CS350: Operating Systems

Lecture 8: Virtual Memory OS

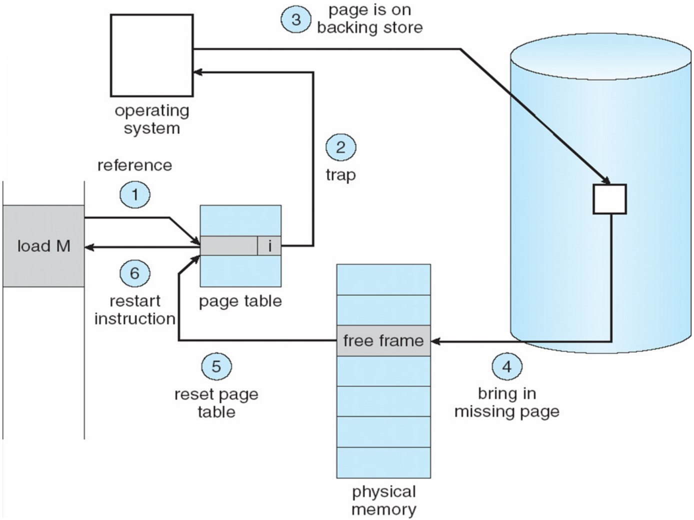
Ali Mashtizadeh

University of Waterloo

Outline

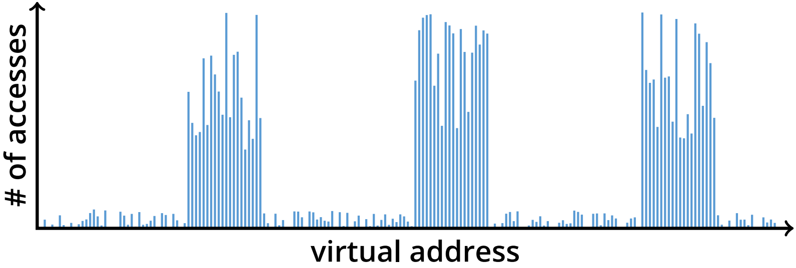
1. Paging
2. Eviction policies
3. Thrashing
4. User-level API
5. Case study: 4.4 BSD

Paging



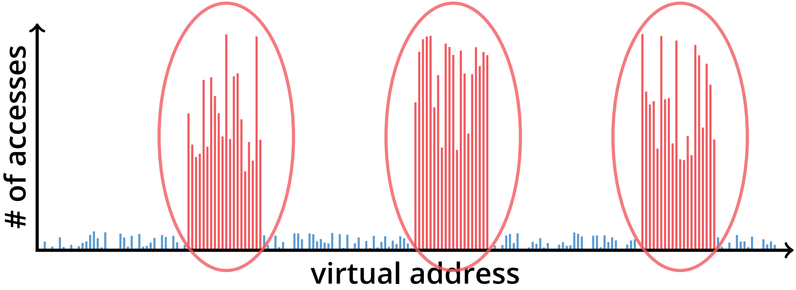
- Use disk to simulate larger virtual than physical mem

Working set model



- Disk much, much slower than memory
  - Goal: run at memory speed, not disk speed
- 80/20 rule: 20% of memory gets 80% of memory accesses
  - Keep the hot 20% in memory
  - Keep the cold 80% on disk

Working set model



- Disk much, much slower than memory
  - Goal: run at memory speed, not disk speed
- 80/20 rule: 20% of memory gets 80% of memory accesses

⟶ Keep the hot 20% in memory
  - Keep the cold 80% on disk

Working set model

- Disk much, much slower than memory
  - Goal: run at memory speed, not disk speed
- 80/20 rule: 20% of memory gets 80% of memory accesses
  - Keep the hot 20% in memory

→ Keep the cold 80% on disk

Paging challenges

- How to resume a process after a fault?
  - Need to save state and resume
  - Process might have been in the middle of an instruction!
- What to fetch from disk?
  - Just needed page or more?
- What to eject?
  - How to allocate physical pages amongst processes?
  - Which of a particular process's pages to keep in memory?

