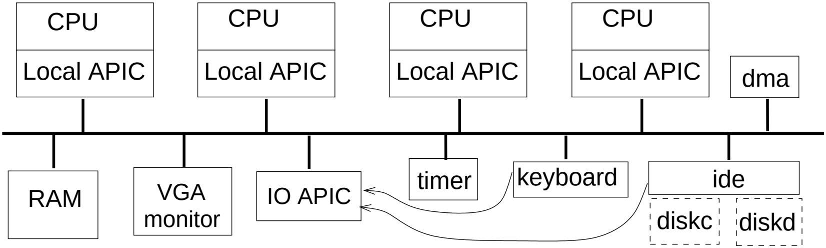
GeekOS

Goal

- Provide a very compact view of GeekOS
- Provide a framework for
  - understanding the internals of GeekOS
  - posing and answering coding questions in exams
  - describing what is to be done in projects

Outline

Hardware configuration



- x86 cpus in SMP (symmetric multi-processing) configuration
- apics (interrupt controllers)
  - local apic: recv intrpts from io-apic, send/recv to other cpus
  - io-apic: route interpts from io devices/timer to local apics
- diskc: kernel image; pfat filesystem with user programs
- emulated by QEMU running on linux (unix) environment

x86 (CPU)

- Has several modes: only “real” and “protected” modes relevant
- Real mode
  - Enters this mode upon power up
  - 16-bit machine (Intel 8086)
  - 20-bit segmented memory address: 1MB
  - 16-bit IO (port) address, 256 interrupts
- Protected mode
  - Enter this mode upon executing a certain instr in real mode
  - 32-bit machine with many more features
  - 4 privilege levels: 0 (kernel mode), 1, 2, 3 (user mode)
  - 32-bit segmented (+ optional paging) memory address: 4GB
  - 16-bit IO (port) address space, 256 interrupts
  - Geekos runs in this mode.
  - Rest of this section deals with protected mode

x86: Addressing

- Address space: 4GB (32-bit address)
- Segment: a contiguous chunk of address space
- Address formed from 16-bit segment selector and 32-bit offset
- Segment selector indexes into a seg descriptor table
  - [which table, index into table, protection level]
  - global descriptor table (gdt), local descriptor table (ldt)
- Yields a 64-bit segment descriptor, which points to a segment
  - [base addr, limit, privilege level, etc]
- If paging is on, the address is divided into [dir, page, offset]

x86: Interrupts

- 256 interrupts: 0–31 hw, rest sw (traps, exceptions, faults, etc)
- Interrupt indexes into a interrupt descriptor table (idt)
- Yields a 64-bit interrupt gate, which points to interrupt handler
  - [seg selector, offset, descriptor privilege level (dpl), etc]
- If interrupt-handler's privilege-level = cpu's privilege-level: cpu pushes on its current stack
  - its eflags, cs, eip, and an error code (for some interrupts)
- If interrupt-handler's privilege-level < cpu's privilege-level: cpu uses another stack whose location is in a task state segment (tss)
  - pushes its ss and esp // interrupted task's stack
  - pushes eflags, cs, eip, error code (if present)
- Return-from-interrupt (IRET) undoes the above (in both cases)

x86: Registers

- eax, ebx, ecx, esi, edi, edx: “general purpose” (32-bit)
- esp (32-bit): stack pointer (in ss segment)
- ebp (32-bit): frame pointer (in ss segment)
- eip (32-bit): instruction pointer (in cs segment)
- segment registers (16-bit), each holds a segment selector
  - cs (code segment), ss (stack segment)
  - ds, es, fs, gs (data segment)
- gdtr (48-bit): addr and size of current gdt
- idtr (48-bit): addr and size of current idt
- ldtr (16-bit): selector to current ldt (via gdt)
- tr (16-bit): selector to current tss (via gdt)
- eflags (32-bit): carry, overflow, sign, interrupt enable, etc
- cr0–cr4 (32-bit): paging enable, page fault, cache enable, etc.

