEUES]; dp++)</pre>
137
                             if (dp->tqh_last == &bp->b_freelist.tqe_next)
138
                                     break;
                    if (dp == &bufqueues[BQUEUES])
139
140
                            panic("bremfree: lost tail");
141
            TAILQ_REMOVE(dp, bp, b_freelist);
142
143
            splx(s);
144 }
                                                     — kern/vfs_bio.c
```

- 124 splbio function blocks hardware interrupts from disks and other storage devices so that the buffer cache coherency is not disturbed.
- 135 Remind that the definition of TAILQ_NEXT and b_freelist member in struct buf as,

```
#define TAILQ_ENTRY(type)
struct {
       struct type *tqe_next; /* next element */
       struct type **tqe_prev; /* address of previous next element */ \
}
. . .
#define TAILQ_NEXT(elm, field)
                                   ((elm)->field.tqe_next)
and
struct buf {
       LIST_ENTRY(buf) b_hash;
                                      /* Hash chain. */
       LIST_ENTRY(buf) b_vnbufs;
                                      /* Buffer's associated vnode. */
       TAILQ_ENTRY(buf) b_freelist;
                                      /* Free list position if not active. */
       TAILQ_ENTRY(buf) b_actq;
                                      /* Device driver queue when active. */
```

line 135 checks whether the buffer cache pointed by bp pointer is the last elemenent in any one of four free lists.

line 136-140 find which free list contains the buffer cache. If the buffer cache to be removed from a free list is not the last element from the free list, there is no need to know the pointer to header.

But, if the buffer cache to be removed from a free list is the last element, there need to know the pointer to header

You may wonder why. As the **line 133** says, we need to know the implementation of tail queues to answer this reason.

 ${f line~142}$ remove the buffer cache from a free list.

From the below definition of TAILQ_REMOVE, we can find the why the pointer to the header of a free list in which the buffer cache pointed by bp lives, when the buffer cache is the last element of the free list.

line 143 Restore the interrupt process condition changed by line 124. For your reference, we show the definition of splbio and splx function of arch/sparc64/include/psl.h as,

arch/sparc64/include/psl.h

79 /* Interesting spl()s */ 80 #define PIL_SCSI 81 #define PIL_FDSOFT 4 82 #define PIL_AUSOFT 83 #define PIL_BIO 355 #define SPLHOLD(name, newpil) \ 356 static __inline int name __P((void)); \ 357 static __inline int name() \ 358 { \ 359 int oldpil; \ 360 __asm __volatile("rdpr %%pil,%0" : "=r" (oldpil)); \ if (newpil <= oldpil) \ 361 362 return oldpil; \ __asm __volatile("wrpr %%g0,%0,%%pil" : : "n" (newpil)); \ 363 return (oldpil); \ 364 365 } 366 #endif

arch/sparc64/include/psl.h

4.7.2

Allocating a New Buffer: getnewbuf function

If a process wants to read data from a file, the kernel determines which file system contains the file and which block in the filesystem contains the data. When about to read data from a particular disk block, the kernel checks the block is in the buffer cache and, if it is not there, assigns a new free buffer using getnewbuf function.

Up to now, we presented elaborated description, and from now on we gives brief explanation to reduce the size of this report :) The algorithm of this function is

```
start:
        if (there is a buffer on AGE free list)
                remove the buffer from AGE free list:
        } else if (there is a buffer on LRU free list)
                remove the buffer from LRU free list;
        } else {
                // There is no buffer in any free lists. Oops !
                sleep (event any buffers on free list);
                return NULL;
        }
        if (the buffer is being flushed to storage) {
                // Note that the buffer under flush is
                // just removed from LRU list
                //
                set the buffer go to AGE list when the flush is done;
                // check whether there is another free buffer */
                //
                goto start;
        }
        set the buffer cache as bust;
        if (buffer is marked for delayed write) {
                // Kernel must write the ''delayed write buffer''
```

```
// to storage and allocate another buffer !
    //
    set the buffer go to AGE list when the flush is done;
    start asynchronous write of the buffer to disk;
    return NULL;
}

// The buffer cache do not have filesystem
// logical block number associated with its data.
// Since logical block number is the hash key,
// the buffer cache no longer exist on hash.
//
disassociate the buffer cache from related vnode;
remove the buffer from old hash entry;
return buffer;
```

When the getnewbuf function returns NULL pointer, the caller of getnewbuf function generally try again calling the getnewbuf function.

— kern/vfs_bio.c 768 /* 769 * Find a buffer which is available for use. 770 * Select something from a free list. 771 * Preference is to AGE list, then LRU list. 772 */ 773 struct buf * 774 getnewbuf(slpflag, slptimeo) int slpflag, slptimeo; 775 776 { 777 struct buf *bp; 778 int s; 779 780 start: 781 s = splbio(); 782 if ((bp = TAILQ_FIRST(&bufqueues[BQ_AGE])) != NULL || 783 (bp = TAILQ_FIRST(&bufqueues[BQ_LRU])) != NULL) { bremfree(bp); 784 785 } else { /* wait for a free buffer of any kind */ 786 787 needbuffer = 1; tsleep(&needbuffer, slpflag|(PRIBIO+1), "getnewbuf", slptimeo); 788 789 splx(s); 790 return (NULL); } 791 792 793 if (ISSET(bp->b_flags, B_VFLUSH)) { 794 795 * This is a delayed write buffer being flushed to disk. Make * sure it gets aged out of the queue when it's finished, and 796 797 * leave it off the LRU queue. 798 799 CLR(bp->b_flags, B_VFLUSH);

```
800
                    SET(bp->b_flags, B_AGE);
801
                    splx(s);
802
                     goto start;
            }
803
804
805
            /* Buffer is no longer on free lists. */
            SET(bp->b_flags, B_BUSY);
806
807
808
             * If buffer was a delayed write, start it and return NULL
809
             * (since we might sleep while starting the write).
810
811
812
            if (ISSET(bp->b_flags, B_DELWRI)) {
                     splx(s);
813
814
                     /*
815
                     * This buffer has gone through the LRU, so make sure it gets
816
                      * reused ASAP.
817
                     */
818
                     SET(bp->b_flags, B_AGE);
819
                    bawrite(bp);
820
                    return (NULL);
821
            }
822
823
            /* disassociate us from our vnode, if we had one... */
824
            if (bp->b_vp)
825
                     brelvp(bp);
826
            splx(s);
827
            if (LIST_FIRST(&bp->b_dep) != NULL && bioops.io_deallocate)
828
829
                     (*bioops.io_deallocate)(bp);
830
831
            /* clear out various other fields */
832
            bp->b_flags = B_BUSY;
            bp->b_dev = NODEV;
833
            bp->b_blkno = bp->b_lblkno = bp->b_rawblkno = 0;
834
835
            bp->b_iodone = 0;
836
            bp->b_error = 0;
            bp->b_resid = 0;
837
838
            bp->b_bcount = 0;
839
840
            bremhash(bp);
841
            return (bp);
842 }
```

kern/vfs_bio.c

Source code is exact implementation of the algorithm that we just described. The only exception is **line 828-829** that can be ignored since these two lines is only effective when *Soft Dependency* facility is enabled.

4.7.3 Adjusting Buffer Size: allocbuf function

The task of allocbuf is to ensure that the buffer has enough physical memory allocated to it. The data are for each buffer is allocated MAXBSIZE bytes of virtual address space by bufinit function.

allocbuf compares the size of the intended data block with the amount of physical memory already allocated to the buffer.

- If there is excess physical memory,
 - and there is a buffer available on the EMPTY list, the excess memory is
 put into the empty buffer, and that buffer is then inserted onto the front
 of the AGE list.
 - If there are no buffers on the *EMPTY* lists, the excess physical memory is retained in the original buffer.
- If the buffer has insufficient memory, it takes memory from other buffers. allocbuf function does this allocation by calling getnewbuf function that we described in the previous subsection, to get a second buffer and transfer the physical memory in the second buffer to the new buffer under construction.
 - If there is memory remaining in the second buffer, the second buffer is released to the front of AGE list, otherwise the second buffer is released to the EMPTY list.
 - If the new buffer still does not have enough physical memory, the process is repeated.

------kern/vfs_bio.c

```
677 /*
678 * Expand or contract the actual memory allocated to a buffer.
679 *
* If the buffer shrinks, data is lost, so it's up to the
681 * caller to have written it out *first*; this routine will not
682 * start a write. If the buffer grows, it's the callers
* responsibility to fill out the buffer's additional contents.
684 */
685 void
686 allocbuf(bp, size)
687
            struct buf *bp;
688
            int size;
689 {
690
            struct buf *nbp;
691
            vsize_t desired_size;
692
            int s;
693
694
            desired_size = round_page((vsize_t)size);
695
            if (desired_size > MAXBSIZE)
                    panic("allocbuf: buffer larger than MAXBSIZE requested");
696
697
698
            if (bp->b_bufsize == desired_size)
699
                    goto out;
700
701
702
             * If the buffer is smaller than the desired size, we need to snarf
             * it from other buffers. Get buffers (via getnewbuf()), and
703
704
             * steal their pages.
705
             */
706
            while (bp->b_bufsize < desired_size) {</pre>
707
                    int amt;
```

```
708
709
                    /* find a buffer */
710
                    while ((nbp = getnewbuf(0, 0)) == NULL)
711
712
713
                    SET(nbp->b_flags, B_INVAL);
714
                    binshash(nbp, &invalhash);
715
716
                    /* and steal its pages, up to the amount we need */
                    amt = min(nbp->b_bufsize, (desired_size - bp->b_bufsize));
717
718
                    pagemove((nbp->b_data + nbp->b_bufsize - amt),
719
                              bp->b_data + bp->b_bufsize, amt);
720
                    bp->b_bufsize += amt;
721
                    nbp->b_bufsize -= amt;
722
723
                    /* reduce transfer count if we stole some data */
724
                    if (nbp->b_bcount > nbp->b_bufsize)
725
                             nbp->b_bcount = nbp->b_bufsize;
726
727 #ifdef DIAGNOSTIC
728
                    if (nbp->b_bufsize < 0)</pre>
729
                             panic("allocbuf: negative bufsize");
730 #endif
731
732
                    brelse(nbp);
733
            }
734
735
736
             * If we want a buffer smaller than the current size,
737
             * shrink this buffer. Grab a buf head from the EMPTY queue,
             \boldsymbol{\ast} move a page onto it, and put it on front of the AGE queue.
738
739
             * If there are no free buffer headers, leave the buffer alone.
740
             */
741
            if (bp->b_bufsize > desired_size) {
742
                    s = splbio();
                    if ((nbp = TAILQ_FIRST(&bufqueues[BQ_EMPTY])) == NULL) {
743
744
                             /* No free buffer head */
745
                             splx(s);
746
                             goto out;
747
748
                    bremfree(nbp);
749
                    SET(nbp->b_flags, B_BUSY);
750
                    splx(s);
751
752
                    /* move the page to it and note this change */
753
                    pagemove(bp->b_data + desired_size,
754
                        nbp->b_data, bp->b_bufsize - desired_size);
755
                    nbp->b_bufsize = bp->b_bufsize - desired_size;
756
                    bp->b_bufsize = desired_size;
757
                    nbp->b_bcount = 0;
758
                    SET(nbp->b_flags, B_INVAL);
759
760
                    /* release the newly-filled buffer and leave */
761
                    brelse(nbp);
```

The only additional information to understand every details of the above code, we think, is

- b_bcount member in struct buf used in line 724-724 represents the size of physical memory allocated to that buffer cache
- The reason that brelse function is called at line **761**, instead of directly putting into the AGE list, is to awake any possible process for the availability of a new buffer.

468 pmap_bootstrap(kernelstart, kernelend, maxctx)

u_int maxctx;

u_long kernelstart, kernelend;

• round_page macro is defined in uvm/uvm_param.h as

467 void

469

470

```
- uvm/uvm_param.h
   151 /*
   152 * Round off or truncate to the nearest page. These will work
   153 * for either addresses or counts (i.e., 1 byte rounds to 1 page).
   154 */
   155 #define round_page(x)
                                (((x) + PAGE_MASK) & ~PAGE_MASK)
   156 #define trunc_page(x)
                                ((x) & ~PAGE_MASK)
                                               — uvm/uvm_param.h
where the PAGE_MASK is defined as
                                           — uvm/uvm_param.h
    96 /*
               All references to the size of a page should be done with PAGE_SIZE
    97 *
               or PAGE_SHIFT. The fact they are variables is hidden here so that
    98 *
    99 *
               we can easily make them constant if we so desire.
    100 */
   101 #define PAGE_SIZE
                                uvmexp.pagesize
                                                        /* size of page */
   102 #define PAGE_MASK
                                uvmexp.pagemask
                                                        /* size of page - 1 */
   103 #define PAGE_SHIFT
                                                        /* bits to shift for pages */
                                uvmexp.pageshift
                                               - uvm/uvm_param.h
where the uvmexp.pagesize is set up in arch/sparc64/sparc64/pamp.c as,
                                  ——- arch/sparc64/sparc64/pmap.c
```

```
471 {
                /*
    491
    492
                  * set machine page size
    493
                  */
    494
                uvmexp.pagesize = NBPG;
    495
                uvmexp.ncolors = pmap_calculate_colors();
    496
                uvm_setpagesize();
                                      -- arch/sparc64/sparc64/pmap.c
where the NBPG is defined to 8192 as
                                        - arch/sparc64/include/param.h
                                                  /* log2(NBPG) */
    298 #define PGSHIFT
    299 #define NBPG
                                  (1<<PGSHIFT)
                                                  /* bytes/page */
    300 #define PGOFSET
                                  (NBPG-1)
                                                  /* byte offset into page */
                                        arch/sparc64/include/param.h
```

Consistency of Physical Memory Mapping

allocbuf function ensures that each physical-memory page is mapped into exactly one buffer at all times. So, the kernel maintains the consistency by purging old buffers when files are shortened or removed as follows.

- Whenever a file is removed,
 - 1. the kernel traverses its list of dirty buffers.
 - 2. For each buffer, the kernel cancels its write requests and
 - 3. marks the buffer invalid, so that the buffer cannot be found in the buffer pool again.
 - 4. Each invalid buffer is put at the front of the AGE list, so that it will be used before any buffers with potentially useful data.
- For a file being partially *truncated*, only the buffers following the truncation point are invalidated.

4.7.4 Getting a Buffer: getblk function

This function is the essential part in reading a logical file block into a buffer cache. The algorithm of getblk function is

```
return NULL;
                       }
                       sleep (until a buffer becomes free);
               }
               mark the buffer cache busy;
               remove the buffer from free list;
        }
        else
        {
                if (try to get a new buffer cache failed ?)
                {
                        goto start;
                }
                place the buffer cache into hash;
                associate the buffer cache with vnode;
        }
        ensure the buffer cache has desired amount of physical memory;
        return the buffer cache;
}
The source code for getblk function of kern/kern_bio.c is
                                                         — kern/vfs_bio.c
   604 /*
   605 * Get a block of requested size that is associated with
   606 * a given vnode and block offset. If it is found in the
   607 * block cache, mark it as having been found, make it busy
   608\ * and return it. Otherwise, return an empty block of the
   609 * correct size. It is up to the caller to insure that the
   610 * cached blocks be of the correct size.
   611 */
   612 struct buf *
   613 getblk(vp, blkno, size, slpflag, slptimeo)
                struct vnode *vp;
   615
                daddr_t blkno;
                int size, slpflag, slptimeo;
   616
   617 {
   618
                struct buf *bp;
   619
                int s, err;
   620
    621 start:
   622
                bp = incore(vp, blkno);
                if (bp != NULL) {
   623
                        s = splbio();
    624
                        if (ISSET(bp->b_flags, B_BUSY)) {
    625
    626
                                if (curproc == uvm.pagedaemon_proc) {
    627
                                        splx(s);
   628
                                        return NULL;
```

if (UVM is using the block ?)

```
}
629
630
                             SET(bp->b_flags, B_WANTED);
631
                             err = tsleep(bp, slpflag | (PRIBIO + 1), "getblk",
632
                                           slptimeo);
633
                             splx(s);
634
                             if (err)
635
                                     return (NULL);
636
                             goto start;
637
638 #ifdef DIAGNOSTIC
639
                     if (ISSET(bp->b_flags, B_DONE|B_DELWRI) &&
640
                         bp->b_bcount < size && vp->v_type != VBLK)
641
                             panic("getblk: block size invariant failed");
642 #endif
                     SET(bp->b_flags, B_BUSY);
643
644
                     bremfree(bp);
645
                     splx(s);
646
            } else {
647
                     if ((bp = getnewbuf(slpflag, slptimeo)) == NULL)
648
                             goto start;
649
650
                     binshash(bp, BUFHASH(vp, blkno));
651
                    bp->b_blkno = bp->b_lblkno = bp->b_rawblkno = blkno;
652
                     s = splbio();
653
                     bgetvp(vp, bp);
654
                     splx(s);
655
            }
            allocbuf(bp, size);
656
657
            return (bp);
658 }
                                                       kern/vfs_bio.c
```

For your reference, we show the code of bgetvp function that associate the buffer cache with vnode.

```
- kern/vfs_subr.c
135 /*
136 * Insq/Remq for the vnode usage lists.
137 */
138 #define bufinsvn(bp, dp)
                                    LIST_INSERT_HEAD(dp, bp, b_vnbufs)
139 #define bufremvn(bp) {
140
            LIST_REMOVE(bp, b_vnbufs);
141
            (bp)->b_vnbufs.le_next = NOLIST;
142 }
857 /*
858 * Associate a buffer with a vnode.
859 */
860 void
861 bgetvp(vp, bp)
862
            struct vnode *vp;
863
            struct buf *bp;
864 {
```

sys/vnode.h

sys/vnode.h

```
865
            int s;
866
            if (bp->b_vp)
867
868
                     panic("bgetvp: not free, bp %p", bp);
869
            VHOLD(vp);
870
            s = splbio();
871
            bp->b_vp = vp;
            if (vp->v_type == VBLK || vp->v_type == VCHR)
872
873
                     bp->b_dev = vp->v_rdev;
874
            else
875
                     bp->b_dev = NODEV;
876
877
              * Insert onto list for new vnode.
878
             */
879
            bufinsvn(bp, &vp->v_cleanblkhd);
880
            splx(s);
881 }
                                                       kern/vfs_subr.c
```

In line 871-873, note that b_vp and b_dev member of the buffer cache is set up to assiciate the vnode with the buffer. The buffer is inserted into the vnode clean list by line 879. The VHOLD vnode operation used in line 869 is defined in sys/vnode.h as

260 #define HOLDRELE(vp) holdrele(vp) 261 #define VHOLD(vp) vhold(vp) 262 #define VREF(vp) vref(vp) 302 /* 303 * increase buf or page ref 304 */ 305 static __inline void 306 vhold(struct vnode *vp) 307 { 308 309 simple_lock(&vp->v_interlock); if ((vp->v_freelist.tqe_prev != (struct vnode **)0xdeadb) && 310 vp->v_holdcnt == 0 && vp->v_usecount == 0) { 311 312 simple_lock(&vnode_free_list_slock); 313 TAILQ_REMOVE(&vnode_free_list, vp, v_freelist); 314 TAILQ_INSERT_TAIL(&vnode_hold_list, vp, v_freelist); 315 simple_unlock(&vnode_free_list_slock); } 316 317 vp->v_holdcnt++; 318 simple_unlock(&vp->v_interlock); 319 }

VHOLD vnode operation marks the vnode as active by incrementing vp->v_holdcnt and moving the vnode from the freelist to the holdlist. Once on the holdlist, the vnode will not be recycled until it is released with holdrele function.

kern/vfs_bio.c

4.8 Allocating and Reading Filesystem with Buffer Cache

From this section, the description is presented briefly as possible as we can, so that we improve on analysis speed.

```
kern/vfs_bio.c
186 static __inline struct buf *
187 bio_doread(vp, blkno, size, cred, async)
            struct vnode *vp;
188
189
            daddr_t blkno;
190
            int size;
191
            struct ucred *cred;
192
            int async;
193 {
194
            struct buf *bp;
195
            struct proc *p = (curproc != NULL ? curproc : &proc0); /* XXX */
196
            bp = getblk(vp, blkno, size, 0, 0);
197
198
199
200
             * If buffer does not have data valid, start a read.
201
             * Note that if buffer is B_INVAL, getblk() won't return it.
202
             * Therefore, it's valid if it's I/O has completed or been delayed.
203
             */
204
            if (!ISSET(bp->b_flags, (B_DONE | B_DELWRI))) {
205
                    /* Start I/O for the buffer. */
                    SET(bp->b_flags, B_READ | async);
206
207
                    VOP_STRATEGY(bp);
208
209
                    /* Pay for the read. */
210
                    p->p_stats->p_ru.ru_inblock++;
211
            } else if (async) {
212
                    brelse(bp);
            }
213
214
215
            return (bp);
216 }
```

line 197 get buffer containing the block or new block from buffer cache hash. This buffer is locked and on hash list, but not on free list.

line 204 check the block is already containing the desired block.

line 207 calls filesystem strategy routine. If the target filesystem is Fast Filesystem, then ufs_strategy is called. The VOP_STRATEGY is defined as,

```
struct vop_strategy_args a;
a.a_desc = VDESC(vop_strategy);
a.a_bp = bp;
return (VCALL(bp->b_vp, VOFFSET(vop_strategy), &a));
sys/vnode_if.h
```

line 211-212 Why should this buffer be returned to free list? Since asyncronoous read is requested for a block already on buffer cache hash, these lines try to return the buffer to free list.

```
ufs/ufs/ufs_vnops.c
1655 /*
1656 * Calculate the logical to physical mapping if not done already,
1657 * then call the device strategy routine.
1658 */
1659 int
1660 ufs_strategy(void *v)
1661 {
1662
             struct vop_strategy_args /* {
1663
                     struct buf *a_bp;
1664
             } */ *ap = v;
             struct buf
1665
                              *bp;
1666
             struct vnode
                              *vp;
             struct inode
1667
                             *ip;
1668
             int
                              error;
1669
             bp = ap->a_bp;
1670
             vp = bp->b_vp;
1671
1672
             ip = VTOI(vp);
             if (vp->v_type == VBLK || vp->v_type == VCHR)
1673
                     panic("ufs_strategy: spec");
1674
             KASSERT(bp->b_bcount != 0);
1675
1676
             if (bp->b_blkno == bp->b_lblkno) {
1677
                     error = VOP_BMAP(vp, bp->b_lblkno, NULL, &bp->b_blkno,
                                       NULL);
1678
                     if (error) {
1679
1680
                             bp->b_error = error;
1681
                             bp->b_flags |= B_ERROR;
1682
                             biodone(bp);
                             return (error);
1683
1684
                     if ((long)bp->b_blkno == -1) /* no valid data */
1685
                             clrbuf(bp);
1686
1687
             }
1688
             if ((long)bp->b_blkno < 0) { /* block is not on disk */
                     biodone(bp);
1689
                     return (0);
1690
             }
1691
             vp = ip->i_devvp;
1692
1693
             bp->b_dev = vp->v_rdev;
1694
             VOCALL (vp->v_op, VOFFSET(vop_strategy), ap);
```

line 1677 changes the logical block number of a file relative to the beginning of a file, to the physical block number of a filesystem relative to the beginning of a partition. b_lblkno member contains the logical block number of a file associated with the vnode. b_blkno member contains the physical block number of a filesystem.

line 1686 clears the buffer's data area. The macro definition is sys/buf.h

line 1692-1694 obtains the vnode for device driver of the filesystem such as CCD pseudo device driver, or SCSI general layer. And then, the strategy function of the driver or layer is called via *specfs* virtual filesystem layer! If the strategy function of the SCSI general layer is called, the function then calls the start function of SCSI device driver such as Adaptec Fast-Wide, or LSI logic controller, using physio function of kern/kern_physio.c.

biodone function is called by a device driver to mark I/O complete on the buffer that is just read or written.

```
kern/vfs_bio.c
869 /*
870 * Mark I/O complete on a buffer.
871 *
872 * If a callback has been requested, e.g. the pageout
873 * daemon, do so. Otherwise, awaken waiting processes.
874 *
875 * [ Leffler, et al., says on p.247:
876 *
            "This routine wakes up the blocked process, frees the buffer
            for an asynchronous write, or, for a request by the pagedaemon
877
878
            process, invokes a procedure specified in the buffer structure" ]
879
880 * In real life, the pagedaemon (or other system processes) wants
881 * to do async stuff to, and doesn't want the buffer brelse()'d.
882 * (for swap pager, that puts swap buffers on the free lists (!!!),
883 * for the vn device, that puts malloc'd buffers on the free lists!)
884 */
885 void
886 biodone(bp)
887
           struct buf *bp;
888 {
```

4.8. ALLOCATING AND READING FILESYSTEM WITH BUFFER CACHE119

```
889
            int s = splbio();
890
891
            if (ISSET(bp->b_flags, B_DONE))
892
                    panic("biodone already");
893
            SET(bp->b_flags, B_DONE);
                                                      /* note that it's done */
894
895
            if (LIST_FIRST(&bp->b_dep) != NULL && bioops.io_complete)
896
                     (*bioops.io_complete)(bp);
897
            if (!ISSET(bp->b_flags, B_READ))
898
                                                      /* wake up reader */
899
                    vwakeup(bp);
900
901
            if (ISSET(bp->b_flags, B_CALL)) {
                                                      /* if necessary, call out */
                                                      /* but note callout done */
902
                    CLR(bp->b_flags, B_CALL);
903
                     (*bp->b_iodone)(bp);
904
            } else {
905
                     if (ISSET(bp->b_flags, B_ASYNC))
                                                              /* if async, release */
906
                             brelse(bp);
907
                    else {
                                                      /* or just wakeup the buffer */
908
                             CLR(bp->b_flags, B_WANTED);
909
                             wakeup(bp);
910
                    }
911
            }
912
            splx(s);
913
914 }
```

line 898-899 Recall that the B_READ flag is set by bio_doread function. If this flag is not set, then biodone is called after write, therefore, decrease number of pending write in vnode structure. The definition of vwakeup function is

```
- kern/vfs_subr.c
630 /*
* Update outstanding I/O count and do wakeup if requested.
632 */
633 void
634 vwakeup(bp)
635
            struct buf *bp;
636 {
637
            struct vnode *vp;
638
639
            if ((vp = bp->b_vp) != NULL) {
640
                     if (--vp->v_numoutput < 0)</pre>
641
                             panic("vwakeup: neg numoutput, vp %p", vp);
642
                     if ((vp->v_flag & VBWAIT) && vp->v_numoutput <= 0) {</pre>
643
                             vp->v_flag &= ~VBWAIT;
644
                             wakeup((caddr_t)&vp->v_numoutput);
                     }
645
            }
646
647 }
```

kern/vfs_bio.c

kern/vfs_subr.c

line 905-906 returns a buffer that just finished asynchronous read to free list, since it is not immediately used. Remember that brelse function clears B_BUSY flag which is set by getblk function.

line 907-910 just wakeup the process waiting from biowait function for the completion of I/O.

4.8.1 Just Read: bread function

The filesystem allocates and fills buffers by calling the bread function. Bread function

- Takes a vnode, a logical block number, and a size, and
- Returns a pointer to a locked buffer.

It is important to remember that any other process that tries to obtain the buffer will be put to sleep until the buffer is released.

```
kern/vfs_bio.c
218 /*
219 * Read a disk block.
220 * This algorithm described in Bach (p.54).
221 */
222 int
223 bread(vp, blkno, size, cred, bpp)
224
            struct vnode *vp;
225
            daddr_t blkno;
226
            int size;
227
            struct ucred *cred;
228
            struct buf **bpp;
229 {
230
            struct buf *bp;
231
232
            /* Get buffer for block. */
233
            bp = *bpp = bio_doread(vp, blkno, size, cred, 0);
234
235
            /* Wait for the read to complete, and return result. */
236
            return (biowait(bp));
237 }
                                                       kern/vfs_bio.c
```

line 236 Remember that this is synchronous read, not asynchronous. The difference between them is that synchronous read wait for the completion of read operation from filesystem, but asynchronous read does not wait. To differentiate this trait, see the breadn function.

```
kern/vfs_bio.c

844 /*

845 * Wait for operations on the buffer to complete.

846 * When they do, extract and return the I/O's error value.

847 */

848 int

849 biowait(bp)
```

4.8. ALLOCATING AND READING FILESYSTEM WITH BUFFER CACHE121

```
850
            struct buf *bp;
851 {
852
            int s;
853
854
            s = splbio();
855
            while (!ISSET(bp->b_flags, B_DONE | B_DELWRI))
                     tsleep(bp, PRIBIO + 1, "biowait", 0);
856
857
            splx(s);
858
            /* check for interruption of I/O (e.g. via NFS), then errors. */
859
            if (ISSET(bp->b_flags, B_EINTR)) {
860
861
                     CLR(bp->b_flags, B_EINTR);
862
                     return (EINTR);
863
            } else if (ISSET(bp->b_flags, B_ERROR))
864
                     return (bp->b_error ? bp->b_error : EIO);
865
            else
866
                     return (0);
867 }
                                                       kern/vfs_bio.c
```

The places where the biowait function is called are,

bread function to wait for the completion of synchronous read.

breadn function to wait for the completion of synchronous read of the only first block: the rest block from the second to the end are asynchronously read, so that the biowait function is not used for the I/O completion of those blocks.

bwrite function to wait for the completion of synchronous write.

line 855-856 sleep until biodone function called by the relevant device driver strategy function, awakens this line.

4.8.2 Read Ahead Multiple Buffers: breadn function

```
kern/vfs_bio.c
239 /*
240 * Read-ahead multiple disk blocks. The first is sync, the rest async.
241 * Trivial modification to the breada algorithm presented in Bach (p.55).
242 */
243 int
244 breadn(vp, blkno, size, rablks, rasizes, nrablks, cred, bpp)
245
            struct vnode *vp;
246
            daddr_t blkno; int size;
247
            daddr_t rablks[]; int rasizes[];
248
            int nrablks;
249
            struct ucred *cred;
250
            struct buf **bpp;
251 {
252
            struct buf *bp;
253
            int i;
254
255
            bp = *bpp = bio_doread(vp, blkno, size, cred, 0);
256
```

```
257
             st For each of the read-ahead blocks, start a read, if necessary.
258
259
260
            for (i = 0; i < nrablks; i++) {
261
                    /* If it's in the cache, just go on to next one. */
262
                    if (incore(vp, rablks[i]))
                             continue;
263
264
265
                    /* Get a buffer for the read-ahead block */
266
                     (void) bio_doread(vp, rablks[i], rasizes[i], cred, B_ASYNC);
267
            }
268
269
            /* Otherwise, we had to start a read for it; wait until it's valid. */
270
            return (biowait(bp));
271 }
                                                      - kern/vfs_bio.c
```

line 270 only waits for the first block. It does not wait for the other blocks to finish I/O, since those blocks are read-ahead blocks and processed with asynchronous read.

4.8.3 Read Ahead a Single Buffer: breada function

```
kern/vfs_bio.c
273 /*
274 * Read with single-block read-ahead. Defined in Bach (p.55), but
275 * implemented as a call to breadn().
276 * XXX for compatibility with old file systems.
277 */
278 int
279 breada(vp, blkno, size, rablkno, rabsize, cred, bpp)
280
            struct vnode *vp;
281
            daddr_t blkno; int size;
            daddr_t rablkno; int rabsize;
282
283
            struct ucred *cred;
284
            struct buf **bpp;
285 {
286
287
            return (breadn(vp, blkno, size, &rablkno, &rabsize, 1, cred, bpp));
288 }
                                                     – kern/vfs_bio.c
```

4.9 Releasing Buffer Cache

A buffer can be relased by four ways: by brelse, bdwrite, bawrite, or bwrite function. The first one releases clean buffer and the latter three releases dirty buffer. dirty buffer means that a buffer which is modified and not yet written to storage.

4.9.1 Just Release: brelse function

brelse function releases a buffer when the buffer has NOT BEEN MODIFIED. This function

- 1. returns the buffer to free list and
- 2. awakens any process that are awaiting for it.

The essential algorithm of this function[2] is

```
1. wakeup all processes that is waiting for ANY buffer to become free
:from getnewbuf() function
```

```
2. wakeup all processes that is waiting for THIS buffer to become free :from getblk() function
```

4. unlock buffer

— kern/vfs_bio.c

```
469 * Release a buffer on to the free lists.
470 * Described in Bach (p. 46).
471 */
472 void
473 brelse(bp)
            struct buf *bp;
474
475 {
            struct bqueues *bufq;
476
477
            int s;
478
479
            KASSERT(ISSET(bp->b_flags, B_BUSY));
480
            /* Wake up any processes waiting for any buffer to become free. */
481
482
            if (needbuffer) {
483
                    needbuffer = 0;
484
                    wakeup(&needbuffer);
            }
485
486
487
            /* Block disk interrupts. */
488
            s = splbio();
489
```

```
490
            /* Wake up any processes waiting for _this_ buffer to become free. */
            if (ISSET(bp->b_flags, B_WANTED)) {
491
492
                    CLR(bp->b_flags, B_WANTED|B_AGE);
493
                    wakeup(bp);
494
            }
495
496
497
             * Determine which queue the buffer should be on, then put it there.
498
             */
499
500
            /* If it's locked, don't report an error; try again later. */
            if (ISSET(bp->b_flags, (B_LOCKED|B_ERROR)) == (B_LOCKED|B_ERROR))
501
502
                    CLR(bp->b_flags, B_ERROR);
503
504
            /* If it's not cacheable, or an error, mark it invalid. */
505
            if (ISSET(bp->b_flags, (B_NOCACHE|B_ERROR)))
506
                    SET(bp->b_flags, B_INVAL);
507
508
            if (ISSET(bp->b_flags, B_VFLUSH)) {
509
510
                     * This is a delayed write buffer that was just flushed to
511
                     * disk. It is still on the LRU queue. If it's become
512
                     * invalid, then we need to move it to a different queue;
513
                     * otherwise leave it in its current position.
514
                     */
515
                    CLR(bp->b_flags, B_VFLUSH);
516
                    if (!ISSET(bp->b_flags, B_ERROR|B_INVAL|B_LOCKED|B_AGE))
517
                             goto already_queued;
518
                    else
519
                            bremfree(bp);
            }
520
521
522
            if ((bp->b_bufsize <= 0) || ISSET(bp->b_flags, B_INVAL)) {
523
524
                     * If it's invalid or empty, dissociate it from its vnode
525
                     * and put on the head of the appropriate queue.
526
                     */
527
                    if (LIST_FIRST(&bp->b_dep) != NULL && bioops.io_deallocate)
528
                             (*bioops.io_deallocate)(bp);
529
                    CLR(bp->b_flags, B_DONE|B_DELWRI);
                    if (bp->b_vp) {
530
531
                            reassignbuf(bp, bp->b_vp);
532
                            brelvp(bp);
533
534
                    if (bp->b_bufsize <= 0)</pre>
535
                             /* no data */
536
                            bufq = &bufqueues[BQ_EMPTY];
537
                    else
538
                             /* invalid data */
539
                            bufq = &bufqueues[BQ_AGE];
540
                    binsheadfree(bp, bufq);
541
            } else {
542
543
                     * It has valid data. Put it on the end of the appropriate
```

kern/vfs_bio.c

```
544
                      * queue, so that it'll stick around for as long as possible.
545
                      * If buf is AGE, but has dependencies, must put it on last
                      * bufqueue to be scanned, ie LRU. This protects against the
546
                      st livelock where BQ_AGE only has buffers with dependencies,
547
548
                      * and we thus never get to the dependent buffers in BQ_LRU.
549
                      */
                    if (ISSET(bp->b_flags, B_LOCKED))
550
                             /* locked in core */
551
                             bufq = &bufqueues[BQ_LOCKED];
552
553
                    else if (!ISSET(bp->b_flags, B_AGE))
                             /* valid data */
554
                             bufq = &bufqueues[BQ_LRU];
555
556
                    else {
557
                             /* stale but valid data */
558
                             int has_deps;
559
560
                             if (LIST_FIRST(&bp->b_dep) != NULL &&
561
                                 bioops.io_countdeps)
                                     has_deps = (*bioops.io_countdeps)(bp, 0);
562
563
                             else
                                     has_deps = 0;
564
                             bufq = has_deps ? &bufqueues[BQ_LRU] :
565
                                 &bufqueues[BQ_AGE];
566
567
                    binstailfree(bp, bufq);
568
569
            }
570
571 already_queued:
572
            /* Unlock the buffer. */
            CLR(bp->b_flags, B_AGE|B_ASYNC|B_BUSY|B_NOCACHE);
573
            SET(bp->b_flags, B_CACHE);
574
575
            /* Allow disk interrupts. */
576
577
            splx(s);
578 }
```

line 501-502 might be disregarded, if you do not focus on LFS, since only the LFS uses the LOCKED free list.

line 505-506 B_NOCACHE flag says that the buffer should not be cached after use. Therefore, it is set up with B_INVAL flag. The buffer with this flag can be on a free list, but the buffer cannot be searched by incore function.

 $line\ 508-520$ B_VFLUSH flag says that the buffer is being flushed to disk. Buffers are set with this flag by

- vinvalbuf function of kern/vfs_subr.c that flush out and invalidate all buffers associated with a vnode.
- ffs_full_fsync function of ufs/ffs/ffs_vnops.c to flush out all dirty data associated with a vnode.
- ffs_fsync function of ufs/ffs_vnops.c to flush out ranged dirty data associated with a vnode.

If otherwise specified, the buffer with B_VFLUSH flag stays in free list longer than other buffers: see line 793-803 of getnewbuf function scheduling a buffer of this kind to move from LRU free list to AGE free list, instead of immediate reuse.

line 557-566 If Soft Dependency facility is not enabled, has_deps variable is set

The reassign function used in line 531 is used to update the status of vnode associated the buffer cache before calling brelvp function in line 532. According to the

```
kern/vfs_subr.c
915 /*
916 * Reassign a buffer from one vnode to another.
917 * Used to assign file specific control information
918 * (indirect blocks) to the vnode to which they belong.
919 *
920 * This function must be called at splbio().
921 */
922 void
923 reassignbuf(bp, newvp)
            struct buf *bp;
924
925
            struct vnode *newvp;
926 {
927
            struct buflists *listheadp;
928
            int delay;
929
930
931
             * Delete from old vnode list, if on one.
932
             */
933
            if (LIST_NEXT(bp, b_vnbufs) != NOLIST)
934
                    bufremvn(bp);
935
            /*
936
             * If dirty, put on list of dirty buffers;
937
             * otherwise insert onto list of clean buffers.
938
             */
939
            if ((bp->b_flags & B_DELWRI) == 0) {
                    listheadp = &newvp->v_cleanblkhd;
940
941
                    if (TAILQ_EMPTY(&newvp->v_uobj.memq) &&
                         (newvp->v_flag & VONWORKLST) &&
942
                        LIST_FIRST(&newvp->v_dirtyblkhd) == NULL) {
943
                            newvp->v_flag &= ~VONWORKLST;
944
945
                            LIST_REMOVE(newvp, v_synclist);
946
                    }
947
            } else {
948
                    listheadp = &newvp->v_dirtyblkhd;
949
                    if ((newvp->v_flag & VONWORKLST) == 0) {
950
                            switch (newvp->v_type) {
                             case VDIR:
951
                                     delay = dirdelay;
952
953
                                    break;
954
                             case VBLK:
955
                                     if (newvp->v_specmountpoint != NULL) {
```

kern/vfs_subr.c

```
956
                                                  delay = metadelay;
    957
                                                  break;
    958
                                         }
    959
                                         /* fall through */
    960
                                 default:
    961
                                         delay = filedelay;
    962
                                         break;
    963
                                 }
    964
                                 if (!newvp->v_mount ||
                                     (newvp->v_mount->mnt_flag & MNT_ASYNC) == 0)
    965
    966
                                         vn_syncer_add_to_worklist(newvp, delay);
                         }
    967
    968
    969
                bufinsvn(bp, listheadp);
    970 }
                                                         - kern/vfs_subr.c
where the definition of brelvp function is
                                                         - kern/vfs_subr.c
    883 /*
    884 * Disassociate a buffer from a vnode.
    885 */
    886 void
    887 brelvp(bp)
    888
                struct buf *bp;
    889 {
    890
                struct vnode *vp;
    891
                int s;
    892
                if (bp->b_vp == NULL)
    893
    894
                        panic("brelvp: vp NULL, bp %p", bp);
    895
    896
                s = splbio();
    897
                vp = bp->b_vp;
    898
                /*
    899
                 * Delete from old vnode list, if on one.
    900
                 */
                if (LIST_NEXT(bp, b_vnbufs) != NOLIST)
    901
    902
                        bufremvn(bp);
    903
    904
                if (TAILQ_EMPTY(&vp->v_uobj.memq) && (vp->v_flag & VONWORKLST) &&
    905
                    LIST_FIRST(&vp->v_dirtyblkhd) == NULL) {
                         vp->v_flag &= ~VONWORKLST;
    906
    907
                        LIST_REMOVE(vp, v_synclist);
    908
                }
    909
    910
                bp->b_vp = NULL;
                HOLDRELE(vp);
    911
    912
                splx(s);
    913 }
```

4.9.2 Delayed Write: bdwrite function

bdwrite function releases a buffer when the buffer has been MODIFIED and EX-PECTED to be modified soon again. This function

- 1. marks the buffer as dirty with B_DIRTY flags, but is not immediately written. Instead,
- 2. returns the buffer to the free list and
- 3. awakens any processes waiting for it.

