Porting and Modifying the Mach 3.0 Microkernel

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Overview

Part I - Getting Started
- Source Code Layout
- Build Tools
- Miscellaneous routines
- Debugging

Part II - Virtual Memory
- Overview of Mach Virtual Memory
- The pmap module

Part III - Saving and Restoring State
- Kernel entry and Exit
- Traps, interrupts and system calls
- Continuations

Part IV - User Code
- Libmach
- Cthreads
- Emulator library
- BSD single server

Part I - Getting Started

Sources of Information

Source Code Layout

C Shell Tricks

Build Magic

Build Tools
- Config
- MiG - The Mach Interface Generator
- Makeboot

Getting Started

Kernel Bootstrap

Miscellaneous Routines

Debugging

Sources of Information

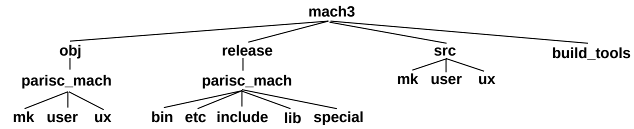
Technical questions
mach3@cs.cmu.edu
Read by CMU, OSF, and 300 other people
To be added contact mach3-request@cs.cmu.edu

Administrative questions
mach@cs.cmu.edu
Read by Mach distribution people

Documentation

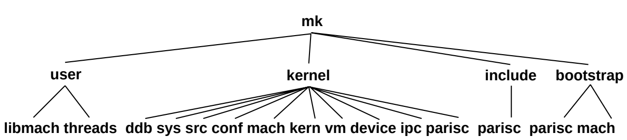
All documentation mentioned is available via anonymous ftp from mach.cs.cmu.edu in the *doc* directory

Source Code Layout



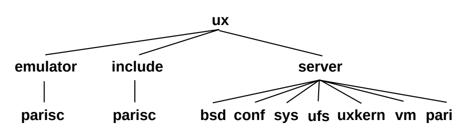
obj	mirror of src area where object files are placed
release	final release area
src	source area
build_tools	ode make, gcc, gmake
mk	micro kernel
user	mach user programs
ux	single server
parisc_mach	machine dependent area for Hewlett-Packard pa-risc machine

MK Source Code Layout



libmach	mach system call library
threads	C threads package
ddb	*Dave's* debugger
sys	various UNIX like include files
src	sources for config, makeboot, MiG...
conf	configuration information
mach	mach include files
kern	clock, syscalls, tasks, threads
vm	virtual memory
device	generic device routines
ipc	interprocess communications
bootstrap	out of kernel default pager
parisc	machine dependent code for Hewlett-Packard pa-risc machine

Single Server Code Layout



emulator	sources for emulation library
include	Makefiles for releasing include files
server	single server sources
bsd	bsd sources
conf	configuration files
sys	UNIX include files
ufs	UNIX file system
uxkern	Mach glue code
vm	virtual memory
parisc	machine dependent code for Hewlett-Packard pa-risc machine

C Shell Tricks

```
setenv M3BASE /usr0/bobw/M3
setenv M3SRC $M3BASE/src
setenv M3OBJ $M3BASE/obj/parisc_mach

alias ksrc cd $M3SRC/mk/kernel
alias ssrc cd $M3SRC/ux/server
alias esrc cd $M3SRC/ux/emulator
alias kobj cd $M3OBJ/mk/kernel
alias sobj cd $M3OBJ/ux/server
alias eobj cd $M3OBJ/ux/emulator

set cdpath=($M3SRC/mk \
    $M3SRC/mk/kernel \
    $M3SRC/ux \
    $M3SRC/ux/server \
    $M3SRC/ux/emulator)

setenv FAKE "-DKERNEL -I. -I.. \
-I$M3OBJ/mk/kernel/STD+ANY-debug"
```

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Strange and Mysterious Build Magic

setvar shell script
Sets environment variables for a specific machine

mk/Makeconf

Tells *make* where the object area is
MAKEOBJDIR
Tells *make* where the source area is
MAKESRCDIRPATH

See
Building Mach 3.0
Mary R.Thompson and Richard P. Draves
Available via anonymous ftp

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Kernel Build Tools

doconf
Reads *MASTER* configuration files and produces input for config

config
Generates include files and Makefile for building kernel

MiG
Mach interface generator, the IPC stub generator

makeboot
Binds a kernel and the default pager into a single bootable image

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Porting Config

Add configuration type to config.h

```
#define CONFTYPE_PARISC 18
```

Add test for configuration type in config.y

```
else if (!strcmp($2, "parisc")) {
    conftype = CONFTYPE_PARISC;
    conftypename = "parisc";
}
```

Add case in main.c

```
case CONFTYPE_PARISC:
    parisc_ioconf();
```

Add routine for ioconf.c in mkioconf.c

```
#ifdef CONFTYPE_PARISC
parisc_ioconf() {}
#endif /* CONFTYPE_PARISC */
```

Add users entry in mkmakefile.c

```
{ 32, 8, 1024 } /* CONFTYPE_PARISC */
```

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The MASTER files

- A simple way to specify configurations
- Read by doconf to create input to config

```
#
#         STD= [ hp700 scsi lan]
#         ANY= [ ]
#

conftype        "parisc"                # <hp700>
platform        HP700                   # <hp700>
config          mach_kernel

options         TRAP_COUNTERS           # <test>

device          sd0                     # <scsi>
device          sd1                     # <scsi>
device          sd2                     # <scsi>
device          sd3                     # <scsi>
device          lan                     # <lan>
pseudo-device   bpf        16           # <lan>
```


The files File

- Specifies options and files to config
- Paths are relative to mk/kernel

Syntax:

```
<OPTIONS | directory>filename \
      <optional opt | standard> \
      [device-driver] [ordered] [|compiler-options]
```