Local APICs and IO APIC

- BIOS stores APICs config info at certain addresses
- Local APIC info starts at `0xFEE00000` (`APIC_Addr`)
  - offset `0x20` (`APIC_ID`) stores the apic id (= cpu id) // 0, 1, ...
- Get_CPU_ID(): // return cpu id of caller thread
  - disable interrupts
  - apicid ← read location `APIC_Addr + APIC_ID`
  - restore interrupts
  - return apicid
- IO APIC info starts at `0xFEC00000` (`IO_APIC_Addr`)

PIT timer + LAPIC timers

- PIT timer: interrupt `TIMER_IRQ` (=0)
- Each Local APIC has a timer: interrupt 32
- PIT timer is used only at boot to calibrate the LAPIC timers

- Global and static variables
  - `g_numTicks` // global tick counter
  - `DEFAULT_MAX_TICKS = 4` // default quantum
  - `g_Quantum = DEFAULT_MAX_TICKS`

LAPIC timer

- `Timer_Interrupt_Handler(istate)`: // simplified
```
id ← Get_CPU_ID()
ct ← get_current_thread()
if id is 0:
  ++g_numTicks
++ct.numTicks
if ct.numTicks >= g_Quantum:
  g_needReschedule[id]
```
- `Init_Timer()`:
```
Install_IRQ(32, Timer_Interrupt_Handler)
enable interrupt 32
```
- `Init_Local_APIC(cpuid)`:
```
Install_IRQ(39, Spurious_Interrupt_Handler)    // SMP
enable interrupt 39
set timer timeout value                        // cpu 0 uses PIT to calibrate
```

VGA screen

- Ports: `CRT_*` regs (`0x3D4`, `0x3D5`, etc)
  - access via io instr // eg, `Out_Byte(port, value)`
  - for refresh, scan rate, blanking, cursor control, etc
- Video memory: `VIDMEM` (`0xb8000`–`0x100000`)
  - holds characters to display // NUMROWS = 25, NUMCOLS = 80
  - access via read/write instrs // eg, VIDMEM[offset] = keycode
- Var console_state: row, col, esc, numeric arg, etc
- `Update_Cursor()` based on console state // ports used here only
- `Put_Char_Imp(c)`: place char c at text cursor position
- `Init_Screen()`: clear screen, set "text cursor" to origin
- `Print(*fmt, ...)`

Keyboard

- Ports
  - input reg: KB_DATA (0x60)
  - control reg: KB_CMD (0x64)
  - status regs: KB_OUTPUT_FULL (0x01), KB_KEY_RELEASE (0x80)
- Interrupt: KB_IRQ (1)
- Static variables (for drivers, interrupt handler)
  - s_queue // queue for incoming keycodes
  - s_keyboardWaitQueue // threads waiting for kbd inputs
  - s_kbdQueueLock // spinlock protecting s_queue
  - scantables // map scancode to keycode
  - kbd state // shift, esc, control, alt, etc

Keyboard

- `Keyboard_Interrupt_Handler(istate)`:
  if ports indicate byte available:
    get byte; convert to keycode or update kbdstate
    add keycode to s_queue // drop if full; spinlock ops
    `wakeup(s_keyboardWaitQueue)`
- `Init_Keyboard()`:
  initialize static variables
  `Install_IRQ(KB_IRQ, Keyboard_Interrupt_Handler)`
  enable kbd interrupt
- `Wait_For_Key()`:
  disable intrpt
  repeat
    if s_queue has key, get it // spinlock ops
    else `wait(s_keyboardWaitQueue)`
  until got key
  restore intrpt

IDE

- 16-bit transfer unit
- 2 hard disks
- PIO and DMA modes
- 256-byte blocks

- Ports
  - IDE_identify regs // show disk features
  - IDE_drive/cylinder/head/sector regs // target disk block
  - IDE_command reg // read/write
  - IDE_data reg // successive words of io block show up here
  - IDE_status/control/etc regs // busy, dma, interrupt, etc

IDE: drivers

- Static variables
  - s_ideWaitQueue: ide server thread waits here
  - s_ideRequestQueue: io requests queued here
- IDE_Read(drive, blocknum, *buffer):
  convert blocknum to cylinder, head, sector
  update control and command regs
  read 256 words from data reg into buffer
- IDE_Write(...): *like* IDE_Read *except* write to data reg
- IDE_Request_Thread():
  forever: req = dequeue from request queue // blocking
  IDE_Read/Write(req) // synchronous, pio
- Init_IDE():
  register drives as block devices
  start kernel thread executing IDE_Request_Thread()