```
kern/vfs_bio.c
380 /*
381 * Delayed write.
382 *
383 * The buffer is marked dirty, but is not queued for I/O.
384 * This routine should be used when the buffer is expected
385 * to be modified again soon, typically a small write that
386 * partially fills a buffer.
387 *
388 * NB: magnetic tapes cannot be delayed; they must be
389 * written in the order that the writes are requested.
390 *
391 * Described in Leffler, et al. (pp. 208-213).
392 */
393 void
394 bdwrite(bp)
395
            struct buf *bp;
396 {
397
            struct proc *p = (curproc != NULL ? curproc : &proc0); /* XXX */
398
            const struct bdevsw *bdev;
399
            int s;
400
            /* If this is a tape block, write the block now. */
401
            /* XXX NOTE: the memory filesystem usurpes major device */
402
403
                         number 4095, which is a bad idea.
404
            if (bp->b_dev != NODEV && major(bp->b_dev) != 4095) {
405
                    bdev = bdevsw_lookup(bp->b_dev);
406
                    if (bdev != NULL && bdev->d_type == D_TAPE) {
407
                            bawrite(bp);
408
                            return:
                    }
409
            }
410
411
412
413
             * If the block hasn't been seen before:
414
                    (1) Mark it as having been seen,
415
                    (2) Charge for the write,
                    (3) Make sure it's on its vnode's correct block list.
416
             */
417
418
            s = splbio();
419
420
            if (!ISSET(bp->b_flags, B_DELWRI)) {
421
                    SET(bp->b_flags, B_DELWRI);
```

```
422
                     p->p_stats->p_ru.ru_oublock++;
423
                     reassignbuf(bp, bp->b_vp);
424
            }
425
426
            /* Otherwise, the "write" is done, so mark and release the buffer. */
427
            CLR(bp->b_flags, B_NEEDCOMMIT|B_DONE);
428
            splx(s);
429
430
            brelse(bp);
431 }
                                                      — kern/vfs_bio.c
```

4.9.3 Asynchronous Write: bawrite function

bawrite function releases a buffer when the buffer has been MODIFIED and NOT EXPECTED to modified soon again. This function

- 1. schedules an I/O on the buffer, but
- 2. allows the caller to continue running while the scheduled I/O completes.

Implementation of bawrite is the same as bwrite function that does synchronous write except the bawrite set B_ASYNC flag. Now we will describe the reason with source code.

```
kern/vfs_bio.c
433 /*
434 * Asynchronous block write; just an asynchronous bwrite().
435 */
436 void
437 bawrite(bp)
438
             struct buf *bp;
439 {
440
441
             SET(bp->b_flags, B_ASYNC);
442
             VOP_BWRITE(bp);
443 }
                                                        - \text{kern/vfs\_bio.c}
```

where the definition of **VOP_BWRITE** is, unless we are compiling assuming we are not using loadable kernel module (LKM),

where the **line 1636** would call, if we are using FFS, vn_bwrite function, since the *vnode operation vector description table* of FFS is defined in ufs/ffs/vfs_vnops.c as, (notice the **line 121**)

```
71 /* Global vfs data structures for ufs. */
72 int (**ffs_vnodeop_p) __P((void *));
73 const struct vnodeopv_entry_desc ffs_vnodeop_entries[] = {
            { &vop_default_desc, vn_default_error },
75
            { &vop_lookup_desc, ufs_lookup },
                                                             /* lookup */
76
            { &vop_create_desc, ufs_create },
                                                             /* create */
77
            { &vop_whiteout_desc, ufs_whiteout },
                                                             /* whiteout */
78
            { &vop_mknod_desc, ufs_mknod },
                                                             /* mknod */
            { &vop_open_desc, ufs_open },
                                                             /* open */
79
            { &vop_close_desc, ufs_close },
                                                             /* close */
80
            { &vop_access_desc, ufs_access },
                                                             /* access */
82
            { &vop_getattr_desc, ufs_getattr },
                                                             /* getattr */
83
            { &vop_setattr_desc, ufs_setattr },
                                                            /* setattr */
            { &vop_read_desc, ffs_read },
                                                             /* read */
84
            { &vop_bwrite_desc, vn_bwrite },
                                                             /* bwrite */
121
124
            { NULL, NULL }
```

The code of vn_bwrite called by FFS VOP_BWRITE operation is,

Therefore, for FFS, bawrite function calls bwrite function after setting B_ASYNC flag on the buffer.

4.9.4 Synchronous Write: bwrite function

bwrite function releases a buffer when the buffer has been MODIFIED. This function ENSURES that the writing the buffer to storage is complete before proceeding.

```
294 bwrite(bp)
295
           struct buf *bp;
296 {
297
            int rv, sync, wasdelayed, s;
298
            struct proc *p = (curproc != NULL ? curproc : &proc0); /* XXX */
299
            struct vnode *vp;
300
           struct mount *mp;
301
302
            vp = bp->b_vp;
            if (vp != NULL) {
303
304
                    if (vp->v_type == VBLK)
305
                            mp = vp->v_specmountpoint;
306
                    else
307
                            mp = vp->v_mount;
308
            } else {
309
                    mp = NULL;
310
            }
311
            /*
312
313
             * Remember buffer type, to switch on it later. If the write was
314
             * synchronous, but the file system was mounted with MNT_ASYNC,
315
            * convert it to a delayed write.
316
            * XXX note that this relies on delayed tape writes being converted
             * to async, not sync writes (which is safe, but ugly).
317
318
319
            sync = !ISSET(bp->b_flags, B_ASYNC);
320
            if (sync && mp != NULL && ISSET(mp->mnt_flag, MNT_ASYNC)) {
321
                    bdwrite(bp);
322
                    return (0);
323
            }
324
325
            /*
326
             * Collect statistics on synchronous and asynchronous writes.
327
             * Writes to block devices are charged to their associated
328
             * filesystem (if any).
329
             */
            if (mp != NULL) {
330
331
                    if (sync)
332
                            mp->mnt_stat.f_syncwrites++;
333
                    else
334
                            mp->mnt_stat.f_asyncwrites++;
335
            }
336
337
            wasdelayed = ISSET(bp->b_flags, B_DELWRI);
338
339
            s = splbio();
340
341
            CLR(bp->b_flags, (B_READ | B_DONE | B_ERROR | B_DELWRI));
342
343
344
             * Pay for the I/O operation and make sure the buf is on the correct
345
             * vnode queue.
346
             */
347
            if (wasdelayed)
```

```
348
                     reassignbuf(bp, bp->b_vp);
349
            else
350
                     p->p_stats->p_ru.ru_oublock++;
351
352
            /* Initiate disk write. Make sure the appropriate party is charged. */
353
            bp->b_vp->v_numoutput++;
354
            splx(s);
355
            VOP_STRATEGY(bp);
356
357
358
            if (sync) {
359
                     /* If I/O was synchronous, wait for it to complete. */
360
                     rv = biowait(bp);
361
                     /* Release the buffer. */
362
363
                     brelse(bp);
364
365
                     return (rv);
            } else {
366
367
                     return (0);
368
            }
369 }
                                                        kern/vfs_bio.c
```

Buffers that are written using bawrite or bwrite function are placed on the appropriate output queue. When the output completes, the brelse function is called to return those buffers to the free list and to awaken any processes that are waiting for them.

For asynchronous write, the buffer is returned to free list by **line 906** of biodone function called by the relevant device driver strategy function.

For synchronous write, the buffer is returned to free list by **line 363** of bwrite function after waiting for the completion of write.

4.10 References to Source Code

4.10.1 kern/vfs_bio.c - 334 lines, 21 functions

Global Variables

```
LIST_HEAD(bufhashhdr, buf) *bufhashtbl, invalhash; // buffer cache hash
u_long bufhash; // buffer cache hash mask
TAILQ_HEAD(bqueues, buf) bufqueues[BQUEUES]; // buffer cache free lists
int needbuffer; // buffer cache locking
struct pool bufpool; // buffers for physio()
```

Functions

```
bremfree()
bufinit()
bio_doread()
bread()
breadn()
breada()
bwrite()
```

```
vn_bwrite()
bdwrite()
bdwrite()
bdirty()
brelse()
incore()
getblk()
geteblk()
allocbuf()
getnewbuf()
biowait()
biodone()
count_lock_queue()
vfs_bufstats()
```

Chapter 5

Vnode

5.1 Introduction

The vnode is the focus of all file activity in NetBSD. There is a unique vnode allocated for each active file, directory, mounted-on file, fifo, domain socket, symbolic link and device. The kernel has no concept of a file's structure and so it relies on the information stored in the vnode to describe the file. Thus, the vnode associated with a file holds all the administration information pertaining to it.

When a process requests an operation on a file, the vfs interface passes control to a file system type dependent function to carry out the opera-tion. If the file system type dependent function finds that a vnode rep-resenting the file is not in main memory, it dynamically allocates a new vnode from the system main memory pool. Once allocated, the vnode is at-tached to the data structure pointer associated with the cause of the vn-ode allocation and it remains resident in the main memory until the sys-tem decides that it is no longer needed and can be recycled.

5.2 Vnode Management Function

The vnode has the following structure:

```
struct vnode {
        struct uvm_object v_uobj;
                                                /* uvm object */
#define v_usecount
                        v_uobj.uo_refs
#define v_interlock
                        v_uobj.vmobjlock
                                                /* size of file */
        voff_t
                        v_size;
                                                /* flags */
        int
                        v_flag;
                                                /* num pending writes */
        int.
                        v_numoutput;
                                                /* ref count of writers */
        long
                        v_writecount;
                        v_holdcnt;
                                                /* page & buffer refs */
        long
        daddr_t
                        v_lastr;
                                                /* last read */
                                                /* capability id */
        u_long
                        v_id;
                        *v_mount;
                                                /* ptr to vfs we are in */
        struct mount
                        (**v_op)(void *);
                                                /* vnode ops vector */
        TAILQ_ENTRY(vnode) v_freelist;
                                                /* vnode freelist */
        LIST_ENTRY(vnode) v_mntvnodes;
                                                /* vnodes for mount pt */
                                                /* clean blocklist head */
        struct buflists v_cleanblkhd;
```

```
/* dirty blocklist head */
       struct buflists v_dirtyblkhd;
       LIST_ENTRY(vnode) v_synclist;
                                             /* dirty vnodes */
       union {
               struct mount *vu_mountedhere;/* ptr to mounted vfs */
               struct socket *vu_socket;
                                            /* unix ipc (VSOCK) */
                                            /* device (VCHR, VBLK) */
               struct specinfo *vu_specinfo;
               struct fifoinfo *vu_fifoinfo; /* fifo (VFIFO) */
       } v_un;
#define v_mountedhere v_un.vu_mountedhere
#define v_socket
                     v un.vu socket
#define v_specinfo
                     v_un.vu_specinfo
                    v_un.vu_fifoinfo
#define v_fifoinfo
       struct nqlease *v_lease;
                                             /* Soft ref to lease */
                                             /* vnode type */
       enum vtype
                      v_type;
                                             /* underlying data type */
       enum vtagtype v_tag;
       struct lock v_lock;
                                            /* lock for this vnode */
       struct lock
                      *v_vnlock;
                                             /* ptr to vnode lock */
                                             /* private data for fs */
       void
                      *v_data;
};
```

Most functions discussed in this page that operate on vnodes cannot be called from interrupt context. The members v_numoutput, v_holdcnt, v_dirtyblkhd, v_cleanblkhd, v_freelist, and v_synclist are modified in interrupt context and must be protected by splbio(9) unless it is certain that there is no chance an interrupt handler will modify them. The vnode lock must not be acquired within interrupt context.

5.2.1 Vnode Flag

Vnode flags are recorded by v_flag. Valid flags are:

```
VROOT
            This vnode is the root of its file system.
VTEXT
            This vnode is a pure text prototype
VEXECMAP
            This vnode has executable mappings
VSYSTEM
            This vnode being used by kernel; only used to skip the
            vflush() operation quota files.
VISTTY
            This vnode represents a tty; used when reading dead vn-
            odes.
           This vnode is currently locked to change underlying
VXLOCK
VXWANT
            A process is waiting for this vnode.
VBWATT
           Waiting for output associated with this vnode to com-
            plete.
VALIASED
            This vnode has an alias.
VDIROP
            This vnode is involved in a directory operation. This
            flag is used exclusively by LFS.
VLAYER
           This vnode is on a layer filesystem.
VONWORKLST This vnode is on syncer work-list.
           This vnode possibly has dirty pages.
VDTR.TY
```

The VXLOCK flag is used to prevent multiple processes from entering the vnode reclamation code. It is also used as a flag to indicate that reclamation is in progress. The VXWANT flag is set by threads that wish to be awaken when reclamation is finished. Before v_flag can be modified,

the v_interlock simplelock must be acquired. See lock(9) for details on the kernel locking API.

vflush(mp, skipvp, flags)

Remove any vnodes in the vnode table belonging to mount point mp. If skipvp is not NULL it is exempt from being flushed. The argument flags is a set of flags modifying the operation of vflush(). If MNT_NOFORCE is specified, there should not be any active vnodes and an error is returned if any are found (this is a user error, not a system error). If MNT_FORCE is specified, active vnodes that are found are detached.

5.2.2 Reference Counts

Each vnode has three reference counts: v_usecount, v_writecount and v_holdcnt. The first is the number of active references within the kernel to the vnode. This count is maintained by vref(), vrele(), and vput(). The second is the number of active references within the kernel to the vnode performing write access to the file. It is maintained by the open(2) and close(2) system calls. The third is the number of references within the kernel requiring the vnode to remain active and not be recycled. This count is maintained by vhold() and holdrele(). When both the v_usecount and v_holdcnt reach zero, the vnode is recycled to the freelist and may be reused for another file. The transition to and from the freelist is handled by getnewvnode(), ungetnewvnode() and vrecycle(). Access to v_usecount, v_writecount and v_holdcnt is also protected by the v_interlock simplelock.

The number of pending synchronous and asynchronous writes on the vnode are recorded in v_numoutput. It is used by fsync(2) to wait for all writes to complete before returning to the user. Its value must only be modified at splbio. See spl(9). It does not track the number of dirty buffers attached to the vnode.

vref(vp)

Increment v_usecount of the vnode vp. Any kernel thread system which uses a vnode (e.g. during the operation of some algorithm or to store in a data structure) should call vref().

VREF(vp)

This function is an alias for vref().

vrele(vp)

Decrement v_usecount of unlocked vnode vp. Any code in the system which is using a vnode should call vrele() when it is finished with the vnode. If v_usecount of the vnode reaches zero and v_holdcnt is greater than zero, the vnode is placed on the holdlist. If both v_usecount and v_holdcnt are zero, the vnode is placed on the freelist.

vput(vp)

Unlock vnode vp and decrement its $v_{\rm u}$ usecount. Depending of the reference counts, move the vnode to the holdlist or the freelist. This operation is functionally equivalent to calling

VOP_UNLOCK(9) followed by vrele().

vhold(vp)

Mark the vnode vp as active by incrementing vp->v_holdcnt and moving the vnode from the freelist to the holdlist. Once on the holdlist, the vnode will not be recycled until it is released with holdrele().

VHOLD(vp)

This function is an alias for vhold().

holdrele(vp)

Mark the vnode vp as inactive by decrementing vp->v_holdcnt and moving the vnode from the holdlist to the freelist.

HOLDRELE(vp)

This function is an alias for holdrele().

getnewvnode(tag, mp, vops, vpp)

Retrieve the next vnode from the freelist. getnewvnode() must choose whether to allocate a new vnode or recycle an existing one. The criterion for allocating a new one is that the total number of vnodes is less than the number desired or there are no vnodes on either free list. Generally only vnodes that have no buffers associated with them are recycled and the next vnode from the freelist is retrieved. If the freelist is empty, vnodes on the holdlist are considered. The new vnode is returned in the address specified by vpp.

The argument mp is the mount point for the file system requested the new vnode. Before retrieving the new vnode, the file system is checked if it is busy (such as currently unmounting). An error is returned if the file system is unmounted.

The argument tag is the vnode tag assigned to *vpp->v_tag. The argument vops is the vnode operations vector of the file system requesting the new vnode. If a vnode is successfully retrieved zero is returned, otherwise and appropriate error code is returned.

ungetnewvnode(vp)

Undo the operation of getnewvnode(). The argument vp is the vn-ode to return to the freelist. This function is needed for VFS_VGET(9) which may need to push back a vnode in case of a locking race condition.

vrecycle(vp, inter_lkp, p)

Recycle the unused vnode vp to the front of the freelist. vrecycle() is a null operation if the reference count is greater than zero.

vcount(vp)

Calculate the total number of reference counts to a special device with vnode $\ensuremath{\text{vp}}.$

5.2.3 Vnode Identifier

Every time a vnode is reassigned to a new file, the vnode capability identifier v_id is changed. It is used to maintain the name lookup cache consistency by providing a unique <vnode *,v_id> tuple without requiring the cache to hold a reference. The name lookup cache can later compare the vnode's capability identifier to its copy and see if the vnode still points to the same file. See namecache(9) for details on the name lookup cache.

5.2.4 Links to Virtual File System Information

The link to the file system which owns the vnode is recorded by v_mount. See vfsops(9) for further information of file system mount status.

The v_op pointer points to its vnode operations vector. This vector describes what operations can be done to the file associated with the vn-ode. The system maintains one vnode operations vector for each file system type configured into the kernel. The vnode operations vector con-tains a pointer to a function for each operation supported by the file system. See vnodeops(9) for a description of vnode operations.

5.2.5 Vnode Cache

When not in use, vnodes are kept on the freelist through v_freelist. The vnodes still reference valid files but may be reused to refer to a new file at any time. Often, these vnodes are also held in caches in the system, such as the name lookup cache. When a valid vnode which is on the freelist is used again, the user must call vget() to increment the reference count and retrieve it from the freelist. When a user wants a new vnode for another file getnewvnode() is invoked to remove a vnode from the freelist and initialise it for the new file.

vget(vp, lockflags)

Reclaim vnode vp from the freelist, increment its reference count and lock it. The argument lockflags specifies the lockmgr(9) flags used to lock the vnode. If the VXLOCK is set in vp's v_flag, vnode vp is being recycled in vgone() and the calling thread sleeps until the transition is complete. When it is awakened, an error is returned to indicate that the vnode is no longer usable (possibly having been recycled to a new file system type).

vgone(vp)

Eliminate all activity associated with the vnode vp in preparation for recycling.

5.2.6 Type of Object

The type of object the vnode represents is recorded by v_type. It is used by generic code to perform checks to ensure operations are performed on valid file system objects. Valid types are:

VNON The vnode has no type.

```
VREG The vnode represents a regular file.

VDIR The vnode represents a directory.

VBLK The vnode represents a block special device.

VCHR The vnode represents a character special device.

VLNK The vnode represents a symbolic link.

VSOCK The vnode represents a socket.

VFIFO The vnode represents a pipe.

VBAD The vnode represents a bad file (not currently used).
```

Vnode tag types are used by external programs only (eg pstat(8)), and should never be inspected by the kernel. Its use is deprecated since new v_tag values cannot be defined for loadable file systems. The v_tag member is read-only. Valid tag types are:

```
VT_NON
            non file system
VT_UFS
             universal file system
VT_NFS
            network file system
VT_MFS
            memory file system
VT_MSDOSFS
            FAT file system
VT_LFS
             log-structured file system
VT_LOFS
            loopback file system
VT_FDESC
            file descriptor file system
VT_PORTAL
            portal daemon
VT_NULL
            null file system layer
VT_UMAP
            sample file system layer
VT_KERNFS
            kernel interface file system
VT_PROCFS
            process interface file system
VT_AFS
            AFS file system
            ISO file system(s)
VT_ISOFS
VT_UNION
            union file system
VT_ADOSFS
            Amiga file system
VT_EXT2FS
            Linux's EXT2 file system
VT_CODA
             Coda file system
VT_FILECORE filecore file system
VT_NTFS
            Microsoft NT's file system
VT_VFS
             virtual file system
VT_OVERLAY
            overlay file system
```

5.2.7 Vnode Lock

All vnode locking operations use v_vnlock. This lock is acquired by calling vn_lock(9) and released by calling vn_unlock(9). The vnode locking operation is complicated because it is used for many purposes. Sometimes it is used to bundle a series of vnode operations (see vnodeops(9)) into an atomic group. Many file systems rely on it to prevent race conditions in updating file system type specific data structures rather than using their own private locks. The vnode lock operates as a multiple-reader (shared-access lock) or single-writer lock (exclusive access lock). The lock may be held while sleeping. While the v_vnlock is acquired, the holder is guaranteed that the vnode will not be reclaimed or invalidated. Most file system functions require that you hold the vnode lock on entry. See lock(9) for details on the kernel locking API.

For leaf file systems (such as ffs, lfs, msdosfs, etc), v_vnlock will

point to v_lock . For stacked filesystems, v_vnlock will generally point to v_vlock of the lowest file system. Additionally, the implementation of the vnode lock is the responsibility of the individual file systems and v_vnlock may also be NULL indicating that a leaf node does not export a lock for vnode locking. In this case, stacked file systems (such as nullfs) must call the underlying file system directly for locking.

vwakeup(bp)

Update outstanding I/O count vp->v_numoutput for the vnode bp->b_vp and do wakeup if requested and vp->vflag has VBWAIT set.

5.2.8 Private Area

Files and file systems are inextricably linked with the virtual memory system and v_uobj contains the data maintained by the virtual memory system. For compatibility with code written before the integration of uvm(9) into NetBSD C-preprocessor directives are used to alias the members of v_uobj.

Each file system underlying a vnode allocates its own private area and hangs it from v_data. If non-null, this area is freed by getnewvnode().

5.2.9 Other Vnode-Manipulating Functions

vaccess(type, file_mode, uid, gid, acc_mode, cred)

Do access checking. The arguments file_mode, uid, and gid are from the vnode to check. The arguments acc_mode and cred are passed directly to VOP_ACCESS(9).

checkalias(vp, nvp_rdev, mp)

Check to see if the new vnode vp represents a special device for which another vnode represents the same device. If such an aliases exists the existing contents and the aliased vnode are deallocated. The caller is responsible for filling the new vnode with its new contents.

bdevvp(dev, vpp)

Create a vnode for a block device. bdevvp() is used for root file systems, swap areas and for memory file system special devices.

cdevvp(dev, vpp)

Create a vnode for a character device. cdevvp() is used for the console and kernfs special devices.

vfinddev(dev, vtype, vpp)

Lookup a vnode by device number. The vnode is returned in the address specified by vpp.

vdevgone(int maj, int min, int minh, enum vtype type)

Reclaim all vnodes that correspond to the specified minor number range minl to minh (endpoints inclusive) of the specified major

maj.

vflushbuf(vp, sync)

Flush all dirty buffers to disk for the file with the locked vn-ode vp. The argument sync specifies whether the I/O should be synchronous and vflushbuf() will sleep until vp->v_numoutput is zero and vp->v_dirtyblkhd is empty.

vinvalbuf(vp, flags, cred, p, slpflag, slptimeo)

Flush out and invalidate all buffers associated with locked vnode vp. The argument p and cred specified the calling process and its credentials. The arguments flags, slpflag and slptimeo are ignored in the present implementation. If the operation is successful zero is returned, otherwise and appropriate error code is returned.

vtruncbuf(vp, lbn, slpflag, slptimeo)

Destroy any in-core buffers past the file truncation length for the locked vnode vp. The truncation length is specified by lbn. vtruncbuf() will sleep while the I/O is performed, The sleep(9) flag and timeout are specified by the arguments slpflag and slptimeo respectively. If the operation is successful zero is returned, otherwise and appropriate error code is returned.

vprint(label, vp)

This function is used by the kernel to dump vnode information during a panic. It is only used if kernel option DIAGNOSTIC is compiled into the kernel. The argument label is a string to prefix the information dump of vnode vp.

5.3 Vnode Attributes

Vnode attributes describe attributes of a file or directory including file permissions, owner, group, size, access time and modication time.

A vnode attribute has the following structure:

```
struct vattr {
          enum vtype
                                                 /* vnode type (for create) */
                            va_type;
                            va_mode;
                                                /* files access mode and type */
          mode t
                            va_nlink;
                                                /* number of references to file */
          nlink_t
                            va_uid;
          uid_t
                                                 /* owner user id */
                                                 /* owner group id */
          gid_t
                            va_gid;
                            long
          long
                          va_size;
          u_quad_t
                                                /* file size in bytes */
         long
                            va_blocksize; /* blocksize preferred for i/o */
         struct timespec va_atime; /* time of last access */
struct timespec va_mtime; /* time of last modification */
struct timespec va_ctime; /* time file changed */
u_long va_gen; /* generation number of file */
u_long va_flags; /* flags defined for file */
dev_t va_rdev; /* device the special file represents */
```

```
u_quad_t va_bytes; /* bytes of disk space held by file */
u_quad_t va_filerev; /* file modification number */
u_int va_vaflags; /* operations flags, see below */
long va_spare; /* remain quad aligned */
};
```

A field value of VNOVAL represents a field whose value is unavailable or which is not to be changed. Valid flag values for va_flags are:

```
VA_UTIMES_NULL utimes argument was NULL VA_EXCLUSIVE exclusive create request
```

Vnode attributes for a file are set by the vnode operation VOP_SETATTR(9). Vnode attributes for a file are retrieved by the vnode operation VOP_GETATTR(9). For more information on vnode operations see vnodeops(9).

5.4 Vnode Operation about Filesystem Hierarchy

The vnode operations vector describes what operations can be done to the file associated with the vnode. The system maintains one vnode operations vector for each file system type configured into the kernel. The vnode operations vector contains a pointer to a function for each operation supported by the file system. Many of the functions described in the vnode operations vector are closely related to their corresponding system calls. In most cases, they are called as a result of the system call associated with the operation being invoked.

If the file system type does not support a specific operation, it must nevertheless assign an appropriate function in the vnode operations vector to do the minimum required of it. In most cases, such functions either do nothing or return an error value to the effect that it is not supported.

5.4.1 Overview

Opening a File

When an applicatin opens a file that does not currently have an in-memory vnode, the client filesystem calls the getnewvnode routine to allocate a new vnode.

The getnewvnode routine removes the least recently used vnode from the front of the free list and calls the reclaim operation to notify the filesystem currently using the vnode that that vnode is about to be reused.

Closing a File

When the final file-entry reference to a file is closed, the usage count on the vnode drops to zero and the vnode interface calls the **inactive** vnode operation. The **inactive** call

- notifies the underlying system that the file is no longer being used.
- The filesystem will often use this call to write dirty data back to the file, but will not typically reclaim the buffers.

Disassociation with Underlying Objects

The reclaim operation

- writes back any dirty data associated with the underlying object such as *inode*,
- removes the underlying object from any lists that it is on (such as hash lists used to find it), and
- frees up any auxiliary storage that was being used by the object.

This ability, combined with the ability to associate new objects with the vnode, provides functionality with usefulness that goes far beyond simply allowing vnodes to be moved from one filesystem to another. By replacing an existing object with an object from the <code>dead filesystem</code>— a filesystem in which all operations except <code>close</code> fail — the kernel revokes the objects. Internally, this revocation of an object is provided by the <code>vgone</code> routine.

The recovation service is used to support forcible unmounting of filesystems. It is also possible to downgrade a mounted filesystem from read-write to read-only. Instead of access being revoked on every active file within the filesystem, only those files with a nonzero number of references for writing have their access revoked. The ability to revoke objects is exported to processes through the revoke system call.

Vnode Locking

The *lock* and *unlock* operators allow the callers of the vnode interface to provide hints to the code that implement operations on the underlying objects. Stateless filesystem suc has NFS ignore these hints. Stateful filesystems such as FFS, however, can use gints to avoid doing extra work.

For example, an open system call requesting that a new file be created requires two major phases: *lookup* and *create*. The details are

- 1. First, a *lookup* call is done to see if the file already exists.
- 2. For stateful filesystem, before the lookup is started, a *lock* request is made on the directory being searched.
- 3. While scanning through the directory checking for the name, the lookup code also identifies a location within the directory that contains enough space to hold the new name.
- 4. If the name does not already exists, the *open* code verifies that the user has permission to create the file. If the user is not eligible to create the new file, then the *abortop* operator is called to release any resources held in reserve.
- 5. Otherwise, *create* operation is called.
- 6. If the filesystem is stateful, then it can simply create the name in the previously identified space.

However, If the filesystem is stateless, then it cannot lock the directory, so the *create* operator must rescan the directory to find space and to verift that the name has not been created since the lookup.

5.4.2 componentname structure

Many of the functions in the vnode operations vector take a component name structure. Is is used to encapsulate many parameters into a single function argument. It has the following structure:

```
struct componentname {
    /*
    * Arguments to lookup.
```

```
/* namei operation */
       u_long cn_nameiop;
                             /* flags to namei */
       u_long cn_flags;
       struct proc *cn_proc; /* process requesting lookup */
       struct ucred *cn_cred; /* credentials */
        * Shared between lookup and commit routines.
        */
       char
                              /* pathname buffer */
               *cn_pnbuf;
       const char *cn_nameptr; /* pointer to looked up name */
       long cn_namelen; /* length of looked up component */
       u_long cn_hash;
                              /* hash value of looked up name */
       long
               cn_consume;
                             /* chars to consume in lookup() */
};
```

The top half of the structure is used exclusively for the pathname lookups using VOP_LOOKUP() and is initialized by the caller. The semantics of the lookup are affected by the operation specified in cn_nameiop and the flags specified in cn_flags. Valid operations are:

```
LOOKUP perform name lookup only
CREATE setup for file creation
DELETE setup for file deletion
RENAME setup for file renaming
OPMASK mask for operation
```

Valid values for cn->cn_flags are:

```
LOCKLEAF lock inode on return

LOCKPARENT want parent vnode returned locked

WANTPARENT want parent vnode returned unlocked

NOCACHE name must not be left in name cache (see namecache(9))

FOLLOW follow symbolic links

NOFOLLOW do not follow symbolic links (pseudo)

MODMASK mask of operational modifiers
```

No vnode operations may be called from interrupt context. Most opera-tions also require the vnode to be locked on entry. To prevent dead-locks, when acquiring locks on multiple vnodes, the lock of parent direc-tory must be acquired before the lock on the child directory.

5.4.3 Pathname Searching

```
int (*vop_lookup)() VOP_LOOKUP Lookup file name in name cache
```

5.4.4 Name Creation

5.4.5 Name Change/Deletion

<pre>int (*vop_rename)()</pre>	VOP_RENAME	Rename a file
<pre>int (*vop_remove)()</pre>	VOP_REMOVE	Remove a file
<pre>int (*vop_rmdir)()</pre>	VOP_RMDIR	Remove a directory

5.4.6 Attribute Manipulation

<pre>int (*vop_access)()</pre>	VOP_ACCESS	Determine file accessibility
<pre>int (*vop_getattr)()</pre>	VOP_GETATTR	Get file attributes
<pre>int (*vop_setattr)()</pre>	VOP_SETATTR	Set file attributes

5.4.7 Object Interpretation

<pre>int (*vop_open)()</pre>	VOP_OPEN	Open a file
<pre>int (*vop_readdir)()</pre>	VOP_READDIR	Read directory entry
<pre>int (*vop_readlink)()</pre>	VOP_READLINK	Read contents of a symlink
<pre>int (*vop_mmap)()</pre>	VOP_MMAP	Map file into user address space
<pre>int (*vop_close)()</pre>	VOP_CLOSE	Close a file
<pre>int (*vop_seek)()</pre>	VOP_SEEK	Test if file is seekable
<pre>int (*vop_bmap)()</pre>	VOP_BMAP	Logical block number conversion
<pre>int (*vop_pathconf)()</pre>	VOP_PATHCONF	Implement POSIX pathconf support
<pre>int (*vop_print)()</pre>	VOP_PRINT	Print debugging information

5.4.8 Process Control

None of these operatos modifies the object in the filestore. They are simply using the object for naming or directing the desired operation.

<pre>int (*vop_advlock)() int (*vop_ioctl)()</pre>	VOP_ADVLOCK VOP_IOCTL	Advisory record locking Perform device-specific I/O
<pre>int (*vop_fcntl)() int (*vop_poll)()</pre>	VOP_FCNTL VOP_POLL	Perform file control Test if poll event has occurred

5.4.9 Object Management

(*vop_lock)()	VOP_LOCK	Sleep until vnode lock is free
(*vop_unlock)()	VOP_UNLOCK	Wake up process sleeping on lock
(*vop_inactive)()	VOP_INACTIVE	Release the inactive vnode
(*vop_reclaim)()	VOP_RECLAIM	Reclaim vnode for another file
(*vop_abortop)()	VOP_ABORTOP	Abort pending operation
(*vop_revoke)()	VOP_REVOKE	Eliminate vode activity
(*vop_islocked)()	VOP_ISLOCKED	Test if vnode is locked
(*vop_lease)()	VOP_LEASE	Validate vnode credentials
(*vop_bwrite)()	VOP_BWRITE	Write a file system buffer
(*vop_whiteout)()	VOP_WHITEOUT	Whiteout vnode
(*vop_strategy)()	VOP_STRATEGY	Read/write a file system buffer
	<pre>(*vop_unlock)() (*vop_inactive)() (*vop_reclaim)() (*vop_abortop)() (*vop_revoke)() (*vop_islocked)() (*vop_lease)() (*vop_bwrite)() (*vop_whiteout)()</pre>	(*vop_unlock)()VOP_UNLOCK(*vop_inactive)()VOP_INACTIVE(*vop_reclaim)()VOP_RECLAIM(*vop_abortop)()VOP_ABORTOP(*vop_revoke)()VOP_REVOKE(*vop_islocked)()VOP_ISLOCKED(*vop_lease)()VOP_LEASE(*vop_bwrite)()VOP_BWRITE(*vop_whiteout)()VOP_WHITEOUT

VOP_INACTIVE(vp, p)

Release the inactive vnode. VOP_INACTIVE() is called when the kernel is no longer using the vnode. This may be because the reference count reaches zero or it may be that the file system

is being forcibly unmounted while there are open files. It can be used to reclaim space for open but deleted files. The argument vp is the locked vnode to be released. The argument p is the calling process. If the operation is successful zero is returned, otherwise an appropriate error code is returned. The vnode vp must be locked on entry, and will be unlocked on return.

5.5 Vnode Operation about Storage

5.5.1 Object Creation and Deletion

<pre>int (*vop_valloc)()</pre>	VOP_VALLOC	Allocate fs-specific data
<pre>int (*vop_vfree)()</pre>	VOP_VFREE	Release file resources
<pre>int (*vop_balloc)()</pre>	VOP_BALLOC	Allocate physical blocks
<pre>int (*vop_reallocblks)()</pre>	VOP_REALLOCBLKS	rearrange blocks as contiguous

5.5.2 Attribute Update

int ((*vop_update)()	VOP UPDATE U1	bdate	time	on	a	file

5.5.3 Object Read and Write

int (*vo	op_blkatoff)()	VOP_BLKATOFF	Retrieve buffer from offset
int (*vo	op_read)()	VOP_READ	Read from a file
int (*vo	op_write)()	VOP_WRITE	Write to a file
int (*vo	op_fsync)()	VOP_FSYNC	Flush pending data to disk
	op_getpages)() op_putpages)()	VOP_GETPAGES VOP_PUTPAGES	Read VM pages from file Write VM pages to file

5.5.4 Change in Space Allocation

```
int (*vop_truncate)() VOP_TRUNCATE Truncate file and free blocks
```

5.6 High-Level Vnode Convenient Function

Vnode operations for a file system type generally should not be called directly from the kernel, but accessed indirectly through the high-level convenience functions discussed in vnsubr(9).

