INF333 - Operating Systems

Lecture VII

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Lecture VII
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Course website

burakarslan.com/inf333

Based On

cs111.stanford.edu

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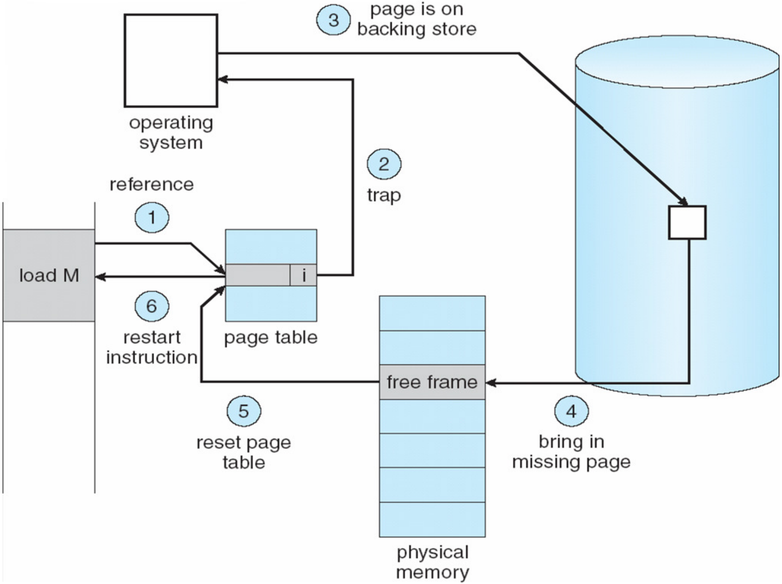
OSC-10 Slides

Virtual Memory

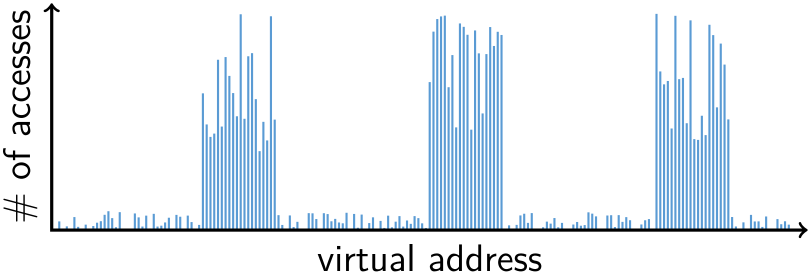
Chapter II

Paging



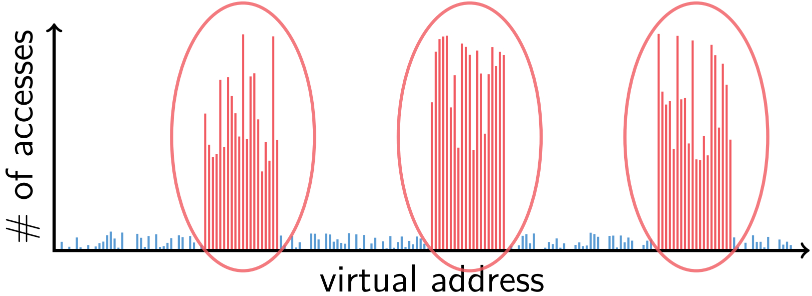
- Use disk to simulate larger virtual than physical mem

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



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  - 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 may have been in the middle of an instruction!

What to fetch from disk?

- Just needed page or more?

What to evict?

- How to allocate physical pages amongst processes?
- Which of a particular process's pages to keep in memory?

Re-starting instructions

Hardware must allow resuming after a fault

HW provides kernel with information about page fault:

- Faulting virtual address (In `%cr2` reg on x86—may see it if you modify Pintos `page_fault` and use `fault_addr`)
- Address of instruction that caused fault
- Was the access a read or a write? Was it an instr. fetch? Was it caused by user access to kernel-only memory?

Re-starting instructions

Observation: **Idempotent** instructions are easy to restart

- E.g., simple load or store instruction can be restarted
- Just re-execute any instruction that only accesses one address

Re-starting instructions

Complex instructions must be re-started, too

- E.g., x86 move string instructions
- Specify src, dst, count in `%esi`, `%edi`, `%ecx` registers
- On fault, registers adjusted to resume where move left off

What to fetch

Bring in page that caused page fault:

- Pre-fetch surrounding pages?
  - Reading 2 disk blocks approximately as fast as reading 1
  - As long as no track/head switch, seek time dominates
  - If application exhibits spacial locality, then it's a 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 evict some pages
- May also have a choice of physical pages