Re-starting instructions

- Hardware provides kernel with information about page fault
  - Faulting virtual address (In `%c0_vaddr` reg on MIPS)
  - Address of instruction that caused fault (`%c0_epc` reg)
  - Was the access a read or write? Was it an instruction fetch? Was it caused by user access to kernel-only memory?
- Hardware must allow resuming after a fault
- Idempotent instructions are easy
  - E.g., simple load or store instruction can be restarted
  - Just re-execute any instruction that only accesses one address

What to fetch

- Bring in page that caused page fault
- Pre-fetch surrounding pages?
  - Reading two disk blocks approximately as fast as reading one
  - As long as no track/head switch, seek time dominates
  - If application exhibits spacial locality, then big win to store and read multiple contiguous pages
- Also pre-zero unused pages in idle loop
  - Need 0-filled pages for stack, heap, anonymously mmapped memory
  - Zeroing them only on demand is slower
  - Hence, many OSes zero freed pages while CPU is idle

Selecting physical pages

- May need to eject some pages
  - More on eviction policy in two slides
- May also have a choice of physical pages
- Direct-mapped physical caches
  - Virtual $\rightarrow$ Physical mapping can affect performance
  - In old days: Physical address A conflicts with $\mathrm{kC} + \mathrm{A}$ (where k is any integer, C is cache size)
  - Applications can conflict with each other or themselves
  - Scientific applications benefit if consecutive virtual pages do not conflict in the cache
  - Many other applications do better with random mapping
  - These days: CPUs more sophisticated than $\mathrm{kC} + \mathrm{A}$

Superpages

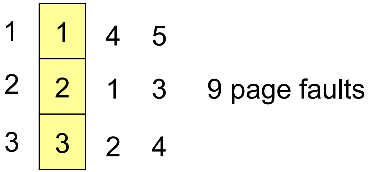
- How should OS make use of “large” mappings
  - x86 has 2/4MB pages that might be useful
  - Alpha has even more choices: 8KB, 64KB, 512KB, 4MB
- Sometimes more pages in L2 cache than TLB entries
  - Don’t want costly TLB misses going to main memory
- Or have two-level TLBs
  - Want to maximize hit rate in faster L1 TLB
- OS can transparently support superpages [Navarro]
  - “Reserve” appropriate physical pages if possible
  - Promote contiguous pages to superpages
  - Does complicate evicting (esp. dirty pages) – demote

Outline

1. Paging
2. Eviction policies
3. Thrashing
4. User-level API
5. Case study: 4.4 BSD

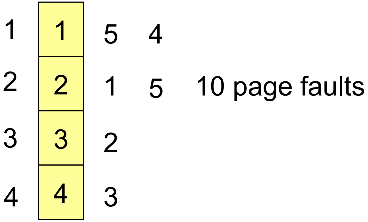
Straw man: FIFO eviction

- Evict oldest fetched page in system
- Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- 3 physical pages: 9 page faults

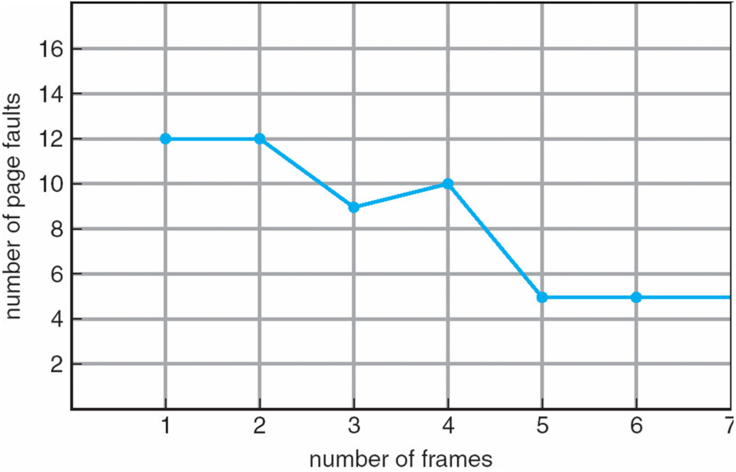


Straw man: FIFO eviction

- **Evict oldest fetched page in system**
- **Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5**
- **3 physical pages: 9 page faults**
- 4 physical pages: 10 page faults