Example:

```
OPTIONS/trap_counters      optional trap_counters

parisc/locore.s            standard ordered
parisc/context.s           standard | -fvolatile
parisc/trap.c              standard
parisc/pmap.c              standard

parisc/sd.c                optional sd device-driver
parisc/lan.c               optional lan device-driver
parisc/bpf.c               optional bpf device-driver
```


Config Output

All output from config is in the object area

Makefile.internal

ioconf.c

platforms.h
    #define HP700 1

trap_counters.h
    #define TRAP_COUNTERS 0

sd.h
    #define NSD 4

lan.h
    #define NLAN 1

bpf.h
    #define NBPF 16

Specifying Options

Two ways to specify options

In MASTER file put in an options line
    options TRAP_COUNTERS #<hp700>

If there is an OPTIONS line in the files file
then config will produce an include file
    trap_counters.h
        #define TRAP_COUNTERS 1

Othewise config will add a -D to the compile line
    -DTRAP_COUNTERS

Use include files if the option will change

MiG - The Mach Interface Generator

Stub Generator for Mach IPC

Mig sources are in .defs files

Uses a PASCAL like syntax for historical reasons

Machine specifics gathered by include files
(Don't have to "port" Mig)

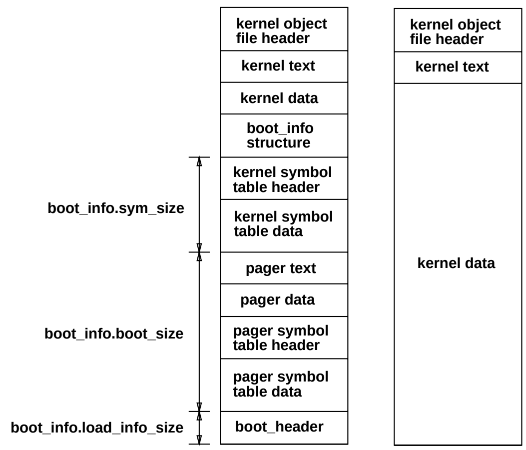
Most kernel MiG output is put in subdirectories in the object area. (include in etags)

Don't try and debug MiG, that's not the problem

Makeboot

Combines the kernel with the default pager into a single bootable image

At runtime move_bootstrap() moves pager out of kernel data area before the BSS section is cleared



Porting Makeboot and Bootstrap

off_t exec_header_size()
Routine to tell the size of the object file header

int ex_get_header(in_file, is_kernel, lp, sym_header, sym_header_size)
Routine to read the object file header

void write_exec_header(out_file, kp, file_size)
Routine to write the object file header

Bootstrap only needs to read the object file header code is very similar to ex_get_header()

Getting Started

Get build tools working

Fake include files

Fake configuration files

Fake genassym.c

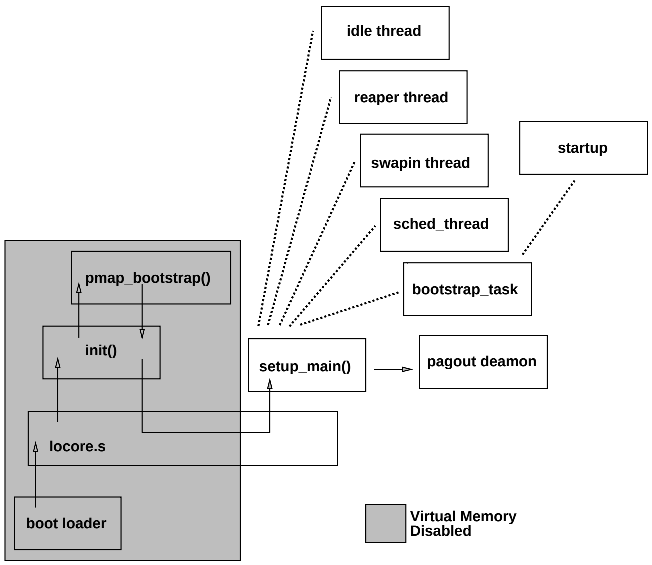
See what comes up undefined

Use grep and etags

Write small utilities like *findsym*

```
#!/bin/sh
for file in *.o;
do
echo $file
nm $file | grep $1
done
```

Kernel Bootstrap



Bootstrap Routines

locore
Establish a stack, initialize hardware and call init()

init()
Move bootstrap image, zero BSS, configure bus, size memory, call pmap_bootstrap()

return from init()
Enable virtual memory (first fault)

setup_main()
Initializes rest of machine independent system

Calls machine_init() for machine dependent initialization (autoconf) after VM is enabled

Starts additional bootstrap threads

Creates bootstrap task (first syscall)

Miscellaneous Routines

void startrtclock()
Set the current time of day and start periodic clock interrupts

void resettodr()
Set the time of day clock

void halt_cpu()
Halt this cpu

void halt_all_cpus(reboot)
Halt all processors and optionally reboot

Device Drivers

Devices are very similar to BSD devices
One table instead of a *cdevsw* and *bdevsw* table

```
struct dev_ops {
    char *d_name;
    int (*d_open)();
    int (*d_close)();
    int (*d_read)();
    int (*d_write)();
    int (*d_getstat)();
    int (*d_setstat)();
    int (*d_mmap)();
    int (*d_async_in)();
    int (*d_reset)();
    int (*d_port_death)();
    int d_subdev;
    int (*d_dev_info)();
};
```

struct dev_ops dev_name_list[];
int dev_name_count;