Superpages

- How should OS make use of "large" mappings
  - x86 has 2/4MiB pages that might be useful
  - Alpha has even more choices: 8KiB, 64KiB, 512KiB, 4MiB
- Sometimes more pages in L2 cache than TLB entries
  - Don't want costly TLB misses going to main memory
  - Try cpuid tool to find CPU's TLB configuration on linux...
    then compare to cache size reported by lscpu
- 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 eviction (esp. dirty pages) – demote

Minor vs Major Page faults

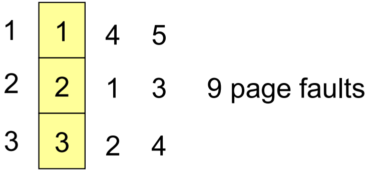
Linux-specific description:

`MAJFLT` Major faults are the number of page faults that caused Linux to read a page from disk on behalf of the process.

`MINFLT` Minor faults are the number of faults that Linux could fulfill without resorting to a disk read.

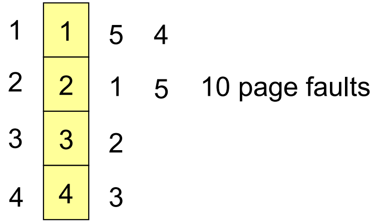
Straw man: FIFO eviction

- 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

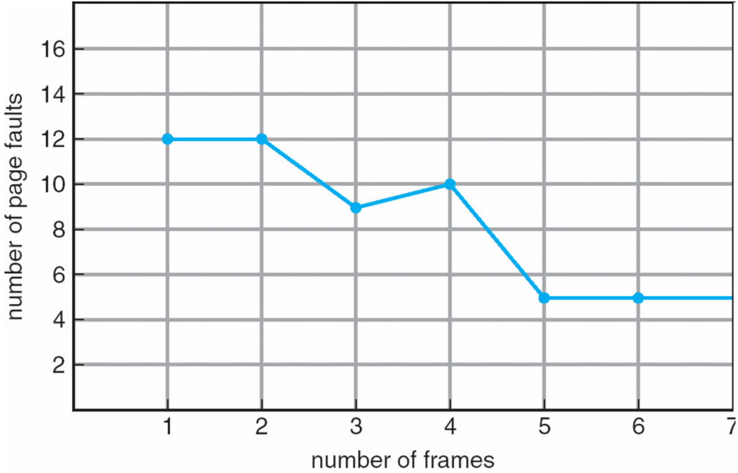


Straw man: FIFO eviction

- 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



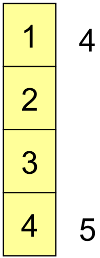
- More physical memory doesn't always mean fewer faults

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:

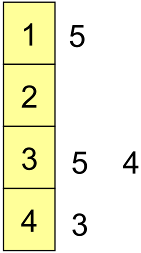


6 page faults

- What do we do when an OS can't predict the future?

LRU page replacement

- Approximate optimal with *least recently used*
- 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

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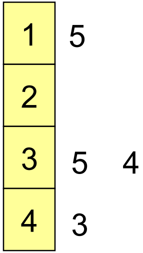

- Problem 1: Can be pessimal — example?
  - Looping over memory (then want MRU eviction)
- Problem 2: How to implement?

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:

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- Keep doubly-linked list of pages
  - On access remove page, place at tail of list
  - Problem: again, very expensive

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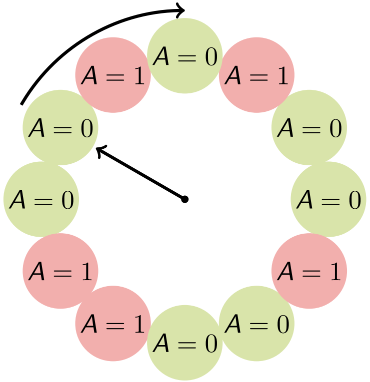
  - Problem: Would double memory traffic!
- Keep doubly-linked list of pages
  - On access remove page, place at tail of list
  - Problem: again, very expensive
- What to do?
  - Just approximate LRU, don't try to do it exactly

Clock algorithm

- Use accessed bit supported by most hardware
  - E.g., x86 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



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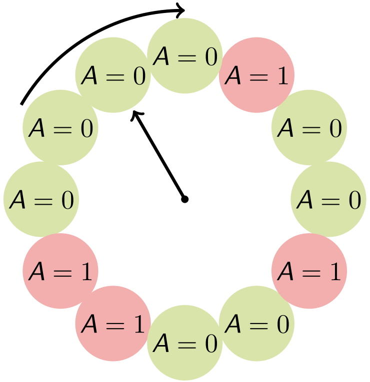