DMA controller (currently not used)

- Registers
  - memory addr
  - byte count
  - control regs (source, destination, transfer unit, etc)
- Usage for ide io
  - cpu sets up ide interface to initiate data transfer
  - cpu sets up dma interface
- `Init_DMA()`
- `Reserve_DMA(chan)`
- `Setup_DMA(direction, chan, *addr, size)`

Outline

Boot

- At power up, BIOS configures
  - one cpu-lapic as primary, with id 0
  - other cpu-lapics as secondaries, halted, with ids 1, 2, ...
  - MP config table in memory
  - loads diskc/block 0 (bootsect.asm) into memory
  - cpu 0 (in real mode) starts executing it
- bootsect.asm // executed by cpu 0
  - load the kernel image (from diskc) into memory and start executing it (setup.asm)
- setup.asm // executed by cpu 0
  - get memory size, redirect interrupts (bypass BIOS)
  - enter protected mode, set cs to KERNEL_CS
  - set ds, es, fs, gs, ss to KERNEL_DS, jump to `main.c:Main`

Kernel initialization: Main()–1 // executed by cpu 0

- blank VGA screen
- init cpu 0's gdt, gdtr // s_GDT[0]; 1: code seg, 2: data seg
  // NUM_GDT_ENTRIES = 32
- organize memory into 4K pages // g_pageList, s_freeList
- init kernel heap
- init cpu 0's tss, tr, gdt[3?] // s_theTSS[0]; one tss per cpu
- init cpu 0's idt, idtr // s_IDT[0]
  - syscall entry's dpl at user level, others at kernel level
  - addresses of interrupt handlers in g_interruptTable[0];
    set them to dummy interrupt handler
- init SMP: for each secondary cpu *i*
  - allocate a page for cpu *i*'s kernel stack (CPUs[i].stack)
  - start cpu *i* executing start_secondary_cpu (in setup.asm)
    // cpu *i* does its initialization, then spins until cpu 0 releases it

Kernel initialization: Main()−2 // executed by cpu 0

- init scheduler(0): create threads // with Kernel_Thread objects
  - current thread {Main} // g_currentThreads[0]
  - idle thread {Idle-#0} // s_runQueue
  - reaper thread {Reaper} // s_runQueue
- init traps: 12: stack exception; 13: GPF; 0x90: syscall
- init devices: Local_APIC(0), keyboard, IDE, DMA
- init PFAT: register filesystem PFAT with vfs
- release SMP
  - allow each secondary cpu to exit its initialization; wait for that
- mount root filesystem
  - mount ide0 as PFAT fs at path "/a"
- spawn initial process // shell program
- hardware shutdown

Secondary cpu initialization // executed by cpu *i*

- start_secondary_cpu (in setup.asm)
  - enter protected mode
  - set ds, es, fs, gs, ss to KERNEL_DS
  - set esp to `CPUs[i].stack` // previously assigned by cpu 0
  - jump to `Secondary_Start()` (in smp.c)
- `Secondary_Start()` (in smp.c)
  - init gdt: point cpu *i*'s gdtr to `s_GDT[0]` // uses cpu 0's gdt
  - init cpu *i*'s tss, tr, gdt[3+*i*?] // `s_theTSS[i]`
  - init cpu *i*'s idt (`s_IDT[i]`), idtr
  - init scheduler(i): create threads // with `Kernel_Thread` objects
    - current thread `{Main}` // `g_currentThreads[i]`
    - idle thread `{Idle-#`*i*`}` // `s_runQueue`
  - init traps, local apic
  - set flag informing cpu 0 that *i* is done
  - `Exit(0)`, which makes cpu enter scheduler

Outline

Kernel threads: context and queues

- Context of a kernel thread:
  - Kernel_Thread struct + stack page
- struct Kernel_Thread:
  - esp, *stackPage, *userContext
  - link for s_allThreadList // constant
  - link for current thread queue // runq, waitq, graveyard
  - numTicks, totalTime, priority, pid, joinq, exitcode, owner, ...
- Thread queues
  - s_allThreadList // all threads
  - s_runQueue // ready (aka runnable) threads
  - s_graveyardQueue // ended and to be reaped
  - various waitQueues // mutex, condition, devices, etc
  - *g_currentThreads[MAX_CPUS] // running thread

