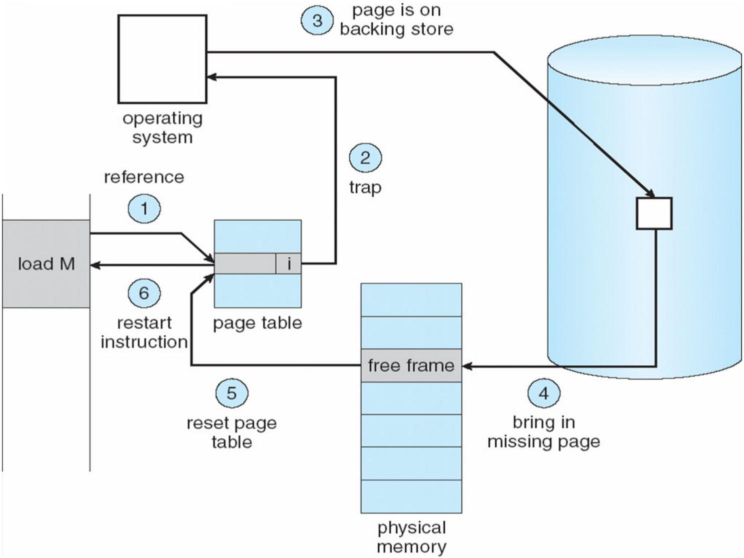
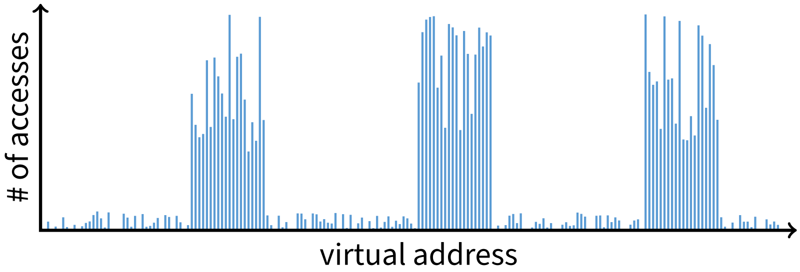
Outline

Paging



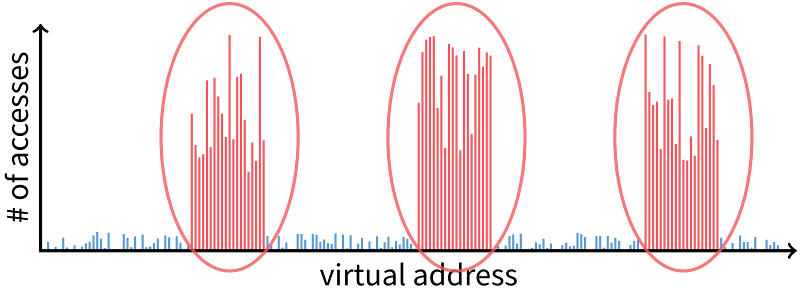
- **Use disk to simulate larger virtual than physical mem**

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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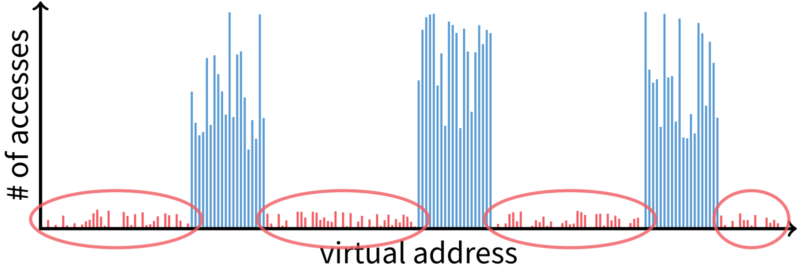

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- **80/20 rule: 20% of memory gets 80% of memory accesses**
  - Keep the hot 20% in memory

  ⟶ Keep the cold 80% on disk

Paging challenges

- **How to resume a process after a fault?**
  - Need to save state and resume
  - Process may 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 must allow resuming after a fault**
- **Hardware 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 write? Was it an instruction fetch? Was it caused by user access to kernel-only memory?
- **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
- **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 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 $kC + A$ (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
- **Set associative caches (more common)**
  - Multiple (e.g., 2–4) possible slots for each physical address
  - Historically n-way associative cache chooses line by $A \bmod (C/n)$
  - These days: CPUs use more sophisticated mapping [Hund]

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 evicting (esp. dirty pages) – demote

Outline

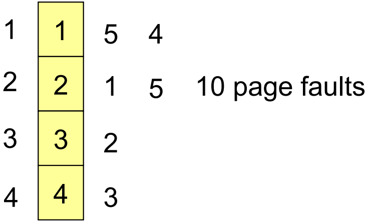
Straw man: FIFO eviction

- 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

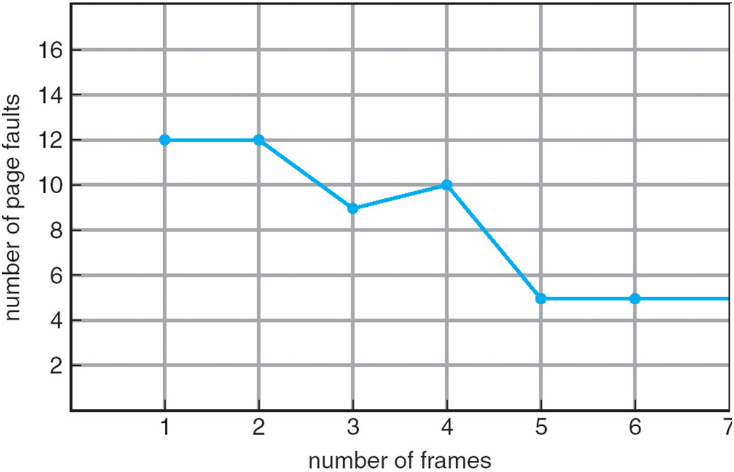
1	1	4	5	
2	2	1	3	9 page faults
3	3	2	4	

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



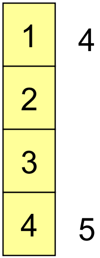
- **More physical memory doesn't always mean fewer faults**