Belady’s Anomaly



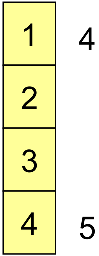
- More physical memory doesn’t always mean fewer faults

Optimal page replacement

- **What is optimal (if you knew the future)?**

Optimal page replacement

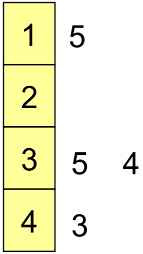
- What is optimal (if you knew the future)?
  - Replace page that will not be used for longest period of time
- Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- With 4 physical pages:



6 page faults

LRU page replacement

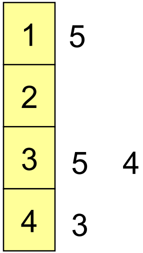
- Approximate optimal with *least recently used*
  - Because past often predicts the future
- Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- With 4 physical pages: 8 page faults



- Problem 1: Can be pessimal – example?
- Problem 2: How to implement?

LRU page replacement

- Approximate optimal with *least recently used*
  - Because past often predicts the future
- Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- With 4 physical pages: 8 page faults



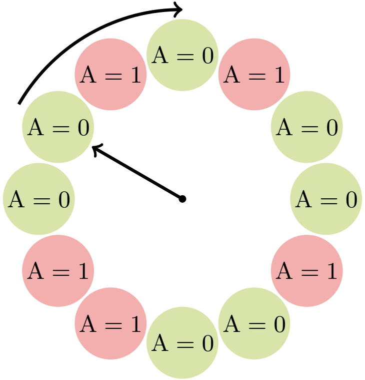
- Problem 1: Can be pessimal – example?
  - Looping over memory (then want MRU eviction)
- Problem 2: How to implement?

Straw man LRU implementations

- Stamp PTEs with timer value
  - E.g., CPU has cycle counter
  - Automatically writes value to PTE on each page access
  - Scan page table to find oldest counter value = LRU page
  - Problem: Would double memory traffic!
- Keep doubly-linked list of pages
  - On access remove page, place at tail of list
  - Problem: again, very expensive
- What to do?
  - Just approximate LRU, don't try to do it exactly

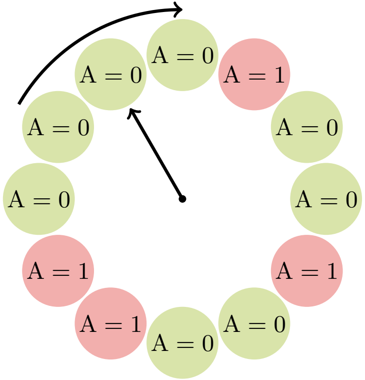
Clock algorithm

- Use accessed bit supported by most hardware
  - E.g., Pentium will write 1 to A bit in PTE on first access
  - Software managed TLBs like MIPS can do the same
- Do FIFO but skip accessed pages
- Keep pages in circular FIFO list
- Scan:
  - page's A bit = 1, set to 0 & skip
  - else if A = 0, evict
- A.k.a. second-chance replacement



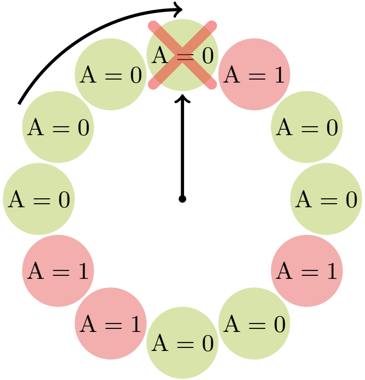
Clock algorithm

- Use accessed bit supported by most hardware
  - E.g., Pentium will write 1 to A bit in PTE on first access
  - Software managed TLBs like MIPS can do the same
- Do FIFO but skip accessed pages
- Keep pages in circular FIFO list
- Scan:
  - page's A bit = 1, set to 0 & skip
  - else if A = 0, evict
- A.k.a. second-chance replacement