Starting kernel threads

- Start_Kernel_Thread(startfunc, arg, priority, detached, name):
  - Create_Thread:
    get memory for kthread context (struct and stack page)
    init struct: stackPage, esp, numTicks, pid
    add to the all-thread-list
  - Setup_Kernel_Thread:
    configure stack so that upon switching in it executes
    Launch_Thread, then startfunc, then Shutdown_Thread

    ```
    // stack (bottom to top):
    //    startfunc arg, Shutdown_Thread addr, startfunc addr
    //    0 (eflags), KERNEL_CS (cs), Launch_Thread addr (eip)
    //    fake error code, intrpt#, fake gp regs
    //    KERNEL_DS (ds), KERNEL_DS (es), 0 (fs), 0 (gs)
    ```
  - Make thread runnable: add struct to runq

Current thread

- CURRENT_THREAD: // return the thread struct of the caller
  - disable interrupts
  - ct $\leftarrow$ g_currentThreads[GET_CPU_ID]
  - restore interrupts

Outline

User process context

- Context of a user process:
  - Kernel_Thread struct + stack page + struct User_Context
- struct User_Context:
  - name[]
  - ldt[2] // code segment, data segment
  - *ldtDescriptor // segment descriptor
  - *memory, size // memory space for process
  - ldtSelector // index into gdt
  - csSelector, dsSelector // index into ldt
  - entryAddr, argBlockAddr, stackPointerAddr
  - *pageDir, *file_descriptor_table[]
  - refCount, mappedRegions, etc

Spawn user process

- Spawn(program, cmd, *kthread, background):
  - read executable file from filesystem // vfs, pfat
  - unpack elf header and content, extract exeFormat // elf
  - mem ← malloc(program maxva + argblock size + stack page)
  - copy program segments into mem space
  - malloc usercontext and set its fields:
    - *memory ← mem
    - ldt, ldt selectors/descriptors
    - entry point, argblock, stack bottom, ...
  - *kthread ← Start_User_Thread(userContext)

Start user thread

- Start_User_Thread(uc, detached): // "uc" is "usercontext"
  - Create_Thread:
    malloc kthread struct and stack, init, add to all-thread-list
  - Setup_User_Thread:
    point kthread.usercontext to uc
    configure kernel stack as if it was interrupted in user mode
    // stack (bottom to top):
    // uc.ds (user ss), uc.stackaddr (user esp)
    // eflags (intrpt on), uc.cs (cs), uc.entryaddr (eip)
    // errorcode, intrpt#, gp regs except esi // fake
    // uc.argblockaddr (esi), uc.ds (ds, es, fs, gs)
    // How is termination handled?
  - Make thread runnable: add struct to runq

Copying between user and kernel spaces

- User_To_Kernel(usercontext, userptr): // kernel addr of useraddr
  return usercontext.memory + userptr

- Copy_From_User(dstInKernel, srcInUser, bufsize):
  ucontext ← CURRENT_THREAD.usercontext
  srcInKernel ← User_To_Kernel(ucontext, srcInUser)
  memcpy(dstInKernel, srcInKernel, bufsize)

- Copy_To_User(dstInUser, srcInKernel, bufsize):
  ucontext ← CURRENT_THREAD.usercontext
  dstInKernel ← User_To_Kernel(ucontext, dstInUser)
  memcpy(dstInKernel, srcInKernel, bufsize)

Outline

Interrupt disable/enable: affects only this CPU

```
Disable_Interrupts():                    // abbrv: disable intrpt
  __asm__ "cli"

Enable_Interrupts():                     // abbrv: enable intrpt
  __asm__ "sti"

Begin_Int_Atomic():                      // abbrv: disable intrpt
  ion ← true iff interrupts enabled
  if ion:
    Disable_Interrupts()
  return ion

End_Int_Atomic(ion):                     // abbrv: restore intrpt
  if ion:
    Enable_Interrupts()
```