Early Stages of a Kernel's Life

- Kernel links
- Kernel loads and toggles lights
- Printf works
- Debugger works
- Pmap initialized
- Virtual memory enabled (first VM fault)
- First user process (bootstrap)
- First system call (from bootstrap)
- Server loads
- Paging file found
- Init doesn't die
- First signal (from /bin/sh)
- Single user # prompt
- Multi-user
- Network works
- Compiles lisp

Debugging

Two schools of thought

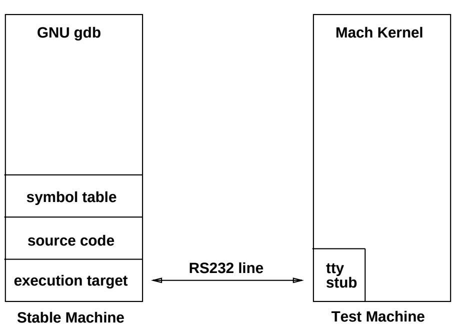
"Hell yes, I'm from Texas"
core dumps
printf
adb

Debugger: use ddb, it's just printf

New Yorker approach
Symbolic
Source Level
Debugging scripts

Debugger: use remote GNU gdb

Sophisticated Debugging



Stable machine
Symbolic source level debugging
Debugging scripts

Test machine
Hooks into tty driver
Hooks into trap handler
Small stub
read/write memory and registers
single step and set breakpoints

Debugging Tips

Investment
This isn't the *last* bug!
Every hour invested in debuggers pays off
Learn how to write GDB scripts
Know your machine

Read the code carefully
Bugs deep in kernels are hard to find

User Level Testing
Interactive testing and scripts
Lex and yacc can build powerful tools
Test modules as you go along

In Kernel Testing
Build a small kernel with printf

Simple Counters
In trap handlers, I/O routines, cache flushes
Do the numbers make sense?

More Debugging Tips

Use assert
assert(addr != 0);

Conditionalized print statements
Powerful if used *with* the debugger
and patched at runtime

```
if (addr == catch_me)
    printf("addr matches catchme\n");
```

Make a special printf syscall
Always prints a string from user space

Build debugging into your system
Flags on interrupt/trap stack frames
Don't hide registers from user
Make debugging output easy to read (PSW)
Whenever possible write in C not assembly

When you're frustrated... build a new tool

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Part II - Virtual Memory

Mach Virtual Memory

Virtual Memory Data Structures

Resolving a Page Fault

Copy-on-write

Physical Maps (pmaps)

Pmap Routines

Page Reference Bits

Virtual Cache Alignment

Zone Package

Grabbing Physical Pages

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Recommended Reading

Machine-Independent Virtual Memory Management for Paged Uniprocessors and Multiprocessor Architectures
Richard Rashid et.al.
CMU technical report CMU-CS-87-140
(also in ASPLOS II, October 1987)

Architecture-Independent Virtual Memory Management for Parallel and Distributed Environments: The Mach Approach
Avadis Tevanian Jr.'s Ph.D. Thesis
CMU technical report CMU-CS-88-106

Exporting a User Interface to Memory Management from a Communication-Oriented Operating System
Michael Youngs's Ph.D. Thesis
CMU technical report CMU-CS-89-202

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Mach Virtual Memory

Basic Data Structures

vm_page
Describes a physical page of memory

vm_object
A contiguous repository of data some
in backing store, some in memory

vm_map_entry
A mapping of contiguous virtual address
space and protection to a vm_object

pmap
A "physical map", the machine dependent
representation for mappings (page tables)

vm_map
A collection of vm_map_entries and a pmap
there is one vm_map per task

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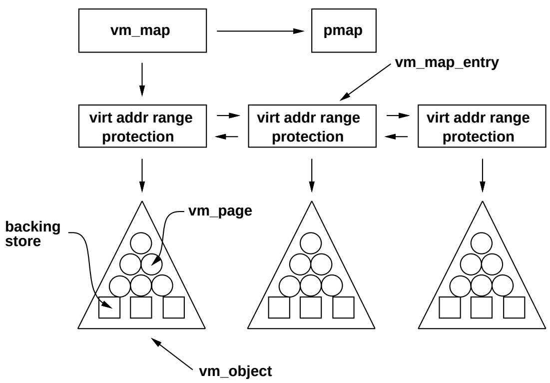
Simple VM Example



Key points

Memory object represents a piece of data and physical memory is a cache of this data

Mapping entries map a contiguous range of virtual addresses with common protection onto a memory object

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vm_page Structure

Fields in vm_page structure

Links for page queues
 double linked page list

Object and offset for page

Physical address

Flags
 inactive, *active* and *free*
  Page list page is on

 busy
  Page in transit from pager

 tabled
  vm_page is in object/offset table

 fictitious
  vm_page is placeholder in object

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Memory Object

Fields in vm_object structure

Size of object
Reference count

Pager for object
Offset into pager

Pointer to shadow object
Pointer to copy object

Miscellaneous flags
 temporary
  Object can not be changed by an external memory manager

 can_persist
  Object can persist after last reference

 internal
  Created by kernel managed by default pager

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Object/Offset Hash Table

What vm_page is in an object at a specific offset?