```
vn_default_error(v)
```

A generic "default" routine that just returns error. It is used by a file system to specify unsupported operations in the vnode operations vector.

5.6.1 Filesystem Hierarchy

```
vn_stat(fdata, sb, p)
```

Common code for a vnode stat operation. The vnode is specified by the argument fdata and sb is the buffer to return the stat information. The argument p is the calling process. vn_stat()

basically calls the vnode operation VOP_GETATTR(9) and transfer the contents of a vattr structure into a struct stat. If the operation is successful zero is returned, otherwise an appropriate error code is returned.

vn_readdir(fp, buf, segflg, count, done, p, cookies, ncookies) Common code
for reading the contents of a directory. The argument fp is the
file structure, buf is the buffer for placing the struct dirent
structures. The arguments cookies and ncookies specify the addresses for the list and number of directory seek cookies generated for NFS. Both cookies and ncookies should be NULL is they
aren't required to be returned by vn_readdir(). If the operation is successful zero is returned, otherwise an appropriate
error code is returned.

vn_isunder(dvp, rvp, p)

Common code to check if one directory specified by the vnode rvp can be found inside the directory specified by the vnode dvp. The argument p is the calling process. vn_isunder() is intended to be used in chroot(2), chdir(2), fchdir(2), etc., to ensure that chroot(2) actually means something. If the operation is successful zero is returned, otherwise 1 is returned.

5.6.2 General File I/O

vn_open(ndp, fmode, cmode)

Common code for vnode open operations. The pathname is described in the nameidata pointer (see namei(9)). The arguments fmode and cmode specify the open(2) file mode and the access permissions for creation. vn_open() checks permissions and invokes the VOP_OPEN(9) or VOP_CREATE(9) vnode operations. If the operation is successful zero is returned, otherwise an appropriate error code is returned.

vn_close(vp, flags, cred, p)

Common code for a vnode close. The argument vp is the locked vnode of the vnode to close. vn_close() simply locks the vnode, invokes the vnode operation VOP_CLOSE(9) and calls vput() to return the vnode to the freelist or holdlist. Note that vn_close() expects an unlocked, referenced vnode and will dereference the vnode prior to returning. If the operation is successful zero is returned, otherwise an appropriate error is returned.

vn_closefile(fp, p)

Common code for a file table vnode close operation. The file is described by fp and p is the calling process. vn_closefile() simply calls vn_close() with the appropriate arguments.

vn_read(fp, offset, uio, cred, flags)

Common code for a file table vnode read. The argument fp is the file structure, The argument offset is the offset into the file. The argument uio is the uio structure describing the memory to read into. The caller's credentials are specified in

cred. The flags argument can define FOF_UPDATE_OFFSET to update the read position in the file. If the operation is successful zero is returned, otherwise an appropriate error is returned.

vn_write(fp, offset, uio, cred, flags)

Common code for a file table vnode write. The argument fp is the file structure, The argument offset is the offset into the file. The argument uio is the uio structure describing the memory to read from. The caller's credentials are specified in cred. The flags argument can define FOF_UPDATE_OFFSET to update the read position in the file. If the operation is successful zero is returned, otherwise an appropriate error is returned.

vn_rdwr(rw, vp, base, len, offset, segflg, ioflg, cred, aresid, p) Common code to package up an I/O request on a vnode into a uio and
then perform the I/O. The argument rw specifies whether the I/O
is a read (UIO_READ) or write (UIO_WRITE) operation. The unlocked vnode is specified by vp. The arguments p and cred are
the calling process and its credentials. The remaining arguments specify the uio parameters. For further information on
these parameters see uiomove(9).

vn_bwrite(ap)

Common code for block write operations.

vn_writechk(vp)

Common code to check for write permission on the vnode vp. A vnode is read-only if it is in use as a process's text image. If the vnode is read-only ETEXTBSY is returned, otherwise zero is returned to indicate that the vnode can be written to.

vn_fcntl(fp, com, data, p)

Common code for a file table vnode fcntl(2) operation. The file is specified by fp. The argument p is the calling process. vn_fcntl() simply locks the vnode and invokes the vnode operation VOP_FCNTL(9) with the command com and buffer data. The vnode is unlocked on return. If the operation is successful zero is returned, otherwise an appropriate error is returned.

vn_ioctl(fp, com, data, p)

Common code for a file table vnode ioctl operation. The file is specified by fp. The argument p is the calling process. $vn_ioctl() \text{ simply locks the vnode and invokes the vnode operation VOP_IOCTL(9)} \text{ with the command com and buffer data}. The vnode is unlocked on return. If the operation is successful zero is returned, otherwise an appropriate error is returned.}$

5.6.3 Advanced I/O

vn_lock(vp, flags)

Common code to acquire the lock for vnode vp. The argument flags specifies the lockmgr(9) flags used to lock the vnode. If the operation is successful zero is returned, otherwise an appropriate error code is returned. The vnode interlock

v_interlock is releases on return.

vn_lock() must not be called when the vnode's reference count is zero. Instead, vget(9) should be used.

vn_poll(fp, events, p)

Common code for a file table vnode poll operation. vn_poll() simply calls VOP_POLL(9) with the events events and the calling process p. If the operation is success zero is returned, otherwise an appropriate error code is returned.

vn_markexec(vp)

Common code to mark the vnode vp as containing executable code of a running process.

vn_setrecurse(vp)

Common code to enable LK_CANRECURSE on the vnode lock for vnode vp. vn_setrecurse() returns the new lockmgr(9) flags after the update.

vn_restorerecurse(vp, flags)

Common code to restore the vnode lock flags for the vnode vp. It is called when done with vn_setrecurse().

5.7 References to Source Code

5.7.1 vfs_subr.c - 2846 lines, 57 functions

Gloval Variables

iftov_tab
vttoif_tab

doforce Switch to permit forcible unmounting

prtactive

[Global System List]

mountlist Mounted filesystem list

vfs_list VFS list

nfs_pub Publicly exported FS

[Root Filesystem and Device Information]

rootfs
rootvnode
root_device

[Locks to Manage Global System Lists]

mountlist_slock
mntid_slock
mntvnode_slock
vnode_free_list_slock
spechash_slock

Functions

[VFS Management]

vfs_busy Mark a mount point as busy, to synchronize access and

to delay unmount

vfs_unbusy

vfs_getvfs Lookup a mount point by filesystem identifier

vfs_getnewfsid Get a new unique fsid

makefstype Make a 'unique' number from a mount type name

vfs_mountedon Check to see if a filesystem is mounted on a block device

vfs_getopsbyname Given a file system name, look up the vfsops

[vnode Management]

vattr_null Set vnode attributes to VNOVAL

getnewvnode Return the next vnode from the free list

ungetnewvnode used by VFS_VGET functions who may need to push back a vnode

insmntque Move a vnode from one mount queue to another

vwakeup Update outstanding I/O count and do wakeup if requested vinvalbuf Flush out and invalidate all buffers associated with a vnode

vtruncbuf Destroy any in core blocks past the truncation length

vflushbuf

bgetvp Associate a buffer with a vnode brelvp Disassociate a buffer with a vnode

reassignbuf Reassign a buffer from one vnode to another

bdevvp Create a vnode for a block device cdevvp Create a vnode for a character device getdevvp Common routine used by bdevvp(), cdevvp()

checkalias Check to see if the new vnode represents a special device

for which we already have a vnode

vget Grab a particular vnode from the free list

vput just unlock and vrele()

vrele vhold holdrele vref

vflush Remove any vnodes in the vnode table belonging to

mount point mp

vclean Disassociate the underlying file system from a vnode vrecycle Recycle an unused vnode to the front of the free list

vgone Eliminate all activity associated with a vnode

vgonel vgone(), with the vp interlock held vfinddev Lookup a vnode by device number

vdevgone Revoke all the vnodes corresponding to the specified

minor number range

```
vcount
    [ Routines About sysctl support ]
    vfs_sysctl
    sysctl_vnode
    [ Exportable File System ]
    vfs_hand_addrlist Build hash lists of net addresses and hang them off
                           the mount point
    vfs_free_netcred
    vfs_free_addrlist Free the net address hash lists that are hanging
                           off the mount points
    vfs_export
    vfs_setpublicfs
                       Set the publicly exported filesystem (WebNFS)
    vfs_export_lookup
    vaccess
                       Do the usual access checking
    [ System Bootstrap and Shutdown ]
    vfs_attach
    vfs_detach
    vfs_reinit
    vfs_unmountall
                       Unmount all file systems
    vfs_shutdown
                       Sync and unmount file systems before shutting down
    vfs_mountroot
                      Mount the root file system
    vfs_rootmountalloc Lookup a filesystem type, and allocate and
                           initialize a mount structure
    [ Diagnostics ]
    vprint
    vfs_buf_print
    vfs_vnode_print
    printlockedvnodes
      vfs_vnops.c - 808 lines, 19 functions
Gloval Variables
    struct fileops vnops = {
            vn_read, vn_write, vn_ioctl, vn_fcntl, vn_poll,
            vn_statfile, vn_closefile, vn_kqfilter
    };
Functions
     [ Exported File Operation ]
                       used by vn_rdwr()
    vn_read
    vn_write
    vn_ioctl
    vn_fcntl
```

```
vn_poll
vn_statfile
                    File table vnode close routine (just cover function)
vn_closefile
vn_kqfilter
                   [?] File table vnode kqfilter routine
[ High-Level Vnode Convenient Function ]
vn_open
                   used by sys_open()
vn_writechk
                   Check for write permissions on the specified vnode.
                   Mark a vnode as having executable mappings
vn markexec
vn_marktext
                   Mark a vnode as being the text of a process
vn_close
vn_rdwr
                   Package up an I/O request on a vnode into a uio and do it
vn_readdir
vn_stat
vn_lock
[ ? Lock Management ]
                    [?] Enable LK_CANRECURSE on lock. Return prior status
vn_setrecurse
vn_restorerecurse
                    [?] Called when done with locksetrecurse
```

5.7.3 vfs_syscalls.c - 3116 lines, 65 functions

Gloval Variables

dovfsusermount When set to 1, any user can mount filesystem mountcompatnames nmountcompatnames

Functions

```
[ System Calls Related with Vnode ! ]
sys_mount
sys_unmount
sys_sync
sys_statfs
sys_fstatfs
sys_getfsstat
sys_fchdir
sys_fchroot
                   Change this process's notion of the root directory
sys_chdir
                   Change notion of root (''/',') directory
sys_chroot
sys_open
                   Get file handle system call
sys_getfh
sys_fhopen
                   Open a file given a file handle
sys_fhstat
                   Returns information about a mounted file system
sys_fhstatfs
sys_mknod
sys_mkfifo
                   Create a named pipe
sys_link
sys_symlink
sys_undelete
                  Delete a whiteout from the filesystem [WOW ! undelete !]
```

```
sys_unlink
sys_lseek
sys_pread
                   Positional read system call
sys_preadv
sys_pwrite
sys_pwritev
sys_access
sys___stat13
sys___lstat13
                   Get configurable pathname variables
sys_pathconf
sys_readlink
sys_chflags
sys_fchflags
sys_lchflags
sys_chmod
sys_fchmod
                   Change mode of a file given a file descriptor
sys_lchmod
                   this version does not follow links
sys_chown
sys_fchown
sys_lchown
sys_utime
sys_futime
sys_lutime
sys_truncate
sys_fruncate
sys_fsync
                   Sync an open file
sys_fdatasync
                   Sync the data of an open file
sys_rename
sys_mkdir
sys_rmdir
                   Read a block of directory in filesystem independent format
sys_getdents
sys_umask
sys_revoke
[ POSIX Compatable System Calls ]
sys___posix_chown
sys___posix_fchown
sys___posix_lchown
sys___posix_rename
[ Support Routine ]
checkdirs
                   Support routine for sys_mount()
dounmount
                   Actual worker for sys_unmount()
getvnode
                   Convert a user file descriptor to a kernel file entry
[ Common Routine ]
change_dir
                   Common routine for chroot and chdir
change_flags
                   Common routine to change flags of a file
change_mode
                   Common routine to change mode of a file
change_owner
```

change_utimes
rename_files

Chapter 6

$\overline{ ext{UVM}}$

6.1 Introduction

UVM is a virtual memory system of the NetBSD/sparc64 release 1.6. UVM has better performance especially in managing memory-mapped files and copy-on-write memory, than the 4.4BSD VM, which is derived from Mach VM. In UVM, the virtual memory object, fault handling, and pager code is replaced from the 4.4BSD VM. And, a new virtual memory based data movement mechanisms is introduced.

6.2 UVM Overview

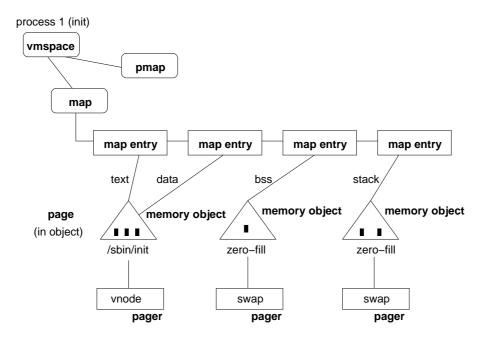


Figure 6.1: The five main machine-independent abstractions in UVM

Both BSD VM and UVM can be divied into two layers: a small mahcine-dependent layer, and a larger machine-independent layer.

The machine-dependent layer used by both BSD VM and UVM is called the *pmap layer*. The pamp layer handles the low level details of programming a processor's MMU. This task conststs of

- managing the mappings of a virtual address.
- managing the mappings of a page of physical memory.

The machine-independent code contains functions that perform the high-level operations of the VM system. Such functions include

- managing a process' file mappings,
- requesting data from backing store,
- paging out memory when it becomes scarce,
- managing the allocation of physical memory, and
- managing copy-on-write memory.

Figure 6.1 shows the five main abstrations that correspond to data structures in both BSD VM and UVM that activities of the machine-independent layer are centered around.

6.2.1 Virtual Memory Space

Virtual memory space describes both the machine dependent and machine independent parts of process's virtual address space. The vmspace structure contains

- pointers to memory map structures, and
- statistics on the process's memory usage.

uvm/uvm_extern.h

459 /*

460 * Shareable process virtual address space.

```
461 * May eventually be merged with vm_map.
462 * Several fields are temporary (text, data stuff).
463 */
464 struct vmspace {
           struct vm_map vm_map; /* VM address map */
465
                                  /* number of references */
466
           int
                   vm_refcnt;
467
           caddr_t vm_shm;
                                  /* SYS5 shared memory private data XXX */
468 /* we copy from vm_startcopy to the end of the structure on fork */
469 #define vm_startcopy vm_rssize
470
           segsz_t vm_rssize;
                                  /* current resident set size in pages */
                                  /* resident set size before last swap */
471
                                  /* text size (pages) XXX */
472
473
                                  /* data size (pages) XXX */
                                  /* stack size (pages) */
474
           segsz_t vm_ssize;
475
           caddr_t vm_taddr;
                                  /* user virtual address of text XXX */
476
           caddr_t vm_daddr;
                                  /* user virtual address of data XXX */
           caddr_t vm_maxsaddr;
                                  /* user VA at max stack growth */
477
478
           caddr_t vm_minsaddr;
                                  /* user VA at top of stack */
479 };
```

______ uvm/uvm_extern.h

6.2.2 Memory Map

Memory map describes the machine-independent part of the virtual address space of a process or the kernel. Each map structure on the system contains a sorted doubly-linked list of map entry structures. Each entry structure contains a record of a mapping in the map's virtual address space. This record includes

- starting and ending virtual address
- a pointer to the memory object mapped into that address range
- the attributes of the mapping

```
uvm/uvm_map.h
114 /*
115 * Address map entries consist of start and end addresses,
116 * a VM object (or sharing map) and offset into that object,
117 * and user-exported inheritance and protection information.
118 * Also included is control information for virtual copy operations.
119 */
120 struct vm_map_entry {
121
            struct vm_map_entry
                                     *prev;
                                                     /* previous entry */
                                                     /* next entry */
122
            struct vm_map_entry
                                     *next;
                                                     /* start address */
123
            vaddr_t
                                     start;
                                                     /* end address */
124
            vaddr_t
                                     end;
125
            union {
126
                    struct uvm_object *uvm_obj;
                                                     /* uvm object */
127
                    struct vm_map
                                                     /* belongs to another map */
                                     *sub_map;
128
            } object;
                                                     /* object I point to */
129
            voff_t
                                     offset;
                                                     /* offset into object */
130
            int
                                                     /* entry type */
                                     etype;
131
            vm_prot_t
                                     protection;
                                                     /* protection code */
132
            vm_prot_t
                                     max_protection; /* maximum protection */
133
            vm_inherit_t
                                     inheritance;
                                                     /* inheritance */
                                                     /* can be paged if == 0 */
134
                                     wired_count;
            int
                                                     /* anonymous overlay */
135
            struct vm_aref
                                     aref;
136
                                     advice;
                                                     /* madvise advice */
137 #define uvm_map_entry_stop_copy flags
                                                     /* flags */
138
            u_int8_t
                                     flags;
139
140 #define UVM_MAP_STATIC
                                     0x01
                                                     /* static map entry */
141 #define UVM MAP KMEM
                                     0x02
                                                     /* from kmem entry pool */
142
143 };
199 struct vm_map {
                                                     /* Physical map */
200
            struct pmap *
                                     pmap;
201
            struct lock
                                                     /* Lock for map data */
                                     lock:
202
            struct vm_map_entry
                                     header;
                                                     /* List of entries */
                                                     /* Number of entries */
203
            int
                                     nentries;
                                                     /* virtual size */
204
            vsize_t
                                     size;
205
            int
                                     ref_count;
                                                     /* Reference count */
                                                     /* Lock for ref_count field */
206
            struct simplelock
                                     ref_lock;
207
            struct vm_map_entry *
                                     hint;
                                                     /* hint for quick lookups */
208
            struct simplelock
                                     hint_lock;
                                                     /* lock for hint storage */
```

```
209
            struct vm_map_entry *
                                    first_free;
                                                    /* First free space hint */
                                                    /* flags */
210
            int
                                    flags;
                                                    /* Lock for flags field */
211
            struct simplelock
                                    flags_lock;
212
            unsigned int
                                    timestamp;
                                                    /* Version number */
213 #define min_offset
                                    header.start
214 #define max_offset
                                    header.end
215 };
216
217 /* vm_map flags */
218 #define VM_MAP_PAGEABLE
                                    0x01
                                                    /* ro: entries are pageable */
219 #define VM_MAP_INTRSAFE
                                    0x02
                                                    /* ro: interrupt safe map */
220 #define VM_MAP_WIREFUTURE
                                                    /* rw: wire future mappings */
                                    0x04
221 #define VM_MAP_BUSY
                                    80x0
                                                    /* rw: map is busy */
                                                    /* rw: want to write-lock */
222 #define VM_MAP_WANTLOCK
                                    0x10
223 #define VM_MAP_DYING
                                    0x20
                                                    /* rw: map is being destroyed */
```

— uvm/uvm_map.h

6.2.3 Memory Object

Memory object describes a file, a zero-fill memory area, or a device that can be mapped into a virtual address space. In UVM, a memory object consists of either a vm_amap or uvm_object structure.

```
- uvm/uvm_object.h
44 /*
45 * uvm_object: all that is left of mach objects.
46 */
47
48 struct uvm_object {
                                                   /* lock on memq */
          struct simplelock
                                   vmobjlock;
           struct uvm_pagerops
                                   *pgops;
                                                   /* pager ops */
                                   memq;
                                                   /* pages in this object */
51
           struct pglist
52
           int
                                                  /* # of pages in memq */
                                   uo_npages;
53
           int
                                   uo_refs;
                                                   /* reference count */
54 };
                                            — uvm/uvm_object.h
                                                - uvm/uvm_amap.h
42 /*
43 * an amap structure contains pointers to a set of anons that are
44 * mapped together in virtual memory (an anon is a single page of
45 * anonymous virtual memory -- see uvm_anon.h). in uvm we hide the
46 * details of the implementation of amaps behind a general amap
47 * interface. this allows us to change the amap implementation
48 * without having to touch the rest of the code. this file is divided
49 * into two parts: the definition of the uvm amap interface and the
50 * amap implementation-specific definitions.
51 */
167 struct vm_amap {
           struct simplelock am_l; /* simple lock [locks all vm_amap fields] */
```

```
169
            int am_ref;
                                    /* reference count */
                                    /* flags */
170
            int am_flags;
            int am_maxslot;
                                    /* max # of slots allocated */
171
172
            int am_nslot;
                                    /* # of slots currently in map ( <= maxslot) */</pre>
173
            int am_nused;
                                    /* # of slots currently in use */
174
           int *am_slots;
                                    /* contig array of active slots */
                                    /* back pointer array to am_slots */
175
           int *am_bckptr;
           struct vm_anon **am_anon; /* array of anonymous pages */
176
177 #ifdef UVM_AMAP_PPREF
178
            int *am_ppref;
                                    /* per page reference count (if !NULL) */
179 #endif
180 };
                                                — uvm/uvm_amap.h
```

6.2.4 Pager

Pager describes how backing store can be accessed. Each memory object on the system has a pager that points to a list of functions used by the object to fetch and store pages between physical memory and backing store.

Pages are read in from backing store

- when a process faults on them, or
- in anticipation of a process faulting on them
- . Pages are written out to backing store
 - at the request of a user (e.g. msync system call),
 - when physica memory is scarce, or
 - when the object that owns the pages is freed.

```
— uvm/uvm_pager.h
90 /*
91 * pager ops
92 */
93
94 struct uvm_pagerops {
95
96
            /* init pager */
                    (*pgo_init) __P((void));
97
            void
98
            /* add reference to obj */
99
100
                    (*pgo_reference)(struct uvm_object *);
            void
101
            /* drop reference to obj */
102
103
                    (*pgo_detach)(struct uvm_object *);
104
            /* special non-standard fault processing */
105
                    (*pgo_fault)(struct uvm_faultinfo *, vaddr_t, struct vm_page **,
106
            int
107
                                  int, int, vm_fault_t, vm_prot_t, int);
108
109
            /* get/read pages */
                    (*pgo_get)(struct uvm_object *, voff_t, struct vm_page **,
110
            int
```

6.2.5 Page

Page describes a page of physical memory. When the system is booted a vm_page structure is allocated for each page of physical memory that can be used by the VM system.

```
— uvm/uvm_page.h
120 struct vm_page {
121
            TAILQ_ENTRY(vm_page)
                                                     /* queue info for FIFO
                                     pageq;
122
                                                      * queue or free list (P) */
123
            TAILQ_ENTRY(vm_page)
                                    hashq;
                                                     /* hash table links (0)*/
            TAILQ_ENTRY(vm_page)
                                                     /* pages in same object (0)*/
124
                                    listq;
125
            struct vm_anon
                                                     /* anon (0,P) */
126
                                     *uanon;
                                                     /* object (0,P) */
127
            struct uvm_object
                                     *uobject;
128
            voff_t
                                     offset;
                                                     /* offset into object (0,P) */
129
            uint16_t
                                     flags;
                                                     /* object flags [0] */
130
            uint16_t
                                                     /* number of active loans
                                     loan_count;
131
                                                      * to read: [O or P]
132
                                                      * to modify: [0 _and_ P] */
133
            uint16_t
                                     wire_count;
                                                     /* wired down map refs [P] */
                                                     /* page queue flags [P] */
134
            uint16_t
                                    pqflags;
135
            paddr_t
                                    phys_addr;
                                                     /* physical address of page */
136
137 #ifdef __HAVE_VM_PAGE_MD
138
            struct vm_page_md
                                    mdpage;
                                                     /* pmap-specific data */
139 #endif
140
141 #if defined(UVM_PAGE_TRKOWN)
            /* debugging fields to track page ownership */
142
                                                     /* proc that set PG_BUSY */
143
            pid_t
                                     owner;
144
                                                     /* why it was set busy */
            char
                                     *owner_tag;
145 #endif
146 };
                                                  – uvm/uvm_page.h
```

Machine-Dependent Page Structure

Machine-dependent page structure for sparc64 platform is

```
- arch/sparc64/include/vmparam.h

152 /*

153 * For each struct vm_page, there is a list of all currently valid virtual

154 * mappings of that page. An entry is a pv_entry_t.

155 */
```

```
156 struct pmap;
    157 typedef struct pv_entry {
    158
                                               /* next pv_entry */
               struct pv_entry *pv_next;
    159
                struct pmap *pv_pmap;
                                                /* pmap where mapping lies */
    160
               vaddr_t
                               pv_va;
                                                /* virtual address for mapping */
   161 } *pv_entry_t;
   162 /* PV flags encoded in the low bits of the VA of the first pv_entry */
   163
    164 struct vm_page_md {
   165
               struct pv_entry mdpg_pvh;
    166 };
                                    ——- arch/sparc64/include/vmparam.h
where struct pmap is defined as
                                       ------ arch/sparc64/include/pmap.h
    111 struct pmap {
               struct uvm_object pm_obj;
    113 #define pm_lock pm_obj.vmobjlock
   114 #define pm_refs pm_obj.uo_refs
               LIST_ENTRY(pmap) pm_list;
    115
    116
                                        /* Current context */
                int pm_ctx;
    117
    118
                /*
                 * This contains 64-bit pointers to pages that contain
    119
    120
                 * 1024 64-bit pointers to page tables. All addresses
    121
                * are physical.
   122
    123
                 * !!! Only touch this through pseg_get() and pseg_set() !!!
   124
                 */
   125
               paddr_t pm_physaddr;
                                       /* physical address of pm_segs */
                int64_t *pm_segs;
    126
    127 };
```

Page Fault

When a process attempts to access an unmapped area of memory a page fault is generated. In order to find which page should be mapped, the UVM system must look in the process' map structure for the netry that corresponds to the faulting address.

- If there is not entry mapping the faulting address, an error signal is generated.
- If an object is mapped at the faulting address,
 - if the requested data is already resident in a page, that page can be mapped in.

— arch/sparc64/include/pmap.h

 if not, then the fault rountine issues a request to the object's pager to make the data resident and resolve the fault.

6.3 UVM External Interface

We describe parts of UVM external interface which is essential to understand FFS filesystem source code. The whole UVM external interfaces can be classified as

- Initialization
- Virtual address space management
- Page fault handling
- Memory mapping files and devices
- Virtual memory I/O
- Management of kernel memory
- Management of physical memory
- Processes
- Page loan
- Miscellaneous functions

struct uvm_object *

From these, we will investigate some functions whose category is *memory mapping* files and devices or allocation of physical memory. The first category is mainly related with open system call. The second is related with buffer cache and filesystem storage operations.

6.4 Memory Mapping Files and Devices

6.4.1 Attaching a Memory Object to Vnode: uvn_attach

```
uvn_attach(void *arg, vm_prot_t accessprot);
        uvn_attach() attaches a UVM object to vnode arg,
        creating the object if necessary. The object is returned.
       The values that accessprot maxprot can take are:
       #define VM_PROT_NONE
                                ((vm_prot_t) 0x00)
        #define VM_PROT_READ
                                ((vm_prot_t) 0x01) /* read permission */
        #define VM_PROT_WRITE
                                ((vm_prot_t) 0x02) /* write permission */
        #define VM_PROT_EXECUTE ((vm_prot_t) 0x04) /* execute permission */
        or
       #define UVM_PROT_MASK
                                0x07
                                        /* protection mask */
       #define UVM_PROT_NONE
                                        /* protection none */
                                0x00
                                        /* everything */
        #define UVM_PROT_ALL
                                0x07
                                        /* read */
        #define UVM_PROT_READ
                                0x01
        #define UVM_PROT_WRITE
                                        /* write */
                               0x02
        #define UVM_PROT_EXEC
                                0x04
                                       /* exec */
                                0x01
                                        /* read */
        #define UVM_PROT_R
```

```
#define UVM_PROT_W
                       0x02
                            /* write */
#define UVM_PROT_RW
                              /* read-write */
                      0x03
#define UVM_PROT_X
                              /* exec */
                      0x04
#define UVM_PROT_RX
                      0x05
                              /* read-exec */
#define UVM_PROT_WX
                       0x06
                              /* write-exec */
#define UVM_PROT_RWX
                      0x07
                              /* read-write-exec */
```

References to Source Code

This uvn_attach function is used in vn_open, vnode high-level operation function which is used to implement open system call.

```
— kern/vfs_vnops.c
 87 /*
 88 * Common code for vnode open operations.
 89 * Check permissions, and call the VOP_OPEN or VOP_CREATE routine.
 90 */
 91 int
 92 vn_open(ndp, fmode, cmode)
            struct nameidata *ndp;
 94
            int fmode, cmode;
 95 {
 96
            struct vnode *vp;
            struct proc *p = ndp->ni_cnd.cn_proc;
 97
 98
            struct ucred *cred = p->p_ucred;
           struct vattr va;
 99
100
           int error;
            if ((error = VOP_OPEN(vp, fmode, cred, p)) != 0)
267
268
                    goto bad;
269
            if (vp->v_type == VREG &&
                uvn_attach(vp, fmode & FWRITE ? VM_PROT_WRITE : 0) == NULL) {
270
271
                    error = EIO;
272
                    goto bad;
273
274
            if (fmode & FWRITE)
275
                    vp->v_writecount++;
276
277
           return (0);
278 bad:
279
            vput(vp);
280
           return (error);
281 }
```

6.4.2 Setting Vnode Size: uvn_vnp_setsize

```
void
uvm_vnp_setsize(struct vnode *vp, voff_t newsize);
```

uvm_vnp_setsize() sets the size of vnode vp to newsize. Caller must hold
a reference to the vnode. If the vnode shrinks, pages no longer used are
discarded.

----- kern/vfs_vnops.c

References to Source Code

void *win;

while (len) {

*/

* XXXUBC invent kzero() and use it

vsize_t bytelen = len;

This uvn_attach function is used in ffs_write, one of the FFS storage function as,

```
57 #define WRITE
                                        ffs_write
. . . . .
   184 /*
   185 * Vnode op for writing.
   186 */
   187 int
   188 WRITE(void *v)
   189 {
               while (uio->uio_resid > 0) {
   312
                        boolean_t extending; /* if we're extending a whole block */
   313
   365
                         * update UVM's notion of the size now that we've
   366
   367
                         * copied the data into the vnode's pages.
   368
   369
                         * we should update the size even when uiomove failed.
   370
                         * otherwise ffs_truncate can't flush soft update states.
   371
   372
                        newoff = oldoff + bytelen;
   373
   374
                        if (vp->v_size < newoff) {</pre>
    375
                                uvm_vnp_setsize(vp, newoff);
   376
                                extended = 1;
   377
                        }
   402
                }
   481 }
6.4.3
      Clearing a Vnode: uvn_vnp_zerorange
    /*
     * uvm_vnp_zerorange: set a range of bytes in a file to zero.
     */
    void
    uvm_vnp_zerorange(vp, off, len)
            struct vnode *vp;
            off_t off;
            size_t len;
    {
```

```
win = ubc_alloc(&vp->v_uobj, off, &bytelen, UBC_WRITE);
    memset(win, 0, bytelen);
    ubc_release(win, 0);

    off += bytelen;
    len -= bytelen;
}
```

References to Source Code

This uvn_zerorange function is used in ffs_truncate vnode operation as,

```
- ffs/ffs/ffs_vnops.c
158 /*
159 * Truncate the inode oip to at most length size, freeing the
160 * disk blocks.
161 */
162 int
163 ffs_truncate(v)
164
            void *v;
165 {
253
            /*
             * When truncating a regular file down to a non-block-aligned size,
254
255
             \ast we must zero the part of last block which is past the new EOF.
256
             * We must synchronously flush the zeroed pages to disk
257
             * since the new pages will be invalidated as soon as we
             * inform the VM system of the new, smaller size.
258
259
             * We must do this before acquiring the GLOCK, since fetching
260
             * the pages will acquire the GLOCK internally.
261
             * So there is a window where another thread could see a whole
262
             * zeroed page past EOF, but that's life.
263
             */
264
265
            offset = blkoff(fs, length);
266
            if (ovp->v_type == VREG && length < osize && offset != 0) {</pre>
267
                    voff_t eoz;
268
269
                    error = ufs_balloc_range(ovp, length - 1, 1, ap->a_cred,
270
                        aflag);
                    if (error) {
271
272
                            return error;
273
274
                    size = blksize(fs, oip, lblkno(fs, length));
275
                    eoz = MIN(lblktosize(fs, lblkno(fs, length)) + size, osize);
276
                    uvm_vnp_zerorange(ovp, length, eoz - length);
277
                    simple_lock(&ovp->v_interlock);
278
                    error = VOP_PUTPAGES(ovp, trunc_page(length), round_page(eoz),
279
                        PGO_CLEANIT | PGO_DEACTIVATE | PGO_SYNCIO);
280
                    if (error) {
281
                            return error;
282
                    }
283
            }
```

456 }

ffs/ffs/ffs_vnops.c

6.5 Management of Physical Memory

6.5.1 Lock Management for Page Queue: uvm_(un)lock_pageq

6.5.2 Activating Physical Page: uvm_pageactivate

```
/*
 * uvm_pageactivate: activate page
 *
 * => caller must lock page queues
 */
void
uvm_pageactivate(struct vm_page *pg)
```

References to Source Code

This function is used in ufs_balloc_range data block allocation function as,

```
ufs/ufs_inode.c
204
205
             * read or create pages covering the range of the allocation and
206
             * keep them locked until the new block is allocated, so there
207
             * will be no window where the old contents of the new block are
208
             * visible to racing threads.
209
             */
210
211
            pagestart = trunc_page(off) & ~(bsize - 1);
212
            npages = MIN(ppb, (round_page(neweob) - pagestart) >> PAGE_SHIFT);
            memset(pgs, 0, npages * sizeof(struct vm_page *));
213
            simple_lock(&uobj->vmobjlock);
214
215
            error = VOP_GETPAGES(vp, pagestart, pgs, &npages, 0,
                VM_PROT_READ, 0, PGO_SYNCIO|PGO_PASTEOF);
216
            if (error) {
217
218
                    return error;
219
220
            simple_lock(&uobj->vmobjlock);
221
            uvm_lock_pageq();
222
            for (i = 0; i < npages; i++) {
223
                    UVMHIST_LOG(ubchist, "got pgs[%d] %p", i, pgs[i],0,0);
                    KASSERT((pgs[i]->flags & PG_RELEASED) == 0);
224
                    pgs[i]->flags &= "PG_CLEAN;
225
226
                    uvm_pageactivate(pgs[i]);
227
            }
228
            uvm_unlock_pageq();
229
            simple_unlock(&uobj->vmobjlock);
```

ufs/ufs_inode.c

6.5.3 Making Unbusy a Page: uvm_page_unbusy

```
/*
 * uvm_page_unbusy: unbusy an array of pages.
 *
 * => pages must either all belong to the same object, or all belong to anons.
 * => if pages are object-owned, object must be locked.
 * => if pages are anon-owned, anons must be locked.
 * => caller must lock page queues if pages may be released.
 */

void
uvm_page_unbusy(struct vm_page **pgs, int npgs);
```

References to Source Code

This function is also used in ufs_balloc_range data block allocation function as,

```
— ufs/ufs_inode.c
247
             * clear PG_RDONLY on any pages we are holding
248
             * (since they now have backing store) and unbusy them.
249
250
             */
251
            simple_lock(&uobj->vmobjlock);
252
            for (i = 0; i < npages; i++) {
253
                    pgs[i]->flags &= ~PG_RDONLY;
254
255
                    if (error) {
                            pgs[i]->flags |= PG_RELEASED;
256
                    }
257
258
            if (error) {
259
260
                    uvm_lock_pageq();
261
                    uvm_page_unbusy(pgs, npages);
262
                    uvm_unlock_pageq();
263
            } else {
264
                    uvm_page_unbusy(pgs, npages);
265
266
            simple_unlock(&uobj->vmobjlock);
                                                — ufs/ufs_inode.c
```

6.5.4 Looking up a Page: uvm_pagelookup

```
/*
 * uvm_pagelookup: look up a page
 *
 * => caller should lock object to keep someone from pulling the page
 * out from under it
 */
struct vm_page *
uvm_pagelookup(struct uvm_object *obj, voff_t off);
```

References to Source Code

Only when the soft dependency facility is used, this function is effective in ffs_putpages as,