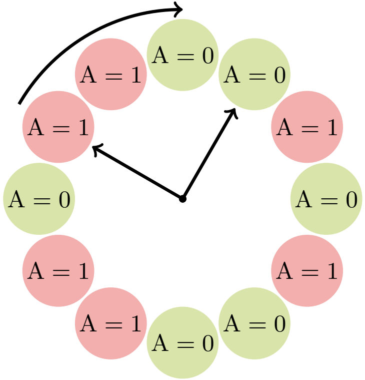


Clock algorithm

- Use accessed bit supported by most hardware
  - E.g., Pentium will write 1 to A bit in PTE on first access
  - Software managed TLBs like MIPS can do the same
- Do FIFO but skip accessed pages
- Keep pages in circular FIFO list
- Scan:
  - page's A bit = 1, set to 0 & skip
  - else if A = 0, evict
- A.k.a. second-chance replacement



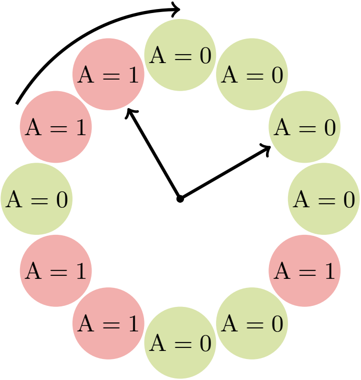
Clock algorithm (continued)

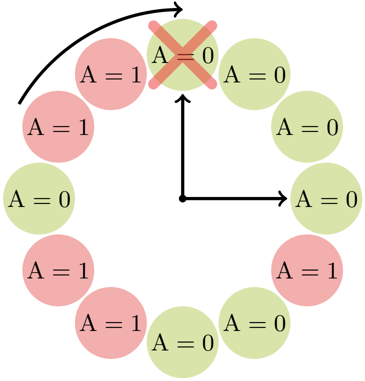


- Large memory may be a problem
  - Most pages referenced in long interval
- Add a second clock hand
  - Two hands move in lockstep
  - Leading hand clears A bits
  - Trailing hand evicts pages with A=0
- Can also take advantage of hardware Dirty bit
  - Each page can be (Unaccessed, Clean), (Unaccessed, Dirty), (Accessed, Clean), or (Accessed, Dirty)
  - Consider clean pages for eviction before dirty
- Or use n-bit accessed *count* instead just A bit
  - On sweep: *count* $= (A \ll (n-1)) \mid ($*count* $\gg 1)$ft
  - Evict page with lowest *count*

Clock algorithm (continued)

- Large memory may be a problem
  - Most pages referenced in long interval
- Add a second clock hand
  - Two hands move in lockstep
  - Leading hand clears A bits
  - Trailing hand evicts pages with A=0
- Can also take advantage of hardware Dirty bit
  - Each page can be (Unaccessed, Clean), (Unaccessed, Dirty), (Accessed, Clean), or (Accessed, Dirty)
  - Consider clean pages for eviction before dirty
- Or use n-bit accessed *count* instead just A bit
  - On sweep: *count* $= (\mathrm{A} \ll (\mathrm{n}-1)) \mid ($*count* $\gg 1)$ft
  - Evict page with lowest *count*