Use a hash table

Hash is a function of object and offset

vm_page_t vm_page_lookup(object, offset)
 Lookup a page in an object

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Mapping Entry

Fields in vm_map_entry structure

Virtual address start and end
  Always page aligned

Current and maximum protection
  read/write/execute

Inheritance with child on fork
  shared, *copied* or *none*

Miscellaneous flags
  needs_copy
    Region marked as copy-on-write

Virtual Memory Map

Fields in vm_map structure

Minimum and maximum virtual address

Size of address map

Reference count

Head and tail of mapping entries list

Hint for mapping entry search

Pmap associated with map

Resolving a Simple Page Fault

1. Start with map and virtual address
2. Find map entry containing virtual address
3. Get object and offset from map entry
4. Add offset into map entry to offset into object
5. Find vm_page structure from object/offset hash table
6. If vm_page is VM_PAGE_NULL then zero fill and enter mapping into pmap
7. If vm_page resident then enter mapping into pmap
8. If vm_page is paged out then ask pager for page when provided enter mapping into pmap

Copy-on-write

Transparent optimization for copying data

Access to page is marked read only to both parties

Writing to a page causes a fault and a new private copy of the page is made

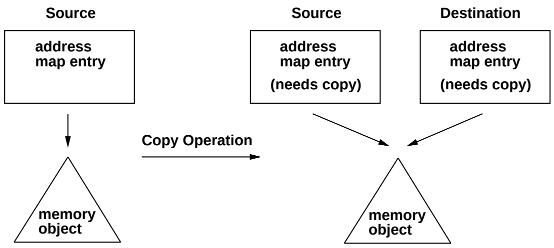
Can only share on a page granularity

Two forms

Symmetric copy-on-write
  Both source and destination treated the same

Asymmetric copy-on-write
  Used when an external memory manager is involved

Symmetric Copy-on-write



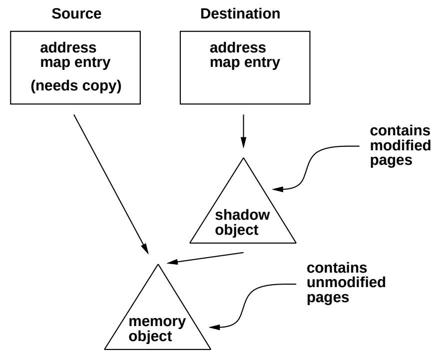
Copy operation

Point destination mapping entry at source object

Set *needs_copy* for both mapping entries

Remove write access to all pages in object
(removed by using physical address)

Write to Page



Write operation

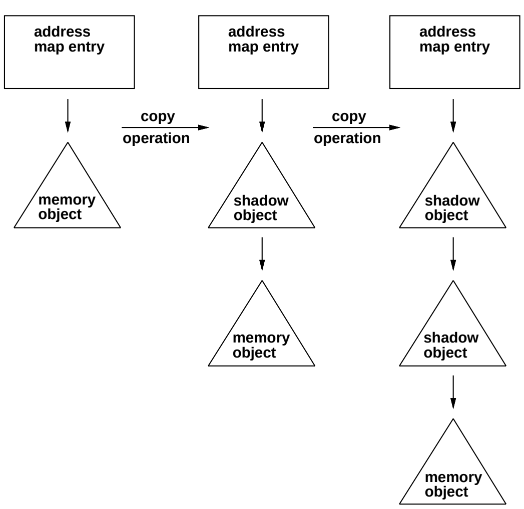
Causes a protection fault

Shadow object is created and a copy of the faulting page is inserted in the shadow object

Unmodified pages are still in original object

Write by source or destination treated the same

Copy-on-write Shadow Chains



Multiple copy-on-write operations can result in a shadow chain

Attempt is made to collapse chain when possible

External Memory Managers

Problem

Object is backed by an external memory manager

Memory manager wants to see all changes to the object

Original object will not see the changes with symmetric copy-on-write

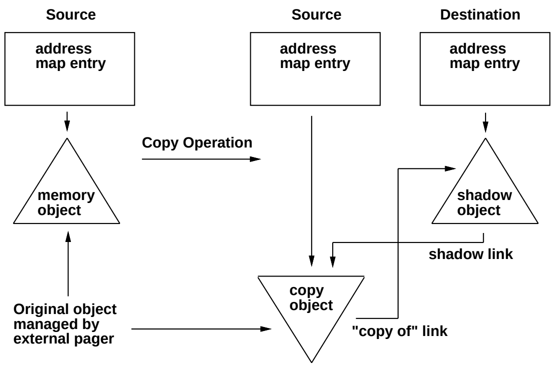
Solution

Make original object a “copy object”

Copy objects push pages up to a shadow object before they are modified

Copy objects reflects all changes

Asymmetric Copy-on-write



Write operation

If first write to page in copy object then push an unmodified copy to shadow and then modify page in copy object

If first write to page in shadow object then pull an unmodified copy from copy object and then modify page in shadow object

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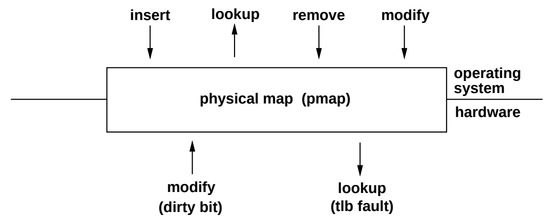
Physical Maps (pmaps)



pmaps

A pmap is simply a dictionary structure that supports the following operations:
- insert
- remove
- modify
- lookup

Both hardware and the operating system query and modify the dictionary

Hardware usually dictates the internal format of the dictionary

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Pmap Dictionary Entry

A pmap dictionary entry consists of

Virtual address

Physical address

Protection
  read/write/execute

Modified flag

Referenced flag

Wired flag

Any non-wired entry can be discarded at any time and regenerated by the machine independent data structures when needed

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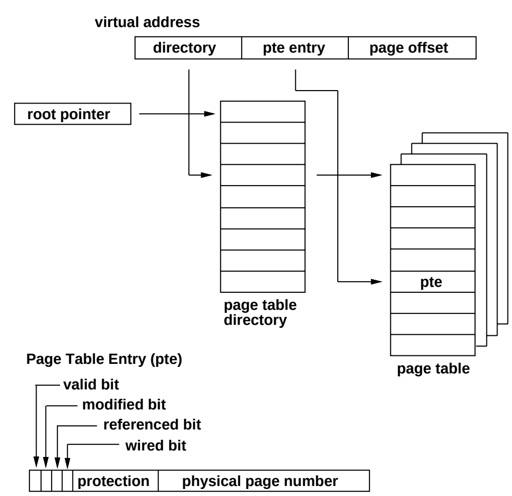
A Forward Page Table Example