```
- ffs/ffs_vnops.c
507 int
508 ffs_putpages(void *v)
509 {
510
            struct vop_putpages_args /* {
511
                    struct vnode *a_vp;
512
                    voff_t a_offlo;
513
                    voff_t a_offhi;
514
                    int a_flags;
            } */ *ap = v;
515
516
            struct vnode *vp = ap->a_vp;
517
            struct uvm_object *uobj = &vp->v_uobj;
            struct inode *ip = VTOI(vp);
518
            struct fs *fs = ip->i_fs;
519
520
            struct vm_page *pg;
521
            off_t off;
522
            ufs_lbn_t lbn;
523
            if (!DOINGSOFTDEP(vp) || (ap->a_flags & PGO_CLEANIT) == 0) {
524
525
                    return genfs_putpages(v);
526
            }
527
528
529
             * for softdep files, force the pages in a block to be written together.
530
             * if we're the pagedaemon and we would have to wait for other pages,
531
             * just fail the request. the pagedaemon will pick a different page.
532
533
534
            ap->a_offlo &= ~fs->fs_qbmask;
535
            lbn = lblkno(fs, ap->a_offhi);
536
            ap->a_offhi = blkroundup(fs, ap->a_offhi);
537
            if (curproc == uvm.pagedaemon_proc) {
538
                    for (off = ap->a_offlo; off < ap->a_offhi; off += PAGE_SIZE) {
539
                            pg = uvm_pagelookup(uobj, off);
540
541
                             /*
                             * we only have missing pages here because the
542
543
                             * calculation of offhi above doesn't account for
544
                              * fragments. so once we see one missing page,
545
                             * the rest should be missing as well, but we'll
546
                             * check for the rest just to be paranoid.
547
                             */
548
549
                            if (pg == NULL) {
550
                                     continue;
551
552
                             if (pg->flags & PG_BUSY) {
553
                                     simple_unlock(&uobj->vmobjlock);
554
                                     return EBUSY;
```

Chapter 7

UBC

7.1 Introduction

Operating systems allow filesystem data to be accessed using two mechanisms: memory mapping calls such as mmap, and I/O system calls such as read or write. In traditional UNIX, the memory mapping requests are handled by the VM system while I/O system calls are handled by the I/O subsystem. Therefore, the VM subsystem and I/O subsystem each have their own data caching mechanisms that operate semi-independently of each other. This lack of integration leads to degrade in performance and flexibility. The function of Unified Buffer Cache(UBC) is to integrate the two cache mechanisms, to improve system performance.

7.2 Traditional Accesses to File

Figure 7.1 shows the flow of data between the disk and the application with a traditional buffer cache and VM page.

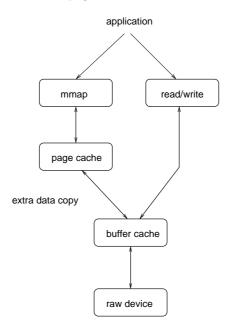


Figure 7.1: NetBSD before UBC

174 CHAPTER 7. UBC

7.2.1 I/O Subsystem: read() and write()

The read system call reads data from disk into the kernel's buffer cache, and then copies data from the buffer cache to the application's address space.

The use of the buffer cache for large amounts of data is generally bad, since

- the static sizing of the buffer cache means that the buffer cache is often too small, so that resulting in excessive cache misses for the single large file.
- the excessively high portion of buffer cache about a single large file leaves too little buffer cache for other files.
- or the buffer cache also has the limitation that cached data must always be mapped into kernel vitrual space, since modern hardware can easily have more RAM than kernel virtual memory.

7.2.2 Virtual Memory Subsystem: mmap()

The mmap system call gives the application direct memory-mapped access to the kernel's page cache data. File data is read into the page cache lazily as processes attempt to access the mappings created with mmap system call and generate page faults.

To write modified data in page caches back to disk,

- 1. the new version is copied back to the buffer cache and
- 2. from the buffer cache, the modified page contents is written to disk.

This double-cacheing of data is a major source of inefficiency, since

- Having two copies of file data means that twice as much memory is used.
- Copying the data back and forth between the buffer cache and the page cache is extra data copy, so that this wastes CPU cycles
- The extra copy also clobbers CPU cache memory and results in performance degrade.
- Having two copies of the dat also allows the possibility that the two sopies will become inconsistent, which can lead to application problems which are difficult to debug

7.3 File Access with Unified Buffer Cache

Figure 7.2 shows the changed data flow with UBC. UBC is a new subsystem which solves the problems with the two-cache model.

- File data is read directly into the page cache without going through the buffer cache by creating two new virtual filesystem operations which calls the device driver to read the data from disk if necessary.
- Since the pages of page cache are not always mapped into kernel virtual address space, a new mechanism for providing temporary mappings of page cache pages is provided, to be used by read and write system call.

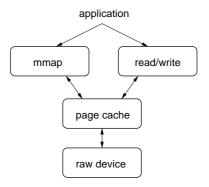


Figure 7.2: NetBSD after UBC

7.4 VFS Support for UVM

These new virtual filesystem operations are provided to allow the UVM system to request ranges of pages to be read into memory from disk or written from memory back to disk.

7.4.1 VOP_GETPAGES Operation

VOP_GETPAGES allocate pages from the UVM system for data which is not already cached and then initiate device I/O operations to read all the disk blocks which contain the data for those pages. The functions is defined in miscfs/genfs_vnops.c

VOP_GETPAGES(vp, offset, m, count, centeridx, access_type, advice, flags)

Read VM pages from file. The argument vp is the locked vnode to read the VM pages from. The argument offset is offset in the file to start accessing and m is an array of VM pages. The argument count specifies the number of pages to read. If the operation is successful zero is returned, otherwise an appropriate error code is returned.

7.4.2 VOP_PUTPAGES Operation

VOP_PUTPAGES initiate device I/Os to write dirty pages back to disk. The functions is defined in miscfs/genfs_vnops.c

VOP_PUTPAGES(vp, offset, len, flags)

Write modified (dirty) VM pages to file. The argument vp is the locked vnode to write the VM pages to and offset and len specifies the range of VM pages to write. There seems to be some confusion in the code whether offset and len specify the start and length of the VM pages for the start and end of the VM pages. The argument flags specifies whether the pages should be written asynchronously and also whether they should be marked invalid one the write back operation has completed. If the operation is successful zero is returned, otherwise an appropriate error code is returned.

176 CHAPTER 7. UBC

7.5 UVM Support for I/O

There are functions that allocate and free temporary mappings of page cache file data.

7.5.1 ubc_alloc Function

ubc_alloc is a page equivalent of the buffer cache function, get_blk. The functions is defined in uvm/uvm_bio.c

ubc_alloc() creates a kernel mappings of uobj starting at offset offset. the desired length of the mapping is pointed to by lenp, but the actual mapping may be smaller than this. lenp is updated to contain the actual length mapped. The flags must be one of

```
#define UBC_READ 0x01 /* mapping will be accessed for read */ #define UBC_WRITE 0x02 /* mapping will be accessed for write */
```

Currently, uobj must actually be a vnode object. Once the mapping is created, it must be accessed only by methods that can handle faults, such as uiomove() or kcopy(). Page faults on the mapping will result in the vnode's VOP_GETPAGES() method being called to resolve the fault.

7.5.2 ubc release Function

ubc_release is a page cache equivalent of the buffer cache function, brelse. The functions is defined in uvm/uvm_bio.c

```
void
ubc_release(void *va, int flags);
```

ubc_release() frees the mapping at va for reuse. The mapping may be cached to speed future accesses to the same region of the object. The flags are currently unused.

7.6 Example

7.6.1 Reading from Disk to Buffer with UBC

- ufs/ufs_readwrite.c

7.6. EXAMPLE 177

```
71
                    int a_ioflag;
                    struct ucred *a_cred;
 72
 73
            } */ *ap = v;
 74
            struct vnode *vp;
 75
            struct inode *ip;
 76
            struct uio *uio;
 77
            FS *fs;
 78
            void *win;
 79
            vsize_t bytelen;
            struct buf *bp;
 80
 81
            ufs_daddr_t lbn, nextlbn;
 82
            off_t bytesinfile;
 83
            long size, xfersize, blkoffset;
 84
            int error;
 85
            boolean_t usepc = FALSE;
 86
 87
            vp = ap->a_vp;
            ip = VTOI(vp);
 88
 89
            uio = ap->a_uio;
 90
            error = 0;
 91
104
            fs = ip->I_FS;
            if ((u_int64_t)uio->uio_offset > fs->fs_maxfilesize)
105
106
                    return (EFBIG);
107
            if (uio->uio_resid == 0)
108
                    return (0);
109
            if (uio->uio_offset >= ip->i_ffs_size) {
110
                    goto out;
111
            }
112
            usepc = vp->v_type == VREG;
114
            if (usepc) {
116
117
                    while (uio->uio_resid > 0) {
118
                             bytelen = MIN(ip->i_ffs_size - uio->uio_offset,
119
                                 uio->uio_resid);
120
                             if (bytelen == 0)
121
                                     break;
122
123
                            win = ubc_alloc(&vp->v_uobj, uio->uio_offset,
                                             &bytelen, UBC_READ);
124
125
                             error = uiomove(win, bytelen, uio);
126
                            ubc_release(win, 0);
127
                             if (error)
128
                                     break;
129
130
                    goto out;
            }
131
175 out:
176
            if (!(vp->v_mount->mnt_flag & MNT_NOATIME)) {
177
                    ip->i_flag |= IN_ACCESS;
```

178 CHAPTER 7. UBC

```
if ((ap->a_ioflag & IO_SYNC) == IO_SYNC)
return (error);

if ((ap->a_ioflag & IO_SYNC) == IO_SYNC)
error = VOP_UPDATE(vp, NULL, NULL, UPDATE_WAIT);

return (error);

182 }
```

— ufs/ufs_readwrite.c

7.6.2 Writing from Buffer to Disk with UBC

ufs/ufs_readwrite.c

```
184 /*
185 * Vnode op for writing.
186 */
187 int
188 ffs_write(void *v)
189 {
190
            struct vop_write_args /* {
191
                   struct vnode *a_vp;
192
                    struct uio *a_uio;
                    int a_ioflag;
193
194
                    struct ucred *a_cred;
            } */ *ap = v;
195
196
           struct vnode *vp;
197
           struct uio *uio;
198
           struct inode *ip;
199
           struct genfs_node *gp;
           FS *fs;
200
201
           struct buf *bp;
202
           struct proc *p;
203
           struct ucred *cred;
204
           ufs_daddr_t lbn;
            off_t osize, origoff, oldoff, preallocoff, endallocoff, nsize;
205
206
            int blkoffset, error, flags, ioflag, resid, size, xfersize;
207
            int bsize, aflag;
208
            int ubc_alloc_flags;
209
            int extended=0;
210
            void *win;
            vsize_t bytelen;
211
            boolean_t async;
212
213
            boolean_t usepc = FALSE;
214
215
           cred = ap->a_cred;
216
           ioflag = ap->a_ioflag;
217
           uio = ap->a_uio;
218
           vp = ap->a_vp;
           ip = VTOI(vp);
219
220
            gp = VTOG(vp);
221
245
           fs = ip->I_FS;
```

7.6. EXAMPLE 179

```
270
           flags = ioflag & IO_SYNC ? B_SYNC : 0;
271
           async = vp->v_mount->mnt_flag & MNT_ASYNC;
272
           origoff = uio->uio_offset;
273
           resid = uio->uio_resid;
274
           osize = ip->i_ffs_size;
275
           bsize = fs->fs_bsize;
           error = 0;
276
311
           ubc_alloc_flags = UBC_WRITE;
312
           while (uio->uio_resid > 0) {
313
                   boolean_t extending; /* if we're extending a whole block */
314
                   off_t newoff;
315
316
                   oldoff = uio->uio_offset;
                   blkoffset = blkoff(fs, uio->uio_offset);
317
318
                   bytelen = MIN(fs->fs_bsize - blkoffset, uio->uio_resid);
319
320
321
                    322
                    * initialize the pages first. if we're extending the file,
323
                    * we can safely allocate blocks without initializing pages
324
                    * since the new blocks will be inaccessible until the write
325
                    * is complete.
326
                    */
338
                           lockmgr(&gp->g_glock, LK_EXCLUSIVE, NULL);
339
                           error = GOP_ALLOC(vp, uio->uio_offset, bytelen,
340
                               aflag, cred);
341
                           lockmgr(&gp->g_glock, LK_RELEASE, NULL);
342
                           if (error) {
343
                                   break;
344
                           }
                           ubc_alloc_flags |= UBC_FAULTBUSY;
345
347
348
                   /*
349
                    * copy the data.
350
351
352
                   win = ubc_alloc(&vp->v_uobj, uio->uio_offset, &bytelen,
353
                       ubc_alloc_flags);
354
                   error = uiomove(win, bytelen, uio);
355
                   if (error && extending) {
356
357
                            * if we haven't initialized the pages yet,
358
                            * do it now. it's safe to use memset here
359
                            * because we just mapped the pages above.
360
361
                           memset(win, 0, bytelen);
362
363
                   ubc_release(win, 0);
364
                   /*
383
```

180 CHAPTER 7. UBC

```
384
                      * flush what we just wrote if necessary.
385
                      * XXXUBC simplistic async flushing.
386
                      */
387
388
                     if (!async && oldoff >> 16 != uio->uio_offset >> 16) {
389
                             simple_lock(&vp->v_interlock);
390
                             error = VOP_PUTPAGES(vp, (oldoff >> 16) << 16,</pre>
                                 (uio->uio_offset >> 16) << 16, PGO_CLEANIT);</pre>
391
392
                             if (error) {
393
                                     break;
394
                             }
                     }
395
            }
396
397
            if (error == 0 && ioflag & IO_SYNC) {
398
                     simple_lock(&vp->v_interlock);
399
                     error = VOP_PUTPAGES(vp, trunc_page(origoff & ~(bsize - 1)),
400
                         round_page(blkroundup(fs, uio->uio_offset)),
401
                         PGO_CLEANIT | PGO_SYNCIO);
            }
402
403
            goto out;
466 out:
            return (error);
480
481 }
```

— ufs/ufs_readwrite.c

Part II Analyzing Fast Filesystem

Chapter 8

Naming

Filesystem contain files, most of which contain ordinary data. Certain files are distinguished as directories and contain pointers to files that may themselves be directories.

8.1 Directories

8.1.1 Chunk

Directories are allocated in unites called *chunks* Chunks are broken up into variable-length directory entries to allow filenames to be of nearly arbitrary length. No directory entry can span multiple chunks. The *chunk* is defined as struct direct in ufs/ufs/dir.h as,

```
54 /*
55 * A directory consists of some number of blocks of DIRBLKSIZ
56 * bytes, where DIRBLKSIZ is chosen such that it can be transferred
57 * to disk in a single atomic operation (e.g. 512 bytes on most machines).
58 *
59 * Each DIRBLKSIZ byte block contains some number of directory entry
60 * structures, which are of variable length. Each directory entry has
61 * a struct direct at the front of it, containing its inode number,
62 * the length of the entry, and the length of the name contained in
63 * the entry. These are followed by the name padded to a 4 byte boundary
64 * with null bytes. All names are guaranteed null terminated.
65 * The maximum length of a name in a directory is MAXNAMLEN.
66
67 * The macro DIRSIZ(fmt, dp) gives the amount of space required to represent
68 * a directory entry. Free space in a directory is represented by
69 * entries which have dp->d_reclen > DIRSIZ(fmt, dp). All DIRBLKSIZ bytes
70 * in a directory block are claimed by the directory entries. This
71 * usually results in the last entry in a directory having a large
72 * dp->d_reclen. When entries are deleted from a directory, the
73 * space is returned to the previous entry in the same directory
74 * block by increasing its dp->d_reclen. If the first entry of
75 * a directory block is free, then its dp->d_ino is set to 0.
76 * Entries other than the first in a directory do not normally have
77 * dp->d_ino set to 0.
```

ufs/ufs/dir.h

```
78 */
79 #undef DIRBLKSIZ
80 #define DIRBLKSIZ
                            DEV_BSIZE
81 #undef MAXNAMLEN
82 #define MAXNAMLEN
83 #define APPLEUFS_DIRBLKSIZ 1024
84
85 struct direct {
86
            u_int32_t d_ino;
                                             /* inode number of entry */
                                             /* length of this record */
87
            u_int16_t d_reclen;
            u_int8_t d_type;
                                             /* file type, see below */
88
                                             /* length of string in d_name */
89
            u_int8_t d_namlen;
90
            char
                      d_name[MAXNAMLEN + 1];/* name with length <= MAXNAMLEN */</pre>
91 };
92
93 /*
94 * File types
95 */
96 #define DT_UNKNOWN
                              0
97 #define DT_FIFO
                              1
98 #define DT_CHR
                              2
99 #define DT_DIR
                              4
100 #define DT_BLK
                              6
101 #define DT_REG
                             8
102 #define DT_LNK
                            10
103 #define DT_SOCK
                            12
104 #define DT_WHT
                             14
                                                        ufs/ufs/dir.h
```

The filesystem records free space in a directory by having entries accumulate the free space in their size fields.

8.1.2 Modification of Directory

When an entry is deleted from a directory, the system coalesces the entry's space into the previous entry in the same directory chunk by increasing the size of the previous entry by the size of the deleted entry.

If the filrst entry of a directory chunk is free, then the pointer to the entry's inode is set to zero to show that the entry is unallocated.

8.2 Finding of Names in Directories

8.2.1 Match Algorithm

First, the length of the sought-after name is compared with the length of the name being checked. If the lengths are identical, a string comparison of the name being sought and the directory entry is made. If they match, the search is complete; if they fail, the search continues with the next entry.

8.2.2 Search Performance Improvement

Before starting a directory scan, the kernel looks for the name in the cache. If either a positive or a negative entry is found, the directory scan can be avoided.

8.3 Pathname Translation

The translation of a pathname requires a series of interactions between the vnode interface and the underlying filesystems. The pathname-translation process proceeds as follows:

- 1. The pathname to be translated is copied in from the user process.
- 2. The starting point if the pathname is determined. The vnode for this directory becomes the *lookup directory* used in the next step.
- 3. The vnode layer calls the filesystem-specific *lookup* opeartion, and passes the remaining components of the pathname and the current *lookup directory*.
- 4. Typically, the underlying filesystem will search the *lookup directory* for the next component of the pathname and will return the resulting vnode or an error if the name does not exist.
- 5. If an error is returned, the top level returns the error. If the pathname has been exhausted, the pathname lookup is done, and the returned vnode is the result of not a directory, then the vnode layer returns "not a directory" error.
- 6. If there are no errors, the top layer checks to see whether the returned directory is a mount point for another filesystem. If it is, then the *lookup directory* becomes the mounted filesystem; otherwise, the *lookup directory* becomes the vnode returned by the lower layer. The lookup then iterates with step 3.

8.4 The Name Cache

Name-cache management is a service that is provided by the vnode management routines. The interface provides a facility

- to add a name and its corresponding vnode,
- to look up a name to get the corresponding vnode,
- to delete a specific name from the cache, and
- to invalidate all names that reference a specific vnode.

8.4.1 Vnode's Capability

Each vnode is given a *capability* — a 32-bit number guaranteed to be unique. A vnode's capability is invalidated each time it is reused by **getnewvnode** or, when specificially requested by a client.

When a name is found during a cached lookup, the capability assigned to the name is compared with that of the vnode. If they match, the lookup is successful; if they do not match, the cache entry is freed and failure is returned.

Directory vnodes can have many names that reference them. Using vnode's *capability*, the kernel need not revoke a names for a vnode by scanning the entire name table, thousands of names, looking for references to the vnode in question.

8.4.2 Negative Caching

If a name is looked up in a directory and is not found, that name can be entered in the cache, along with a null pointer for its corresponding vnode. When the directory is modified, the kernel must invalidate all the negative names for that directory vnode by assigning the directory a new capability.

8.4.3 Special Device Handling

The name and attributes of special devices and FIFOs are maintained by the filesystem in which they reside. However, their operations are maintained by the kernel.

A Dilemma

Since a special device is identified solely by its major and minor number, it is possible for two or more instances of the same device to appear within the filesystem name space. Each of these different names has its own vnode and underlying object, Yet all these vnodes must be treated as one from the perspective of identifying blocks in the buffer cache and in other places where the vnode and logical block number are used as a key.

A Solution

To ensure that the set of vnodes is treated as a single vnode, the vnode layer provides a routine checkalias that is called each time that a new special device vnode comes into existence. This routine looks for other instances of the device, and if it finds them, links them together so that they can act as one.

8.5 Links

8.5.1 Hard Links

Each file has a single inode, but multiple directory entries in the same filesystem may reference that inode by creating *hard links*.

8.5.2 Soft Links

The *symbolic link*, or *soft link* is implemented as a file that contains a pathname. If a symbolic link contains an relative pathname, the contents of the symbolic link are evaluated relative to the location of the link, not relative to the current working directory).

8.5.3 The Differences

- A symbolic link can refer to a directory or to a file on a different filsystem; A hard link cannot
- Since symbolic links may cause loops in the filesystem, the kernel prevents looping by allowing at most eight symbolic link travesal in a single pathname tralslation. If the limit is reached, the kernel produces an ELOOP error.

8.6 References to Source Code

8.6.1 vfs_cache.c - 537 lines, 17 functions

Gloval Variables

[Positive Name Cache]

nchashtbl Name cache hash table

nchash Magic number to generate hash key

numcache Number of cache entries allocated

nclruhead LRU chain

nchstats Cache effectiveness statistics

namecache_pool Pool

doingcache Switch to enable cache

[Negative Name Cache]

ncvhashtbl Name cache hash table

ncvhash Magic number to generate hash key

Functions

[Name Cache Management]

cache_lookup Look for a the name in the cache

cache_revlookup Scan cache looking for name of directory entry pointing at vp

cache_enter Add an entry to the cach

cache_purge Cache flush, a particular vnode; called when a vnode is renamed

[Name Cache Initialization]

nchinit nchreinit

[Diagnostic]

 $namecache_print$

8.6.2 vfs_lookup.c - 777 lines, 4 functions

Gloval Variables

pnbuf_pool Pathname buffer pool
pnbuf_cache Pathname buffer cache

Functions

namei Convert a pathname into a pointer to a locked inode namei_hash Determine the namei hash (for cn_hash) for name

lookup Search a pathname

relookup [?] Reacquire a path name component

Chapter 9

Inode

9.1 The Structures of an Inode

To allow files to be allocated concurrently and random access within files, 4.4BSD uses the concept of an *index node*, namely *inode*.

The inode contains information about the contents of the file. Notably missing in the inode is the filename. Chunks are broken up into variable-length directory entries to allow filenames to be of arbitrary length. The fixed parts of a directory entry includes

- An index into a table of on-disk inode structures. This inode structure describes the file.
- The size of the entry in bytes
- The type of the entry.
- The length of the filename contained in the entry in bytes.

The structure definition of the inode is located in ufs/ufs/inode.h as,

```
ufs/ufs/inode.h
67 /*
68 * The inode is used to describe each active (or recently active) file in the
69 * UFS filesystem. It is composed of two types of information. The first part
70 * is the information that is needed only while the file is active (such as
71 * the identity of the file and linkage to speed its lookup). The second part
72 * is the permanent meta-data associated with the file which is read in
73 * from the permanent dinode from long term storage when the file becomes
74
   * active, and is put back when the file is no longer being used.
75 */
76 struct inode {
77
           struct genfs_node i_gnode;
78
           LIST_ENTRY(inode) i_hash;/* Hash chain. */
79
           struct vnode *i_vnode; /* Vnode associated with this inode. */
           struct vnode *i_devvp; /* Vnode for block I/O. */
80
                                  /* flags, see below */
81
           u_int32_t i_flag;
82
           dev_t
                    i_dev;
                                   /* Device associated with the inode. */
                                   /* The identity of the inode. */
83
           ino_t
                     i_number;
84
85
           union {
                                   /* Associated filesystem. */
```

```
86
                    struct fs *fs;
                                            /* FFS */
 87
                    struct lfs *lfs;
                                           /* LFS */
                    struct m_ext2fs *e2fs; /* EXT2FS */
 88
 89
            } inode_u;
 90 #define i_fs
                    inode_u.fs
 91 #define i_lfs
                    inode_u.lfs
 92 #define i_e2fs inode_u.e2fs
 93
 94
                    buflists i_pcbufhd;
                                           /* softdep pagecache buffer head */
            struct
                     dquot *i_dquot[MAXQUOTAS]; /* Dquot structures. */
 95
            struct
                                   /* Revision level for NFS lease. */
            u_quad_t i_modrev;
 96
            struct lockf *i_lockf;/* Head of byte-level lock list. */
 97
 98
 99
             * Side effects; used during directory lookup.
100
101
            */
            int32_t
                      i_count;
                                    /* Size of free slot in directory. */
102
103
                      i_endoff;
                                    /* End of useful stuff in directory. */
            doff_t
                                    /* Offset in dir, where we found last entry. */
104
            doff_t
                      i_diroff;
105
            doff_t
                     i_offset;
                                    /* Offset of free space in directory. */
106
            u_int32_t i_reclen;
                                   /* Size of found directory entry. */
107
                     i_ffs_effnlink; /* i_nlink when I/O completes */
            int
108
            /*
109
            * Inode extensions
110
            */
111
           union {
                    /* Other extensions could go here... */
112
113
                    struct ext2fs_inode_ext e2fs;
114
                    struct lfs_inode_ext lfs;
115
            } inode_ext;
116 #define i_e2fs_last_lblk
                                    inode_ext.e2fs.ext2fs_last_lblk
117 #define i_e2fs_last_blk
                                    inode_ext.e2fs.ext2fs_last_blk
118 #define i_lfs_effnblks
                                    inode_ext.lfs.lfs_effnblocks
119 #define i_lfs_fragsize
                                    inode_ext.lfs.lfs_fragsize
120 #define i_lfs_osize
                                    inode_ext.lfs.lfs_osize
121
122
            * The on-disk dinode itself.
123
            */
124
           union {
125
                    struct dinode ffs_din; /* 128 bytes of the on-disk dinode. */
126
                    struct ext2fs_dinode e2fs_din; /* 128 bytes of the on-disk
127
                                                       dinode. */
128
            } i_din;
130
131 #define i_ffs_atime
                                    i_din.ffs_din.di_atime
132 #define i_ffs_atimensec
                                    i_din.ffs_din.di_atimensec
133 #define i_ffs_blocks
                                    i_din.ffs_din.di_blocks
134 #define i_ffs_ctime
                                    i_din.ffs_din.di_ctime
135 #define i_ffs_ctimensec
                                    i_din.ffs_din.di_ctimensec
136 #define i_ffs_db
                                    i_din.ffs_din.di_db
137 #define i_ffs_flags
                                    i_din.ffs_din.di_flags
138 #define i_ffs_gen
                                    i_din.ffs_din.di_gen
139 #define i_ffs_gid
                                   i_din.ffs_din.di_gid
140 #define i_ffs_ib
                                    i_din.ffs_din.di_ib
```

```
141 #define i_ffs_mode
                                       i_din.ffs_din.di_mode
   142 #define i_ffs_mtime
                                       i_din.ffs_din.di_mtime
   143 #define i_ffs_mtimensec
                                       i_din.ffs_din.di_mtimensec
    144 #define i_ffs_nlink
                                       i_din.ffs_din.di_nlink
    145 #define i_ffs_rdev
                                       i_din.ffs_din.di_rdev
    146 #define i_ffs_shortlink
                                       i_din.ffs_din.di_shortlink
    147 #define i_ffs_size
                                       i_din.ffs_din.di_size
    148 #define i_ffs_uid
                                       i_din.ffs_din.di_uid
                                                      - ufs/ufs/inode.h
where struct dinode of line 125 is defined as
                                                  ---- ufs/ufs/dinode.h
    62 /*
    63 * A dinode contains all the meta-data associated with a UFS file.
    64 * This structure defines the on-disk format of a dinode. Since
    65 * this structure describes an on-disk structure, all its fields
    66 * are defined by types with precise widths.
    67 */
    68
    69 typedef int32_t ufs_daddr_t;
    70 typedef long ufs_lbn_t;
    71
    72 #define NDADDR 12
                                               /* Direct addresses in inode. */
    73 #define NIADDR 3
                                               /* Indirect addresses in inode. */
    75 struct dinode {
                                                    0: IFMT, permissions; see below. */
    76
               u_int16_t
                               di_mode;
                                               /*
                                               /*
                                                    2: File link count. */
    77
               int16_t
                               di_nlink;
    78
               union {
    79
                       u_int16_t oldids[2];
                                              /*
                                                    4: Ffs: old user and group ids. */
                       u_int32_t inumber;
                                               /* 4: Lfs: inode number. */
    80
               } di_u;
    81
                                               /* 8: File byte count. */
    82
               u_int64_t
                               di_size;
                                               /* 16: Last access time. */
    83
               int32_t
                               di_atime;
    84
               int32_t
                              di_atimensec;
                                               /* 20: Last access time. */
    85
               int32_t
                              di_mtime;
                                               /* 24: Last modified time. */
                                              /* 28: Last modified time. */
               int32_t
                              di_mtimensec;
    86
    87
               int32_t
                              di_ctime;
                                               /* 32: Last inode change time. */
                                             /* 36: Last inode change time. */
    88
               int32 t
                              di_ctimensec;
                             di_db[NDADDR]; /* 40: Direct disk blocks. */
    89
               ufs_daddr_t
                               di_ib[NIADDR]; /* 88: Indirect disk blocks. */
    90
               ufs_daddr_t
                                               /* 100: Status flags (chflags). */
    91
               u_int32_t
                               di_flags;
    92
                               di_blocks;
                                               /* 104: Blocks actually held. */
               u_int32_t
    93
                                               /* 108: Generation number. */
               int32_t
                               di_gen;
    94
               u_int32_t
                               di_uid;
                                              /* 112: File owner. */
               u_int32_t
                               di_gid;
                                              /* 116: File group. */
                               di_spare[2]; /* 120: Reserved; currently unused */
    96
               int32_t
    97 };
    98
    99 /*
    100 * The di_db fields may be overlaid with other information for
```

101 * file types that do not have associated disk storage. Block

ufs/ufs/dinode.h

```
102 * and character devices overlay the first data block with their
103 * dev_t value. Short symbolic links place their path in the
104 * di_db area.
105 */
106 #define di_inumber
                            di_u.inumber
107 #define di_ogid
                            di_u.oldids[1]
108 #define di_ouid
                            di_u.oldids[0]
109 #define di_rdev
                            di_db[0]
110 #define di_shortlink
                            di_db
111 #define MAXSYMLINKLEN
                            ((NDADDR + NIADDR) * sizeof(ufs_daddr_t))
112
113 /* NeXT used to keep short symlinks in the inode even when using
114 * FS_42INODEFMT. In that case fs->fs_maxsymlinklen is probably -1,
115 * but short symlinks were stored in inodes shorter than this:
116 */
117 #define APPLEUFS_MAXSYMLINKLEN 60
119 /* File permissions. */
120 #define IEXEC
                                            /* Executable. */
                            0000100
121 #define IWRITE
                            0000200
                                            /* Writeable. */
122 #define IREAD
                            0000400
                                            /* Readable. */
123 #define ISVTX
                                            /* Sticky bit. */
                            0001000
124 #define ISGID
                                            /* Set-gid. */
                            0002000
125 #define ISUID
                            0004000
                                            /* Set-uid. */
127 /* File types. */
128 #define IFMT
                                            /* Mask of file type. */
                            0170000
129 #define IFIFO
                            0010000
                                            /* Named pipe (fifo). */
130 #define IFCHR
                            0020000
                                            /* Character device. */
131 #define IFDIR
                                            /* Directory file. */
                            0040000
132 #define IFBLK
                            0060000
                                            /* Block device. */
133 #define IFREG
                            0100000
                                            /* Regular file. */
134 #define IFLNK
                            0120000
                                            /* Symbolic link. */
                                            /* UNIX domain socket. */
135 #define IFSOCK
                            0140000
136 #define IFWHT
                                            /* Whiteout. */
                            0160000
137
138 /* Size of the on-disk inode. */
139 #define DINODE_SIZE
                            (sizeof(struct dinode))
                                                            /* 128 */
```

9.1.1 File Flags

4.4BSD added two new system calls, chflags and fchflags, that set a 32-bit flags — di_flags member of dinode structure.

The owner of the file or the superuser can set the low 16 bits. Only the superuser can set the high 16 bits. Once set, the append-only and immutable flags in the top 16 bits cannot be cleared when the system is in *secure mode*.

The flags are defined in sys/stat.h as,

```
sys/stat.h
232 /*
233 * Definitions of flags stored in file flags word.
234 *
```

```
235
    * Super-user and owner changeable flags.
236 */
237 #define UF_SETTABLE
                            0x0000ffff
                                            /* mask of owner changeable flags */
238 #define UF_NODUMP
                            0x00000001
                                            /* do not dump file */
239 #define UF_IMMUTABLE
                            0x0000002
                                            /* file may not be changed */
240 #define UF_APPEND
                            0x00000004
                                            /* writes to file may only append */
241 #define UF_OPAQUE
                            80000000x0
                                            /* directory is opaque wrt. union */
242 /*
243 * Super-user changeable flags.
244 */
245 #define SF_SETTABLE
                                            /* mask of superuser changeable flags */
                            0xffff0000
246 #define SF_ARCHIVED
                                            /* file is archived */
                            0x00010000
247 #define SF_IMMUTABLE
                            0x00020000
                                            /* file may not be changed */
248 #define SF_APPEND
                            0x00040000
                                            /* writes to file may only append */
```

_____ sys/stat.h

Files marked immutable by the superuiser cannot be changed, except by someone with physical access to either the machine or the system console. It is useful in safeguarding the login or su program from the danger of hacking. The appendonly flag is typically used for critical system logs. Although simple in concept, these two features improve the security of a system dramatically.

9.1.2 Inode Flags

Unlike *file flags*, *inode flags* is only used to internal purpose by filesystem hierarchy manipulation functions such as rename. They are defined in ufs/ufs/inode.h as,

```
ufs/ufs/inode.h
170 /* These flags are kept in i_flag. */
171 #define IN_ACCESS
                            0x0001
                                             /* Access time update request. */
172 #define IN_CHANGE
                             0x0002
                                             /* Inode change time update request. */
173 #define IN_UPDATE
                             0x0004
                                             /* Modification time update request. */
174 #define IN_MODIFIED
                                             /* Inode has been modified. */
                             8000x0
175 #define IN_ACCESSED
                                             /* Inode has been accessed. */
                             0x0010
176 #define IN_RENAME
                            0x0020
                                             /* Inode is being renamed. */
177 #define IN_SHLOCK
                                             /* File has shared lock. */
                             0x0040
178 #define IN_EXLOCK
                             0x0080
                                             /* File has exclusive lock. */
179 #define IN_CLEANING
                             0x0100
                                             /* LFS: file is being cleaned */
                                             /* LFS: dirop in progress */
180 #define IN_ADIROP
                             0 \times 0200
181 #define IN_SPACECOUNTED 0x0400
                                             /* Blocks to be freed in free count. */
```

ufs/ufs/inode.h

9.1.3 Inode for Root Directory

Filesystems contain files, most of which contain ordinary data. Certain files are distinguished as directories and contain pointers to files that may themselves be directories. Therefore, an inode can point to a directory as well as to a file.

By convention,

• inode 2 is always reserved for the root directory of a filesystem.

9.2 Inode Management

9.2.1 Opening a File

Steps in opening a file is

- 1. Find the file's associated vnode.
 - (a) The lookup request is given to the filesystem associated with the directory currently being searched.
 - (b) When the local filesystem finds the name in the directory, it gets the inode number of the associated file. If the inode is not in the table, such as the first time a file is opened, the filesystem must request a new vnode. When a new vnode is allocated to the local filesyste, a new structure to hold inode is allocated
 - (c) The filesystem searches its collection of inodes to see whether the requested inode is already in memory. To avoid doing a linear scan of all its entries, the system keeps a set of hash chains keyed on *inode number* and *filesystem identifier*.
- 2. Locate the disk block containing the inode
 - (a) When the disk I/O completes, the inode is copied from the disk buffer into the newly allocated inode entry.
 - (b) The inode table itself maintains supplement information while the inode is in memory including
 - $\bullet\,$ hash chains managing the inode table
 - flags showing the inode's status
 - reference counts on the inode's use
 - information to manage locks
 - pointers to the superblock.
- 3. Read the block containg the inode into a buffer in system memory.

9.2.2 Closing a File

When the last reference to a file is closed,

- 1. The local filesystem is notified that the file has become inactive.
- 2. The inode times will be updated, and the inode may be written to disk.
- 3. However, it remains on the hash list so that it can be found if it is reopened.
- 4. After being inactive for a period determined by the vnode layer based on demand for vnodes in all the filesyste, the vnode will be reclaimed.
- 5. When a vnode for a local file is reclaimed, the inode is removed from the previous filesystem's hash chain and, if the inode is dirty, its contents are written back to disk.
- 6. Then, the space for the inode is deallocated, so that the vnode will be ready for use by a new filesystem client.

9.3. QUOTAS 195

9.3 Quotas

The quota mechanism sets limits on both the number of files and the number of disk blocks that a user or members of group may allocate. Quotas connect into the system primarilt as an adjunct to the allocation routines.

9.3.1 Soft and Hard Quota

When a process exceeds its soft limit, a warning is printed on the user's terminal; the offending process is not prevented from allocating space unless it exceeds its hard limit. If a user fails to correct the problem for longer than a *grace period*, the soft limit starts to be enforced as the hard limit.

9.3.2 Quota Imposing Mechanism

Quota is checked by chkdq function. When a new block is requested from the allocation routines, the request is first validated by the quota system with the following steps:

- 1. If there is a user quota associated with the file, the quota system consults the quota associated with the owner of the file. If the owner has reached or exceeded their limit, the request is denied.
- 2. The same check is done for the group quota.
- 3. If the quota tests pass, the request is permitted and is added to the usage statistics for the file.

Quotas are asigned to a filesystem after it has been mounted. For each quota to be imposed, the system opens the appropriate quota file and holds a reference to it in the mount-table nety associated with the mounted filesystem.

9.3.3 Quota Records

Quota files are maintained as an array of quota records indexed by user or group identifiers. The Quota record is defined in ufs/ufs/quota.h as,

```
- ufs/ufs/quota.h
94 /*
95 * The following structure defines the format of the disk quota file
96 * (as it appears on disk) - the file is an array of these structures
97 * indexed by user or group number. The setquota system call establishes
    * the vnode for each quota file (a pointer is retained in the ufsmount
98
99
    * structure).
100 */
101 struct dqblk {
                                            /* absolute limit on disk blks alloc */
102
            u_int32_t dqb_bhardlimit;
103
            u_int32_t dqb_bsoftlimit;
                                            /* preferred limit on disk blks */
            u_int32_t dqb_curblocks;
                                            /* current block count */
104
            u_int32_t dqb_ihardlimit;
                                            /* maximum # allocated inodes + 1 */
105
106
            u_int32_t dqb_isoftlimit;
                                            /* preferred inode limit */
                                            /* current # allocated inodes */
107
            u_int32_t dqb_curinodes;
                     dqb_btime;
                                            /* time limit for excessive disk use */
108
            int32_t
109
            int32_t
                      dqb_itime;
                                            /* time limit for excessive files */
110 };
```

ufs/ufs/quota.h

ufs/ufs/quota.h

9.3.4 Active Quota Entry: dquot

Active quotas are held in system memory in a dquot structure defined in ufs/ufs/quota.h as,

```
ufs/ufs/quota.h
115 /*
 116 * The following structure records disk usage for a user or group on a
     * filesystem. There is one allocated for each quota that exists on any
 118 * filesystem for the current user or group. A cache is kept of recently
 119 * used entries.
 120 */
 121 struct dquot {
             LIST_ENTRY(dquot) dq_hash;
                                             /* hash list */
 122
             TAILQ_ENTRY(dquot) dq_freelist; /* free list */
 123
 124
             u_int16_t dq_flags;
                                             /* flags, see below */
                                             /* count of active references */
 125
             u_int16_t dq_cnt;
 126
             u_int16_t dq_spare;
                                             /* unused spare padding */
             u_int16_t dq_type;
                                             /* quota type of this dquot */
 127
 128
             u_int32_t dq_id;
                                             /* identifier this applies to */
                                             /* filesystem that this is taken from */
 129
             struct ufsmount *dq_ump;
                                             /* actual usage & quotas */
 130
            struct dqblk dq_dqb;
 131 };
 132 /*
 133 * Flag values.
 134 */
                                             /* this quota locked (no MODS) */
 135 #define DQ_LOCK
                             0x01
 136 #define DQ_WANT
                             0x02
                                             /* wakeup on unlock */
 137 #define DQ_MOD
                             0x04
                                             /* this quota modified since read */
 138 #define DQ_FAKE
                             80x0
                                             /* no limits here, just usage */
                                             /* has been warned about blk limit */
 139 #define DQ_BLKS
                             0x10
 140 #define DQ_INODS
                             0x20
                                             /* has been warned about inode limit */
```

The task of finding the dquot structure associated with a file is done when the file is first opened for writing. If one or more quotas exist, the inode is set up to hold a reference to the appropriate dquot, by setting dquot member of the inode structure. If a user or a group has multiple files open on the same filesystem, all inodes describing those files point to the same dquot entry.

Improvement in Searching a dquot Entry

To avoid doing a linear scan of all the dquot entries, the system keeps a set of hash chains keyed on the *filesystem* and on the *user* or *group identifier*.

If the dquot entry is not resident, such as the first time a file is opened for writing, the system must reallocate a dquot entry and read in the quota from disk.

When the reference count on a dquot structure drops to zero, the system puts that entry onto the end the LRU chain. The dquot structure is not removed from its hash chain, so if the structure is needed again soon, it can still be located.

Dummy dquot Entries

To prevent cost of going to disk and reading the quota file to discover that a user has no quota, the system maintains dummy dquot entries. For a dummy entry, chkdq routine updates the usage fields, but will not impose any limits.

9.3.5 Consistency Maintenance

If the system crashes, leaving the quotas in an inconsistent state, the system administrator must run the quotacheck program to rebuild the usage information in the quota files.

9.4 References to Source Code

9.4.1 ufs_bmap.c - 325 lines, 3 functions

Gloval Variables

none

Functions