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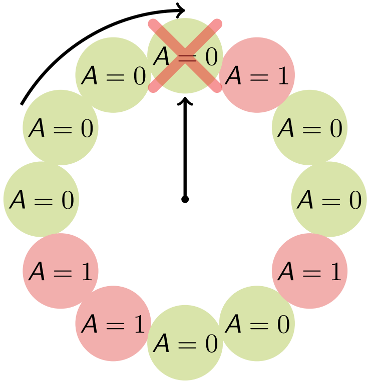
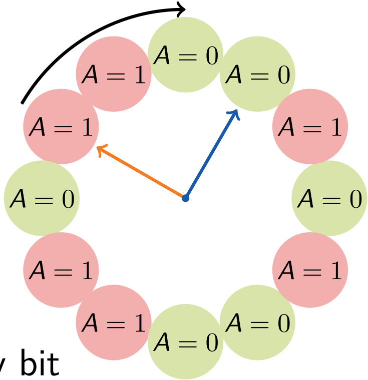
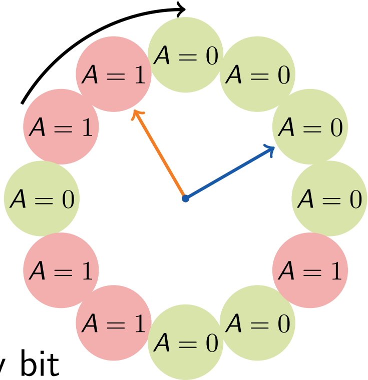


Clock algorithm (continued)



- 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: $count = (A \ll (n-1)) \mid (count \gg 1)$
  - Evict page with lowest *count*

Clock algorithm (continued)



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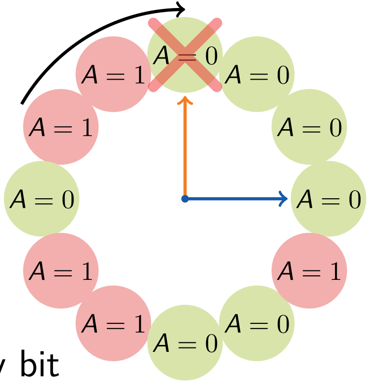

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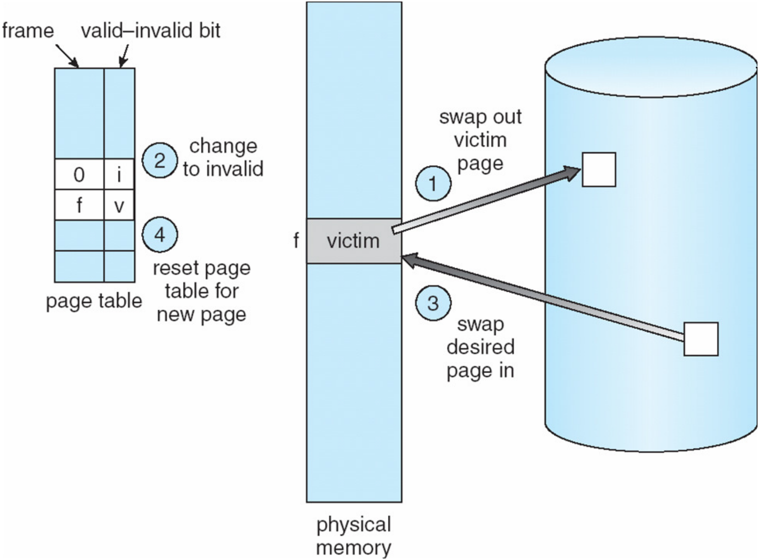
Other replacement algorithms

- Random eviction
  - Dirt simple to implement
  - Not overly horrible (avoids Belady & pathological cases)
- *LFU* (least frequently used) eviction
  - Instead of just A bit, count # times each page accessed
  - Least frequently accessed must not be very useful
    (or maybe was just brought in and is about to be used)
  - Decay usage counts over time (for pages that fall out of usage)
- *MFU* (most frequently used) algorithm
  - Because page with the smallest count was probably just brought in and has yet to be used
- Neither LFU nor MFU used very commonly

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%:

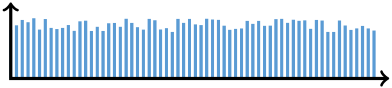
  - Doesn't protect you from memory pigs
    (imagine P_2 keeps looping through array that is size of mem)
- Local allocation isolates processes (or users)
  - Separately determine how much memory each process should have
  - Then use LRU/clock/etc. to determine which pages to evict within each process

Thrashing

- 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
  - Disk 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