Spinlocks

- Spinlock in assembly: an int that is 0 iff unlocked

```
Spin_Lock_INTERNAL(x):
  repeat
    busy wait until *x is 0
    set eax to 1
    atomically swap eax and *x
  until eax equals 0

Spin_Unlock_INTERNAL(x):
  set eax to 0
  atomically swap eax and *x
```

- Spinlock in C: struct {lock, locker, ra, lastlocker}
- Spin_Lock(x): wrapper of assembly fn + update to locker, ra, ...
- Spin_Unlock(x): " " " " " " "

- Ensure interrupts disabled before acquiring a spinlock // Why?
- Restore interrupts after releasing a spinlock

Some spinlock variables

- globalLock // lockKernel(), unlockKernel(); smp.c
- kthreadLock // kthread.c, user.c
- Every *list_t* in `DEFINE_LIST(`*list_t*, *node_t*`)` has a spinlock lock
  - Guards the list in list operations (append, remove, etc)
  - eg, Thread_Queue: s_graveyardQueue.lock, waitQueue.lock
- pidLock // k.thread.c
- kbdQueueLock // keyboard.c
- s_free_space_spin_lock // paging.c
- run_queue_spinlock // sched.c
- mutex->guard // synch.c

Wait and Wakeup

- Wait(waitq):
  disable intrpt, Spin_Lock(waitq.lock)
  add current thread to waitq
  Schedule_And_Unlock(waitq.lock)
  restore intrpt
- Wake_Up(waitq):
  disable intrpt, Spin_Lock(waitq.lock)
  move all threads in waitq to runq
  Spin_Unlock(waitq.lock), restore intrpt
- Wake_Up_One(waitq):
  if waitq not empty:
    move waitq.front thread to runq

Mutex

- struct Mutex: {state, guard (spinlock), owner, waitq} // waitQueue

- Mutex_Lock(x)

```
disable intrpt
Spin_Lock(x.guard)
if x.state is locked:
  add current thread to x.waitq
  Schedule_And_Unlock(x.guard)
else:
  set x.state to locked
  Spin_Unlock(x.guard)
set x.owner to current thread
restore intrpt
```

Mutex_Unlock(x)

```
disable intrpt
Spin_Lock(x.guard)
if x.waitq not empty:
  set x.owner to waitq.front
  wakeup x.waitq.front
else:
  set x.state to unlocked
Spin_Unlock(x.guard)
restore intrpt
```

- Mutex_Unlock_And_Schedule(x)

```
Mutex_Unlock(x) w/o last two lines
Schedule_And_Unlock(x.guard)
restore intrpt
```

Condition

- struct Condition: {waitq} // waitQueue

- Cond_Wait(cv, x)
  disable intrpt, Spin_Lock(x.guard)
  add current thread to cv.waitq
  Mutex_Unlock(x) w/o first two and last two lines
  Schedule_And_Unlock(x.guard)
  restore intrpt
  Mutex_Lock(x)

- Cond_Signal(cv)
  disable intrpt
  wakeup cv.waitq.front
  restore intrpt

Cond_Broadcast(cv)
  disable intrpt
  wakeup cv.waitq
  restore intrpt

Outline

Scheduling

- Flags checked at every potential switch:
  - g_preemptionDisabled[MAX_CPUS]
  - g_needReschedule[MAX_CPUS]

- Schedule():
  - // current thread voluntarily giving up cpu,
    // eg, Wait(), Mutex_Lock(), Cond_Lock(), Yield().
    // current thread already in runq or a waitq.
  - set g_preemptionDisabled[this cpu] to false
  - runme ← remove a thread from runq
  - Switch_To_Thread(runme)

- Schedule_And_Unlock(x): // x is a spinlock
  - like Schedule() but unlocks x before Switch_To_Thread(runme)

Outline

Handling an interrupt

- Handle_Interrupt():

  // Here on intrpt. save regs, [choose new thread], push regs, iret
  // Using current thread's kernel stack, containing:
  //   user.ss/esp (iff user mode), eflags, cs, eip, errorcode, intrpt#

  - push cpu's gp and seg regs // complete interrupt-state
  - call C interrupt handler // with ptr to interrupt-state as arg
  - if not g_preemptionDisabled and g_needReschedule:
    move current thread to runq
    update current thread's state wrt esp, numticks
    get a thread from runq and make it current
  - activate user context (if any) // update ldtr, s_TSS, ...
  - process signal (if any)
  - restore gp and seg regs
  - iret

Switching a thread

- Switch_To_Thread(thrdptr):

  // called from Schedule(). interrupts off.
  // using current thread's kernel stack. stack has return addr.
  // current thread struct already in runq or a waitq.
  // save current thread context, activate thread passed as param.