```
ufs_bmap converts a the logical block number to its physical block ufs_bmaparray does the real conversion for ufs_bmap (used by ufs_bmaparray)
```

9.4.2 ufs_ihash.c - 194 lines, 7 functions

Gloval Variables

Functions

9.4.3 ufs_inode.c - 268 lines, 3 functions

Gloval Variables

none

Functions

```
ufs_inactive Last reference to an inode. If necessary, write or delete it ufs_reclaim Reclaim an inode so that it can be used for other purposes ufs_balloc_range Allocate a range of blocks in a file
```

9.4.4 ufs_lookup.c - 1216 lines, 9 functions

Gloval Variables

none

Functions

ufs_lookup Convert a pathname into a pointer to a locked inode ufs_dirbad

ufs_dirbadentry Do consistency checking on a directory entry

ufs_makedirentry Construct a new directory entry after a call to namei

ufs_direnter Write a directory entry after a call to namei ufs_dirremove Remove a directory entry after a call to namei

ufs_dirrewrite Rewrite an existing directory entry to point at the inode supplied

ufs_checkpath Check if source directory is in the path of the target directory

9.4.5 ufs_quota.c - 960 lines, 20 functions

Gloval Variables

none

Functions

getinoquota Set up the quotas for an inode
chkdq Update disk usage, and take corrective action
chkdqchg Check for a valid change to a users allocation

chkiq Check for a valid change to a users allocation chkiq Check the inode limit, applying corrective action chkiqchg Check for a valid change to a users allocation

chkdquot Diagnostic

[Code to process quotactl system calls]

quotaon Q_QUOTAON - set up a quota file for a particular file system

quotaoff Q_QUOTAOFF - turn off disk quotas for a filesystem getquota Q_GETQUOTA - return current values in a dqblk structure

setquota $Q_SETQUOTA$ - assign an entire dqblk structure setuse Q_SETUSE - set current inode and block usage

qsync Q_SYNC - sync quota files to disk

[Code managing hash table for dquot structures]

dqinit Initialize the quota system

dqreinit

dqdone Free resources held by quota system

dqget Obtain a dquot structure for the specified identifier and quota fi

dqref Obtain a reference to a dquot dqrele Release a reference to a dquot

dqsync Update the disk quota in the quota file

dqflush Flush all entries from the cache for a particular vnode

9.4.6 ufs_readwrite.c - 481 lines, 4 functions

Gloval Variables

none

Functions

ffs_read

```
ffs_write
lfs_read
lfs_write
```

9.4.7 ufs_vfsops.c - 262 lines, 8 functions

Gloval Variables

ufs_initcount

Functions

ufs_startReturn the vnode for root of a filesystemufs_quotactlDo operations associated with quotasufs_check_exportVerify a remote client has export rightsufs_fhtovpgeneric part of fhtovpufs_initufs_reinitufs_done

9.4.8 ufs_vnops.c - 2074 lines, 30 functions

Gloval Variables

ufs_remove ufs_rename ufs_rmdir ufs_setattr ufs_strategy ufs_symlink

none

Functions

```
ufs_vinit
                   Initialize the vnode associated with a new inode
ufs_makeinode
                   Allocate a new inode
[ Virtual Filesystem Operations for FFS ]
ufs_access
ufs_advlock
ufs_close
ufs_create
ufs_getattr
ufs_inactive
ufs_link
ufs_lookup
ufs_mkdir
ufs_mknod
ufs_open
ufs_pathconf
ufs_print
ufs_readdir
ufs_readlink
```

```
ufs_whiteout
[ Virtual Filesystem Operations for Special File ]
ufsspec_close
ufsspec_read
ufsspec_write
[ Virtual Filesystem Operations for FIFO ]
ufsfifo_read
ufsfifo_write
ufsfifo_close
[ Generalized Virtual Filesystem Operations ]
#define ufs_lock
                       genfs_lock
#define ufs_mmap
                       genfs_mmap
                       genfs_revoke
#define ufs_revoke
                       genfs_seek
#define ufs_seek
#define ufs_poll
                       genfs_poll
#define ufs_unlock
                       genfs_unlock
#define ufs_abortop
                       genfs_abortop
                       genfs_fcntl
#define ufs_fcntl
                       genfs_enoioctl
#define ufs_ioctl
#define ufs_islocked genfs_islocked
#define ufs_lease_check genfs_lease_check
```

Chapter 10

Berkeley Fast File System

The FFS fielsore was designed on the assumption that buffer caches would be small and thus that files would need to be read often. It tries to place files likely to be accessed together in the same general location on the disk.

The LFS filestore was designed for fast machines with large buffer caches. It assumes that writing data to disk is the bottleneck, and it tries to avoid seeking by writing all data together in the order in which they were created. It assumes that active files will remain in the buffer cache, so is little concerned with the time that it takes to retrieve files from the filestore.

10.1 Filestore Services

The filestore implementation converts from the user abstraction of a file as an array of bytes to the structure imposed by the underlying physical medium. This operation is called by $Block\ I/O$.

The $Block\ I/O$ is done by

- 1. First, the system breaks the user's request into a set of operations to be done on *logical blocks* of the file.
- 2. The data in each logical block are accessed via physical block on the disk.
- 3. A physical disk block is constructed from one or more contiguous sectors.

Vnode operations about storage is implemented by underlying filestore based on $block\ I/O.$

10.1.1 Allocating and Freeing Objects

There are four operators for allocating and freeing objects.

```
VOP_VALLOC(pvp, mode, cred, vpp)
```

Allocate file system type specific data a new file in the file system. The argument pvp specifies the vnode of the directory to create the new file. The argument mode specifies file system type specific flags and cred are the credentials of the calling process. The vnode of the new file is returned in the address specified by vpp.

(implemented as ffs_valloc in ufs/ffs/ffs_alloc.c)
(used by ufs_mkdir, ufs_makeinode)

VOP_BALLOC(vp, startoffset, size, cred, flags, bpp)

Allocate the physical blocks on a device given the vnode vp and the offset logical block number startoffset in a file. The argument size specifies the size to be allocated. The credentials of the calling processing are specified by cred. If the argument bpp is not NULL, the buffer is written to the allocated blocks. The argument flags is a set of flags controlling the low-level allocation when the buffer is written. Valid values defined in <sys/buf.h> are:

B_CLRBUF request allocated buffer be cleared B_SYNC do all allocations synchronously

If the operation is successful zero is returned, otherwise an appropriate error is returned.

(implemented as ffs_balloc in ufs/ffs/ffs_balloc.c)
(used by ufs_direnter, ffs_write, ufs_mkdir)

VOP_REALLOCBLKS(vp, buflist)

Rearrange block in a file to be contiguous. The argument vp is the vnode of the file to manipulate. The argument buflist is a list of buffers to rearrange. If the operation is successful zero is returned, otherwise an appropriate error is returned.

(implemented as ffs_valloc in ufs/ffs/ffs_alloc.c)
(used by NONE !)

VOP_VFREE(pvp, ino, mode)

Release file resources. This function is used by the file system to release cached file system specific data associated with the file when the vnode is recycled.

(implemented as ffs_vfree in ufs/ffs/ffs_alloc.c)
(used by ufs_mkdir, ufs_makeinode)

10.1.2 Updating Inode Attribute

VOP_UPDATE(vp, access, modify, flags)

Update times on file with vnode vp. The access and modification times are specified by the arguments access and modify respectively. The change time is always taken from the current time. The argument flags is a set of file system type dependent flags indicating which times should be updated.

ffs_reallocblks, ffs_balloc, ffs_truncate,
ffs_fsync, ffs_full_fsync, ffs_read, ffs_write)

10.1.3 Manipulating Existing Objects

The blkatoff operator is similar to the read operator, except that the blkatoff operator simply returns a pointer to a kernel memory buffer with the requested data, instead of copying the data.

VOP_READ(vp, uio, ioflag, cred)

Read the contents of a file. The argument vp is the vnode of the file to read from, uio is the location to read the data into, ioflag is a set of flags and cred are the credentials of the calling process.

The ioflag argument is used to give directives and hints to the file system. When attempting a read, the high 16 bits are used to provide a read-ahead hint (in unit of file system blocks) that the file system should attempt. The low 16 bits are a bit mask which can contain the following flags:

IO_UNIT do I/O as atomic unit
IO_APPEND append write to end
IO_SYNC do I/O synchronously

IO_NODELOCKED underlying node already locked IO_NDELAY FNDELAY flag set in file table IO_VMIO data already in VMIO space

Zero is returned on success, otherwise an error is returned. The vnode should be locked on entry and remains locked on exit.

VOP_WRITE(vp, uio, ioflag, cred)

Write to a file. The argument vp is the vnode of the file to write to, uio is the location of the data to write, ioflag is a set of flags and cred are the credentials of the calling process.

The ioflag argument is used to give directives and hints to the file system. The low 16 bits are a bit mask which can contain the same flags as $VOP_READ()$.

Zero is returned on success, otherwise an error is returned. The vnode should be locked on entry and remains locked on exit.

VOP_FSYNC(vp, cred, flags, offlo, offhi, p)

Flush pending data buffers for a file to disk. The argument vp is the locked vnode of the file for flush. The argument cred is the caller's credentials and p the calling process. The argument flags is a set of flags. If FSYNC_WAIT is specified in flags, the function should wait for I/O to complete before returning. The argument offlo and offhi specify the range of file to flush. If the operation is successful zero is returned, otherwise an appropriate error code is returned.

This function implements the sync(2) and fsync(2) system calls.

VOP_BLKATOFF(vp, offset, res, bpp)

Return buffer bpp with the contents of block offset from the be-

ginning of directory specified by vnode vp. If res is non-zero, fill it in with a pointer to the remaining space in the directory.

(implemented as ffs_blkatoff in ufs/ffs/ffs_subr.c)
(used by ufs_lookup, ufs_dirrenter, ufs_dirremove, ufs_dirrewrite)

10.1.4 Changing in Space Allocation

Historically, it could be used only to decrease the size of an object. In 4.4BSD, it can be used both to increase and to decrease the size of an object.

VOP_TRUNCATE(vp, length, flags, cred, p)

Truncate the file specified by the vnode vp to at most length size and free the unused disk blocks. The arguments p and cred is the calling process and its credentials respectively. The argument flags is a set of I/O flags. Valid values are:

IO_UNIT do I/O as atomic unit
IO_APPEND append write to end
IO_SYNC sync I/O file integrity completion
IO_NODELOCKED underlying node already locked
IO_NDELAY FNDELAY flag set in file table
IO_DSYNC sync I/O data integrity completion
IO_ALTSEMANTICS use alternate i/o semantics

If the operation is successful zero is returned, otherwise an appropriate error is returned.

(implemented as ffs_truncate in ufs/ffs/ffs_inode.c)
(used by ufs_inactive, ufs_direnter, ffs_write, ufs_setattr,
 ufs_rename, ufs_rmdir)

10.1.5 Virtual Memory System Support

VOP_GETPAGES(vp, offset, m, count, centeridx, access_type, advice, flags)

Read VM pages from file. The argument vp is the locked vnode to
read the VM pages from. The argument offset is offset in the
file to start accessing and m is an array of VM pages. The argument count specifies the number of pages to read. If the operation is successful zero is returned, otherwise an appropriate
error code is returned.

This function is primarily used by the page-fault handing mechanism.

(implemented as genfs_getpages in miscfs/genfs_vnops.c)
(used by ubc_fault, ubc_alloc, uvn_get)

VOP_PUTPAGES(vp, offset, len, flags)

Write modified (dirty) VM pages to file. The argument vp is the locked vnode to write the VM pages to and offset and len specifies the range of VM pages to write. There seems to be some confusion in the code whether offset and len specify the start

and length of the VM pages for the start and end of the VM pages. The argument flags specifies whether the pages should be written asynchronously and also whether they should be marked invalid one the write back operation has completed. If the operation is successful zero is returned, otherwise an appropriate error code is returned.

The function is primarily used by the pageout handling mechanism.

(implemented as genfs_putpages in miscfs/genfs/genfs_vnops.c)
(used by uvn_put)

10.2 Organization of the FFS

To describe the design motivation of the FFS, we describes the problems of traditional UNIX filesystem before BSD UNIX appeared.

Long Seek Problem Traditional UNIX filesystem consists of two area: inodes area followed by data area. Separation of inode information from the data resulted a long seek from the file's inode to its data.

Too Frequent Accesses Problem The traditional UNIX filesystem uses a 512-byte physical block size. So seeks between small 512-byte data transfers are required with long seek frequently.

As a result, the old filesystem was using only about 4 percent of the maximum disk throughput. The main single reason was that the order of blocks on the free list quickly became scrambled, occurring too frequeny access to small blocks with long seek.

10.2.1 Superblock

A 4.4BSD filesystem is described by its *superblock*, located at the beginning of the filesystem's disk partition. The superblock data do not change after filesystem creation.

The structure of superblock is defined in fs structure of ffs/ffs/fs.h as,

```
- ffs/ffs/fs.h
171 /*
172 * Super block for an FFS file system in memory.
173 */
174 struct fs {
           int32_t fs_firstfield;
                                            /* historic file system linked list, */
175
176
           int32_t fs_unused_1;
                                            /*
                                                   used for incore super blocks */
                                           /* addr of super-block in filesys */
177
           ufs_daddr_t fs_sblkno;
178
           ufs_daddr_t fs_cblkno;
                                           /* offset of cyl-block in filesys */
179
           ufs_daddr_t fs_iblkno;
                                           /* offset of inode-blocks in filesys */
           ufs_daddr_t fs_dblkno;
                                           /* offset of first data after cg */
180
           int32_t fs_cgoffset;
                                           /* cylinder group offset in cylinder */
181
182
           int32_t fs_cgmask;
                                           /* used to calc mod fs_ntrak */
           int32_t fs_time;
                                           /* last time written */
183
                                          /* number of blocks in fs */
184
           int32_t fs_size;
                                          /* number of data blocks in fs */
185
           int32_t fs_dsize;
```

```
186
           int32_t fs_ncg;
                                          /* number of cylinder groups */
           int32_t fs_bsize;
187
                                          /* size of basic blocks in fs */
           int32_t fs_fsize;
                                          /* size of frag blocks in fs */
188
           int32_t fs_frag;
189
                                          /* number of frags in a block in fs */
190 /* these are configuration parameters */
           int32_t fs_minfree;
                                          /* minimum percentage of free blocks */
192
           int32_t fs_rotdelay;
                                          /* num of ms for optimal next block */
193
           int32_t fs_rps;
                                          /* disk revolutions per second */
194 /* these fields can be computed from the others */
                                          /* ''blkoff'' calc of blk offsets */
           int32 t fs bmask:
196
           int32_t fs_fmask;
                                          /* ''fragoff'' calc of frag offsets */
           int32_t fs_bshift;
                                          /* ''lblkno'' calc of logical blkno */
197
           int32_t fs_fshift;
                                          /* ''numfrags'' calc number of frags */
198
199 /* these are configuration parameters */
           int32_t fs_maxcontig;
200
                                          /* max number of contiguous blks */
201
           int32_t fs_maxbpg;
                                          /* max number of blks per cyl group */
202 /* these fields can be computed from the others */
203
          int32_t fs_fragshift;
                                         /* block to frag shift */
           int32_t fs_fsbtodb;
204
                                          /* fsbtodb and dbtofsb shift constant */
           int32_t fs_sbsize;
                                          /* actual size of super block */
205
                                         /* csum block offset (now unused) */
206
           int32_t fs_csmask;
                                         /* csum block number (now unused) */
207
           int32_t fs_csshift;
208
           int32_t fs_nindir;
                                         /* value of NINDIR */
209
           int32_t fs_inopb;
                                         /* value of INOPB */
          int32_t fs_nspf;
                                         /* value of NSPF */
211 /* yet another configuration parameter */
212
           int32_t fs_optim;
                                          /* optimization preference, see below */
213 /* these fields are derived from the hardware */
           int32_t fs_npsect;
                                          /* # sectors/track including spares */
214
215
           int32_t fs_interleave;
                                          /* hardware sector interleave */
           int32_t fs_trackskew;
                                          /* sector 0 skew, per track */
216
217 /* fs_id takes the space of the unused fs_headswitch and fs_trkseek fields */
           int32_t fs_id[2];
                                         /* unique file system id */
219 /* sizes determined by number of cylinder groups and their sizes */
          ufs_daddr_t fs_csaddr;
220
                                       /* blk addr of cyl grp summary area */
221
           int32_t fs_cssize;
                                          /* size of cyl grp summary area */
           int32_t fs_cgsize;
                                          /* cylinder group size */
223 /* these fields are derived from the hardware */
224
          int32_t fs_ntrak;
                                         /* tracks per cylinder */
225
           int32_t fs_nsect;
                                          /* sectors per track */
           int32_t fs_spc;
                                          /* sectors per cylinder */
227 /* this comes from the disk driver partitioning */
           int32_t fs_ncyl;
228
                                          /* cylinders in file system */
229 /* these fields can be computed from the others */
230
           int32_t fs_cpg;
                                          /* cylinders per group */
231
           int32_t fs_ipg;
                                          /* inodes per group */
232
           int32_t fs_fpg;
                                          /* blocks per group * fs_frag */
233 /* this data must be re-computed after crashes */
          struct csum fs_cstotal;
                                          /* cylinder summary information */
235 /* these fields are cleared at mount time */
                                         /* super block modified flag */
236
          int8_t fs_fmod;
237
                   fs_clean;
                                          /* file system is clean flag */
           int8_t
238
           int8_t fs_ronly;
                                         /* mounted read-only flag */
                                         /* see FS_ flags below */
239
           int8_t fs_flags;
```

```
240
            u\_char
                     fs_fsmnt[MAXMNTLEN];
                                            /* name mounted on */
241 /* these fields retain the current block allocation info */
                                            /* last cg searched (UNUSED) */
242
            int32_t fs_cgrotor;
                                            /* padding; was list of fs_cs buffers */
243
            void
                    *fs_ocsp[NOCSPTRS];
244
            u_int16_t *fs_contigdirs;
                                            /* # of contiguously allocated dirs */
245
            struct csum *fs_csp;
                                            /* cg summary info buffer for fs_cs */
            int32_t *fs_maxcluster;
                                            /* max cluster in each cyl group */
246
            int32_t fs_cpc;
                                            /* cyl per cycle in postbl */
247
            int16_t fs_opostbl[16][8];
                                            /* old rotation block list head */
248
249
            int32_t fs_snapinum[20];
                                            /* RESERVED for snapshot inode nums */
            int32_t fs_avgfilesize;
                                            /* expected average file size */
250
                                            /* expected # of files per directory */
251
            int32_t fs_avgfpdir;
252
            int32_t fs_sparecon[26];
                                            /* RESERVED for future constants */
253
            int32_t fs_pendingblocks;
                                            /* blocks in process of being freed */
254
            int32_t fs_pendinginodes;
                                            /* inodes in process of being freed */
257
            int32_t fs_inodefmt;
                                            /* format of on-disk inodes */
            u_int64_t fs_maxfilesize;
                                            /* maximum representable file size */
258
259
            int64_t fs_qbmask;
                                            /* ~fs_bmask for use with 64-bit size */
                                            /* ~fs_fmask for use with 64-bit size */
            int64_t fs_qfmask;
260
261
            int32_t fs_state;
                                            /* validate fs_clean field (UNUSED) */
262
            int32_t fs_postblformat;
                                            /* format of positional layout tables */
            int32_t fs_nrpos;
263
                                            /* number of rotational positions */
            int32_t fs_postbloff;
                                            /* (u_int16) rotation block list head */
264
265
            int32_t fs_rotbloff;
                                            /* (u_int8) blocks for each rotation */
266
            int32_t fs_magic;
                                            /* magic number */
267
            u_int8_t fs_space[1];
                                            /* list of blocks for each rotation */
268 /* actually longer */
269 };
```

Block Size

So that files as large as 2^{32} bytes can be created with only two levels of indirection, the minimum size of a filesystem block is 4096 bytes. The block size is recorded in the filesystem's supportblock, as fs_bsize member.

Filesystem Parameterization

The goal of parameterizing the processor capabilities and mass-storage characteristics, is to allocate blocks in an optimum configuration-dependent way.

Important parameter maintained by file system is contained in superblock and they includes,

fs_rotdelay The expected time in milliseconds to service disk interrupt and to schedule a new disk transfer, depending the speed of the main CPU. It is used to decide how much rotational spacing to place between successive blocks in a file.

For modern high speed workstation, such as SUN Ultra 1, this parameter should be set to zero, since the the expected time is less than one milliseconds.

fs_maxcontig This specifies the maximum number of contiguous blocks that will be laid out before forcing a rotational delay. The default value is one, since most device drivers require an interrupt per disk transfer. Device drivers that

can chain sev- eral buffers together in a single transfer should set this to the maximum chain length.

fs_maxbpg This indicates the maximum number of blocks any single file can allocate out of a cylinder group before it is forced to begin allocating blocks from another cylinder group. Typically this value is set to about one quarter of the total blocks in a cylinder group. The intent is to prevent any single file from using up all the blocks in a single cylinder group, thus degrading access times for all files subsequently allocated in that cylinder group. The effect of this limit is to cause big files to do long seeks more frequently than if they were allowed to allocate all the blocks in a cylinder group before seeking elsewhere. For file systems with exclusively large files, this parameter should be set higher.

fs_rps Number of disk platter revolution per second

fs_ntrak Number of tracks per cylinder

fs_nsect Number of sectors per track

fs_npsect Number of sectors including spares per track

fs_minfree This value specifies the percentage of space held back from normal users; the minimum free space threshold. The default value used is 10factor of three in throughput will be lost over the performance obtained at a 10above the current usage level, users will be unable to allocate files until enough files have been deleted to get under the higher threshold.

fs_interleave Hardware sector interleave. Used to describe perturbations in the media format to compensate for a slow controller. In- terleave is physical sector interleave on each track, speci- fied as the denominator of the ratio: sectors read/sectors passed over Thus an interleave of 1/1 implies contiguous layout, while 1/2 implies logical sector 0 is separated by one sector from logical sector 1.

fs_trackskew This specifies the skew in sectors from one track to the next in a cylinder. The default value is zero, indicating that each track in a cylinder begins at the same rotational position.

fs_optim The file system can either try to minimize the time spent allocating blocks, or it can attempt to minimize the space fragmentation on the disk. If the value of minfree (see above) is less than 10running out of full sized blocks. For values of minfree greater than or equal to 10problematical, and the file system can be optimized for time. fs_optim can be specified as either space or time.

From fs_nsect and fs_rps, the allocation routines calculates the number of milliseconds required to skip over a block. With it and processor performance peramater fs_rotdelay, the allocation routines calculate the number of blocks to skip over such that the next block in the file will come into position under the disk head in the expected amount of time that it takes to start a new disk-transfer operation.

In fact, for modern SCSI storage device, these parameterization is actually useless, since storage device is internally designed so that it provides optimal performace, without disk interleave regarding disk rotational speed.

- ffs/ffs/fs.h

10.2.2 Cylinder Group

The FFS filesystem organization divides a disk partition into one or more area, each of which is called a *vylinder group*.

The rationale for using cylinder groups is to create clusters of inodes that are close to the blocks that they reference, instead of them all being located at the beginning of the disk. Then the filesystem attempts to allocate file blocks close to the inodes that describes them to avoid long seeks between getting the inode and getting its associated data.

For each cylinder group, a static number of inodes is allocated at filesystemcreation time. The default policy is to allocate one inode for each 2048 bytes of space in the cylinder group, with the expectation that this amount will be far more than will ever be needed.

Cylinder group contains information including

- a redundant copy of the superblock
- space for inodes
- bitmap describing available blocks in the cylinder group
- summary information describing the usage of data blocks within the cylinder group

To be safe from capastrophic loss, all the bookeeping information about cylinder group is not placed at the beginning of each cylinder group. The offset from each cylinder group is calculated to be about one track father from the beginning than is the preceding cylinder group. In this way, the redundant information spirals down into the pack, so that single track, cylinder, or platter can be lost without all copies of the superblock also being lost.

The structure of cylinder group is defined as struct cg of ffs/ffs/fs.h as

```
343 /*
344 * Cylinder group block for a file system.
345 */
346 #define CG_MAGIC
                            0x090255
347 struct cg {
348
            int32_t cg_firstfield;
                                            /* historic cyl groups linked list */
                                            /* magic number */
349
            int32_t cg_magic;
                                            /* time last written */
350
            int32_t cg_time;
            int32_t cg_cgx;
                                            /* we are the cgx'th cylinder group */
351
                                            /* number of cyl's this cg */
352
            int16_t cg_ncyl;
                                            /* number of inode blocks this cg */
353
            int16_t cg_niblk;
                                            /* number of data blocks this cg */
354
            int32_t cg_ndblk;
            struct csum cg_cs;
                                            /* cylinder summary information */
355
                                            /* position of last used block */
356
            int32_t cg_rotor;
                                            /* position of last used frag */
357
            int32_t cg_frotor;
358
            int32_t cg_irotor;
                                            /* position of last used inode */
359
            int32_t cg_frsum[MAXFRAG];
                                            /* counts of available frags */
                                            /* (int32) block totals per cylinder */
            int32_t cg_btotoff;
360
            int32_t cg_boff;
                                            /* (u_int16) free block positions */
361
362
            int32_t cg_iusedoff;
                                            /* (u_int8) used inode map */
363
            int32_t cg_freeoff;
                                            /* (u_int8) free block map */
364
            int32_t cg_nextfreeoff;
                                            /* (u_int8) next available space */
            int32_t cg_clustersumoff;
                                            /* (u_int32) counts of avail clusters */
365
```

```
366
                int32_t cg_clusteroff;
                                                 /* (u_int8) free cluster map */
                                                 /* number of clusters this cg */
    367
                int32_t cg_nclusterblks;
                                                 /* reserved for future use */
    368
                int32_t cg_sparecon[13];
    369
                u_int8_t cg_space[1];
                                                 /* space for cylinder group maps */
    370 /* actually longer */
                                                              ffs/ffs/fs.h
where the struct csum is defined as
                                                              ffs/ffs/fs.h
    158 /*
    159 * Per cylinder group information; summarized in blocks allocated
    160 * from first cylinder group data blocks. These blocks have to be
    161 * read in from fs_csaddr (size fs_cssize) in addition to the
    162 * super block.
    163 */
    164 struct csum {
                                                 /* number of directories */
    165
                int32_t cs_ndir;
                                                 /* number of free blocks */
    166
                int32_t cs_nbfree;
    167
                int32_t cs_nifree;
                                                 /* number of free inodes */
    168
                int32_t cs_nffree;
                                                 /* number of free frags */
    169 };
                                                             - ffs/ffs/fs.h
```

10.2.3 Fragment

As the block size increases, the amount of space reserved for inodes decreases, but the amount of unused data space at the end of blocks rises quickly to an intolerable level with a minimum allocation of 8192-byte filesystem blocks. To increase space efficiency, the filesystem allow the division of a single filesystem block into one or more *fragments*.

Block Map

The block map associated with each cylinder group records the space available in a cylinder group in fragments.

Fragmentation Policy

If an 11,000 byte file is to be stored on 4096/1024 filesystem (block/fragment size),

- 1. this file would use two full-sized blocks and three fragments portion of another block.
- 2. If no block with three aligned fragments were available at the time, a full-sized block would be split, yielding the necessary three fragments and a single unused fragment.
- 3. The remaining fragment could be allocated to another file as needed.

10.3 Reading a File

Since NetBSD uses *Unified Buffer Cache (UBC)*, the mechanism of reading and writing to a file is different from 4.4BSD. Since UBC integrates filesystem buffer cache and virtual memory caches of file data, *cluster* interface used in 4.4BSD is no longer used.

Key architecture of NetBSD filesystem file read and write is

- The buffer cache functions such as bread or bwrite, read and write with a device driver strategy routine via ufs_strategy function.
- The vnode operation such as VOP_READ or VOP_WRITE, read and write with UBC interface via ffs_read or ffs_write function.

10.3.1 Regular File Reading Algorithm: using UBC

For 4.4BSD, reading a general file in FFS is processed as, using UBC,

- 1. read system call from user application program
- 2. sys_read kernel system call
- 3. vn_read vnode high-level file operation
- 4. VOP_READ VFS vnode operation
- 5. ffs_read FFS vnode operation
- 6. UBC interaction

10.3.2 Non-regular File Reading Algorithm: without UBC

Reading a non-regular file such as directory in FFS is processed as, without using UBC,

- 1. read system call from user application program
- 2. sys_read kernel system call
- 3. vn_read vnode high-level file operation
- 4. VOP_READ VFS vnode operation
- 5. ffs_read FFS vnode operation
- 6. breadn Buffer Cache
- 7. VOP_STRATEGY VFS vnode operation
- 8. ufs_strategy FFS vnode operation
- 9. VOP_BMAP convert logical file block number to physical disk block number
- 10. VOP_STRATEGY device driver's vnode operation
- 11. spec_strategy special filesystem vnode operation
- 12. *bdev->d_strategy device driver strategy function

10.3.3 Implementation

```
— ufs/ufs/ufs_readwrite.c
 61 /*
 62 * Vnode op for reading.
 63 */
64 /* ARGSUSED */
65 int
66 READ(void *v)
67 {
68
            struct vop_read_args /* {
                    struct vnode *a_vp;
69
70
                    struct uio *a_uio;
71
                    int a_ioflag;
72
                    struct ucred *a_cred;
73
            } */ *ap = v;
74
            struct vnode *vp;
75
            struct inode *ip;
76
            struct uio *uio;
77
            FS *fs;
78
            void *win;
79
            vsize_t bytelen;
            struct buf *bp;
80
            ufs_daddr_t lbn, nextlbn;
81
            off_t bytesinfile;
83
            long size, xfersize, blkoffset;
84
            int error;
85
            boolean_t usepc = FALSE;
86
87
            vp = ap->a_vp;
88
            ip = VTOI(vp);
89
            uio = ap->a_uio;
90
            error = 0;
91
 92 #ifdef DIAGNOSTIC
            if (uio->uio_rw != UIO_READ)
93
                    panic("%s: mode", READ_S);
94
95
96
            if (vp->v_type == VLNK) {
97
                    if ((int)ip->i_ffs_size < vp->v_mount->mnt_maxsymlinklen ||
                        (vp->v_mount->mnt_maxsymlinklen == 0 &&
98
99
                          ip->i_ffs_blocks == 0))
100
                            panic("%s: short symlink", READ_S);
101
            } else if (vp->v_type != VREG && vp->v_type != VDIR)
102
                    panic("%s: type %d", READ_S, vp->v_type);
103 #endif
104
            fs = ip \rightarrow I_FS;
105
            if ((u_int64_t)uio->uio_offset > fs->fs_maxfilesize)
106
                    return (EFBIG);
            if (uio->uio_resid == 0)
107
                    return (0);
108
109
            if (uio->uio_offset >= ip->i_ffs_size) {
110
                    goto out;
            }
111
```

```
112
113 #ifndef LFS_READWRITE
            usepc = vp->v_type == VREG;
114
115 #endif
116
            if (usepc) {
117
                    while (uio->uio_resid > 0) {
118
                             bytelen = MIN(ip->i_ffs_size - uio->uio_offset,
119
                                 uio->uio_resid);
120
                             if (bytelen == 0)
121
                                     break;
122
123
                             win = ubc_alloc(&vp->v_uobj, uio->uio_offset,
124
                                              &bytelen, UBC_READ);
125
                             error = uiomove(win, bytelen, uio);
126
                             ubc_release(win, 0);
127
                             if (error)
128
                                     break;
129
130
                    goto out;
            }
131
132
133
            for (error = 0, bp = NULL; uio->uio_resid > 0; bp = NULL) {
134
                    bytesinfile = ip->i_ffs_size - uio->uio_offset;
135
                    if (bytesinfile <= 0)</pre>
136
                             break;
137
                    lbn = lblkno(fs, uio->uio_offset);
138
                    nextlbn = lbn + 1;
139
                    size = BLKSIZE(fs, ip, lbn);
140
                    blkoffset = blkoff(fs, uio->uio_offset);
141
                    xfersize = MIN(MIN(fs->fs_bsize - blkoffset, uio->uio_resid),
142
                         bytesinfile);
143
144
                    if (lblktosize(fs, nextlbn) >= ip->i_ffs_size)
145
                             error = bread(vp, lbn, size, NOCRED, &bp);
146
                    else {
147
                             int nextsize = BLKSIZE(fs, ip, nextlbn);
148
                             error = breadn(vp, lbn,
149
                                 size, &nextlbn, &nextsize, 1, NOCRED, &bp);
150
                    }
151
                    if (error)
152
                             break:
153
154
155
                      * We should only get non-zero b_resid when an I/O error
156
                      * has occurred, which should cause us to break above.
                      * However, if the short read did not cause an error,
157
158
                      * then we want to ensure that we do not uiomove bad
159
                      * or uninitialized data.
                      */
160
                    size -= bp->b_resid;
161
                    if (size < xfersize) {</pre>
162
163
                             if (size == 0)
164
                                     break;
165
                             xfersize = size;
```

```
166
167
                     error = uiomove((char *)bp->b_data + blkoffset, xfersize, uio);
168
                     if (error)
169
                             break;
170
                    brelse(bp);
171
            if (bp != NULL)
172
                    brelse(bp);
173
174
175
    out:
            if (!(vp->v_mount->mnt_flag & MNT_NOATIME)) {
176
                     ip->i_flag |= IN_ACCESS;
177
                     if ((ap->a_ioflag & IO_SYNC) == IO_SYNC)
178
179
                             error = VOP_UPDATE(vp, NULL, NULL, UPDATE_WAIT);
180
            }
181
            return (error);
182 }
```

ufs/ufs/ufs_readwrite.c

10.4 Writing a File

10.4.1 Regular File Writing Algorithm

Writing a regular file in FFS is processed as, using UBC,

- 1. write system call from user application program
- 2. sys_write kernel system call
- 3. vn_write vnode high-level file operation
- 4. VOP_WRITE VFS vnode operation
- 5. ffs_write FFS vnode operation
- 6. UBC interation

Writing a non-regular file in FFS such as directory is processed, without using UBC, as shown in the previous subsection.

10.4.2 Non-regular File Writing Algorithm

If the file needs to be extended, the request is rounded up to the next fragment size, and only that much space is allocated by VOP_BALLOC.

10.4.3 Implementation

```
ufs/ufs/ufs_readwrite.c

184 /*

185 * Vnode op for writing.