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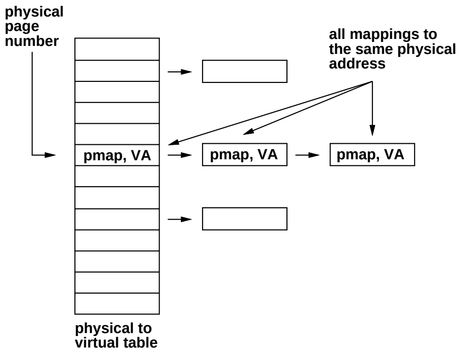
The Physical to Virtual Table



The pmap module must find entries given either the virtual or physical address

Length of table is the number of physical pages of memory managed by virtual memory system

Each entry is a linked list of (pmap, virtual address) pairs mapped to that physical page of memory

A Word on Addresses

All addresses, both virtual and physical, are byte addresses unless specifically stated otherwise

Virtual addresses are always qualified by the pmap module they are in

A range of addresses, whether specified as a start and end address or a start and length, always includes the first address and excludes the last address

The addresses for a page of memory will be given as the first address in the page

The page size must be a multiple of the physical page size but need not be the same

Pmap Bootstrap Routines

void pmap_bootstrap()
Called by init to setup enough of the pmap module to allow the kernel to run with virtual memory enabled

pmap_bootstrap is not part of the pmap interface

unsigned int pmap_free_pages()
Return the number of free physical pages that have not been allocated (used to size the object/offset hash table)

void pmap_init()
Called by vm_init() to initialize any structures or zones that the pmap system needs to map virtual memory

Pmap Bootstrap Options

Two options for bootstrapping
Define MACHINE_PAGES in pmap.h if the pmap module wants complete control of page allocation

A useful thing to do is map all of physical memory by the kernel (with block TLB entries if possible)

If you define MACHINE_PAGES then implement

vm_offset_t pmap_steal_memory(size)
Allocate and return the address of a piece of kernel memory that is *size* bytes long

void pmap_startup(startp, endp)
Allocate and initialize a vm_page_t structure for all physical memory to be managed and return the starting and ending virtual address for the kernel in *startp* and *endp*

Non MACHINE_PAGES option

If you don't define MACHINE_PAGES then implement

void pmap_virtual_space(startp, endp)
Return the starting and ending virtual address for the kernel in *startp* and *endp*

boolean_t pmap_next_page(phys_addr)
Return TRUE if there is another page of physical memory to be allocated and return the physical address of the page in *phys_addr*

Pmap Create and Delete

pmap_t pmap_create()
Create and return a pmap

void pmap_reference(pmap)
Increment the reference count of this pmap

void pmap_destroy(pmap)
Decrement the pmap's reference count and delete the pmap if zero

All entries will be removed from the pmap before the final pmap_destroy is called

Pmap Context Switch

void PMAP_ACTIVATE(pmap, thread, cpu)
Activate the pmap for use by this thread on this cpu

void PMAP_DEACTIVATE(pmap, thread, cpu)
Deactivate the pmap used by this thread on this cpu

void PMAP_CONTEXT(pmap, thread)
Switch pmap to a new thread in the same task

These are typically #define macros in pmap.h and are sometimes null macros

In our example PMAP_ACTIVATE would just set the root page table pointer, the other two would be null macros

Zero Fill and Copy Physical Pages

void pmap_zero_page(phys_addr)
Zero fill a page of memory at the specified physical address

void pmap_copy_page(src_addr, dst_addr)
Copy a page of memory at physical address *src_addr* to physical address *dst_addr*

The source page for pmap_copy_page may or may not be mapped, the destination page will never be mapped

Miscellaneous Routines

pmap_t pmap_kernel()
Return the pmap for the kernel

int pmap_resident_count(pmap)
Return the number of physical pages mapped by this pmap

vm_offset_t pmap_phys_address(phys_page)
Return the byte address of physical page *phys_page*
Note: *phys_page* is the machine dependent physical page number not a byte address

These routines are small enough that they are usually implemented as #define macros in pmap.h

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Pmap Insert Routine

void pmap_enter(pmap, virt_addr, phys_addr, min_prot, max_prot, wired)
Create a mapping in *pmap* for virtual address *virt_addr* to physical address *phys_addr*

The minimum protection required is *min_prot* which is the protection passed to vm_fault()

The maximum protection allowed is *max_prot*

If the *wired* flag is set then this mapping must never cause a page fault

Pmap_enter is the only routine that can increase access to a page of memory

min_prot was added for machines with split instruction and data TLBs that are software loaded

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Pmap Lookup Routines

vm_offset_t pmap_extract(pmap, virt_addr)
Return the physical address mapped by the virtual address in the specified pmap or 0 if there is no known mapping

boolean_t pmap_is_referenced(phys_addr)
Return whether the page at the specified physical address has been referenced since the last call to pmap_clear_reference() was made

boolean_t pmap_is_modified(phys_addr)
Return whether the page at the specified physical address has been modified since the last call to pmap_clear_modify() was made

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Pmap Modification Routines

void pmap_set_modify(phys_addr)
Set the modification bit on the page at the specified physical address

void pmap_clear_modify(phys_addr)
Clear the modification bit on the page at the specified physical address

void pmap_clear_reference(phys_addr)
Clear the reference bit on the page at the specified physical address

void pmap_change_wiring(pmap, virt_addr, wired)
Change the wiring status for the specified virtual address