  - change stack content to an intrpt state by adding:
    cs, eflags, fake errorcode/intrpt#, gp and seg regs
  - make thrdptr (in arg) as current thread
  - activate user context (if any) // update ldtr, s_TSS, ...
  - process signal (if any)
  - clear APIC interrupt info
  - restore gp and seg regs
  - iret

Outline

VFS: static vars and structs – 1

- Static variables
  - s_vfsLock: Mutex, to protect vfs structures
  - s_fileSystemList: Filesystem struct for every registered fs type
  - s_mountPointList: Mount_Point struct for every mounted fs

- struct Filesystem
  - ops: functions Format and Mount provided by fs type
  - fsname: name of fs type // eg, "pfat", "gfs3"

- struct Mount_Point
  - ops: mountpoint functions provided by mounted fs
    - eg, Open, Create_Directory, Stat, ...
  - pathpfx: where fs is mounted // eg, "/", "/c"
  - dev: block device containing fs // eg, ide0
  - fsdata: for use by fs implementation

VFS: static vars and structs – 2

- struct File
  - ops: file functions provided by mounted fs
    - eg, FStat, Read, Write, Close, ...
  - filepos: current position in the file
  - endpos: end position (length of the file)
  - fsdata: for use by fs implementation
  - mode: mode
  - mountpoint: of filesystem that file is part of

VFS functions: Register, Fs.ops wrappers

- `Register_Filesystem(fsname, fsOps)`:
  fs ← fill a Filesystem struct
  add fs to s_fileSystemList // protected by Mutex s_vfsLock
- `Format(devname, fstype)`: // Fs.ops
  fs ← s_fileSystemList[fstype]
  Open_Block_Device(devname, dev)
  fs.ops.Format(dev) // return result
  Close_Block_Device(dev)
- `Mount(devname, pathpfx, fstype)`: // Fs.ops
  fs ← s_fileSystemList[fstype]
  Open_Block_Device(devname, *dev)
  mp ← fill a Mount_Point struct
  fs.ops.Mount(mp) // return result
  add mp to mountPointList // protected by Mutex s_vfsLock

VFS functions: Mp.ops wrappers

- `Open(path, mode, *file)`:
  split path into pathpfx, pathsfx
  mp ← s_mountPointList[pathpfx]
  mp.ops.Open(mp, path, mode, file) // return result
  file.mode, file.mountpoint ← mode, mp
- `Open_Directory(path, *dir)`:
  like Open() but with mp.ops.Open_Directory
- `Create_Directory(path)`:
  split path into pathpfx, pathsfx
  mp ← s_mountPointList[pathpfx]
  mp.ops.Create_Directory(mp, pathsfx) // return result
- `Stat(.)`, `Delete(.)`, ..., `Dist_Properties(.)`
  similar to above
- `Sync()`:
  similar, but do Sync(.) of every mounted fs

VFS functions: F.ops wrappers

- `Close(*file)`:
  file.ops.Close(file) // return result
- `FStat(*file, *stat)`:
  file.ops.Fstat(file, stat) // return result
- `Read(*file, *buf, len)`:
  file.ops.Read(file, buf, len) // return result
- `Write(*file, *buf, len)`, `Seek(*file, pos)`, `Read_Entry(*dir, *entry)`
  similar to above

- `Read_Fully(path, *buf, *len)`:
  Stat path and allocate buf of stat.size
  Open file; Read^{+} stat.size; Close file

VFS: paging device

- Static variable
  - s_pagingDevice: registered Paging_Device struct
- struct Paging_Device
  - filename: name of paging file
  - dev: block device of paging file
  - startSector
  - numSectors
- `Register_Paging_Device(pagingdevice)`:
  settor for s_pagingDevice
- `Get_Paging_Device()`:
  gettor for s_pagingDevice