186 */

187 int

188 WRITE(void *v)

189 {
```

```
190
       struct vop_write_args /* {
          struct vnode *a_vp;
191
192
           struct uio *a_uio;
193
           int a_ioflag;
194
           struct ucred *a_cred;
195
       } */ *ap = v;
196
       struct vnode *vp;
197
       struct uio *uio;
198
      struct inode *ip;
199
      struct genfs_node *gp;
200
      FS *fs;
201
       struct buf *bp;
202
       struct proc *p;
203
     struct ucred *cred;
204
      ufs_daddr_t lbn;
205
       off_t osize, origoff, oldoff, preallocoff, endallocoff, nsize;
206
       int blkoffset, error, flags, ioflag, resid, size, xfersize;
207
       int bsize, aflag;
208
       int ubc_alloc_flags;
209
       int extended=0;
210
       void *win;
       vsize_t bytelen;
211
212
      boolean_t async;
213
      boolean_t usepc = FALSE;
214
215
      cred = ap->a_cred;
216
      ioflag = ap->a_ioflag;
217
       uio = ap->a_uio;
218
       vp = ap -> a_vp;
219
       ip = VTOI(vp);
220
       gp = VTOG(vp);
221
222
       KASSERT(vp->v_size == ip->i_ffs_size);
223 #ifdef DIAGNOSTIC
if (uio->uio_rw != UIO_WRITE)
225
           panic("%s: mode", WRITE_S);
226 #endif
227
228
      switch (vp->v_type) {
229
      case VREG:
           if (ioflag & IO_APPEND)
230
231
               uio->uio_offset = ip->i_ffs_size;
232
           if ((ip->i_ffs_flags & APPEND) && uio->uio_offset != ip->i_ffs_size)
233
               return (EPERM);
           /* FALLTHROUGH */
234
235
      case VLNK:
236
          break;
237
       case VDIR:
238
           if ((ioflag & IO_SYNC) == 0)
239
               panic("%s: nonsync dir write", WRITE_S);
240
           break;
241
       default:
242
           panic("%s: type", WRITE_S);
243
```

```
244
245
        fs = ip->I_FS;
        if (uio->uio_offset < 0 ||
246
247
            (u_int64_t)uio->uio_offset + uio->uio_resid > fs->fs_maxfilesize)
248
            return (EFBIG);
249 #ifdef LFS_READWRITE
250
        /* Disallow writes to the Ifile, even if noschg flag is removed */
251
        /* XXX can this go away when the Ifile is no longer in the namespace? */
252
        if (vp == fs->lfs_ivnode)
253
            return (EPERM);
254 #endif
255
256
257
         * Maybe this should be above the vnode op call, but so long as
258
         * file servers have no limits, I don't think it matters.
259
         */
260
        p = uio->uio_procp;
261
        if (vp->v_type == VREG && p &&
262
            uio->uio_offset + uio->uio_resid >
263
            p->p_rlimit[RLIMIT_FSIZE].rlim_cur) {
264
            psignal(p, SIGXFSZ);
265
            return (EFBIG);
        }
266
        if (uio->uio_resid == 0)
267
268
            return (0);
269
270
        flags = ioflag & IO_SYNC ? B_SYNC : 0;
271
        async = vp->v_mount->mnt_flag & MNT_ASYNC;
        origoff = uio->uio_offset;
272
273
       resid = uio->uio_resid;
274
        osize = ip->i_ffs_size;
275
        bsize = fs->fs_bsize;
276
        error = 0;
277
278 #ifndef LFS_READWRITE
        usepc = vp->v_type == VREG;
280 #endif
281
      if (!usepc) {
282
            goto bcache;
283
284
285
        preallocoff = round_page(blkroundup(fs, MAX(osize, uio->uio_offset)));
286
        aflag = ioflag & IO_SYNC ? B_SYNC : 0;
287
        nsize = MAX(osize, uio->uio_offset + uio->uio_resid);
288
        endallocoff = nsize - blkoff(fs, nsize);
289
290
        /*
291
         * if we're increasing the file size, deal with expanding
292
         * the fragment if there is one.
293
         */
294
295
        if (nsize > osize && lblkno(fs, osize) < NDADDR &&
296
            lblkno(fs, osize) != lblkno(fs, nsize) &&
297
            blkroundup(fs, osize) != osize) {
```

```
298
            error = ufs_balloc_range(vp, osize, blkroundup(fs, osize) -
299
                osize, cred, aflag);
300
            if (error) {
301
                goto out;
302
303
            if (flags & B_SYNC) {
304
                vp->v_size = blkroundup(fs, osize);
305
                simple_lock(&vp->v_interlock);
306
                VOP_PUTPAGES(vp, trunc_page(osize & ~(bsize - 1)),
                    round_page(vp->v_size), PGO_CLEANIT | PGO_SYNCIO);
307
308
            }
        }
309
310
       ubc_alloc_flags = UBC_WRITE;
311
312
       while (uio->uio_resid > 0) {
313
            boolean_t extending; /* if we're extending a whole block */
314
            off_t newoff;
315
316
            oldoff = uio->uio_offset;
317
            blkoffset = blkoff(fs, uio->uio_offset);
318
            bytelen = MIN(fs->fs_bsize - blkoffset, uio->uio_resid);
319
320
            /*
321
            * if we're filling in a hole, allocate the blocks now and
             * initialize the pages first. if we're extending the file,
323
             * we can safely allocate blocks without initializing pages
324
             * since the new blocks will be inaccessible until the write
325
             * is complete.
326
             */
327
            extending = uio->uio_offset >= preallocoff &&
328
                uio->uio_offset < endallocoff;</pre>
329
330
            if (!extending) {
331
                error = ufs_balloc_range(vp, uio->uio_offset, bytelen,
                    cred, aflag);
332
333
                if (error) {
334
                    break;
335
                }
336
                ubc_alloc_flags &= ~UBC_FAULTBUSY;
337
            } else {
                lockmgr(&gp->g_glock, LK_EXCLUSIVE, NULL);
338
339
                error = GOP_ALLOC(vp, uio->uio_offset, bytelen,
340
                    aflag, cred);
341
                lockmgr(&gp->g_glock, LK_RELEASE, NULL);
342
                if (error) {
343
                    break;
344
                }
345
                ubc_alloc_flags |= UBC_FAULTBUSY;
346
            }
347
            /*
348
349
             * copy the data.
350
             */
351
```

```
352
            win = ubc_alloc(&vp->v_uobj, uio->uio_offset, &bytelen,
353
                ubc_alloc_flags);
354
            error = uiomove(win, bytelen, uio);
355
            if (error && extending) {
356
                /*
357
                 * if we haven't initialized the pages yet,
358
                 * do it now. it's safe to use memset here
                 * because we just mapped the pages above.
359
360
361
                memset(win, 0, bytelen);
362
            }
363
            ubc_release(win, 0);
364
365
366
             * update UVM's notion of the size now that we've
367
             * copied the data into the vnode's pages.
368
369
             * we should update the size even when uiomove failed.
370
             * otherwise ffs_truncate can't flush soft update states.
371
372
373
            newoff = oldoff + bytelen;
            if (vp->v_size < newoff) {</pre>
374
375
                uvm_vnp_setsize(vp, newoff);
376
                extended = 1;
377
            }
378
            if (error) {
379
380
                break;
381
382
383
            /*
384
             * flush what we just wrote if necessary.
385
             * XXXUBC simplistic async flushing.
386
             */
387
388
            if (!async && oldoff >> 16 != uio->uio_offset >> 16) {
389
                simple_lock(&vp->v_interlock);
                error = VOP_PUTPAGES(vp, (oldoff >> 16) << 16,</pre>
390
391
                     (uio->uio_offset >> 16) << 16, PGO_CLEANIT);</pre>
                if (error) {
392
393
                    break;
394
                }
395
            }
396
        }
397
        if (error == 0 && ioflag & IO_SYNC) {
398
            simple_lock(&vp->v_interlock);
399
            error = VOP_PUTPAGES(vp, trunc_page(origoff & ~(bsize - 1)),
400
                round_page(blkroundup(fs, uio->uio_offset)),
                PGO_CLEANIT | PGO_SYNCIO);
401
        }
402
403
        goto out;
404
405 bcache:
```

```
406
        simple_lock(&vp->v_interlock);
        VOP_PUTPAGES(vp, trunc_page(origoff), round_page(origoff + resid),
407
408
            PGO_CLEANIT | PGO_FREE | PGO_SYNCIO);
409
        while (uio->uio_resid > 0) {
410
            lbn = lblkno(fs, uio->uio_offset);
411
            blkoffset = blkoff(fs, uio->uio_offset);
412
            xfersize = MIN(fs->fs_bsize - blkoffset, uio->uio_resid);
413
            if (fs->fs_bsize > xfersize)
414
                flags |= B_CLRBUF;
415
            else
416
                flags &= ~B_CLRBUF;
417
            error = VOP_BALLOC(vp, uio->uio_offset, xfersize,
418
419
                ap->a_cred, flags, &bp);
420
421
            if (error)
422
                break:
423
            if (uio->uio_offset + xfersize > ip->i_ffs_size) {
424
                ip->i_ffs_size = uio->uio_offset + xfersize;
425
                uvm_vnp_setsize(vp, ip->i_ffs_size);
426
                extended = 1;
427
428
            size = BLKSIZE(fs, ip, lbn) - bp->b_resid;
429
            if (xfersize > size)
430
                xfersize = size;
431
432
            error = uiomove((char *)bp->b_data + blkoffset, xfersize, uio);
433
434
435
             * if we didn't clear the block and the uiomove failed,
436
             * the buf will now contain part of some other file,
437
             * so we need to invalidate it.
438
             */
439
            if (error && (flags & B_CLRBUF) == 0) {
                bp->b_flags |= B_INVAL;
440
441
                brelse(bp);
442
                break;
            }
443
444 #ifdef LFS_READWRITE
445
                error = lfs_reserve(fs, vp, btofsb(fs, (NIADDR + 1) << fs->lfs_bshift));
446
447
            (void) VOP_BWRITE(bp);
448
            if (!error)
449
                lfs_reserve(fs, vp, -btofsb(fs, (NIADDR + 1) << fs->lfs_bshift));
450 #else
451
            if (ioflag & IO_SYNC)
452
                (void)bwrite(bp);
453
            else if (xfersize + blkoffset == fs->fs_bsize)
454
                bawrite(bp);
455
            else
456
                bdwrite(bp);
457 #endif
458
            if (error || xfersize == 0)
459
                break;
```

```
460
        }
461
462
         * If we successfully wrote any data, and we are not the superuser
463
         * we clear the setuid and setgid bits as a precaution against
464
         * tampering.
465
466 out:
        ip->i_flag |= IN_CHANGE | IN_UPDATE;
467
468
        if (resid > uio->uio_resid && ap->a_cred && ap->a_cred->cr_uid != 0)
            ip->i_ffs_mode &= ~(ISUID | ISGID);
469
470
        if (resid > uio->uio_resid)
            VN_KNOTE(vp, NOTE_WRITE | (extended ? NOTE_EXTEND : 0));
471
472
        if (error) {
473
            (void) VOP_TRUNCATE(vp, osize, ioflag & IO_SYNC, ap->a_cred,
474
                uio->uio_procp);
475
            uio->uio_offset -= resid - uio->uio_resid;
476
            uio->uio_resid = resid;
477
        } else if (resid > uio->uio_resid && (ioflag & IO_SYNC) == IO_SYNC)
478
            error = VOP_UPDATE(vp, NULL, NULL, UPDATE_WAIT);
479
        KASSERT(vp->v_size == ip->i_ffs_size);
480
        return (error);
481 }
```

ufs/ufs_readwrite.c

10.5 Layout Policies

Two methods for improving filesystem performance are to increase locality, and to make larger transfers possible.

Local allocation routine uses a locally optimal scheme to lay out data blocks.

The global layout policies try to improve performance by spreading unrelated data among different cylinder groups. The global policies, using summary information, try to balance the two conflicting goals of localizing data that are concurrently accessed while spreading out unrelated data.

10.5.1 Inode Layout Policy

- Try to place all the inodes of files in a directory in the same cylinder group.
- Try to place new directories in cylinder group with a greater-than-average number of free inodes and with the smallest number of directories.

10.5.2 Data Block Layout Policy

- Try to place data blocks for a file in the same cylinder group.
- Make the spillover points to force block allocation to be redirected when any file has used about 25 percent of the data blocks in a cylinder group. The newly chosen cylinder group for block allocation is the next cylinder group that has a greater-than-average number of free blocks.

10.6 Data Block Allocation Mechanisms

The task of managing block and fragment allocation is done by ffs_balloc function.

10.6.1 Work Flow

- 1. The global-policy routines call local-allocation routines with requests for specific blocks, using heuristics based on the partial information that is available.
- 2. The local-allocation routines will always allocate the requested block if it is free; otherwise, if a requested block is not available, the local allocator uses a four-level allocation strategy:
 - (a) Use the next available block rotationally closet to the requested block on the same cylinder.
 - (b) If no blocks are available on the same cylinder, choose a block within the same cylinder group.
 - (c) If the cylinder group is full, quadratically hash the cylinder group number to choose another cylinder group in which to look for a free block.
 - (d) Even so, if the free block is not found, apply an exhaustive search to all cylinder group.

Two conditions when the new block is allocated is

- The file contains no fragmented block, and the final block in the file contains insufficient space to hold the new data.
 - 1. If the remainder of the new data consists of more than a full block, a full block is allocated. This process is repeated until less than a full block of new data remains.
 - 2. A block with the necessary number of fragments is located.
- The file contains one or more fragments, but the fragments contain insufficient space to hold the new data.
 - 1. A new block is allocated
 - 2. The contents of the gragments are copied to the beginning of the block
 - 3. The remainder of the block is filled with new data.
 - 4. The process then continues as in the first condition.

10.6.2 Main Function that Does Allocation: ffs_balloc

We describe the algorithm of data block allocation with pseudo code shown below. Be sure that the following is simplified algorithm skeleton, and the real source code, ffs/ffs_ffs_alloc.c and ffs/ffs_balloc.c, is more complex.

```
if (fragment is already allocated ?)
        // Try to extend a fragment
        ffs_realloccg();
    else
    // Condition 1: When the file contains no fragmented block
        // Allocate a new block or gragment
        ffs_alloc();
}
/* [H]
 * Select the desired position for the next block in a file. The file is
 st logically divided into sections. The first section is composed of the
 * direct blocks. Each additional section contains fs_maxbpg blocks.
 * If no blocks have been allocated in the first section, the policy is to
 * request a block in the same cylinder group as the inode that describes
 * the file. If no blocks have been allocated in any other section, the
 * policy is to place the section in a cylinder group with a greater than
 * average number of free blocks. An appropriate cylinder group is found
 * by using a rotor that sweeps the cylinder groups. When a new group of
 * blocks is needed, the sweep begins in the cylinder group following the
 \boldsymbol{\ast} cylinder group from which the previous allocation was made. The sweep
 * continues until a cylinder group with greater than the average number
 * of free blocks is found. If the allocation is for the first block in an
 * indirect block, the information on the previous allocation is unavailable;
 * here a best guess is made based upon the logical block number being
 * allocated.
 * If a section is already partially allocated, the policy is to
 \ast contiguously allocate fs_maxcontig blocks. The end of one of these
 * contiguous blocks and the beginning of the next is physically separated
 * so that the disk head will be in transit between them for at least
 * fs_rotdelay milliseconds. This is to allow time for the processor to
 * schedule another I/O transfer.
 */
ufs_daddr_t
ffs_blkpref()
{
   return (appropriate next block number); // if not found return zero;
```

10.6.3 Cylinder Overflow Algorithm: ffs_hashalloc

```
/* [C] Implement the cylinder overflow algorithm.
       The policy implemented by this algorithm is:
         1) allocate the block in its requested cylinder group.
         2) quadradically rehash on the cylinder group number.
         3) brute force search for a free block.
 */
ffs_hashalloc( *func_ptr_to_allocator )
{
    // Try to find a fragment from preferred cylinder group
    if (*func_ptr_to_allocator() succeeded ?)
        return OK;
    // Quadratic rehash
    for (i = 1; i < fs->fs_ncg; i *= 2)
        intended cylinder group numer += i;
        adjust cylinder group number overflow;
        if (*func_ptr_to_allocator() succeeded ?)
            return OK;
    }
    // Brute force search
    for (i = 2; i < fs->fs_ncg; i++)
        intended cylinder group number = i;
        if (*func_ptr_to_allocator() succeeded ?)
            return OK;
    }
   return FAIL;
}
```

10.6.4 Global Policy 1 - Extending an Fragment: ffs_reallocg

```
// Calculate a new disk location from which to allocate a new fragment
        switch ((int)fs->fs_optim) {
        case FS_OPTSPACE:
            // Allocate an exact sized fragment. Although this makes
            // best use of space, we will waste time relocating it if
            // the file continues to grow. If the fragmentation is
            // less than half of the minimum free reserve, we choose
            // to begin optimizing for time.
             . . . . .
            break;
        case FS_OPTTIME:
            // At this point we have discovered a file that is trying to
            // grow a small fragment to a larger fragment. To save time,
            // we allocate a full sized block, then free the unused portion.
            // If the file continues to grow, the 'ffs_fragextend' call
            // above will be able to grow it in place without further
            // copying. If aberrant programs cause disk fragmentation to
             // grow within 2% of the free reserve, we choose to begin
             // optimizing for space.
            break;
        }
        // Try to allocate a new fragment honoring the calculated location
        if (ffs_hashalloc( ffs_alloccg ) succeeded ?)
            return OK;
        return FAIL;
    }
    /* [E] Determine whether a fragment can be extended.
           Check to see if the necessary fragments are available, and
           if they are, allocate them.
     */
    ffs_fragextend()
    }
        Global Policy 2 - Get a New Block: ffs_alloc
10.6.5
    /* [F] Allocate a block in the file system.
```

```
multiple of fs_fsize and <= fs_bsize.
           A preference may be optionally specified. If a preference is given
           the following hierarchy is used to allocate a block:
             1) allocate the requested block.
             2) allocate a rotationally optimal block in the same cylinder.
             3) allocate a block in the same cylinder group.
             4) quadradically rehash into other cylinder groups, until an
                 available block is located.
           If no block preference is given the following hierarchy is used
           to allocate a block:
              1) allocate a block in the cylinder group that contains the
                 inode for the file.
             2) quadradically rehash into other cylinder groups, until an
                 available block is located.
     */
    ffs_alloc()
        \ensuremath{//} Set cylinder group number according to the above rules
        cg = ....;
        // Try to allocate a block
        if (ffs_hashalloc( ffs_alloccg ) succeeded ?)
            return OK;
        return FAIL;
    }
10.6.6 Local Policy - Allocate a Block or Fragment: ffs_allocg
    /* [D] Determine whether a block can be allocated.
     *
           From the specified cylinder group and block,
           check to see if a block of the appropriate size is available,
           and if it is, allocate it.
     */
    ffs_alloccg()
        //
        // [1] When the called requested a block
        //
             if (requested size == block ?)
            {
                 // Allocate a new block and return the block number
                return ffs_alloccgblk();
            }
        // [2] When the caller requested fragments
         //
```

The size of the requested block is given, which must be some

// Allocate a new block from which to allocate requested fragments

```
// Check the cylinder group has free fragments having the requested size
        // (allocsiz is the number of fragments which will be allocated)
        frags = numfrags(fs, size); // calculate number of requested fragments
        for (allocsiz = frags; allocsiz < fs->fs_frag; allocsiz++) {
                if (cgp->cg_frsum[allocsiz] != 0) // if there available frag ?
                        break;
        }
        // When there is no fragments having the requested size
        if (allocsiz == fs->fs_frag)
            if (if the given cylinder group has the not any free fragment?)
                // Say that there is no fragment in the given cylinder group
                return 0;
            // Try to allocate a new block
            bno = ffs_alloccgblk();
            // Allocate the requested fragments
            // Mark the filesystem that fragments are allocated
            return bno;
        }
        // Now there are certainly fragments having the requested size,
        // in the requested cylinder group
        // Find the block number !
        bno = ffs_mapresearch( allocsiz );
        // Allocate necessary fragments;
        return (block number);
}
/* [G] Allocate a block in a cylinder group.
       This algorithm implements the following policy:
```

```
1) allocate the requested block.
         2) allocate a rotationally optimal block in the same cylinder.
         3) allocate the next available block on the block rotor for the
            specified cylinder group.
       Note that this routine only allocates fs_bsize blocks; these
       blocks may be fragmented by the routine that allocates them.
 */
ffs_alloccgblk
{
    //
    // [1] if the requested block is available, use it
        if (ffs_isblock(...) says that there is available block?)
            goto STEP_YES;
        if (fs->fs_nrpos <= 1 || fs->fs_cpc == 0)
            // Block layout information is not available.
            // Leaving bpref unchanged means we take the
            // next available free block following the one
            // we just allocated. Hopefully this will at
            // least hit a track cache on drives of unknown
            // geometry (e.g. SCSI).
            goto STEP_3;
        }
        // check for a block available on the same cylinder
        if (cg_blktot(...) says that there is no available block ?)
            goto STEP_3;
    //
    // [2] check the summary information to see if a block is
           available in the requested cylinder starting at the
    //
           requested rotational position and proceeding around.
    //
        // Get the rotational-layout table from superblock
        cylbp = cg_blks(fs, cgp, cylno, needswap);
        // Calculate the intended rotational position
        pos = cbtorpos(fs, bpref);
        // Search for a block to allocate through the summary information for
        // a rotational position with a nonzero block count
        for (i = pos; i < fs->fs_nrpos; i++)
            if (cylbp[i] > 0)
                break;
```

```
// Search after wrapping
        if (i == fs->fs_nrpos)
            for (i = 0; i < pos; i++)
                if (cylbp[i] > 0)
                    break;
        }
        // When found a rotational position
        if (cylbp[i] > 0)
            // Find the actual block. A panic if none is actually there.
            . . . . .
        }
STEP_3:
    //
    // [3] no blocks in the requested cylinder, so take next
           available one in this cylinder group.
    //
    //
        bno = ffs_mapsearch(...);
        if (bno < 0)
            return FAIL;
STEP_YES:
    mark to the filesystem that the block is allocated;
    return block number;
}
```

10.6.7 Searching Fragment Descriptor Table: ffs_mapsearch

If an appropriate-sized fragment is listed in the fragment summary, then the allocation routine expects to find it in the allocation map. To speed up the process of scanning the potentially large allocation map, the filesystem uses a table-driven algorithm. Each byte in the map is treated as an index into a *fragment descriptor table*. Each entry in the fragment descriptor table describes the fragment that are free for that corresponding map entry.

The fragment descriptor table is defined in ffs_tables.c as,

```
ffs/ffs/ffs_tables.c

60 /*
61 * Given a block map bit pattern, the frag tables tell whether a
62 * particular size fragment is available.
63 *
64 * used as:
65 * if ((1 << (size - 1)) & fragtbl[fs->fs_frag][map] {
66 * at least one fragment of the indicated size is available
```

```
67 * }
    68 *
    69 \,* These tables are used by the scanc instruction on the VAX to
    70 * quickly find an appropriate fragment.
    71 */
    72 const u_char fragtbl124[256] = {
               0x00, 0x16, 0x16, 0x2a, 0x16, 0x16, 0x26, 0x4e,
   104
                0x9e, 0x9e, 0x9e, 0xbe, 0xaa, 0xbe, 0xce, 0x8a,
   105 };
   106
   107 const u_char fragtbl8[256] = {
   108
               0x00, 0x01, 0x01, 0x02, 0x01, 0x01, 0x02, 0x04,
               0x10, 0x11, 0x11, 0x12, 0x20, 0x21, 0x40, 0x80,
   139
   140 };
   141
   142 /*
   143 * The actual fragtbl array.
   145 const u_char * const fragtbl[MAXFRAG + 1] = {
               0, fragtbl124, fragtbl124, 0, fragtbl124, 0, 0, 0, fragtbl8,
   146
   147 };
                                                     - ffs/ffs/ffs_tables.c
The ffs_mapsearch function that implements this algorithm is
                                                      ffs/ffs/ffs_alloc.c
   1708 /*
   1709 * Find a block of the specified size in the specified cylinder group.
   1711 * It is a panic if a request is made to find a block if none are
   1712 * available.
   1713 */
   1714 static ufs_daddr_t
   1715 ffs_mapsearch(fs, cgp, bpref, allocsiz)
              struct fs *fs;
   1716
   1717
               struct cg *cgp;
   1718
               ufs_daddr_t bpref;
               int allocsiz;
   1719
  1720 {
               ufs_daddr_t bno;
   1721
               int start, len, loc, i;
   1722
   1723
               int blk, field, subfield, pos;
   1724
               int ostart, olen;
   1725 #ifdef FFS_EI
   1726
               const int needswap = UFS_FSNEEDSWAP(fs);
   1727 #endif
   1728
                /*
   1729
                 * find the fragment by searching through the free block
   1730
   1731
                 * map for an appropriate bit pattern
   1732
                 */
```

```
1733
             if (bpref)
1734
                     start = dtogd(fs, bpref) / NBBY;
1735
             else
1736
                     start = ufs_rw32(cgp->cg_frotor, needswap) / NBBY;
1737
             len = howmany(fs->fs_fpg, NBBY) - start;
1738
             ostart = start;
1739
             olen = len;
             loc = scanc((u_int)len,
1740
1741
                     (const u_char *)&cg_blksfree(cgp, needswap)[start],
1742
                     (const u_char *)fragtbl[fs->fs_frag],
                     (1 << (allocsiz - 1 + (fs->fs_frag & (NBBY - 1)))));
1743
             if (loc == 0) {
1744
1745
                     len = start + 1;
1746
                     start = 0;
1747
                     loc = scanc((u_int)len,
1748
                              (const u_char *)&cg_blksfree(cgp, needswap)[0],
1749
                              (const u_char *)fragtbl[fs->fs_frag],
1750
                              (1 << (allocsiz - 1 + (fs->fs_frag & (NBBY - 1)))));
                     if (loc == 0) {
1751
                             printf("start = %d, len = %d, fs = %s\n",
1752
1753
                                  ostart, olen, fs->fs_fsmnt);
                             printf("offset=%d %ld\n",
1754
                                      ufs_rw32(cgp->cg_freeoff, needswap),
1755
1756
                                      (long)cg_blksfree(cgp, needswap) - (long)cgp);
                             panic("ffs_alloccg: map corrupted");
1757
1758
                              /* NOTREACHED */
                     }
1759
1760
             bno = (start + len - loc) * NBBY;
1761
1762
             cgp->cg_frotor = ufs_rw32(bno, needswap);
1763
1764
              * found the byte in the map
1765
              * sift through the bits to find the selected frag
1766
             for (i = bno + NBBY; bno < i; bno += fs->fs_frag) {
1767
1768
                     blk = blkmap(fs, cg_blksfree(cgp, needswap), bno);
1769
                     blk <<= 1;
                     field = around[allocsiz];
1770
                     subfield = inside[allocsiz];
1771
1772
                     for (pos = 0; pos <= fs->fs_frag - allocsiz; pos++) {
                              if ((blk & field) == subfield)
1773
1774
                                      return (bno + pos);
                             field <<= 1;
1775
                             subfield <<= 1;</pre>
1776
                     }
1777
1778
1779
             printf("bno = %d, fs = %s\n", bno, fs->fs_fsmnt);
1780
             panic("ffs_alloccg: block not in map");
             return (-1);
1781
1782 }
```

ffs/ffs/ffs_alloc.c

where the scanc function is defined in lib/libkern/scanc.c as,

Notice line 1740-1760 of ffs_mapsearch function. The first part scans from start to len. The second part scans from 0 to start.

10.6.8 Rotational Layout Table

10.7 Inode Allocation Mechanism

10.7.1 Global Policy: ffs_valloc

```
* Allocate an inode in the file system.
 * If allocating a directory, use ffs_dirpref to select the inode.
 * If allocating in a directory, the following hierarchy is followed:
     1) allocate the preferred inode.
     2) allocate an inode in the same cylinder group.
     3) quadradically rehash into other cylinder groups, until an
        available inode is located.
 * If no inode preference is given the following hierarchy is used
 * to allocate an inode:
     1) allocate an inode in cylinder group 0.
     2) quadradically rehash into other cylinder groups, until an
        available inode is located.
 */
ffs_valloc(v)
        // If allocating a directory, use ffs_dirpref to select the inode.
        if ((mode & IFMT) == IFDIR)
                ipref = ffs_dirpref(pip);
        // Set preferred inode and cylinder group according to the above rules.
        ipref = ....;
        cg = ....;
        // Try to allocate
        ffs_hashalloc( ffs_nodealloccg );
}
```

10.7.2 Local Policy 1: ffs_dirpref

```
/*
 * Find a cylinder group in which to place a directory.
 *
 * The policy implemented by this algorithm is to allocate a
 * directory inode in the same cylinder group as its parent
 * directory, but also to reserve space for its files inodes
 * and data. Restrict the number of directories which may be
 * allocated one after another in the same cylinder group
 * without intervening allocation of files.
 *
 * If we allocate a first level directory then force allocation
 * in another cylinder group.
 */
static ino_t
ffs_dirpref(pip)
{
    .....
}
```

10.7.3 Local Policy 2: ffs_nodealloccg

```
/*
 * Determine whether an inode can be allocated.
 *
 * Check to see if an inode is available, and if it is,
 * allocate it using the following policy:
 * 1) allocate the requested inode.
 * 2) allocate the next available inode after the requested
 * inode in the specified cylinder group.
 */
static ufs_daddr_t
ffs_nodealloccg(ip, cg, ipref, mode)
{
    .....
}
```

10.8 Synchronous Operations

To ensure that the on-disk state of the filesystem can always be returned to a consistent state, the system must do three operations synchronously.

- Write a newly allocated inode to disk before its name is entered into a directory containing the file indicated by the inode.
- Remove a directory name before the inode is deallocated.
- Write a deallocated inode to disk before its blocks are placed into the cylinder group free list.

10.9 Filesystem Semantics

10.9.1 Large File Sizes

4.4 BSD FFS support 64-bit file size. However, the interface to the filesystem is still limited to 31-bit sizes!

This is not quite enough for modern enormous storage systems. Therefore if we want to extend it to 128-bit file size, we shold redefine off_t type and make many changes to FFS functions that implement system calls including, but not limited to.

- lseek
- stat, fstat, lstat
- truncate
- mmap
- getrlimit, setrlimit

10.10 References to Source Code

10.10.1 fs.h - 574 lines

Type Definitions

```
struct fs Superblock
struct csum Cylinder group summary information
struct cg Cylinder hroup
struct ocg Old cylinder hroup
struct appleufslabel Apple UFS superblock
```

Macro Functions

fsbtodb(fs, b)

dbtofsb(fs, b)

```
Get the base address of positional layout table
fs_postbl(fs, cylno)
fs_rotbl(fs)
                            Get blocks for each rotation
CGSIZE(fs)
                            Get the size of a cylinder group
                            Get the base address of cylinder group summary info
fs_cs(fs, indx)
[ Macros for access to cylinder group without regard to superblock version ]
cg_blktot(cgp, ns)
                            Get the block totals per cylinder
cg_blks(fs, cgp, cylno, ns) Get the base address of free block positions
cg_inosused(cgp, ns)
                            Get the base address of used inode map
                            Get the base address of free block map
cg_blksfree(cgp, ns)
cg_chkmagic(cgp, ns)
                           Get the filesystem version magic number
cg_clustersfree(cgp, ns)
                           Get base address of free cluster map
cg_clustersum(cgp, ns)
                            Get the counts of available clusters
```

[Converter between from filesystem block number and disk block address]

Reverse

From the filesystem block to disk block

```
[ Macros to locate things in cylinder groups ]
cgbase(fs, c)
                             Locate the cylinder group base
cgdmin(fs, c)
                             Locate the data block
cgimin(fs, c)
                            Locate the inode block
cgsblock(fs, c)
                            Locate the superblock
cgtod(fs, c)
                            Locate the cylinder group block itself
cgstart(fs, c)
                             Locate the cylinder start some after base
[ Convert inode number to some other things ]
ino_to_cg(fs, x)
                             Convert to cylinder group number
                             Convert to ????????
ino_to_fsba(fs, x)
                             Convert to ????????
ino_to_fsbo(fs, x)
[ Convert filesystem block number to some other things ]
dtog(fs, d)
                             Convert to cylinder group number
dtogd(fs, d)
                             Convert to cylinder group block number
[?]
blkmap(fs, map, loc)
                             ?
cbtocylno(fs, bno)
cbtorpos(fs, bno)
[ Determine the number of available frags given a percent to hold in reserve ]
freespace(fs, percentreserv) ?
[ Determining the size of a file block in the file system ]
blksize(fs, ip, lbn)
                             ?
                             ?
dblksize(fs, dip, lbn)
[ Convert something into the number of sectors ]
NSPB(fs)
                             Convert a block size
NSPF(fs)
                             Convert a sector size
[ Convert something into the number of inodes ]
INOPB(fs)
                             Convert a block size
INOPF(fs)
                             Convert a fragment size
[ Misc. ]
blkoff(fs, loc)
                            /* calculates (loc % fs->fs_bsize) */ \
fragoff(fs, loc)
                            /* calculates (loc % fs->fs_fsize) */ \
lblktosize(fs, blk)
                            /* calculates ((off_t)blk * fs->fs_bsize) */ \
lblkno(fs, loc)
                           /* calculates (loc / fs->fs_bsize) */ \
numfrags(fs, loc)
                           /* calculates (loc / fs->fs_fsize) */ \
blkroundup(fs, size)
                           /* calculates roundup(size, fs->fs_bsize) */ \
```

```
fragroundup(fs, size)  /* calculates roundup(size, fs->fs_fsize) */ \
fragstoblks(fs, frags)  /* calculates (frags / fs->fs_frag) */ \
blkstofrags(fs, blks)  /* calculates (blks * fs->fs_frag) */ \
fragnum(fs, fsb)  /* calculates (fsb % fs->fs_frag) */ \
blknum(fs, fsb)  /* calculates rounddown(fsb, fs->fs_frag) */ \
NINDIR(fs)  [?] Number of indirects in a file system block
```

10.10.2 ffs_vfsops.c - 1518 lines, 18 functions

Gloval Variables

```
ffs_vnodeopv_descs
ffs_vfsops
ffs_genfsops
ffs_inode_pool
```

Functions

```
ffs_mountroot
ffs_mount
ffs_reload
ffs_mountfs
ffs_oldfscompat
ffs_unmount
ffs_flushfiles
ffs_statfs
ffs_sync
                   Read a FFS dinode using inode cache
ffs_vget
ffs_fhtovp
ffs_vptofh
ffs_init
ffs_reinit
ffs_done
ffs_sysctl
ffs_sbupdate
ffs_cgupdate
```

10.10.3 ffs_vnops.c - 580 lines, 6 functions

Gloval Variables

```
ffs_vnodeop_opv_desc
ffs_specop_opv_desc
ffs_fifoop_opv_desc
```

Functions

```
ffs_fsync
ffs_full_fsync
ffs_reclaim
ffs_getpages
ffs_putpages
ffs_gop_size
    Return the last logical file offset that should be written
```

10.10.4 ffs_alloc.c - 1895 lines, 18 functions

Gloval Variables

none

Functions

[Block Allocation]

ffs_alloc Provide a global policy for getting a new block
ffs_realloccg Provide a global policy for extending an fragment
ffs_alloccg Allocate a block or fragment with a local policy

ffs_fragextend Extend an fragment

ffs_alloccgblk Allocate a block in the specified cylinder group

ffs_blkpref Guess a proper location of a new block ffs_hashalloc Implement cylinder overflow algorithm

ffs_reallocblks Gather blocks together [Disabled Now]

ffs_clusteralloc Determine whether a cluster can be allocated [Disabled Now]

[Inode Allocation]

ffs_valloc Provide a global policy for allocating a new inode ffs_dirpref Guess a proper cylinder group for a new directory

ffs_nodealloccg Allocate a new inode

[Block & Inode De-allocation]

ffs_blkfree Free a block or fragment

ffs_vfree Cover function for freeing an inode ffs_freefile Do the actual free operation for an inode

[Misc.]

ffs_mapsearch Find a block or fragments of the specified size from a cyl.

ffs_clusteracct Update the cluster map because of an allocation of free

[Debug]

ffs_fserr Prints the name of a filesystem with an error diagnostic

10.10.5 ffs_balloc.c - 552 lines, 2 functions

Gloval Variables

none

Functions

ffs_balloc Non-UBC: Allocate a requested block or fragments

ffs_gop_alloc UBC: Allocate blocks

10.10.6 ffs_inode.c - 582 lines, 3 functions

Gloval Variables

none

Functions

ffs_update Update the access, modified, and inode change time ffs_truncate Force the length of the inode to a specified value ffs_indirtrunc Called by ffs_truncate to deal indirect pointer

10.10.7 ffs_subr.c - 295 lines, 7 functions

Gloval Variables

none

Functions

ffs_blkatoff Return buffer with the contents of block
ffs_fragacct Update Fragment Summary

ffs_isblock Check if a block is available
ffs_isfreeblock Check if a block is free

ffs_clrblock Take a block out of the map

ffs_setblock Put a block into the map

ffs_checkoverlap Diagnostic

10.10.8 ffs_tables.c - 147 lines, 0 functions

Gloval Variables

fragtbl Fragment table for fast free fragment searching

Functions

none

10.10.9 ffs_swap.c - 158 lines, 3 functions

Gloval Variables

none

Functions

ffs_sb_swap Adjust superblock for machine indenpendent meta-data ffs_dinode_swap Adjust inode for machine indenpendent meta-data ffs_csum_swap Adjust cyl group summary information for the same reason

Chapter 11

Mounting Root File System

In this chapter, the procedure involved in mounting root filesystem is described.

11.1 System Bootstrapping

After bootstrap, the system initialization is started in main function of kern/init_main.c as follows.

main function initialize the world, create process 0, mount root filesystem, and fork to create init and pagedaemon. Most of the hard work is done in the lower-level initialization routines including start function of arch/sparc64/sparc64/locore.s, which does memory initialization and autoconfiguration.

```
kern/init_main.c
171 void
172 main(void)
173 {
188
             * Initialize the current process pointer (curproc) before
189
190
             * any possible traps/probes to simplify trap processing.
191
            /* Initialize kqueues. */
219
235
            /* Initialize the sysctl subsystem. */
236
            sysctl_init();
237
248
             * Create process 0 (the swapper).
249
250
344
            /* Configure virtual memory system, set vm rlimits. */
            uvm_init_limits(p);
345
346
            /* Initialize the file systems. */
347
361
            vfsinit();
```

kern/init_main.c

At line 361, virtual filesystem layer initialization is started by calling vfsinit function.

Note that before virtual filesystem layer is initialized, various system initializing procedure including creation of swapper and initialization of UVM[3] virtual memory system.

As we described at previous section, Virtual filesystem initialization is initiated in main function of kern/init_main.c which is practically the first function executed after machine bootstrap.

That function calls vfsinit function of kern/vfs_init.c which we studied in the previous chapter.

11.2 Before Mounting

Up to now, we followed execution of main function in kern/init_main.c just after kernel bootstrap. Now let keep going on analyzing kern/init_main.c just after we have traced.

We will show the whole source code that will be described in this section and then describe each part of it. To minimize the list, all optional parts (ifdef block) are removed.

```
kern/init_main.c
        /* Configure the system hardware. This will enable interrupts. */
364
        configure();
365
366
        ubc_init();
                                 /* must be after autoconfig */
367
368
        /* Lock the kernel on behalf of proc0. */
        KERNEL_PROC_LOCK(p);
369
        /* Attach pseudo-devices. */
386
387
        for (pdev = pdevinit; pdev->pdev_attach != NULL; pdev++)
388
            (*pdev->pdev_attach)(pdev->pdev_count);
389
390
391
         * Initialize protocols. Block reception of incoming packets
         * until everything is ready.
392
393
         */
394
        s = splnet();
395
        ifinit();
        domaininit();
396
397
        if_attachdomain();
398
        splx(s);
405
        /* Initialize system accouting. */
406
        acct_init();
411
         * Initialize signal-related data structures, and signal state
412
413
         * for proc0.
414
415
        signal_init();
```

```
416
       p->p_sigacts = &sigacts0;
417
        siginit(p);
418
419
        /* Kick off timeout driven events by calling first time. */
420
       schedcpu(NULL);
421
422
       /*
423
       * Create process 1 (init(8)). We do this now, as Unix has
424
        * historically had init be process 1, and changing this would
425
        * probably upset a lot of people.
426
427
        * Note that process 1 won't immediately exec init(8), but will
428
        * wait for us to inform it that the root file system has been
429
        * mounted.
430
        */
431
        if (fork1(p, 0, SIGCHLD, NULL, 0, start_init, NULL, NULL, &initproc))
432
            panic("fork init");
433
434
       /*
435
         * Create any kernel threads who's creation was deferred because
436
         * initproc had not yet been created.
437
438
       kthread_run_deferred_queue();
439
440
441
       * Now that device driver threads have been created, wait for
442
        * them to finish any deferred autoconfiguration. Note we don't
443
        * need to lock this semaphore, since we haven't booted any
444
         * secondary processors, yet.
445
        */
446
       while (config_pending)
447
            (void) tsleep((void *)&config_pending, PWAIT, "cfpend", 0);
448
449
       /*
450
        * Finalize configuration now that all real devices have been
451
        * found. This needs to be done before the root device is
452
        * selected, since finalization may create the root device.
453
        */
        config_finalize();
454
455
456
457
        * Now that autoconfiguration has completed, we can determine
458
         * the root and dump devices.
459
460
       cpu_rootconf();
461
        cpu_dumpconf();
462
463
       /* Mount the root file system. */
464
       do {
465
            domountroothook();
            if ((error = vfs_mountroot())) {
466
467
                printf("cannot mount root, error = %d\n", error);
468
                boothowto |= RB_ASKNAME;
469
                setroot(root_device,
```

```
470
                        (rootdev != NODEV) ? DISKPART(rootdev) : 0);
            }
471
472
        } while (error != 0);
473
        mountroothook_destroy();
474
475
        CIRCLEQ_FIRST(&mountlist)->mnt_flag |= MNT_ROOTFS;
476
        CIRCLEQ_FIRST(&mountlist)->mnt_op->vfs_refcount++;
477
478
         * Get the vnode for '/'. Set filedesc0.fd_fd.fd_cdir to
479
480
         * reference it.
481
        if (VFS_ROOT(CIRCLEQ_FIRST(&mountlist), &rootvnode))
482
483
                panic("cannot find root vnode");
484
        cwdi0.cwdi_cdir = rootvnode;
485
        VREF(cwdi0.cwdi_cdir);
486
        VOP_UNLOCK(rootvnode, 0);
487
        cwdi0.cwdi_rdir = NULL;
488
489
490
         * Now that root is mounted, we can fixup initproc's CWD
491
         * info. All other processes are kthreads, which merely
492
         * share proc0's CWD info.
493
         */
494
        initproc->p_cwdi->cwdi_cdir = rootvnode;
495
        VREF(initproc->p_cwdi->cwdi_cdir);
496
        initproc->p_cwdi->cwdi_rdir = NULL;
497
498
499
        * Now can look at time, having had a chance to verify the time
500
         * from the file system. Reset p->p_rtime as it may have been
501
         * munched in mi_switch() after the time got set.
502
         */
503
        proclist_lock_read();
504
        s = splsched();
505
        for (p = LIST_FIRST(&allproc); p != NULL;
506
             p = LIST_NEXT(p, p_list)) {
507
                p->p_stats->p_start = mono_time = boottime = time;
508
                if (p->p_cpu != NULL)
509
                        p->p_cpu->ci_schedstate.spc_runtime = time;
510
                p->p_rtime.tv_sec = p->p_rtime.tv_usec = 0;
511
        }
512
        splx(s);
513
        proclist_unlock_read();
514
        /* Create the pageout daemon kernel thread. */
515
516
        uvm_swap_init();
517
        if (kthread_create1(uvm_pageout, NULL, NULL, "pagedaemon"))
                panic("fork pagedaemon");
518
519
520
        /* Create the process reaper kernel thread. */
521
        if (kthread_create1(reaper, NULL, NULL, "reaper"))
522
                panic("fork reaper");
523
```

```
524
        /* Create the filesystem syncer kernel thread. */
525
        if (kthread_create1(sched_sync, NULL, NULL, "ioflush"))
526
                panic("fork syncer");
527
528
        /* Create the aiodone daemon kernel thread. */
529
        if (kthread_create1(uvm_aiodone_daemon, NULL, NULL, "aiodoned"))
530
                panic("fork aiodoned");
531
536
537
        /* Initialize exec structures */
538
        exec_init(1);
539
544
545
546
         * Okay, now we can let init(8) exec! It's off to userland!
547
         */
548
        start_init_exec = 1;
549
        wakeup((void *)&start_init_exec);
550
551
        /* The scheduler is an infinite loop. */
552
        uvm_scheduler();
        /* NOTREACHED */
553
554 }
                                                    kern/init_main.c
```

11.2.1 Creating stopped init process

line 366-421 is out of our concern, since it is not directly related with filesystem code. Where the init process is created is line 422-432

kernel level fork1 function creates a new process out of start_init function of init_main.c, which is assumed to be the current process.