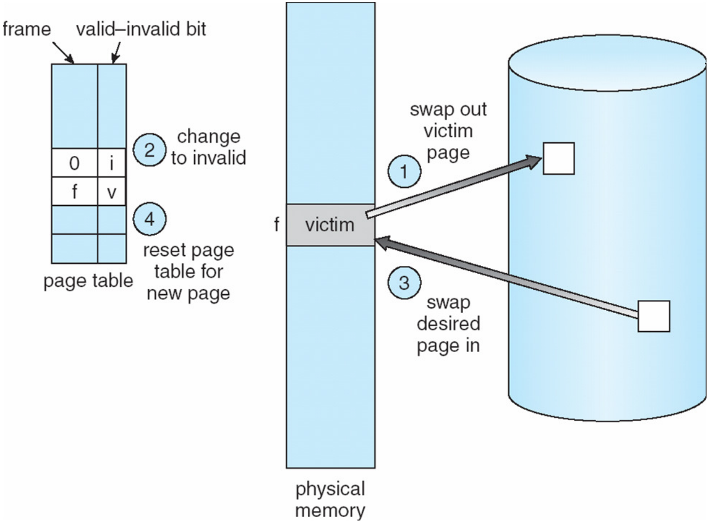


- Large memory may be a problem
  - Most pages referenced in long interval
- Add a second clock hand
  - Two hands move in lockstep
  - Leading hand clears A bits
  - Trailing hand evicts pages with A=0
- Can also take advantage of hardware Dirty bit
  - Each page can be (Unaccessed, Clean), (Unaccessed, Dirty), (Accessed, Clean), or (Accessed, Dirty)
  - Consider clean pages for eviction before dirty
- Or use n-bit accessed *count* instead just A bit
  - On sweep: $\mathit{count} = (\mathrm{A} \ll (n-1)) \mid (\mathit{count} \gg 1)$ft
  - Evict page with lowest *count*

Other replacement algorithms

- Random eviction
  - Simple to implement
  - Not overly horrible (avoids Belady & pathological cases)
  - Used in hypervisors to avoid double swap [Waldspurger]
- *LFU* (least frequently used) eviction
- *MFU* (most frequently used) algorithm
- Neither LFU nor MFU used very commonly
- Workload specific policies: Databases

Naïve paging



- Naïve page replacement: 2 disk I/Os per page fault

Page buffering

- Idea: reduce # of I/Os on the critical path
- Keep pool of free page frames
  - On fault, still select victim page to evict
  - But read fetched page into already free page
  - Can resume execution while writing out victim page
  - Then add victim page to free pool
- Can also yank pages back from free pool
  - Contains only clean pages, but may still have data
  - If page fault on page still in free pool, recycle

Page allocation

- Allocation can be *global* or *local*
- Global allocation doesn't consider page ownership
  - E.g., with LRU, evict least recently used page of any proc
  - Works well if P_1 needs 20% of memory and P_2 needs 70%:

  - Doesn't protect you from memory pigs
    (imagine P_2 keeps looping through array that is size of mem)
- Local allocation isolates processes (or users)
  - Separately determine how much memory each process should have
  - Then use LRU/clock/etc. to determine which pages to evict within each process

Outline

1. Paging
2. Eviction policies
3. Thrashing
4. User-level API
5. Case study: 4.4 BSD

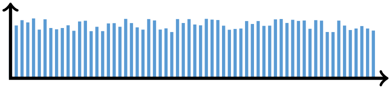
Thrashing

Thrashing is when an application is in a constantly swapping pages in and out preventing the application from making forward progress at any reasonable rate.

- Processes require more memory than system has
  - Each time one page is brought in, another page, whose contents will soon be referenced, is thrown out
  - Processes will spend all of their time blocked, waiting for pages to be fetched from disk
  - I/O devs at 100% utilization but system not getting much useful work done
- What we wanted: virtual memory the size of disk with access time the speed of physical memory
- What we got: memory with access time of disk

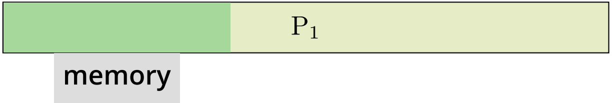
Reasons for thrashing

- Access pattern has no temporal locality (past $\neq$ future)