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Change Protection

void pmap_protect(pmap, start, end, prot)
Change the protection on the range of virtual addresses in the specified pmap

void pmap_page_protect(phys_addr, prot)
Change the protection for all mappings to the specified physical page

A protection of VM_PROT_NONE should remove the mapping

If the caller attempts to increase access then remove the mapping, only pmap_enter() can increase access

Machine Specific Attributes

kern_return_t pmap_attribute(pmap, address, size, attribute, value)
Set a specific attribute on a range of addresses in the given pmap

Attributes
MATTR_CACHE
Cachability

Value
MATTR_VAL_CACHE_FLUSH
Flush all caches
MATTR_VAL_DCACHE_FLUSH
Flush data caches
MATTR_VAL_ICACHE_FLUSH
Flush instruction caches

Add machine specific attributes if needed

Optional Pmap Routines

void pmap_collect(pmap)
Garbage collect pages for this pmap that are no longer used

void pmap_copy(dst_pmap, src_pmap, dst_addr, length, src_addr)
Copy the source pmap entries from for the address range *src_addr* to *src_addr + length* into the destination pmap at address *dst_addr*

void pmap_pageable(pmap, start, end, pageable)
Make the specified pages in the given pmap pageable (or not) as requested. pmap_enter() will also specify that these pages are to be wired down if appropriate

These routines are optional and may be provided as null macros in pmap.h

Memory Manipulation Routines

void bcopy(src, dst, length)
Copy *length* bytes from *src* to *dst*

void bzero(addr, length)
Zero *length* bytes starting at *addr*

kern_return_t copyin(src, dst, length)
Copy *length* bytes from the current thread's address *src* to the kernel address *dst*

kern_return_t copyout(src, dst, length)
Copy *length* bytes from the kernel address *src* to the current thread's address *dst*

kern_return_t copyinmsg(src, dst, length)
kern_return_t copyoutmsg(src, dst, length)
Same as copyin and copyout except that *src* and *dst* are word aligned and *length* is a multiple of 4

Bad User Addresses

Bad user addresses in copyin or copyout

Before accessing user space load error recovery routine in *recover* in thread structure

Clear *recover* when completed

In fault handler if kernel data fault and recover is not null then patch program counter to return to error recovery routine

Alternate method

Hard code start and ending addressed of copyin and copyout routines and the recovery routine

Page Reference Bits

If your hardware doesn't have page reference bits you might find it advantageous to let the machine dependent code simulate them

To do this add the following two lines to pmap.h

```
#define pmap_is_referenced(phys) (FALSE)
#define pmap_clear_reference(phys) \
    pmap_page_protect(phys, VM_PROT_NONE)
```

See the paper
Page Replacement and Reference Bit Emulation in Mach
by Richard P. Draves

Virtual Cache Alignment

If you have virtual caches then you can allow the pmap module to influence the placement of shared memory between address spaces

#define PMAP_ALIGN in pmap.h

Requires a few new routines to be written
pmap_align_init
pmap_align_copy
pmap_align_set
pmap_align_propose

See the pmap module for the Hewlett-Packard parisc machines

Also see the paper
Consistency Management for Virtually Indexed Caches
Bob Wheeler and Brian N. Bershad
CMU technical report CMU-CS-92-182
(also in ASPLOS V, October 1992)

Zone Package

Zones allow fast allocation of a fixed size structure

zone_t zinit(size, max, alloc, pageable, name)
Initialize a new zone with elements of *size* bytes using at more *max* bytes of memory, allocate space in *alloc* byte chunks, *pageable* declares if the zone may be paged while *name* is the name of the zone

vm_offset_t zalloc(zone)
Allocate an element from the zone

vm_offset_t zget(zone)
Allocate an element from the zone without blocking and return 0 if none available

void zfree(zone, elem)
Free an element back to the specified zone

Grabbing Physical Pages

Routines for grabbing a physical page from the free list

vm_page_t vm_page_grab()
Remove a page from the free list or return VM_PAGE_NULL if the free list is too small

void vm_page_wait(continuation)
Wait for a free page to become available

```
while ((p = vm_page_grab()) == VM_PAGE_NULL)
    vm_page_wait((void (*)()) 0);
```

void vm_page_release(mem)
Return a page to the free list

int vm_page_grab_phys_addr()
Grab a page of memory from the free list and return the physical address or -1 if no page is available use this only if the page will never be freed

Part III - Saving and Restoring State

Task and thread data structures

Kernel entry and exit
- System calls
- Trap and interrupts

Kernel and interrupt stack

Saved_state Structure

Where to save state

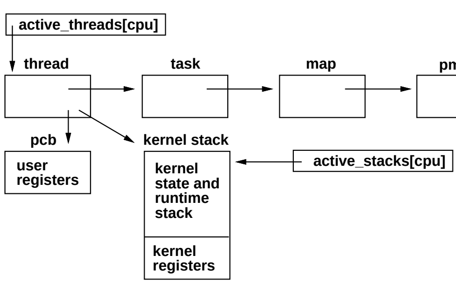
Continuations

State routines

Trap handlers

Asynchronous system traps

Task and Thread Data Structures



thread	thread state & scheduling information
pcb	user state on entry to kernel
kernel regs	registers saved across context switch
kernel stack	thread's kernel runtime stack
task	common task information
map	task's virtual memory map
pmap	task's physical map

Pointers to structures have a "_t" on the end of them, (i.e. task_t, thread_t)