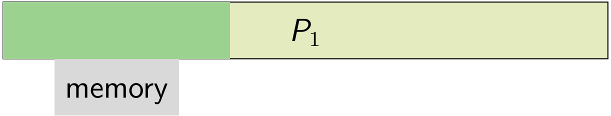
Reasons for thrashing

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

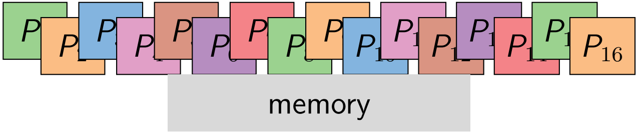


(80/20 rule has broken down)

- Hot memory does not fit in physical memory

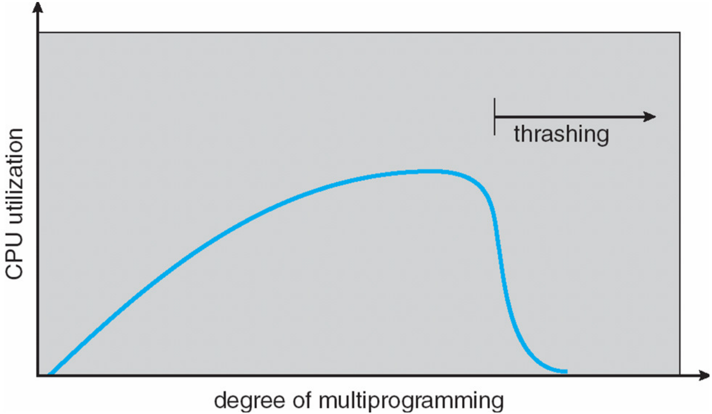


- Each process fits individually, but too many for system



  - At least this case is possible to address

Multiprogramming & Thrashing

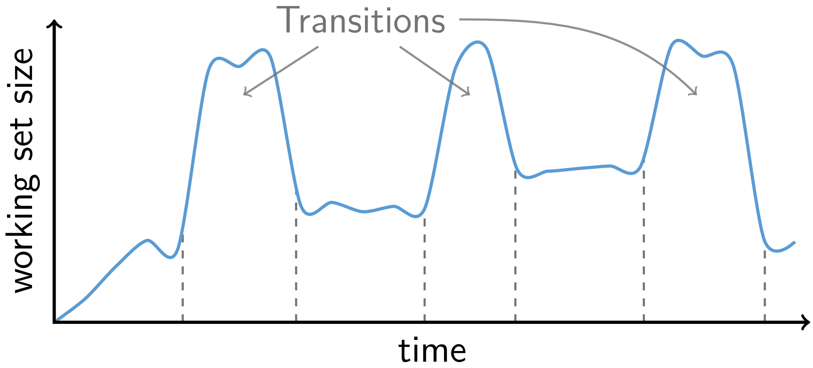


- Must shed load when thrashing

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

Calculating the working set

- Working set: all pages that process will access in next T time
  - Can't calculate without predicting future
- Approximate by assuming past predicts future
  - So working set $\approx$ pages accessed in last T time
- Keep idle time for each page
- Periodically scan all resident pages in system
  - **A** bit set? Clear it and clear the page's idle time
  - **A** bit clear? Add CPU consumed since last scan to idle time
  - Working set is pages with idle time $< T$

Two-level scheduler

- Divide processes into *active* & *inactive*
  - Active – means working set resident in memory
  - Inactive – working set intentionally not loaded
- Balance set: union of all active working sets
  - Must keep balance set smaller than physical memory
- Use long-term scheduler [L05S29]
  - Moves procs active $\rightarrow$ inactive until balance set small enough
  - Periodically allows inactive to become active
  - As working set changes, must update balance set
- Complications
  - How to chose idle time threshold T?
  - How to pick processes for active set
  - How to count shared memory (e.g., libc.so)