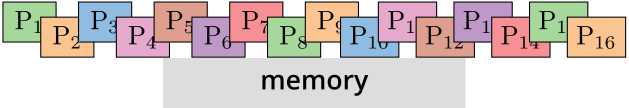


(80/20 rule has broken down)

- Hot memory does not fit in physical memory



- Each process fits individually, but too many for system

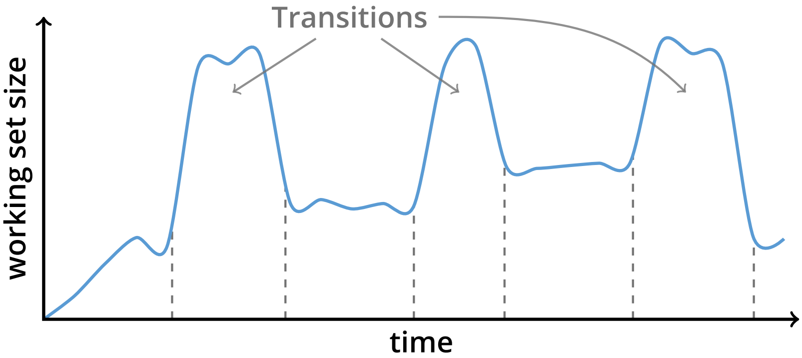


  - At least this case is possible to address

Dealing with thrashing

- Approach 1: working set
  - Thrashing viewed from a caching perspective: given locality of reference, how big a cache does the process need?
  - Or: how much memory does the process need in order to make reasonable progress (its working set)?
  - Only run processes whose memory requirements can be satisfied
- Approach 2: page fault frequency
  - Thrashing viewed as poor ratio of fetch to work
  - PFF = page faults / instructions executed
  - If PFF rises above threshold, process needs more memory.
    Not enough memory on the system? Swap out.
  - If PFF sinks below threshold, memory can be taken away

Working sets

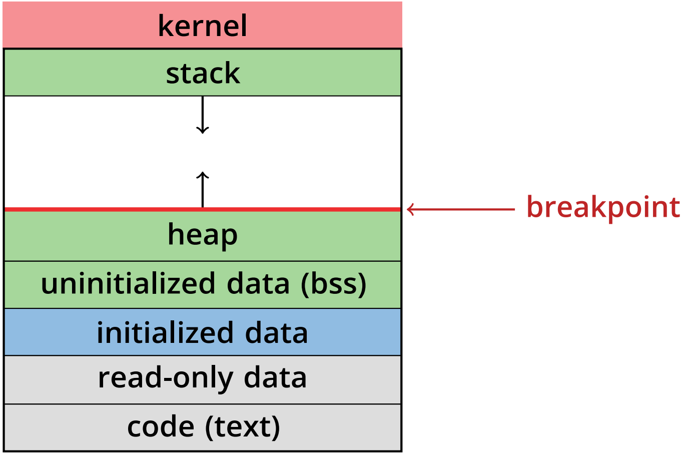


- Working set changes across phases
  - Baloons during phase transitions

Outline

1. Paging
2. Eviction policies
3. Thrashing
4. User-level API
5. Case study: 4.4 BSD

Recall typical virtual address space

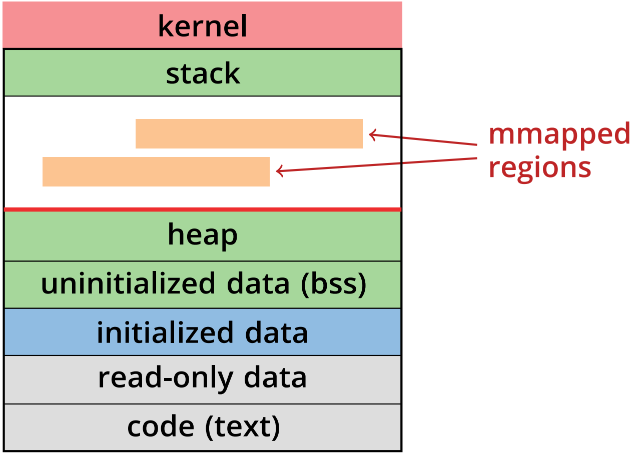


- Dynamically allocated memory goes in heap
- Top of heap called *breakpoint*
  - Addresses between breakpoint and stack all invalid