Kernel Entry and Exit

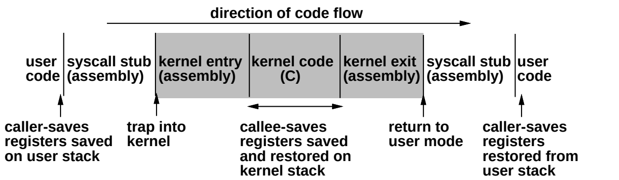
Three types of kernel entry

- System call
- Trap
- Interrupt

Calling conventions

- Caller saves registers
- Callee saves registers

System Calls



User code saves caller-saves registers before syscall

Only use caller-saves registers in syscall stub or kernel entry and exit code

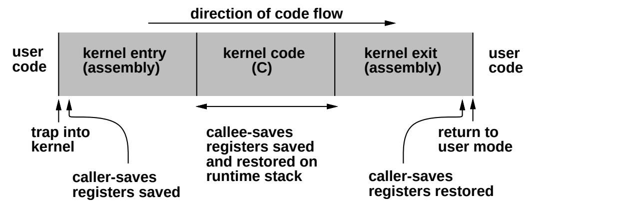
User registers are saved in the pcb

Should only have to save a few things like the return pointer and the user stack pointer

Switch to kernel address space and onto kernel stack

Kernel code will save callee-saves registers

Trap or Interrupt in User Mode

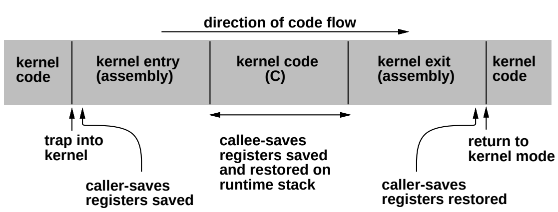


User code *doesn't* save caller-saves registers before a trap or interrupt

Kernel entry and exit must save and restore caller saves registers

Have to use some "temporary" kernel registers to get started

Trap or Interrupt in Kernel Mode



Very similar to user mode trap or interrupt

Don't have to change address space to kernel

Kernel and Interrupt Stack

Each thread has a kernel stack which is typically small (4k bytes)

Each cpu has an interrupt stack which is typically larger (20k - 40k bytes)

Could have only kernel stacks but then each would have to be much larger

Using an interrupt stack allows nested interrupts without overflowing a kernel stack

Thread may block if using kernel stack

Thread may not block if using interrupt stack

Saved_state Structure

Layout for registers saved on kernel entry and exit

Add debugging flags such as reason for kernel entry

Add flag to allow partial register reload for debuggers and thread_setstatus()

Make life easier and use the same structure for pcb, kernel stack, interrupt stack and thread_status

Make room for all registers from the start

Saved State and Runtime Stack

save state in ...

on stack	event		
	syscall	trap	interrupt
user	pcb	pcb	pcb
kernel	can't happen	current stack	interrupt stack
interrupt	can't happen	current stack	current stack

use stack ...

on stack	event		
	syscall	trap	interrupt
user	kernel stack	kernel stack	interrupt stack
kernel	can't happen	current stack	interrupt stack
interrupt	can't happen	current stack	current stack

Continuations

Problem
Kernel stacks must be wired which requires lots of physical memory

Solution
Many threads are blocked in a known state

Discard kernel stack when blocked thread will return immediately to user mode and provide instead a routine to call to leave kernel

Complication
Must save user callee-saves registers if continuation is possible

See the paper
Using Continuations to Implement Thread Management and Communication in Operating Systems
Richard P. Draves, et.al.
Thirteenth SOSP, October 1991

Native System Calls

```
typedef struct {
    int mach_trap_arg_count;
    int (*mach_trap_function)();
    boolean_t mach_trap_stack;
    int mach_trap_unused;
} mach_trap_t;
```

mach_trap_t mach_trap_table[];

int mach_trap_count

Continuation Stack Routines

void stack_attach(thread, stack, continuation)
Attach the stack to the thread and set the return pointer to run the continuation

boolean_t stack_alloc_try(thread, continuation)
Non-blocking attempt to allocate and attach a kernel stack

void stack_alloc(thread, continuation)
Allocate and attach a kernel stack, may block

void stack_free(thread)
Free a thread's kernel stack

void stack_collect()
Free excess kernel stacks

Carnegie Mellon

Continuation Routines

void call_continuation(routine)
Reset kernel stack pointer to base of kernel stack and call the specified routine

void thread_syscall_return(return_value)
Place the argument in the syscall return register, restore state from pcb and return to user mode

void thread_set_syscall_return(return_value)
Set the eventual return value for this syscall

void thread_exception_return()
Restore state from pcb and return to user mode

void thread_bootstrap_return()
Return to user mode for the first time

Carnegie Mellon

PCB Routines

void pcb_module_init()
Called at bootstrap time to initialize pcb data structures

void pcb_init(thread)
Allocate and initialize a pcb and attach it to the specified thread

void pcb_terminate(thread)
Free the pcb attached to the specified thread

kern_return_t thread_setstatus(thread, flavor, state, count)
Set the user registers in the pcb

kern_return_t thread_getstatus(thread, flavor, state, count)
Get the user registers from the pcb

Carnegie Mellon

Context Switch

Save and restore callee-saves registers and stack

Save and restore the context from the bottom of the kernel stack

void load_context(new_thread)
Load the context of the first thread

void switch_context(old_thread, continuation, new_thread)
Save the context of the old thread, set swap_func in the old_thread's thread structure to run the continuation when resumed, restore the context of the new_thread

Keep *old_thread* in arg0 for thread_continue and return *old_thread* for switch_context

stack_handoff(old_thread, new_thread)
Move the stack from the old thread to the new one