```
- \text{kern/init\_main.c}
586 static void
587 start_init(void *arg)
588 {
604
605
         * Now in process 1.
606
        strncpy(p->p_comm, "init", MAXCOMLEN);
607
608
609
         * Wait for main() to tell us that it's safe to exec.
610
611
         */
612
        while (start_init_exec == 0)
613
             (void) tsleep((void *)&start_init_exec, PWAIT, "initexec", 0);
                                                      - kern/init_main.c
```

After main function of kern/init_main.c mounts root filesystem, the temporally stopped execution of start_init function at line 612-613 is continued.

11.2.2 Finding Where is the Root File System

line 460-461 in main function of kern/init_main.c finds where the root filesystem are. It also finds where the dump device is.

cpu_rootconf function does the work and this function is machine dependent.

```
-- arch/sparc64/sparc64/autoconf.c
491 void
492 cpu_rootconf()
493 {
494
            struct bootpath *bp;
495
            struct device *bootdv;
496
            int bootpartition;
497
498
            bp = nbootpath == 0 ? NULL : &bootpath[nbootpath-1];
499
            bootdv = bp == NULL ? NULL : bp->dev;
500
            bootpartition = bootdv == NULL ? 0 : bp->val[2];
501
502
            setroot(bootdv, bootpartition);
503 }
                                      - arch/sparc64/sparc64/autoconf.c
```

setroot function of kern/kern_subr.c set global variable struct device *root_device to proper value.

You may wonder how the root device specified in bootpath entry of Sparc PROM is delivered to nbootpath variable in line 498 of arch/sparc64/sparc64/autoconf.c The answer is at configure function at the line 364 of kern/init_main.c. This configure function is,

```
- kern/subr_autoconf.c
226 /*
227 * Configure the system's hardware.
228 */
229 void
230 configure(void)
231 {
232
233
        /* Initialize data structures. */
234
        config_init();
235
236 #ifdef USERCONF
        if (boothowto & RB_USERCONF)
237
238
            user_config();
239 #endif
240
241
        /*
242
         * Do the machine-dependent portion of autoconfiguration. This
         * sets the configuration machinery here in motion by "finding"
243
         * the root bus. When this function returns, we expect interrupts
244
245
         * to be enabled.
246
247
        cpu_configure();
248
```

```
249
250
         * Now that we've found all the hardware, start the real time
251
         * and statistics clocks.
252
253
        initclocks();
254
255
        cold = 0; /* clocks are running, we're warm now! */
256
257
        * Now callback to finish configuration for devices which want
258
259
         * to do this once interrupts are enabled.
260
261
        config_process_deferred(&interrupt_config_queue, NULL);
262 }
```

This configure function calls machine dependent cpu_configure function of arch/sparc64/sparc64/autoconf.c,

```
- arch/sparc64/sparc64/autoconf.c
458 /*
459 * Determine mass storage and memory configuration for a machine.
460 * We get the PROM's root device and make sure we understand it, then
461 * attach it as 'mainbus0'. We also set up to handle the PROM 'sync'
462 * command.
463 */
464 void
465 cpu_configure()
466 {
467
            /* build the bootpath */
468
469
            bootpath_build();
470
471 #if notyet
           /* FIXME FIXME FIXME This is probably *WRONG!!!**/
472
473
            OF_set_callback(sync_crash);
474 #endif
475
476
            /* block clock interrupts and anything below */
477
            splclock();
478
            /* Enable device interrupts */
479
            setpstate(getpstate()|PSTATE_IE);
480
481
            if (config_rootfound("mainbus", NULL) == NULL)
482
                    panic("mainbus not configured");
483
            /* Enable device interrupts */
484
485
            setpstate(getpstate()|PSTATE_IE);
486
487
            (void)spl0();
488 }
```

-- arch/sparc64/sparc64/autoconf.c

This cpu_configure function calls again bootpath_build function and this function reads bootpath entry of SPARC PROM!

```
-- arch/sparc64/sparc64/autoconf.c
274 static void
275 bootpath_build()
276 {
277
        register char *cp, *pp;
278
        register struct bootpath *bp;
279
        register long chosen;
280
        char buf[128];
281
        bzero((void*)bootpath, sizeof(bootpath));
282
283
        bp = bootpath;
284
285
        /*
286
         * Grab boot path from PROM
287
288
        chosen = OF_finddevice("/chosen");
        OF_getprop(chosen, "bootpath", buf, sizeof(buf));
289
        cp = buf;
290
291
        while (cp != NULL && *cp == '/') {
292
            /* Step over '/' */
293
            ++cp;
294
            /* Extract name */
295
            pp = bp->name;
296
            while (*cp != '0' && *cp != '/' && *cp != '\0')
297
                *pp++ = *cp++;
298
            *pp = '\0';
299
            if (*cp == '0') {
300
                cp = str2hex(++cp, &bp->val[0]);
301
                if (*cp == ',')
302
                     cp = str2hex(++cp, &bp->val[1]);
303
                if (*cp == ':')
304
                     /* XXX - we handle just one char */
305
                     bp - val[2] = *++cp - 'a', ++cp;
306
            } else {
307
                bp \rightarrow val[0] = -1; /* no #'s: assume unit 0, no
                             sbus offset/adddress */
308
309
310
            ++bp;
311
            ++nbootpath;
312
313
        bp->name[0] = 0;
314
315
        bootpath_print(bootpath);
316
317
        /* Setup pointer to boot flags */
318
        OF_getprop(chosen, "bootargs", buf, sizeof(buf));
319
        cp = buf;
320
321
        /* Find start of boot flags */
322
        while (*cp) {
323
            while(*cp == ', ', || *cp == '\t') cp++;
```

```
if (*cp == '-' || *cp == '\0')
324
325
            while(*cp != ', ' && *cp != '\t' && *cp != '\0') cp++;
326
327
328
329
        if (*cp != '-')
330
            return;
331
332
        for (;*++cp;) {
333
            int fl;
334
            fl = 0;
335
336
            BOOT_FLAG(*cp, fl);
337
            if (!fl) {
338
                 printf("unknown option '%c'\n", *cp);
339
                 continue;
340
            }
341
            boothowto |= fl;
342
343
            /* specialties */
344
            if (*cp == 'd') {
345 #if defined(KGDB)
                kgdb_debug_panic = 1;
346
347
                kgdb_connect(1);
348 #elif defined(DDB)
349
                Debugger();
350 #else
351
                 printf("kernel has no debugger\n");
352 #endif
353
            } else if (*cp == 't') {
                 /* turn on traptrace w/o breaking into kdb */
354
355
                 extern int trap_trace_dis;
356
357
                 trap_trace_dis = 0;
            }
358
359
        }
```

This function reads bootpath, from SPARC PROM, such as

```
bootpath: /sbus@1f,0/SUNW,fas@e,8800000/sd@0,0
```

and stores this machine dependent struct bootpath structure.

For the time being, it is sufficient for us only to know that after execution of cpu_rootconf function at line 460 of kern/init_main.c, we obtains the location of the root device in global variable struct device *root_device. There is no need for us to analyze the very detail of this function, since we are only interested in filesystem related code! Instead, we summarize how kernel founds root filesystem.

Pay attention the three variables that is set by setroot function.

1. mountroot pointer to function indicates the function to mount root filesystem. For example, if root filesystem is FFS, this function pointer is set to ffs_mountroot function of ufs/ffs/ffs_vfsops.c.

mountroot variable is defined in automatically generated swapnetbsd.c by config program as,

 $arch/sparc64/compile/MY_KERNEL/swapnetbsd.c$

arch/sparc64/compile/MY_KERNEL/swapnetbsd.c

where rootspec, dumpdev variable is set to other value, if you specified root device or dump device in kernel configuration file. If kernel configuration file set this variable to other values, it overrides the value of SPARC PROM's bootpath entry!

- 2. rootdev is major number of device driver controlling a storage device containing root file system. dev_t type is simply defined as u_int32_t in /usr/include/sys/types.h
- root_device is defined as structure device. It contains device information corresponding to rootdev variable. structure device is defined in sys/device.h as,

```
- sys/device.h

107 struct device {

108    enum    devclass dv_class;    /* this device's classification *
```

```
109
            TAILQ_ENTRY(device) dv_list;
                                            /* entry on list of all devices */
110
            struct cfdata *dv_cfdata;
                                            /* config data that found us
                                                (NULL if pseudo-device) */
111
112
            struct cfdriver *dv_cfdriver; /* our cfdriver */
113
            struct cfattach *dv_cfattach; /* our cfattach */
114
            int
                    dv_unit;
                                            /* device unit number */
                                            /* external name (name + unit) */
115
            char
                    dv_xname[16];
            struct device *dv_parent;
                                            /* pointer to parent device
116
117
                                                (NULL if pesudo- or root node) */
118
            int
                    dv_flags;
                                            /* misc. flags; see below */
119 };
                                        - sys/device.h
```

11.2.3 Executing Root Mount Hook

After somewhat long preparation after system bootstrap, the system is now ready to mount the root filesystem. line 463-476 of kern/init_main.c does the work.

Root mount hook is a list of functions that should be called before root filesystem mount as a preparation process.

mountroothook_establish registers a function that should be executed before root filesystem, we can register with mountrootbook_establish.

domountroothook executes all registered root mount hook.

For reference, we listed the source code below.

```
kern/kern_subr.c
504 /*
* "Mountroot hook" types, functions, and variables.
506 */
507
508 hook_list_t mountroothook_list;
509
510 void *
511 mountroothook_establish(fn, dev)
512
            void (*fn) __P((struct device *));
            struct device *dev;
513
514 {
515
            return hook_establish(&mountroothook_list, (void (*)__P((void *)))fn,
516
                dev):
517 }
518
519 void
520 mountroothook_disestablish(vhook)
521
           void *vhook;
522 {
523
            hook_disestablish(&mountroothook_list, vhook);
524 }
525
526 void
527 mountroothook_destroy()
528 {
529
            hook_destroy(&mountroothook_list);
```

```
530 }
531
532 void
533 domountroothook()
534 {
535
            struct hook_desc *hd;
536
           LIST_FOREACH(hd, &mountroothook_list, hk_list) {
537
538
                    if (hd->hk_arg == (void *)root_device) {
539
                            (*hd->hk_fn)(hd->hk_arg);
540
                            return;
                    }
541
            }
542
543 }
                                                    kern_subr.c
```

where hook_establish, hook_disestablish, and hook_destroy functions are simply implemented in kern/kern_subr.c as,

```
kern/kern_subr.c
383 static void *
384 hook_establish(list, fn, arg)
385
           hook_list_t *list;
386
            void (*fn) __P((void *));
387
            void *arg;
388 {
389
            struct hook_desc *hd;
390
391
            hd = malloc(sizeof(*hd), M_DEVBUF, M_NOWAIT);
            if (hd == NULL)
392
393
                    return (NULL);
394
395
            hd->hk_fn = fn;
396
            hd->hk_arg = arg;
397
            LIST_INSERT_HEAD(list, hd, hk_list);
398
399
            return (hd);
400 }
401
402 static void
403 hook_disestablish(list, vhook)
404
            hook_list_t *list;
405
            void *vhook;
406 {
407 #ifdef DIAGNOSTIC
408
           struct hook_desc *hd;
409
410
            LIST_FOREACH(hd, list, hk_list) {
                    if (hd == vhook)
411
412
                            break;
413
            }
414
           if (hd == NULL)
415
```

kern/kern_subr.c

```
416
                    panic("hook_disestablish: hook %p not established", vhook);
417 #endif
418
            LIST_REMOVE((struct hook_desc *)vhook, hk_list);
419
            free(vhook, M_DEVBUF);
420 }
421
422 static void
423 hook_destroy(list)
            hook_list_t *list;
425 {
426
            struct hook_desc *hd;
427
428
            while ((hd = LIST_FIRST(list)) != NULL) {
429
                    LIST_REMOVE(hd, hk_list);
430
                    free(hd, M_DEVBUF);
431
            }
432 }
```

Those functions can be used by software RAID, since before mounting root filesystem, kernel should get information to mount root file system from the unconfigured RAID. That information from unconfigured RAID, can be obtained by mount root hook.

For more important, if you want to newly design any RAID-like filesystem, and want to mount it as a root filesystem, you may need to use *root mount hook*.

11.3 Let's Mount the Root File System!

11.3.1 Telling the VFS to Mount the Root Filesystem

In this section, we will show how VFS calls a FFS function for mounting root filesystem. For you reference, we again shows the code mounting root file system: the line 464-476 of kern/init_main.c.

```
kern/init_main.c
463
            /* Mount the root file system. */
464
            do {
465
                    domountroothook();
466
                     if ((error = vfs_mountroot())) {
467
                             printf("cannot mount root, error = %d\n", error);
468
                             boothowto |= RB_ASKNAME;
469
                             setroot(root_device,
470
                                 (rootdev != NODEV) ? DISKPART(rootdev) : 0);
471
472
            } while (error != 0);
473
            mountroothook_destroy();
                                                     kern/init_main.c
```

vfs_mountroot function of kern/vfs_subr.c does the work and its source code is

```
kern/vfs_subr.c
```

```
2549 /*
2550 * Mount the root file system. If the operator didn't specify a
2551 * file system to use, try all possible file systems until one
2552 * succeeds.
2553 */
2554 int
2555 vfs_mountroot()
2556 {
2557
             struct vfsops *v;
2558
2559
             if (root_device == NULL)
2560
                     panic("vfs_mountroot: root device unknown");
2561
2562
             switch (root_device->dv_class) {
2563
             case DV_IFNET:
2564
                     if (rootdev != NODEV)
2565
                             panic("vfs_mountroot: rootdev set for DV_IFNET "
                                  "(0x\%08x -> \%d,\%d)", rootdev,
2566
2567
                                 major(rootdev), minor(rootdev));
2568
                     break;
2569
2570
             case DV_DISK:
2571
                     if (rootdev == NODEV)
2572
                             panic("vfs_mountroot: rootdev not set for DV_DISK");
2573
                     break;
2574
2575
             default:
2576
                     printf("%s: inappropriate for root file system\n",
                         root_device->dv_xname);
2577
2578
                     return (ENODEV);
             }
2579
2580
2581
2582
              * If user specified a file system, use it.
2583
2584
             if (mountroot != NULL)
2585
                     return ((*mountroot)());
2586
2587
             /*
2588
              * Try each file system currently configured into the kernel.
2589
              */
2590
             for (v = LIST_FIRST(&vfs_list); v != NULL; v = LIST_NEXT(v, vfs_list)) {
2591
                     if (v->vfs_mountroot == NULL)
2592
                             continue;
2593 #ifdef DEBUG
2594
                     printf("mountroot: trying %s...\n", v->vfs_name);
2595 #endif
2596
                     if ((*v->vfs_mountroot)() == 0) {
2597
                             printf("root file system type: %s\n", v->vfs_name);
2598
                             break;
                     }
2599
2600
             }
2601
             if (v == NULL) {
2602
```

Suppose that the SPARC PROM bootpath entry is set to indicate a partition containing FFS filesystem. Then mountroot variable in line 2585 of kern/vfs_subr.c is already set to ffs_mountroot function by setroot function. We described how mountroot variable is set, in the previous subsection.

Now we turn to ffs_mountroot function of ufs/ffs_vfsops.c.

```
ufs/ffs/ffs_vfsops.c
130 int
131 ffs_mountroot()
132 {
133
            struct fs *fs;
134
            struct mount *mp;
135
            struct proc *p = curproc;
                                             /* XXX */
            struct ufsmount *ump;
136
137
            int error;
138
139
            if (root_device->dv_class != DV_DISK)
                    return (ENODEV);
140
141
142
143
             * Get vnodes for rootdev.
144
145
            if (bdevvp(rootdev, &rootvp))
                    panic("ffs_mountroot: can't setup bdevvp's");
146
147
148
            if ((error = vfs_rootmountalloc(MOUNT_FFS, "root_device", &mp))) {
149
                    vrele(rootvp);
150
                    return (error);
151
            if ((error = ffs_mountfs(rootvp, mp, p)) != 0) {
152
153
                    mp->mnt_op->vfs_refcount--;
154
                    vfs_unbusy(mp);
155
                    free(mp, M_MOUNT);
156
                    vrele(rootvp);
157
                    return (error);
158
            }
159
            simple_lock(&mountlist_slock);
            CIRCLEQ_INSERT_TAIL(&mountlist, mp, mnt_list);
160
161
            simple_unlock(&mountlist_slock);
162
            ump = VFSTOUFS(mp);
            fs = ump->um_fs;
163
164
            memset(fs->fs_fsmnt, 0, sizeof(fs->fs_fsmnt));
165
            (void)copystr(mp->mnt_stat.f_mntonname, fs->fs_fsmnt, MNAMELEN - 1, 0);
```

11.3.2 Getting Vnode for Root Device

11.3.3 Allocating Mount Structure

```
126 struct mount {
127
           CIRCLEQ_ENTRY(mount) mnt_list;
                                                /* mount list */
128
           struct vfsops *mnt_op;
                                                /* operations on fs */
                                               /* vnode we mounted on */
129
           struct vnode
                          *mnt_vnodecovered;
                                                /* syncer vnode */
130
           struct vnode
                          *mnt_syncer;
                                               /* list of vnodes this mount */
131
           struct vnodelst mnt_vnodelist;
132
           struct lock mnt_lock;
                                               /* mount structure lock */
133
                                                /* flags */
          int
                         mnt_flag;
                                                /* max size of short symlink */
134
           int
                          mnt_maxsymlinklen;
135
                                                /* offset shift for lblkno */
           int
                         mnt_fs_bshift;
136
           int
                         mnt_dev_bshift;
                                                /* shift for device sectors */
137
           struct statfs mnt_stat;
                                                /* cache of filesystem stats */
138
                                               /* private data */
           void
                         *mnt_data;
                                               /* count of vfs_busy waiters */
139
           int
                         mnt_wcnt;
                                               /* who is unmounting */
140
           struct proc
                         *mnt_unmounter;
141 };
```

11.3.4 Reading Superblock

```
171 /*
172 * Super block for an FFS file system in memory.
173 */
174 struct fs {
          int32_t fs_firstfield;
                                          /* historic file system linked list, */
175
176
           int32_t fs_unused_1;
                                         /* used for incore super blocks */
          ufs_daddr_t fs_sblkno;
                                         /* addr of super-block in filesys */
177
           ufs_daddr_t fs_cblkno;
                                         /* offset of cyl-block in filesys */
178
           ufs_daddr_t fs_iblkno;
                                         /* offset of inode-blocks in filesys */
179
180
           ufs_daddr_t fs_dblkno;
                                         /* offset of first data after cg */
181
           int32_t fs_cgoffset;
                                         /* cylinder group offset in cylinder */
           int32_t fs_cgmask;
                                         /* used to calc mod fs_ntrak */
182
183
           int32_t fs_time;
                                         /* last time written */
184
           int32_t fs_size;
                                         /* number of blocks in fs */
           int32_t fs_dsize;
                                         /* number of data blocks in fs */
185
           int32_t fs_ncg;
                                         /* number of cylinder groups */
186
           int32_t fs_bsize;
187
                                         /* size of basic blocks in fs */
188
           int32_t fs_fsize;
                                         /* size of frag blocks in fs */
189
           int32_t fs_frag;
                                          /* number of frags in a block in fs */
190 /* these are configuration parameters */
```

```
191
           int32_t fs_minfree;
                                        /* minimum percentage of free blocks */
                                        /* num of ms for optimal next block */
192
           int32_t fs_rotdelay;
          int32_t fs_rps;
                                        /* disk revolutions per second */
193
194 /* these fields can be computed from the others */
195
         int32_t fs_bmask;
                                       /* ''blkoff'' calc of blk offsets */
                                        /* ''fragoff'' calc of frag offsets */
196
          int32_t fs_fmask;
197
          int32_t fs_bshift;
                                        /* ''lblkno'' calc of logical blkno */
                                        /* ''numfrags'' calc number of frags */
          int32_t fs_fshift;
198
199 /* these are configuration parameters */
          int32_t fs_maxcontig;
                                         /* max number of contiguous blks */
                                         /* max number of blks per cyl group */
201
          int32_t fs_maxbpg;
202 /* these fields can be computed from the others */
203
          int32_t fs_fragshift;
                                       /* block to frag shift */
                                        /* fsbtodb and dbtofsb shift constant */
204
           int32_t fs_fsbtodb;
205
                                       /* actual size of super block */
          int32_t fs_sbsize;
206
          int32_t fs_csmask;
                                       /* csum block offset (now unused) */
207
          int32_t fs_csshift;
                                       /* csum block number (now unused) */
208
          int32_t fs_nindir;
                                        /* value of NINDIR */
           int32_t fs_inopb;
                                        /* value of INOPB */
209
           int32_t fs_nspf;
                                        /* value of NSPF */
210
211 /* yet another configuration parameter */
         int32_t fs_optim;
                                         /* optimization preference, see below */
212
213 /* these fields are derived from the hardware */
                                       /* # sectors/track including spares */
214
       int32_t fs_npsect;
          int32_t fs_interleave;
                                        /* hardware sector interleave */
215
216
          int32_t fs_trackskew;
                                       /* sector 0 skew, per track */
217 /* fs_id takes the space of the unused fs_headswitch and fs_trkseek fields */
218
          int32_t fs_id[2];
                                         /* unique file system id */
219 /* sizes determined by number of cylinder groups and their sizes */
220
          221
          int32_t fs_cssize;
                                        /* size of cyl grp summary area */
222
          int32_t fs_cgsize;
                                        /* cylinder group size */
223 /* these fields are derived from the hardware */
          int32_t fs_ntrak;
                                        /* tracks per cylinder */
224
225
          int32_t fs_nsect;
                                        /* sectors per track */
226
           int32_t fs_spc;
                                        /* sectors per cylinder */
227 /* this comes from the disk driver partitioning */
         int32_t fs_ncyl;
                                        /* cylinders in file system */
229 /* these fields can be computed from the others */
230
         int32_t fs_cpg;
                                        /* cylinders per group */
           int32_t fs_ipg;
                                         /* inodes per group */
231
          int32_t fs_fpg;
                                        /* blocks per group * fs_frag */
232
233 /* this data must be re-computed after crashes */
234
          struct csum fs_cstotal;
                                         /* cylinder summary information */
235 /* these fields are cleared at mount time */
236
                                        /* super block modified flag */
          int8_t fs_fmod;
237
          int8_t fs_clean;
                                        /* file system is clean flag */
238
          int8_t fs_ronly;
                                        /* mounted read-only flag */
239
                                        /* see FS_ flags below */
          int8_t fs_flags;
          u_char fs_fsmnt[MAXMNTLEN]; /* name mounted on */
240
241 /* these fields retain the current block allocation info */
                                       /* last cg searched (UNUSED) */
242
        int32_t fs_cgrotor;
243
          void *fs_ocsp[NOCSPTRS]; /* padding; was list of fs_cs buffers */
                                       /* # of contiguously allocated dirs */
244
          u_int16_t *fs_contigdirs;
```

/* cg summary info buffer for fs_cs */

245

struct csum *fs_csp;

```
int32_t *fs_maxcluster;
                                                /* max cluster in each cyl group */
    246
    247
                int32_t fs_cpc;
                                                /* cyl per cycle in postbl */
                int16_t fs_opostbl[16][8];
    248
                                                /* old rotation block list head */
                int32_t fs_snapinum[20];
                                                /* RESERVED for snapshot inode nums */
    249
    250
                int32_t fs_avgfilesize;
                                                /* expected average file size */
    251
                int32_t fs_avgfpdir;
                                                /* expected # of files per directory */
                                                /* RESERVED for future constants */
    252
                int32_t fs_sparecon[26];
    253
                int32_t fs_pendingblocks;
                                                /* blocks in process of being freed */
                                                /* inodes in process of being freed */
    254
                int32_t fs_pendinginodes;
    255
                int32_t fs_contigsumsize;
                                                /* size of cluster summary array */
                int32_t fs_maxsymlinklen;
                                                /* max length of an internal symlink */
    256
                int32_t fs_inodefmt;
    257
                                                /* format of on-disk inodes */
    258
                u_int64_t fs_maxfilesize;
                                                /* maximum representable file size */
                                                /*~{\rm \tilde{f}s\_bmask} for use with 64-bit size */
    259
                int64_t fs_qbmask;
    260
                int64_t fs_qfmask;
                                                /* ~fs_fmask for use with 64-bit size */
    261
                int32_t fs_state;
                                                /* validate fs_clean field (UNUSED) */
    262
                int32_t fs_postblformat;
                                                /* format of positional layout tables */
                int32_t fs_nrpos;
                                                /* number of rotational positions */
    263
                int32_t fs_postbloff;
    264
                                                /* (u_int16) rotation block list head */
    265
                int32_t fs_rotbloff;
                                                /* (u_int8) blocks for each rotation */
    266
                int32_t fs_magic;
                                                /* magic number */
                                                /* list of blocks for each rotation */
    267
                u_int8_t fs_space[1];
    268 /* actually longer */
--- ufs/ffs/fs.h
     71 /* This structure describes the UFS specific mount structure data. */
     72 struct ufsmount {
     73
                struct mount *um_mountp;
                                                        /* filesystem vfs structure */
     74
                                                        /* device mounted */
                dev_t um_dev;
     75
                struct vnode *um_devvp;
                                                        /* block device mounted vnode */
                                                        /* UFS-specific flags - see below
     76
                u_int32_t um_flags;
     77
                                                        /* pointer to superblock */
                union {
     78
                                                        /* FFS */
                        struct fs *fs;
     79
                        struct lfs *lfs;
                                                        /* LFS */
     80
                        struct m_ext2fs *e2fs; /* EXT2FS */
                } ufsmount_u;
     82 #define um_fs
                       ufsmount_u.fs
     83 #define um_lfs ufsmount_u.lfs
     84 #define um e2fs ufsmount u.e2fs
    85 #define um_e2fsb ufsmount_u.e2fs->s_es
    86
     87
                struct vnode *um_quotas[MAXQUOTAS];
                                                        /* pointer to quota files */
     88
                struct ucred *um_cred[MAXQUOTAS];
                                                        /* quota file access cred */
     89
                                                        /* indirect ptrs per block */
                u_long um_nindir;
     90
                u_long um_lognindir;
                                                        /* log2 of um_nindir */
     91
                u_long um_bptrtodb;
                                                        /* indir ptr to disk block */
                                                       /* inc between seq blocks */
     92
                u_long um_seqinc;
                time_t um_btime[MAXQUOTAS];
                                                       /* block quota time limit */
     93
     94
                time_t um_itime[MAXQUOTAS];
                                                       /* inode quota time limit */
     95
                char
                        um_qflags[MAXQUOTAS];
                                                       /* quota specific flags */
     96
                struct netexport um_export;
                                                       /* export information */
                                                       /* XXX - limit maxfilesize */
     97
                u_int64_t um_savedmaxfilesize;
```

98 }; --- ufs/ufsmount.h

- 11.3.5 Mount!
- 11.4 What Must Be Done after Mount?
- 11.4.1 Find vnode for '/' root directory
- 11.4.2 Set current working directory of init process
- 11.4.3 Check File System Time
- 11.4.4 Create Kernel Threads about File System
- 11.4.5 Start Up init processor

Part III Storage Systems

Chapter 12

Storage Device

In this chapter, we describes how we can manages to storage devices such as SCSI hard disk drives.

12.1 Generic Disk Framework

The NetBSD generic disk framework is designed to provide flexible, scalable, and consistent handling of disk state and metrics information.

12.1.1 disk Structure

The fundamental component of this framework is the disk structure, which is defined in as follows:

```
sys/disk.h
100 struct disk {
101
            TAILQ_ENTRY(disk) dk_link;
                                            /* link in global disklist */
102
            char
                            *dk_name;
                                            /* disk name */
                                            /* block devices open */
103
            int
                            dk_bopenmask;
104
            int
                            dk_copenmask;
                                            /* character devices open */
105
            int
                            dk_openmask;
                                            /* composite (bopen|copen) */
106
            int
                            dk_state;
                                            /* label state
                                                              ### */
                                            /* shift to convert DEV_BSIZE to blks */
107
                            dk_blkshift;
            int
                                            /* shift to convert bytes to blks */
108
            int
                            dk_byteshift;
109
110
            /*
             * Metrics data; note that some metrics may have no meaning
111
112
             * on certain types of disks.
             */
113
                                            /* busy counter */
114
            int
                            dk_busy;
                                            /* total number of read transfers */
115
            u_int64_t
                            dk_rxfer;
116
            u_int64_t
                            dk_wxfer;
                                            /* total number of write transfers */
117
            u_int64_t
                            dk_seek;
                                            /* total independent seek operations */
                                            /* total bytes read */
            u_int64_t
                            dk_rbytes;
118
                                            /* total bytes written */
119
            u_int64_t
                            dk_wbytes;
120
            struct timeval dk_attachtime; /* time disk was attached */
                                            /* timestamp of last unbusy */
121
            struct timeval dk_timestamp;
122
            struct timeval dk_time;
                                            /* total time spent busy */
123
```

```
struct dkdriver *dk_driver;
                                            /* pointer to driver */
124
125
126
             * Disk label information. Storage for the in-core disk label
127
128
             * must be dynamically allocated, otherwise the size of this
129
             * structure becomes machine-dependent.
130
             */
                                                    /* sector containing label */
131
            daddr_t
                            dk_labelsector;
                                           /* label */
132
            struct disklabel *dk_label;
            struct cpu_disklabel *dk_cpulabel;
133
134 };
                                                        sys/disk.h
```

The system maintains a global linked-list of all disks attached to the system. This list, called disklist, may grow or shrink over time as disks are dynamically added and removed from the system. Drivers which currently make use of the detachment capability of the framework are the *ccd* and *vnd* pseudo-device drivers.

12.1.2 Disk Interfaces

<pre>disk_init()</pre>	Initialize the disklist and other data structures used by the framework. Called by main() before autoconfigu- ration.		
<pre>disk_attach()</pre>	Attach a disk; allocate storage for the disklabel, set the ''attached time'' timestamp, insert the disk into the disklist, and increment the system disk count.		
<pre>disk_detach()</pre>	Detach a disk; free storage for the disklabel, remove the disk from the disklist, and decrement the system disk count. If the count drops below zero, panic.		
disk_busy()	Increment the disk's 'busy counter'. If this counter goes from 0 to 1, set the timestamp corresponding to this transfer.		
disk_unbusy()	Decrement a disk's busy counter. If the count drops below zero, panic. Get the current time, subtract it from the disk's timestamp, and add the difference to the disk's running total. Set the disk's timestamp to the current time. If the provided byte count is greater than 0, add it to the disk's running total and increment the number of transfers performed by the disk.		
<pre>disk_resetstat()</pre>	Reset the running byte, transfer, and time totals.		
<pre>disk_find()</pre>	Return a pointer to the disk structure corresponding to the name provided, or NULL if the disk does not exist.		

disk_attach function

 kern,	$^{\prime} m disk_subr.c$

```
206 /*
207 * Attach a disk.
208 */
209 void
210 disk_attach(struct disk *diskp)
211 {
212
       int s;
213
214
       * Allocate and initialize the disklabel structures. Note that
215
216
        * it's not safe to sleep here, since we're probably going to be
217
        * called during autoconfiguration.
218
        diskp->dk_label = malloc(sizeof(struct disklabel), M_DEVBUF, M_NOWAIT);
219
220
        diskp->dk_cpulabel = malloc(sizeof(struct cpu_disklabel), M_DEVBUF,
221
            M_NOWAIT);
222
       if ((diskp->dk_label == NULL) || (diskp->dk_cpulabel == NULL))
223
           panic("disk_attach: can't allocate storage for disklabel");
224
225
        memset(diskp->dk_label, 0, sizeof(struct disklabel));
226
       memset(diskp->dk_cpulabel, 0, sizeof(struct cpu_disklabel));
227
228
       /*
229
        * Set the attached timestamp.
230
        */
231
       s = splclock();
232
       diskp->dk_attachtime = mono_time;
233
       splx(s);
234
235
236
        * Link into the disklist.
237
238
       simple_lock(&disklist_slock);
239
       TAILQ_INSERT_TAIL(&disklist, diskp, dk_link);
240
        simple_unlock(&disklist_slock);
241
       ++disk_count;
242 }
                                                  kern/disk_subr.c
```

disk_busy function

```
267 /*
268 * Increment a disk's busy counter. If the counter is going from
269 * 0 to 1, set the timestamp.
270 */
271 void
272 disk_busy(struct disk *diskp)
273 {
274   int s;
275
276   /*
277   * XXX We'd like to use something as accurate as microtime(),
```

```
278  * but that doesn't depend on the system TOD clock.
279  */
280  if (diskp->dk_busy++ == 0) {
281     s = splclock();
282     diskp->dk_timestamp = mono_time;
283     splx(s);
284  }
285 }
```

disk_unbusy function

```
287 /*
288 * Decrement a disk's busy counter, increment the byte count, total busy
289 * time, and reset the timestamp.
290 */
291 void
292 disk_unbusy(struct disk *diskp, long bcount, int read)
293 {
294
        int s;
295
        struct timeval dv_time, diff_time;
296
        if (diskp->dk_busy-- == 0) {
297
298
            printf("%s: dk_busy < 0\n", diskp->dk_name);
299
            panic("disk_unbusy");
300
301
302
        s = splclock();
303
        dv_time = mono_time;
304
        splx(s);
305
306
        timersub(&dv_time, &diskp->dk_timestamp, &diff_time);
307
        timeradd(&diskp->dk_time, &diff_time, &diskp->dk_time);
308
309
        diskp->dk_timestamp = dv_time;
        if (bcount > 0) {
310
311
            if (read) {
312
                diskp->dk_rbytes += bcount;
                diskp->dk_rxfer++;
313
314
            } else {
315
                diskp->dk_wbytes += bcount;
316
                diskp->dk_wxfer++;
317
            }
318
        }
319 }
```

disk_unbusy function

```
244 /*
245 * Detach a disk.
246 */
247 void
248 disk_detach(struct disk *diskp)
249 {
250
             /*
251
252
             * Remove from the disklist.
253
             */
            if (--disk_count < 0)</pre>
254
255
                     panic("disk_detach: disk_count < 0");</pre>
256
            simple_lock(&disklist_slock);
257
            TAILQ_REMOVE(&disklist, diskp, dk_link);
258
            simple_unlock(&disklist_slock);
259
260
261
             * Free the space used by the disklabel structures.
262
263
            free(diskp->dk_label, M_DEVBUF);
264
            free(diskp->dk_cpulabel, M_DEVBUF);
265 }
```

12.1.3 Using the Framework

This section includes a description on basic use of the framework and example usage of its functions. Actual implementation of a device driver which utilizes the framework may vary.

A special routine, disk_init, is provided to perform basic initialization of data structures used by the framework. It is called exactly once by the system, in main function, before device autoconfiguration.

Attaching

Each device in the system uses a "softc" structure which contains autoconfiguration and state information for that device. In the case of disks, the softc should also contain one instance of the disk structure, e.g.:

In order for the system to gather metrics data about a disk, the disk must be registered with the system. The disk_attach routine performs all of the functions currently required to register a disk with the system including allocation of disklabel storage space, recording of the time since boot that the disk was attached, and insertion into the disklist. Note that since this function allocates storage space for the disklabel, it must be called before the disklabel is read from the media or used in any other way. Before disk_attach is called, a portions of the disk structure must be initialized with data specific to that disk. For example, in the "foo" disk driver, the following would be performed in the autoconfiguration "attach" routine:

The foodkdriver above is the disk's "driver" switch. This switch currently includes a pointer to the disk's "strategy" routine. This switch needs to have global scope and should be initialized as follows:

```
void foostrategy(struct buf *);
struct dkdriver foodkdriver = { foostrategy };
```

Gathering Metrics during Disk Operations

Once the disk is attached, metrics may be gathered on that disk. In order to gather metrics data, the driver must tell the framework when the disk starts and stops operations. This functionality is provided by the disk_busy and disk_unbusy routines. The disk_busy routine should be called immediately before a command to the disk is sent, e.g.:

When disk_busy is called, a timestamp is taken if the disk's busy counter moves from 0 to 1, indicating the disk has gone from an idle to non-idle state. Note that disk_busy must be called at splbio(). At the end of a transaction, the disk_unbusy routine should be called. This routine performs some consistency checks, such as ensuring that the calls to disk_busy and disk_unbusy are balanced. This routine

12.2. DISK LABEL 267

also performs the actual metrics calculation. A timestamp is taken, and the difference from the timestamp taken in disk_busy is added to the disk's total running time. The disk's timestamp is then updated in case there is more than one pending transfer on the disk. A byte count is also added to the disk's running total, and if greater than zero, the number of transfers the disk has performed is incremented.