Early VM system calls

- OS keeps "Breakpoint" – top of heap
  - Memory regions between breakpoint & stack fault on access
- `char *brk (const char *addr);`
  - Set and return new value of breakpoint
- `char *sbrk (int incr);`
  - Increment value of the breakpoint & return old value
- Can implement `malloc` in terms of `sbrk`
  - But hard to "give back" physical memory to system

Memory mapped files



- Other memory objects between heap and stack

mmap system call

- ```
  void *mmap (void *addr, size_t len, int prot,
              int flags, int fd, off_t offset)
  ```
  - Map file specified by `fd` at virtual address `addr`
  - If `addr` is null, let kernel choose the address
- `prot` – protection of region
  - OR of prot_exec, prot_read, prot_write, prot_none
- `flags`
  - map_anon – anonymous memory (`fd` should be -1)
  - map_private – modifications are private
  - map_shared – modifications seen by everyone
  ```

More VM system calls

- `int munmap(void *addr, size_t len)`
  - Removes memory-mapped object
- `int mprotect(void *addr, size_t len, int prot)`
  - Changes protection on pages to or of `PROT_...`
- `int msync(void *addr, size_t len, int flags);`
  - Flush changes of mmapped file to backing store
- `int mincore(void *addr, size_t len, char *vec)`
  - Returns in `vec` which pages present
- `int madvise(void *addr, size_t len, int behav)`
  - Advise the OS on memory use

Exposing page faults

```
struct sigaction {
  union {             /* signal handler */
    void (*sa_handler)(int);
    void (*sa_sigaction)(int, siginfo_t *, void *);
  };
  sigset_t sa_mask; /* signal mask to apply */
  int sa_flags;
};

int sigaction (int sig, const struct sigaction *act,
               struct sigaction *oact)
```

- Can specify function to run on SIGSEGV
  (Unix signal raised on invalid memory access)

Example: OpenBSD/i386 siginfo

```
struct sigcontext {
  int sc_gs; int sc_fs; int sc_es; int sc_ds;
  int sc_edi; int sc_esi; int sc_ebp; int sc_ebx;
  int sc_edx; int sc_ecx; int sc_eax;

  int sc_eip; int sc_cs; /* instruction pointer */
  int sc_eflags;         /* condition codes, etc. */
  int sc_esp; int sc_ss; /* stack pointer */

  int sc_onstack;        /* sigstack state to restore */
  int sc_mask;           /* signal mask to restore */