Outline

PFAT structs – 1

- struct PFAT_Instance: // kept in vfs.Mount_Point.fsdata
  - bootsector fsinfo
  - int *fat
  - directoryEntry *rootDir
  - directoryEntry rootDirEntry
  - Mutex lock // protects fileList
  - PFAT_File_List fileList
- struct PFAT_File: // kept in vfs.File.fsdata
  - directoryEntry *entry
  - ulong numBlocks
  - char *fileDataCache
  - Mutex lock // guards concurrent access

PFAT structs – 2

- struct bootSector: // kept in vfs.Mount_Point.fsdata
  - magic
  - fileAllocationOffset/Length // FAT blocks
  - rootDirectoryOffset/Count // rootdir blocks
  - setupStart/Size // secondary loader blocks
  - kernelStart/Size // kernel image blocks
- struct directoryEntry:
  - readOnly, hidden, systemFile, directory, ... // 1-bit flags
  - time, date
  - firstBlock, fileSize
  - acls

PFAT functions – 1

- PFAT_Mount(mp):

  pfi ← Malloc `PFAT_Instance`
  pfi.fsinfo ← read bootsector from mp.dev *block 0*

  pfi.fat ← Malloc FATsize // avail in pfi.fsinfo
  pfi.fat ← read mp.dev *fat blocks* // " " "

  pfi.rootDir ← Malloc rootdir size // " " "
  pfi.rootDir ← read mp.dev *rootdir blocks* // " " "

  pfi.rootDirEntry ← fake_rootdir_entry

  initialize pfi.lock, pfi.filelist, pfi.filelist.lock

  PFAT_Register_Paging_File(mp, pfi)

  mp.ops ← {`PFAT_Open`, `PFAT_Open_Dir`}
  mp.fsdata ← pfi

PFAT functions – 2

- PFAT_Register_Paging_File(mp, pfi):

  quit if a pagefile is already registered or mp pfi has no pagefile

  pfe ← dirEntry of PAGEFILE_FILENAME in mp.pfi

  pdev ← Malloc Paging_Device // vfs

  pdev.fileName ← mp.pathpfx / PAGEFILE_FILENAME

  pdev.dev ← mp.dev

  pdev.startSector ← pfe.firstBlock

  pdev.numSectors ← pfe.fileSize/SECTOR_SIZE

  Register_Paging_Device(pdev) // vfs

PFAT functions – 3

- Get_PFAT_File(pfi, direntry):

  if pfi.filelist has a PFAT_File obj for direntry: return it
  else add a new obj for direntry to pfi.filelist, return it

- PFAT_Open(mp, path, mode, *file):

  pfi ← mp.fsdata
  quit if mode attempts to create file or if path not in pfi
  pfatfile ← Get_PFAT_File(pfi, direntry of path)
  *file ← vfs.File for pfatfile with ops
  `PFAT_ FStat/Read/Write/Seek/Close`

- PFAT_Open_Directory(mp, path, mode, *dir):

  below assumes path is "/"
  pfi ← mp.fsdata
  *dir ← vfs.File obj for pfi.rootDir with ops
  `PFAT_ FStat_Dir/Close_Dir/Read_Entry`

PFAT functions – 4

- PFAT_Read(file, buf, nbytes):

  pfatfile ← file.fsdata
  pfi ← file.mp.fsdata
  Mutex_Lock(pfatfile.lock)
  nbytes ← min(endpos, filepos + nbytes)
  traverse FAT (in file.mp.fsdata) for the blocks of the file:
    for each block not in cache, read it into cache, then to buf
    update filepos
  Mutex_Unlock(pfatfile.lock)
  return nbytes

- PFAT_Write(file, buf, nbytes):

  like PFAT_Read but only in sector-units and within file

- Init_PFAT():

  Register_Filesystem("pfat", PFAT_Mount)

Outline

Blockdev structs – 1

- struct Block_Request:
  - dev
  - type // BLOCK_READ, BLOCK_WRITE
  - blocknum
  - state // PENDING, COMPLETED, ERROR
  - errorcode
  - satisfied // Condition (with s_blockdevRequestLock)
- struct Block_Device:
  - name
  - ops // Open(dev), Close(dev), Get_Num_Blocks(dev)
  - unit
  - inUse // closed or open
  - waitqueue // for requesting thread
  - reqqueue // for requests to this device