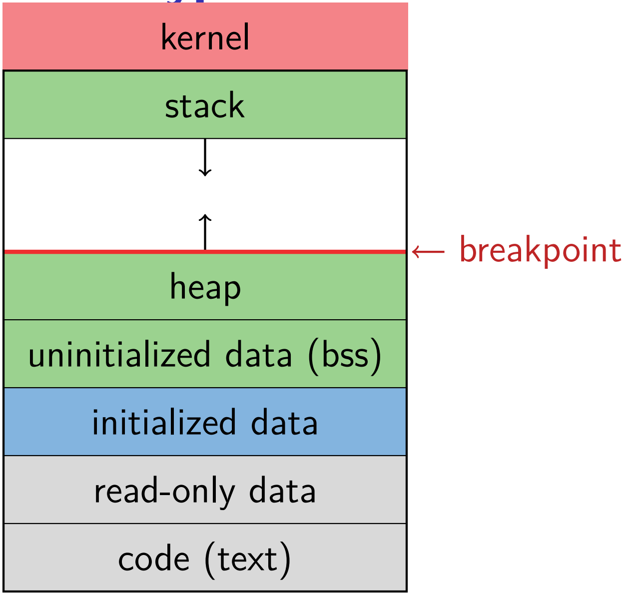
Some complications of paging

- What happens to available memory?
  - Some physical memory tied up by kernel VM structures
- What happens to user/kernel crossings?
  - More crossings into kernel
  - Pointers in syscall arguments must be checked
    (can't just kill process if page not present—might need to page in)
- What happens to IPC?
  - Must change hardware address space
  - Increases TLB misses
  - Context switch flushes TLB entirely on old x86 machines
    (But not on MIPS because MIPS tags TLB entries with PID)

64-bit address spaces

- Recall x86-64 only has 48-bit virtual address space
- What if you want a 64-bit virtual address space?
  - Straight hierarchical page tables not efficient
  - But software TLBs (like MIPS) allow other possibilities
- Solution 1: Hashed page tables
  - Store Virtual $\rightarrow$ Physical translations in hash table
  - Table size proportional to physical memory
  - Clustering makes this more efficient [Talluri]
- Solution 2: Guarded page tables [Liedtke]
  - Omit intermediary tables with only one entry
  - Add predicate in high level tables, stating the only virtual address range mapped underneath + # bits to skip

Recall typical virtual address space

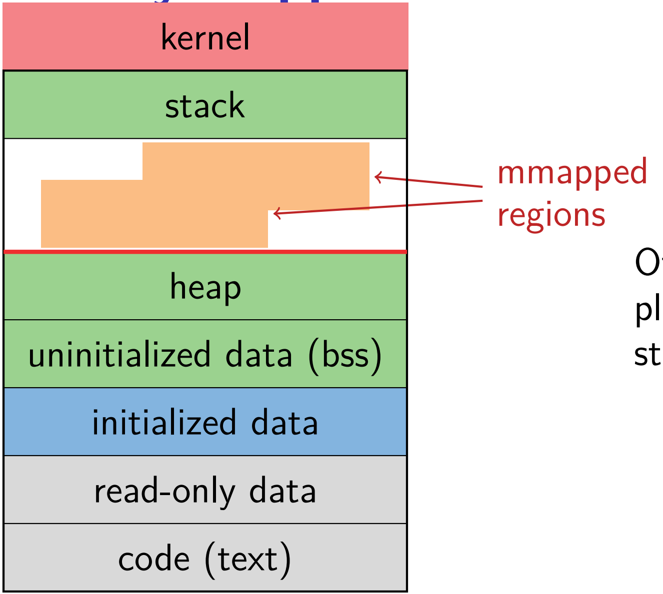


- Dynamically allocated memory goes in heap
- Top of heap called *breakpoint*
  - Addresses between breakpoint and stack all invalid

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 are placed 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 msync(void *addr, size_t len, int flags);`
  - Flush changes of mmapped file to backing store
- `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 bitwise or of some `PROT_`...values
- `int mincore(void *addr, size_t len, char *vec)`
  - Returns in `vec` which pages present

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

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 nested structures that won't all fit on one slide

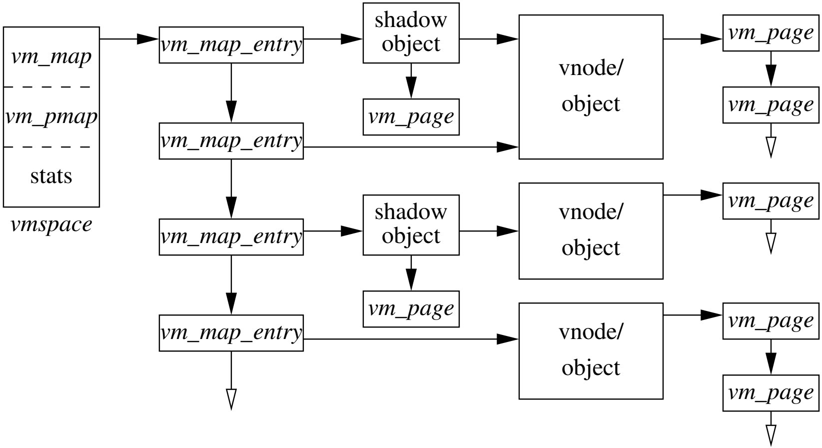
VM tricks at user level

- 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)

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 → file object
    - r/w data segment → shadow object → file object
    - r/w stack → 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)