  int sc_trapno;
  int sc_err;
};
```

- Linux uses `ucontext_t` – same idea, just uses nested structures that won't all fit on one slide

VM tricks at user level

- Combination of `mprotect`/`sigaction` very powerful
  - Can use OS VM tricks in user-level programs [Appel]
  - E.g., fault, unprotect page, return from signal handler
- Technique used in object-oriented databases
  - Bring in objects on demand
  - Keep track of which objects may be dirty
  - Manage memory as a cache for much larger object DB
- Other interesting applications
  - Useful for some garbage collection algorithms
  - Snapshot processes (copy on write)

Outline

Overview

- Windows and most UNIX systems seperate the VM system into two parts
  - *VM PMap*: Manages the hardware interface (e.g. TLB in MIPS)
  - *VM Map*: Machine independent representation of memory
- 4.4 BSD VM is based on [Mach VM]
- VM Map consists of one or more *objects* (or *segments*)
- Each object consists of a contiguous `mmap()`
- Objects can be backed by files and/or shared between processes
- VM PMap manages the hardware (often caches mappings)

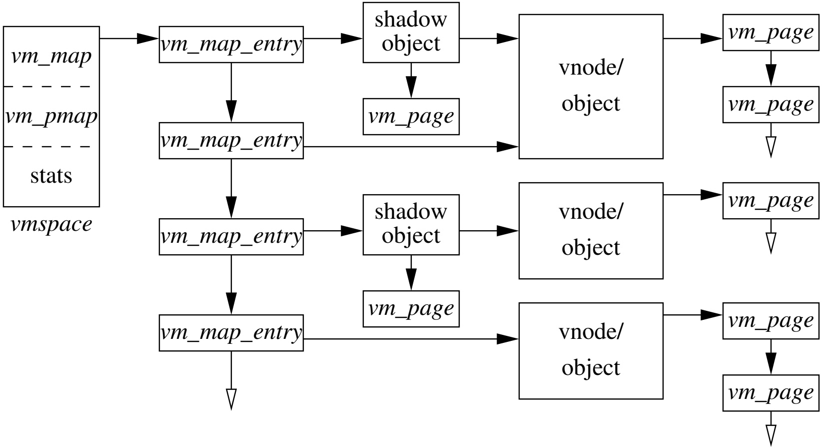
Operation

- Calls into `mmap()`, `munmap()`, `mprotect()`
  - Update VM Map
  - VM Map routines call into the VM PMap to invalidate and update the TLB
- Page faults
  - Exception handler calls into the VM PMap to load the TLB
  - If the page isn't in the PMap we call VM Map code
- Low memory options
  - PMap is a cache and can be discarded during a low memory condition

4.4 BSD VM system [McKusick]

- Each process has a *vmspace* structure containing
  - *vm_map* – machine-independent virtual address space
  - *vm_pmap* – machine-dependent data structures
  - statistics – e.g. for syscalls like *getrusage ()*
- *vm_map* is a linked list of *vm_map_entry* structs
  - *vm_map_entry* covers contiguous virtual memory
  - points to *vm_object* struct
- *vm_object* is source of data
  - e.g. vnode object for memory mapped file
  - points to list of *vm_page* structs (one per mapped page)
  - *shadow objects* point to other objects for copy on write

4.4 BSD VM data structures



Pmap (machine-dependent) layer

- Pmap layer holds architecture-specific VM code
- VM layer invokes pmap layer
  - On page faults to install mappings
  - To protect or unmap pages
  - To ask for dirty/accessed bits
- Pmap layer is lazy and can discard mappings
  - No need to notify VM layer
  - Process will fault and VM layer must reinstall mapping
- Pmap handles restrictions imposed by cache

Example uses

- *vm_map_entry* structs for a process
  - r/o text segment $\rightarrow$ file object
  - r/w data segment $\rightarrow$ shadow object $\rightarrow$ file object
  - r/w stack $\rightarrow$ anonymous object
- New *vm_map_entry* objects after a fork:
  - Share text segment directly (read-only)
  - Share data through two new shadow objects (must share pre-fork but not post-fork changes)
  - Share stack through two new shadow objects
- Must discard/collapse superfluous shadows
  - E.g., when child process exits

What happens on a fault?

- Traverse *vm_map_entry* list to get appropriate entry
  - No entry? Protection violation? Send process a SIGSEGV
- Traverse list of [shadow] objects
- For each object, traverse *vm_page* structs
- Found a *vm_page* for this object?
  - If first *vm_object* in chain, map page
  - If read fault, install page read only
  - Else if write fault, install copy of page
- Else get page from object
  - Page in from file, zero-fill new page, etc.

Paging in day-to-day use

- Demand paging
  - Read pages from *vm_object* of executable file
- Copy-on-write (`fork`, `mmap`, etc.)
  - Use shadow objects
- Growing the stack, BSS page allocation
  - A bit like copy-on-write for `/dev/zero`
  - Can have a single read-only zero page for reading
  - Special-case write handling with pre-zeroed pages
- Shared text, shared libraries
  - Share *vm_object* (shadow will be empty where read-only)
- Shared memory
  - Two processes `mmap` same file, have same *vm_object* (no shadow)