Blockdev static vars

- Mutex s_blockdevLock: protects block device list
- Mutex s_blockdevRequestLock: for all requests
- Condition s_blockdevRequestCond
- s_deviceList: list of all registered block devices

Blockdev functions – 1

- Register_Block_Device(name, ops, unit, driverdata, waitq, reqq):

  dev ← [name, ops, unit, ..., reqq, inUse = false]
  Mutex_Lock(s_blockdevLock)
  add dev to s_deviceList
  Mutex_Unlock(s_blockdevLock)

- Open_Block_Device(name, *dev):

  Mutex_Lock(s_blockdevLock)
  find dev in s_deviceList
  dev.ops.Open(dev)
  Mutex_Unlock(s_blockdevLock)

- Close_Block_Device(name, *dev):

  like Open_Block_Device but using dev.ops.Close(dev)

Blockdev functions – 2

- Block_Read(dev, blocknum, buf):

```
Mutex_Lock(s_blockdevLock)
req ← Block_Request(dev, BLOCK_READ, blocknum, buf,
                    PENDING, Cond_Init(satisfied))
Mutex_Lock(s_blockdevRequestLock)               // post req
add req to dev.requestQueue
Cond_Broadcast(s_blockdevRequestCond)           // awaken server
while req.state is PENDING:                     // wait for req to be served
  Cond_Wait(req.satisfied, s_blockdevRequestLock)
Mutex_Lock(s_blockdevRequestLock)
Mutex_Unlock(s_blockdevLock)
// and return req.errorcode
```

- Block_Write(dev, blocknum, buf):

  like Block_Read

Blockdev functions – 3

- Dequeue_Request(reqqueue): // executed by device driver thread

  Mutex_Lock(s_blockdevRequestLock)
  while reqqueue is empty:
    Cond_Wait(s_blockdevRequestCond, s_blockdevRequestLock)
  get req from reqqueue
  Mutex_Lock(s_blockdevRequestLock)

  return req

- // executed by device driver thread or interrupt handler

  Notify_Request_Completion(req, state, errorcode):

  req.state ← state
  req.errorcode ← errorcode
  Cond_Signal(req.satisfied)

Outline

Bufcache structs

- struct FS_Buffer: // buffer for one fs block
  - fsblocknum // of the fs block in data (if inuse)
  - data // 4K page allocated separately
  - flags // dirty, inuse
- struct FS_Buffer_Cache:
  - dev // block device
  - fsblocksize // size of fs block
  - numCached // current number of buffers
  - bufferList
  - mutex
  - cond // Condition: waiting for a buffer

Bufcache functions – 1

- Create_FS_Buffer_Cache(dev, fsblocksize):
  cache ← Malloc(dev, fsblocksize, numCached = 0,
  Clear(bufferList), Init(mutex), Init(cond))
- Sync_FS_Buffer_Cache(cache):
  Mutex_Lock(cache.mutex)
  for every buf in cache.bufferList:
  if buf is dirty, write buf.data to disk and set buf clean
  Mutex_Unlock(cache.mutex)
- Destroy_FS_Buffer_Cache(buf):
  Mutex_Lock(cache.mutex)
  for every buf in cache.bufferList: sync and free mem
  clear cache.bufferList
  Mutex_Unlock(cache.mutex)
  free cache

Bufcache functions – 2

- Get_FS_Buffer(cache, fsblocknum, *buf):

  Mutex_Lock(cache.mutex)
  if there is a buffer with fsblocknum in cache.bufferList:
    buf ← buffer, await(cache.cond) not inuse, set inuse, return 0

  if cache.numCached at maxlimit, all buffers inuse: return ENOMEM

  if cache.numCached < maxlimit:
    allocate memory for buf and buf.data   // never fails?
    add buf to cache.bufferList front
  else:
    buf ← lru not-inuse buffer in cache.bufferList
    sync buf, move buf to bufferList front

  set buf's fields, read disk blocks into buf.data

  Mutex_Unlock(cache.mutex)
  return 0