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Miscellaneous State Routines

vm_offset_t set_user_regs(stack_base, stack_size, entry, arg_size)
Allocate argument area, set registers for first user thread and return where to store the arguments on the stack

vm_offset_t user_stack_low(stack_size)
Return preferred address of user stack, always returns low address of stack

Trap Handlers

Calls made from trap handlers

Virtual memory faults
kern_return_t vm_fault(map, vaddr, fault_type, change_wiring, resume, continuation)

Clock interrupt
void clock_interrupt(usec, usermode, basepri)

Exceptions
void exception(exception_type, code, subcode)

Asynchronous System Traps

ASTs are a way to force a thread to take a trap when it about to return to user mode

AST state is a per processor state

Used to implement involuntary context switches

If MACHINE_AST is defined then implement

astoff(cpu)
called to disable AST trap on cpu

aston(cpu)
called to enable AST trap on cpu

Else use the value of need_ast[cpu]

Interrupt Priority Level

Spl is the level of interrupts that we are blocking

only return from interrupt can lower spl

kernel uses (from highest to lowest)

int splhigh()	block all interrupts
int splclock()	block clock and below
int splsched()	block clock and below
int splbio()	block block I/O and below
int splimp()	block network and below
int spltty()	block terminal and below
int splsoftclock()	block softclock and below
int spl0()	interrupts not blocked

Above routines return old spl level

void splx(s)	set spl to level s

void set_softclock()
Called from clock_interrupt to schedule a lower level interrupt

Part IV - User Code

Libmach

Cthread locks

Cthread routines

Emulated system calls

Emulator routines

Signals

BSD single server

Libmach

Contains all the stubs to call the kernel

Machine dependent code

_setjmp and _longjmp

bzero and bcopy

fork
Special fork that calls mach_init() in child

crt0.s
Special version that calls mach_init() and cthread_init() routines

Cthread Locks

spin_lock_t
Typedef for a lock

SPIN_LOCK_INITIALIZER
Static initializer for a lock

spin_lock_init(s)
Dynamic initializer for a lock

spin_lock_locked(s)
Test if a lock is locked

Cthread Locks Continued

spin_try_lock(s)
Try and acquire a lock, return 0 if successful

spin_unlock(s)
Spin unlock

If you are on a uniprocessor you might want to look at

Fast Mutual Exclusion for Uniprocessors
Brian N. Bershad et.al.
CMU technical report CMU-CS-92-183
(also in ASPLOS V, October 1992)

Cthread Routines

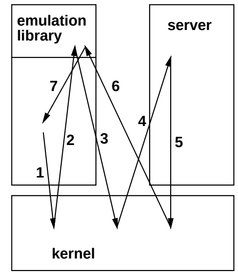
cproc_setup(child, thread, routine)
Set up the initial state of a cthread so that it will invoke routine(*child*) when it is resumed

void cproc_switch(cur, next, lock)
Suspend the current thread and resume the next one

void cproc_start_wait(parent_context, child, stackp, lock)
Save the current threads state, switch to a new stack and call cproc_waiting(*child*)

void cproc_prepare(child, child_context, stack)
Create a call frame and context on the given stack so that when invoked by cproc_switch it calls cthread_body(*child*)

Emulated System Calls



1. User process executes syscall trap
2. Emulated system call redirected to emulator
3. Emulator builds message, calls mach_msg_send
4. A server thread that previously called mach_msg_receive and is waiting in the kernel takes message to server
5. The server does mach_msg_send to send a reply
6. The user's thread waiting in the kernel takes the reply message to the emulator
7. As an optimization the emulator returns directly to the server

Emulated Syscall Data Structures

```
typedef struct eml_dispatch {
    decl_simple_lock_data(, lock)
        int ref_count;
        int disp_count;
        int disp_min;
        eml_routine_t disp_vector[1];
} *eml_dispatch_t;
```

The emulated syscall dispatch table pointer in active_threads[0] $\rightarrow$ task $\rightarrow$ eml_dispatch

If you cache the emulation dispatch pointer...

void syscall_emulation_sync(task)
Called when the task's emulation vector changes

Emulator Routines

void emul_setup(task)

Call task_set_emulation(task, routine, syscall_number) for each system call

Most syscalls are redirected to *emul_common* except *e_fork* which is directed to *emul_save_regs*

Positive syscall numbers are UNIX syscalls negative numbers are CMU extensions

Emul_common

Non-fork system calls

1. Save essential caller-saves registers
2. Acquire *emul_stack_lock*
3. Call emul_stack_alloc() to get a stack
4. Release *emul_stack_lock*
5. Switch to emulator stack
8. Call emul_syscall() to create message to server
9. Acquire *emul_stack_lock*
10. Turn in emulator stack and return to user stack
11. Release *emul_stack_lock*
12. Check for signals and call signal handler
13. Clean up and return to user

Emul_save_regs

Similar to emul_common except that you must save and restore argument and syscode registers in parent

In child you must call child_init() to initialize the emulator

Emul_syscall

Collects arguments and calls MiG stub to start remote procedure call to server

On return checks for system calls to be restarted

Checks for signals and dispatches them if needed

Signals

void take_signal(...)

Call bsd_take_signal to get any signals pending

Build signal context
Fake return so that you go to handler

sigreturn

Called by signal handler

```
if using mapped U area
    call e_shared_sigreturn()
else
    call bsd_sigreturn()
```

The server may need assistance from the kernel to restore the state

BSD Single Server

A few machine specific routines needed for loading executable, delivering signals, ptrace()...

boolean_t machine_exception(...)
Where the exception() call ends up, translates a mach exception into a UNIX exception

Create *cdevsw* and *bdevsw* tables in conf.c

Most single server devices use generic devices to interface with the kernel