```
void
foodone(xfer)
        struct foo_xfer *xfer;
        struct foo_softc = (struct foo_softc *)xfer->xf_softc;
        struct buf *bp = xfer->xf_buf;
        long nbytes;
        [ \ldots ]
        /*
         * Get number of bytes transfered. If there is no buf
         * associated with the xfer, we are being called at the
         * end of a non-I/O command.
         */
        if (bp == NULL)
                nbytes = 0;
        else
                nbytes = bp->b_bcount - bp->b_resid;
        [ . . . ]
        /* Notify the disk framework that we've completed the transfer. */
        disk_unbusy(&sc->sc_dk, nbytes);
        [ . . . ]
}
```

Like disk_busy, disk_unbusy must be called at splbio().

At some point a driver may wish to reset the metrics data gathered on a particular disk. For this function, the disk_resetstat routine is provided.

12.2 Disk Label

12.2.1 What does it have?

Each disk or disk pack on a system may contain a disk label which provides detailed information about

- the geometry of the disk and
- the partitions into which the disk is divided.

It should be initialized when the disk is formatted, and may be changed later with the disklabel(8) pro- gram.

This information is used by

- the system disk driver and
- by the bootstrap program to determine how to program the drive and where to find the filesystems on the disk partitions.

• Additional information is used by the filesystem in order to use the disk most efficiently and to locate important filesystem information.

The description of each partition contains an identifier for the partition type (standard filesystem, swap area, etc.). The filesystem updates the in-core copy of the label if it contains incomplete information about the filesystem.

12.2.2 disklabel structure

```
sys/disklabel.h
 98 struct disklabel {
                                             /* the magic number */
99
            u_int32_t d_magic;
100
            u_int16_t d_type;
                                             /* drive type */
101
            u_int16_t d_subtype;
                                             /* controller/d_type specific */
                      d_typename[16];
102
            char
                                             /* type name, e.g. "eagle" */
103
104
            /*
105
             * d_packname contains the pack identifier and is returned when
             * the disklabel is read off the disk or in-core copy.
106
107
             * d_boot0 and d_boot1 are the (optional) names of the
             \ast primary (block 0) and secondary (block 1-15) bootstraps
108
             * as found in /usr/mdec. These are returned when using
109
             * getdiskbyname(3) to retrieve the values from /etc/disktab.
110
111
             */
112
            union {
113
                    char
                            un_d_packname[16];
                                                     /* pack identifier */
114
                    struct {
115
                            char *un_d_boot0;
                                                     /* primary bootstrap name */
                                                     /* secondary bootstrap name */
116
                            char *un_d_boot1;
117
                    } un_b;
118
            } d_un;
119 #define d_packname
                            d_un.un_d_packname
                            d_un.un_b.un_d_boot0
120 #define d_boot0
121 #define d_boot1
                            d_un.un_b.un_d_boot1
122
123
                            /* disk geometry: */
124
            u_int32_t d_secsize;
                                            /* # of bytes per sector */
            u_int32_t d_nsectors;
                                            /* # of data sectors per track */
125
            u_int32_t d_ntracks;
                                            /* # of tracks per cylinder */
126
            u_int32_t d_ncylinders;
                                            /* # of data cylinders per unit */
127
128
            u_int32_t d_secpercyl;
                                            /* # of data sectors per cylinder */
            u_int32_t d_secperunit;
                                            /* # of data sectors per unit */
129
130
131
132
             * Spares (bad sector replacements) below are not counted in
133
             * d_nsectors or d_secpercyl. Spare sectors are assumed to
134
             * be physical sectors which occupy space at the end of each
135
             * track and/or cylinder.
136
             */
137
            u_int16_t d_sparespertrack;
                                             /* # of spare sectors per track */
138
            u_int16_t d_sparespercyl;
                                             /* # of spare sectors per cylinder */
139
            /*
140
             * Alternative cylinders include maintenance, replacement,
             * configuration description areas, etc.
141
```

```
142
            u_int32_t d_acylinders;
                                          /* # of alt. cylinders per unit */
143
144
145
                            /* hardware characteristics: */
146
147
             * d_interleave, d_trackskew and d_cylskew describe perturbations
148
             * in the media format used to compensate for a slow controller.
             * Interleave is physical sector interleave, set up by the
149
150
             * formatter or controller when formatting. When interleaving is
             * in use, logically adjacent sectors are not physically
151
152
             * contiguous, but instead are separated by some number of
             * sectors. It is specified as the ratio of physical sectors
153
154
             * traversed per logical sector. Thus an interleave of 1:1
            * implies contiguous layout, while 2:1 implies that logical
155
            * sector 0 is separated by one sector from logical sector 1.
156
157
            * d_{trackskew} is the offset of sector 0 on track N relative to
158
             * sector 0 on track N-1 on the same cylinder. Finally, d_cylskew
159
             st is the offset of sector 0 on cylinder N relative to sector 0
160
             * on cylinder N-1.
161
             */
162
            u_int16_t d_rpm;
                                            /* rotational speed */
            u_int16_t d_interleave;
                                           /* hardware sector interleave */
163
                                           /* sector 0 skew, per track */
            u_int16_t d_trackskew;
164
                                           /* sector 0 skew, per cylinder */
165
            u_int16_t d_cylskew;
           u_int32_t d_headswitch;
                                           /* head switch time, usec */
166
167
           u_int32_t d_trkseek;
                                           /* track-to-track seek, usec */
168
            u_int32_t d_flags;
                                           /* generic flags */
169 #define NDDATA 5
            u_int32_t d_drivedata[NDDATA]; /* drive-type specific information */
170
171 #define NSPARE 5
          u_int32_t d_spare[NSPARE];
                                            /* reserved for future use */
172
173
           u_int32_t d_magic2;
                                            /* the magic number (again) */
174
                                           /* xor of data incl. partitions */
           u_int16_t d_checksum;
175
176
                            /* filesystem and partition information: */
177
           u_int16_t d_npartitions;
                                          /* number of partitions in following */
178
            u_int32_t d_bbsize;
                                           /* size of boot area at sn0, bytes */
179
           u_int32_t d_sbsize;
                                           /* max size of fs superblock, bytes */
            struct partition {
                                           /* the partition table */
180
181
                   u_int32_t p_size;
                                          /* number of sectors in partition */
                                          /* starting sector */
182
                    u_int32_t p_offset;
183
                    union {
                            u_int32_t fsize; /* FFS, ADOS:
184
185
                                                filesystem basic fragment size */
186
                            u_int32_t cdsession; /* ISO9660: session offset */
187
                    } __partition_u2;
                           __partition_u2.fsize
188 #define p_fsize
189 #define p_cdsession
                            __partition_u2.cdsession
                    u_int8_t p_fstype;
                                           /* filesystem type, see below */
190
191
                                           /* filesystem fragments per block */
                    u_int8_t p_frag;
                    union {
192
193
                            u_int16_t cpg; /* UFS: FS cylinders per group */
194
                            u_int16_t sgs; /* LFS: FS segment shift */
195
                    } __partition_u1;
```

and machine dependent definition in sparc64 architecture is,

12.2.3 Where is the Disk Label?

The label is located in sector number LABELSECTOR of the drive, usually sector 0 where it may be found without any information about the disk ge- ometry. It is at an offset LABELOFFSET from the beginning of the sector, to allow room for the initial bootstrap. The disk sector containing the label is normally made read-only so that it is not accidentally overwrit- ten by pack-to-pack copies or swap operations; the DIOCWLABEL ioctl(2), which is done as needed by the disklabel(8) program.

 ${\tt LABELSECTOR} \ {\tt and} \ {\tt LABELOFFSET} \ {\tt macros} \ {\tt are} \ {\tt machine-dependent} \ {\tt parameter} \ {\tt and} \ {\tt defined} \ {\tt in} \ {\tt arch/sparc64/include/disklabel.h} \ {\tt as}$

```
-- arch/sparc64/include/disklabel.h
      1 /*
                  $NetBSD: disklabel.h,v 1.2 2002/07/20 11:52:21 mrg Exp $
      2
      3 #include <sparc/disklabel.h>
                                          -- arch/sparc64/include/disklabel.h
where arch/sparc/include/disklabel.h is
                                             - arch/sparc/include/disklabel.h
     36 #define LABELSECTOR
                                  0
                                                           /* sector containing label */
     37 #define LABELOFFSET
                                  128
                                                           /* offset of label in sector */
     38 #define MAXPARTITIONS
                                                           /* number of partitions */
                                  8
     39 #define RAW_PART
                                                           /* raw partition: xx?c */
     40
     41 struct cpu_disklabel {
     42
                         cd_block[512];
                char
     43 };
                                            - arch/sparc/include/disklabel.h
```

12.2.4 General Disk Label Interfaces

```
/* get and set disklabel; DIOCGPART used internally */

DIOCGDINFO _IOR('d', 101, struct disklabel) /* get */
DIOCSDINFO _IOW('d', 102, struct disklabel) /* set */
DIOCWDINFO _IOW('d', 103, struct disklabel) /* set, update disk */
DIOCGPART _IOW('d', 104, struct partinfo) /* get partition */

/* do format operation, read or write */

DIOCRFORMAT _IOWR('d', 105, struct format_op)
_IOWR('d', 106, struct format_op)
```

12.2. DISK LABEL 271

```
_IOW('d', 107, int)
                                               /* set step rate */
DIOCSSTEP
                _IOW('d', 108, int)
                                               /* set # of retries */
DIOCSRETRIES
                _IOW('d', 119, int)
                                                /* keep/drop label on close? */
DIOCKLABEL
DIOCWLABEL
                _IOW('d', 109, int)
                                                /* write en/disable label */
DIOCSBAD
                _IOW('d', 110, struct dkbad)
                                                /* set kernel dkbad */
                _IOW('d', 112, int)
                                                /* eject removable disk */
DIOCEJECT
ODIOCEJECT
                _IO('d', 112)
                                                /* eject removable disk */
                _IOW('d', 113, int)
DIOCLOCK
                                                /* lock/unlock pack */
                /* get default label, clear label */
DIOCGDEFLABEL
                _IOR('d', 114, struct disklabel)
                _IO('d', 115)
DIOCCLRLABEL
                /* disk cache enable/disable */
DIOCGCACHE
                _IOR('d', 116, int)
                                                /* get cache enables */
                _IOW('d', 117, int)
                                                /* set cache enables */
DIOCSCACHE
DKCACHE_READ
                0x000001
                                                /* read cache enabled */
DKCACHE_WRITE
                                                /* write(back) cache enabled */
                0x000002
                                                /* read enable is changeable */
DKCACHE_RCHANGE 0x000100
DKCACHE_WCHANGE 0x000200
                                                /* write enable is changeable */
DKCACHE_SAVE
                0x010000
                                    /* cache parameters are savable/save them */
                /* sync disk cache */
#define DIOCCACHESYNC
                        _IOW('d', 118, int)
                                              /* sync cache (force?) */
```

Terms

in-core label: The content of disklabel which is read in memory.

on-disk label: The actual disklabel stored in storage device.

12.2.5 Reading Diak Label: DIOCGDINFO

A copy of the in-core label for a disk can be obtained with the DIOCGDINFO ioctl(2); this works with a file descriptor for a block or character ("raw") device for any partition of the disk.

Reading in-core label means that the contents are not directly from storage device, but from the kernel structure which is filled when the storage device drive attaches the disk at the initial configuration stage.

```
dev/scsipi/sd.c
896 /*
897 * Perform special action on behalf of the user
898 * Knows about the internals of this device
899 */
900 int
901 sdioctl(dev, cmd, addr, flag, p)
902 dev_t dev;
```

```
903
        u_long cmd;
904
        caddr_t addr;
905
        int flag;
906
        struct proc *p;
907 {
908
        struct sd_softc *sd = sd_cd.cd_devs[SDUNIT(dev)];
909
        struct scsipi_periph *periph = sd->sc_periph;
        int part = SDPART(dev);
910
        int error;
911
        switch (cmd) {
946
        case DIOCGDINFO:
947
948
            *(struct disklabel *)addr = *(sd->sc_dk.dk_label);
949
            return (0);
                                                       dev/scsipi/sd.c
```

Writing In-Core Disk Label: DIOCSDINFO 12.2.6

The in-core copy of the label is set by the DIOCSDINFO ioctl(2).

The kernel device drivers will not allow the size of a disk partition to be decreased or the offset of a partition to be changed while it is open. Some device drivers create a label containing only a single large partition if a disk is unlabeled; thus, the label must be written to the "a" partition of the disk while it is open. This sometimes requires the de- sired label to be set in two steps, the first one creating at least one other partition, and the second setting the label on the new partition while shrinking the "a" partition.

12.2.7Writing On-Disk Disk Label: DIOCWDINFO

Finally, the DIOCWDINFO ioctl(2) operation sets the in-core label and then updates the on-disk label; there must be an existing label on the disk for this operation to succeed. Thus, the initial label for a disk or disk pack must be installed by writing to the raw disk. All of these operations are normally done using disklabel(8).

```
900 int
901 sdioctl(dev, cmd, addr, flag, p)
        dev_t dev;
902
903
        u_long cmd;
904
        caddr_t addr;
905
        int flag;
906
        struct proc *p;
907 {
908
        struct sd_softc *sd = sd_cd.cd_devs[SDUNIT(dev)];
909
        struct scsipi_periph *periph = sd->sc_periph;
910
        int part = SDPART(dev);
        int error;
911
        switch (cmd) {
946
966
        case DIOCWDINFO:
967
        case DIOCSDINFO:
```

12.2. DISK LABEL 273

```
972
           {
   973
               struct disklabel *lp;
   982
               lp = (struct disklabel *)addr;
   983
   984
               if ((flag & FWRITE) == 0)
                   return (EBADF);
   985
   986
               if ((error = sdlock(sd)) != 0)
   987
   988
                   return (error);
   989
               sd->flags |= SDF_LABELLING;
   990
   991
               error = setdisklabel(sd->sc_dk.dk_label,
   992
                   lp, /*sd->sc_dk.dk_openmask : */0,
   993
                    sd->sc_dk.dk_cpulabel);
   994
               if (error == 0) {
                   if (cmd == DIOCWDINFO)
   995
                        error = writedisklabel(SDLABELDEV(dev),
  1000
  1001
                            sdstrategy, sd->sc_dk.dk_label,
  1002
                            sd->sc_dk.dk_cpulabel);
               }
  1003
               sd->flags &= ~SDF_LABELLING;
  1005
               sdunlock(sd);
  1006
  1007
               return (error);
  1008
. . . . .
```

where sdlock and sdunlock is defined as

```
322 /*
323 * Wait interruptibly for an exclusive lock.
324 *
325 * XXX
326 * Several drivers do this; it should be abstracted and made MP-safe.
327 */
328 int
329 sdlock(sd)
330
       struct sd_softc *sd;
331 {
332
       int error;
333
334
       while ((sd->flags & SDF_LOCKED) != 0) {
335
            sd->flags |= SDF_WANTED;
336
            if ((error = tsleep(sd, PRIBIO | PCATCH, "sdlck", 0)) != 0)
               return (error);
337
       }
338
339
       sd->flags |= SDF_LOCKED;
340
       return (0);
341 }
```

```
342
343 /*
344 * Unlock and wake up any waiters.
345 */
346 void
347 sdunlock(sd)
348
        struct sd_softc *sd;
349 {
350
351
        sd->flags &= ~SDF_LOCKED;
        if ((sd->flags & SDF_WANTED) != 0) {
352
            sd->flags &= ~SDF_WANTED;
353
354
            wakeup(sd);
355
356 }
```

12.2.8 Restrictions of Disk Label in sparc64

On the sparc, sparc64, sun2 and sun3 NetBSD systems, the size of each partition must be a multiple of the number of sectors per cylinder (i.e. each partition must be an integer number of cylinders), or the boot ROMs will declare the label invalid and fail to boot the system.

If the disk partition is not specified in the disk name (i.e. "xy0" instead of "/dev/rxy0c"), disklabel will construct the full pathname of the disk and use the "a" partition on the tahoe, the "d" partition on i386 or hpcmips or arc, and the "c" partition on all others including sparc64.

On some machines the bootstrap code may not fit entirely in the area allocated for it by some filesystems. As a result, it may not be possible to have filesystems on some partitions of a "bootable" disk. When in-stalling bootstrap code, disklabel checks for these cases. If the in-stalled boot code would overlap a partition of type FS_UNUSED it is marked as type FS_BOOT. The newfs(8) utility will disallow creation of filesystems on FS_BOOT partitions. Conversely, if a partition has a type other than FS_UNUSED or FS_BOOT, disklabel will not install bootstrap code that overlaps it.

12.3 Concatenated Disk Driver

12.3.1 Strcture

```
struct ccdbuf {
                                         /* new I/O buf */
        struct buf
                        cb_buf;
                                         /* ptr. to original I/O buf */
        struct buf
                        *cb_obp;
                                         /* pointer to ccd softc */
        struct ccd_softc *cb_sc;
                                         /* target component */
        int
                        cb_comp;
                                        /* fifo of component buffers */
        SIMPLEQ_ENTRY(ccdbuf) cb_q;
};
/*
 * This structure is used to configure a ccd via ioctl(2).
struct ccd_ioctl {
                **ccio_disks;
                                         /* pointer to component paths */
        char
                                         /* number of disks to concatenate */
        u_int
                ccio_ndisks;
```

```
/* interleave (DEV_BSIZE blocks) */
              ccio_ileave;
                                     /* see sc_flags below */
       int
              ccio_flags;
                                     /* unit number: use varies */
               ccio_unit;
       int
                                     /* (returned) size of ccd */
       size_t ccio_size;
};
/*
 * Component info table.
* Describes a single component of a concatenated disk.
 */
struct ccdcinfo {
                     *ci_vp;
                                             /* device's vnode */
       struct vnode
               ci_dev;
                                            /* XXX: device's dev_t */
       dev_t
                     ci_size;
                                            /* size */
       size_t
                                            /* path to component */
       char
                     *ci_path;
       size_t
                     ci_pathlen;
                                            /* length of component path */
};
/*
 * Interleave description table.
* Computed at boot time to speed irregular-interleave lookups.
* The idea is that we interleave in "groups". First we interleave
 * evenly over all component disks up to the size of the smallest
 * component (the first group), then we interleave evenly over all
 * remaining disks up to the size of the next-smallest (second group),
 * and so on.
 * Each table entry describes the interleave characteristics of one
 st of these groups. For example if a concatenated disk consisted of
 * three components of 5, 3, and 7 DEV_BSIZE blocks interleaved at
 * DEV_BSIZE (1), the table would have three entries:
       ndisk startblk
                              startoff
       3
                                             0, 1, 2
               Ω
                              0
       2
                                             0, 2
               9
                              3
       1
               13
                              5
                                              2
 * which says that the first nine blocks (0-8) are interleaved over
 * 3 disks (0, 1, 2) starting at block offset 0 on any component disk,
 * the next 4 blocks (9-12) are interleaved over 2 disks (0, 2) starting
 * at component block 3, and the remaining blocks (13-14) are on disk
 * 2 starting at offset 5.
struct ccdiinfo {
       int ii_ndisk;
                              /* # of disks range is interleaved over */
       daddr_t ii_startblk; /* starting scaled block # for range */
       daddr_t ii_startoff; /* starting component offset (block #) */
             *ii_index;
                              /* ordered list of components in range */
};
 * Concatenated disk pseudo-geometry information.
 */
```

```
struct ccdgeom {
                                     /* # bytes per sector */
       u_int32_t
                      ccg_secsize;
                      ccg_nsectors; /* # data sectors per track */
       u_int32_t
       u_int32_t
                      ccg_ntracks;
                                      /* # tracks per cylinder */
       u_int32_t
                      ccg_ncylinders; /* # cylinders per unit */
};
struct ccdbuf;
* A concatenated disk is described after initialization by this structure.
*/
struct ccd_softc {
       int
                       sc_flags;
                                             /* flags */
                                             /* size of ccd */
       size_t
                       sc_size;
       int
                      sc_ileave;
                                             /* interleave */
                      sc_nccdisks;
                                             /* number of components */
       u\_int
#define CCD_MAXNDISKS 65536
       struct ccdcinfo *sc_cinfo;
                                             /* component info */
       struct ccdiinfo *sc_itable;
                                             /* interleave table */
                                             /* pseudo geometry info */
       struct ccdgeom sc_geom;
                                            /* XXX external name */
                    sc_xname[8];
       char
       struct disk sc_dkdev;
struct lock sc_lock;
                                             /* generic disk device info */
                                             /* lock on this structure */
};
```

12.3.2 Gloval Variables

12.3.3 Functions

```
[ Common Device Driver Entry ]
int ccdopen (dev_t dev, int flags, int fmt, struct proc *p);
int ccdclose (dev_t dev, int flags, int fmt, struct proc *p);
int ccdioctl (dev_t dev, u_long cmd, caddr_t data, int flag, struct proc *p);
[ Block Device Driver Entry ]

void ccdstrategy (struct buf *bp);
int ccdsize (dev_t dev);
```

```
ccddump
                  (dev_t dev, daddr_t blkno, caddr_t va, size_t size);
int
[ Character Device Driver Entry ]
     ccdread
                  (dev_t dev, struct uio *uio, int flags);
int
      ccdwrite
                  (dev_t dev, struct uio *uio, int flags);
[ Device Driver Autoconfiguration ]
void ccdattach
                  (int num);
[ Sub-function ]
ccdinit
                        used by ccdioctl() - CCDIOCSET
ccdinterleave
                        used by ccdinit()
ccdstart
                        used by ccdstrategy()
ccdbuffer
                        used by ccdstart()
ccdintr
                        used by ccdiodone()
ccdiodone
                        used by biodone() which is called by ccdintr()
ccdlookup
                        used by ccdioctl() - CCDIOCSET
ccdgetdefaultlabel
                        used by ccdgetdisklabel(), ccdioctl() - DIOCGDEFLABEL
ccdgetdisklabel
                        used by ccdopen(), ccdioctl() - DIOCSET
ccdmakedisklabel
                        used by ccdgetdisklabel()
```

Chapter 13

Logical Volume Manager

RAIDframe is a kind of Logical Volume Manager not included in NetBSD/sparc64. In this chapter, we describes other logical volume manager, such as VERITAS Volume Manager 3.1 under HP-UX 11i, and LVM under HP-UX 10.

13.1 RAIDframe

13.1.1 Introduction

The raid driver provides RAID 0, 1, 4, and 5 (and more!) capabilities to NetBSD. This document assumes that the reader has at least some famil-iarity with RAID and RAID concepts. The reader is also assumed to know how to configure disks and pseudo-devices into kernels, how to generate kernels, and how to partition disks.

RAIDframe provides a number of different RAID levels including:

- ${\tt RAID}\ {\tt O}\ \ {\tt provides}\ {\tt simple}\ {\tt data}\ {\tt striping}\ {\tt across}\ {\tt the}\ {\tt components}.$
- RAID 1 provides mirroring.
- RAID 4 provides data striping across the components, with parity stored on a dedicated drive (in this case, the last component).
- RAID 5 provides data striping across the components, with parity distributed across all the components.

There are a wide variety of other RAID levels supported by RAIDframe, in-cluding Even-Odd parity, RAID level 5 with rotated sparing, Chained declustering, and Interleaved declustering. The reader is referred to the RAIDframe documentation mentioned in the HISTORY section for more detail on these various RAID configurations.

Depending on the parity level configured, the device driver can support the failure of component drives. The number of failures allowed depends on the parity level selected. If the driver is able to handle drive failures, and a drive does fail, then the system is operating in "degraded mode". In this mode, all missing data must be reconstructed from the data and parity present on the other components. This results

in much slower data accesses, but does mean that a failure need not bring the system to a complete halt.

13.1.2 Component Labels

The RAID driver supports and enforces the use of 'component labels'. A 'component label' contains important information about the component, in-cluding a user-specified serial number, the row and column of that component in the RAID set, and whether the data (and parity) on the component is 'clean'. If the driver determines that the labels are very inconsis-tent with respect to each other (e.g. two or more serial numbers do not match) or that the component label is not consistent with it's assigned place in the set (e.g. the component label claims the component should be the 3rd one a 6-disk set, but the RAID set has it as the 3rd component in a 5-disk set) then the device will fail to configure. If the driver de-termines that exactly one component label seems to be incorrect, and the RAID set is being configured as a set that supports a single failure, then the RAID set will be allowed to configure, but the incorrectly la-beled component will be marked as 'failed', and the RAID set will begin operation in degraded mode. If all of the components are consistent among themselves, the RAID set will configure normally.

Component labels are also used to support the auto-detection and auto-configuration of RAID sets. A RAID set can be flagged as auto-config-urable, in which case it will be configured automatically during the ker-nel boot process. RAID filesystems which are automatically configured are also eligible to be the root filesystem. There is currently only limited support (alpha and pmax architectures) for booting a kernel directly from a RAID 1 set, and no support for booting from any other RAID sets. To use a RAID set as the root filesystem, a kernel is usually ob-tained from a small non-RAID partition, after which any auto-configuring RAID set can be used for the root filesystem.

13.1.3 Hot Spares

The driver supports 'hot spares', disks which are on-line, but are not actively used in an existing filesystem. Should a disk fail, the driver is capable of reconstructing the failed disk onto a hot spare or back on-to a replacement drive. If the components are hot swapable, the failed disk can then be removed, a new disk put in its place, and a copyback operation performed. The copyback operation, as its name indicates, will copy the reconstructed data from the hot spare to the previously failed (and now replaced) disk. Hot spares can also be hot-added.

13.1.4 Hierarchical Organization

If a component cannot be detected when the RAID device is configured, that component will be simply marked as 'failed'. The user-land utility for doing all raid configuration and other opera-tions is raidctl command. Most importantly, raidctl command must be used with the -i option to initialize all RAID sets. In particular, this initialization

includes re-building the parity data. This rebuilding of parity data is also required when either a) a new RAID device is brought up for the first time or b) after an unclean shutdown of a RAID device. By using the -P option to raidctl command, and performing this on-demand recomputation of all parity before doing a fsck command or a newfs command, filesystem integrity and parity integrity can be ensured. It bears repeating again that parity recomputation is required before any filesystems are created or used on the RAID device. If the parity is not correct, then missing data cannot be correctly recovered.

RAID levels may be combined in a hierarchical fashion. For example, a RAID 0 device can be constructed out of a number of RAID 5 devices (which, in turn, may be constructed out of the physical disks, or of other RAID devices).

13.1.5 Kernel Configuration

It is important that drives be hard-coded at their respective addresses (i.e. not left free-floating, where a drive with SCSI ID of 4 can end up as /dev/sd0c) for well-behaved functioning of the RAID device. This is true for all types of drives, including IDE, HP-IB, etc. For normal SCSI drives, for example, the following can be used to fix the device address-es:

```
at scsibus0 target 0 lun ?
                                        \# SCSI disk drives
sd1
        at scsibus0 target 1 lun ?
                                        \# SCSI disk drives
        at scsibus0 target 2 lun ?
                                        \# SCSI disk drives
sd2
        at scsibus0 target 3 lun ?
sd3
                                        \# SCSI disk drives
        at scsibus0 target 4 lun ?
                                        \# SCSI disk drives
sd4
sd5
        at scsibus0 target 5 lun ?
                                        \# SCSI disk drives
sd6
        at scsibus0 target 6 lun ?
                                        \# SCSI disk drives
```

The rationale for fixing the device addresses is as follows: Consider a system with three SCSI drives at SCSI ID's 4, 5, and 6, and which map to components /dev/sd0e, /dev/sd1e, and /dev/sd2e of a RAID 5 set. If the drive with SCSI ID 5 fails, and the system reboots, the old /dev/sd2e will show up as /dev/sd1e. The RAID driver is able to detect that component positions have changed, and will not allow normal configuration. If the device addresses are hard coded, however, the RAID driver would detect that the middle component is unavailable, and bring the RAID 5 set up in degraded mode. Note that the auto-detection and auto-configuration code does not care about where the components live. The auto-configuration code will correctly configure a device even after any number of the components have been rearranged.

The first step to using the raid driver is to ensure that it is suitably configured in the kernel. This is done by adding a line similar to:

```
pseudo-device raid 4 \# RAIDframe disk device
```

to the kernel configuration file. The 'count' argument ('4', in this case), specifies the number of RAIDframe drivers to configure. To turn on component auto-detection and auto-configuration of RAID sets, simply add:

options RAID_AUTOCONFIG

to the kernel configuration file.

All component partitions must be of the type FS_BSDFFS (e.g. 4.2BSD) or FS_RAID. The use of the latter is strongly encouraged, and is required if auto-configuration of the RAID set is desired. Since RAIDframe leaves room for disklabels, RAID components can be simply raw disks, or partitions which use an entire disk.

It is highly recommended that the steps to reconstruct, copyback, and re-compute parity are well understood by the system admin-istrators before a component failure. Doing the wrong thing when a component fails may result in data loss.

Additional internal consistency checking can be enabled by specifying:

options RAID_DIAGNOSTIC

These assertions are disabled by default in order to improve performance.

13.2 VERITAS Volume Manager

This section describes what VERITAS Volume Manager is, how it works, how you can communicate with it through the user interfaces, and Volume Manager concepts.

13.2.1 Introduction

Volume Manager provides easy-to-use online disk storage management for computing environments. Traditional disk storage management often requires that machines be taken off-line at a major inconvenience to users. In the distributed client/server environment, databases and other resources must maintain high availability, be easy to access, and be Volume Manager provides the tools to improve performance and ensure data availability and integrity. Volume Manager also dynamically configures disk storage while the system is active.

13.2.2 Volume Manager Overview

The Volume Manager uses objects to do storage management. The two types of objects used by Volume Manager are *physical objects* and *virtual objects*.

physical objects Volume Manager uses two physical objects: physical disks and partitions. Partitions are created on the physical disks

virtual objects Volume Manager creates virtual objects, called volumes. Each volume records and retrieves data from one or more physical disks. Volumes are accessed by a file system, a database, or other applications in the same way that physical disks are accessed. Volumes are also composed of other virtual objects that are used to change the volume configuration. Volumes and their virtual components are called virtual objects.

13.2.3 Physical Objects

A physical disk is the basic storage device (media) where the data is ultimately stored. You can access the data on a physical disk by using a device name (devname) to locate the disk. The physical disk device name varies with the computer system you use. Not all parameters are used on all systems. Typical device names can include: c#t#d#, where:

```
c\# is the controller
t\# is the target ID
d\# is the disk number
```

On some computer systems, a physical disk can be divided into one or more partitions. The partition number, or s#, is added at the end of the device name. Note that a partition can be an entire physical disk.

13.2.4 Volumes and Virtual Objects

Volume Manager creates virtual objects and makes logical connections between the objects. The *virtual objects* are then used by Volume Manager to do storage management tasks.

A *volume* is a virtual disk device that appears to applications, databases, and file systems as a physical disk. However, a volume does not have the limitations of a physical disk. When you use Volume Manager, applications access volumes created on Volume Manager disks (VM Disks) rather than physical disks.

Volume Manager Disks

When you place a physical disk under Volume Manager control, a *Volume Manager disk (or VM Disk)* is assigned to the physical disk. A VM Disk is under Volume Manager control and is usually in a disk group. Each VM disk corresponds to at least one physical disk. Volume Manager allocates storage from a contiguous area of Volume Manager disk space.

A VM disk typically includes a *public region* (allocated storage) and a *private region* where Volume Manager internal configuration information is stored.

Each VM Disk has a unique disk *media name* (a virtual disk name). You can supply the disk name or allow Volume Manager to assign a default name that typically takes the form disk##.

Disk Groups

A disk group is a collection of VM disks that share a common configuration. A disk group configuration is a set of records with detailed information about related Volume Manager objects, their attributes, and their connections. The default disk group is rootdg (the root disk group).

You can create additional disk groups as necessary. Disk groups allow the administrator to group disks into logical collections. A disk group and its components can be moved as a unit from one host machine to another.

Volumes are created within a disk group. A given volume must be configured from disks in the same disk group.

Subdisks

A *subdisk* is a set of contiguous disk blocks. A block is a unit of space on the disk. Volume Manager allocates disk space using subdisks. A VM disk can be divided

into one or more subdisks. Each subdisk represents a specific portion of a VM disk, which is mapped to a specific region of a physical disk.

The default name for a VM disk is disk## (such as disk01) and the default name for a subdisk is disk##-##.

A VM disk can contain multiple subdisks, but subdisks cannot overlap or share the same portions of a VM disk.

Any VM disk space that is not part of a subdisk is free space. You can use free space to create new subdisks.

Volume Manager release 3.0 or higher supports the concept of layered volumes in which subdisk objects can contain volumes. For more information, see "Layered Volumes".

Plexes

The Volume Manager uses subdisks to build virtual objects called plexes. A plex consists of one or more subdisks located on one or more physical disks.

You can organize data on the subdisks to form a plex by using these methods:

- concatenation
- striping (RAID-0)
- striping with parity (RAID-5)
- mirroring (RAID-1)

Volumes

A volume is a virtual disk device that appears to applications, databases, and file systems like a physical disk device, but does not have the physical limitations of a physical disk device. A volume consists of one or more plexes, each holding a copy of the selected data in the volume. Due to its virtual nature, a volume is not restricted to a particular disk or a specific area of a disk. The configuration of a volume can be changed by using the Volume Manager user interfaces. Configuration changes can be done without causing disruption to applications or file systems that are using the volume. For example, a volume can be mirrored on separate disks or moved to use different disk storage.

The Volume Manager uses the default naming conventions of vol## for volumes and vol##-## for plexes in a volume. Administrators must select meaningful names for their volumes.

A volume can consist of up to 32 plexes, each of which contains one or more subdisks. A volume must have at least one associated plex that has a complete set of the data in the volume with at least one associated subdisk. Note that all subdisks within a volume must belong to the same disk group.

Appendix

A. References to NetBSD Kernel Sources

```
src/syssrc/sys
                                       73,735 lines
           /kern .....
               /vfs_??? (VFS).....
                                       10,822 lines <<<<
                                       31,066 lines
           /sys .....
           /ufs
               38,381 lines
              /ufs .....
                                       6,975 lines <<<<
                                      12,970 lines
              /ffs .....
                                       6,639 lines <<<<
              /ffs (without softdep) ....
                                      10,529 lines
              /lfs .....
              /ext2fs .....
                                       6,994 lines
              /mfs .....
                                         912 lines
           /msdosfs .....
                                        7,832 lines
           /ntfs .....
                                        5,358 lines
           54,785 lines
               /sparc64 .....
                                       24,905 lines
           /uvm ......
           /net ......
                                       56,506 lines
                                       47,558 lines
           /netinet (IPv4) .....
           /netinet6 (IPv6) .....
                                       38,958 lines
                                      938,890 lines
           /dev .....
           /nfs .....
                                       23,235 lines
ultra1: {205} ls kern
CVS
                                makesyscalls.sh
                                                tty_conf.c
               kern_event.c
Make.tags.inc
               kern_exec.c
                                subr_autoconf.c
                                                tty_pty.c
Makefile
               kern exit.c
                                subr devsw.c
                                                tty_subr.c
                                subr_disk.c
cnmagic.c
               kern_fork.c
                                                tty_tb.c
core_elf32.c
               kern_kthread.c
                                subr_extent.c
                                                tty_tty.c
                                subr_log.c
core_elf64.c
               kern_ktrace.c
                                                uipc_domain.c
               kern_lkm.c
                                subr_pool.c
                                                uipc_mbuf.c
core_netbsd.c
exec_aout.c
               kern_lock.c
                                subr_prf.c
                                                uipc_mbuf2.c
exec_conf.c
               kern_malloc.c
                                subr_prof.c
                                                uipc_proto.c
exec_ecoff.c
               kern_malloc_debug.c subr_prop.c
                                                uipc_socket.c
exec_elf32.c
               kern_ntptime.c
                                subr_userconf.c
                                                uipc_socket2.c
exec_elf64.c
                                subr_xxx.c
               kern_physio.c
                                                uipc_syscalls.c
exec_elf_common.c
               kern_proc.c
                                sys_generic.c
                                                uipc_usrreq.c
exec_macho.c
               kern_prot.c
                                sys_pipe.c
                                                vfs_bio.c
exec_script.c
                                sys_pmc.c
                                                vfs_cache.c
               kern_ras.c
exec_subr.c
               kern_resource.c
                                sys_process.c
                                                vfs_getcwd.c
```

genassym.awk	kern_sig.c	sys_socket.c	vfs_init.c
genassym.sh	kern_subr.c	syscalls.c	vfs_lockf.c
genlintstub.awk	kern_synch.c	syscalls.conf	vfs_lookup.c
init_main.c	kern_sysctl.c	syscalls.master	vfs_subr.c
init_sysent.c	kern_systrace.c	sysv_ipc.c	vfs_syscalls.c
kern_acct.c	kern_time.c	sysv_msg.c	vfs_vnops.c
kern_allocsys.c	kern_verifiedexec.c	sysv_sem.c	<pre>vnode_if.c</pre>
kern_clock.c	kern_xxx.c	sysv_shm.c	vnode_if.sh
kern_descrip.c	kgdb_stub.c	tty.c	vnode_if.src

Bibliography

- [1] Marshall Kirk McKusick, Keith Bostic, Michael J. Karels, and John S. Quarterman, *The design and implementation of the 4.4BSD Operating System*, pp. 193-196, Addision Wesley, 1996.
- [2] Maurice J. Bach, *Design of the Unix Operating System*, pp. 46-56, Prentice Hall, 1986.
- [3] Chales D. Cranor, "The Design and Implementation of the UVM Virtual Mem-ory System", *Ph.D. Dissertation*, Department of Computer Science, Washington University, 1998.
- [4] Uresh Vahalia, UNIX internals: the new frontiers, Prentice Hall, 1996.
- [5] Chuck Silvers, UBC: An Efficient Unified I/O and Memory Caching Subsystem for NetBSD, i n Proceedings of USENIX Annual Technical Conference, June 2000, pp. 285-290.