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:**

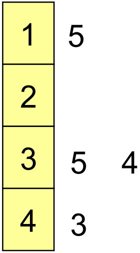


6 page faults

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

LRU page replacement

- **Approximate optimal with *least recently used***
  - 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

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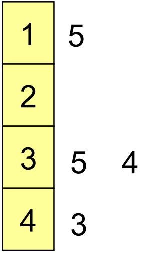


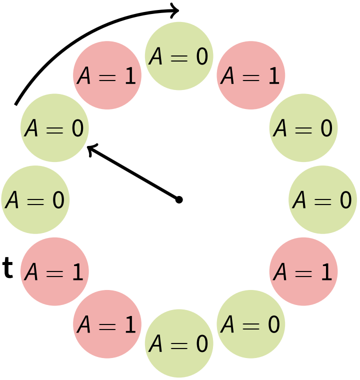
- **Problem 1: Can be pessimal – example?**
  - Looping over memory (then want MRU eviction)
- **Problem 2: How to implement?**

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: 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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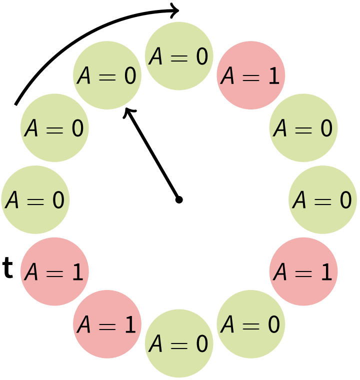

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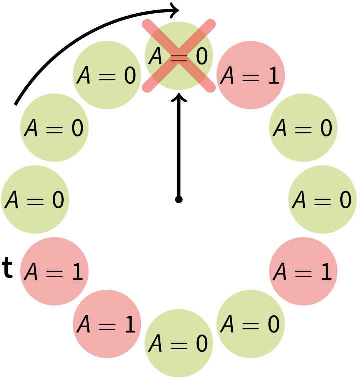
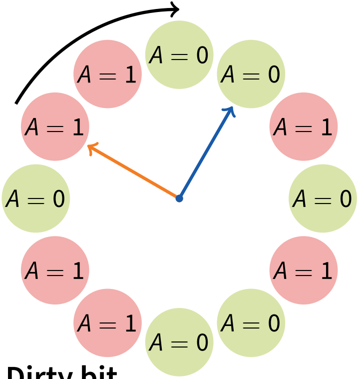


Clock algorithm (continued)



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  - 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*

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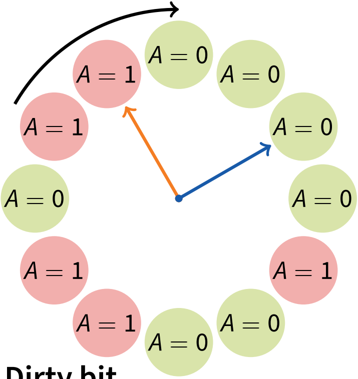

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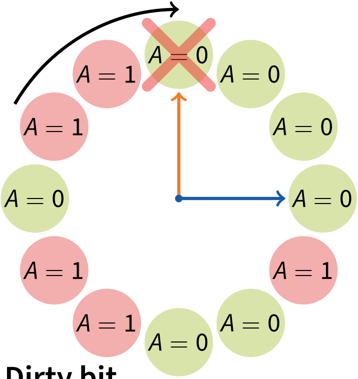

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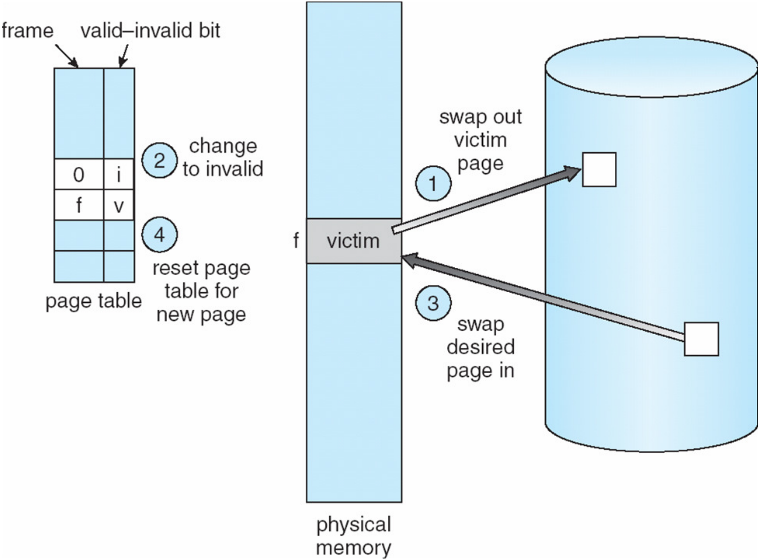
Other replacement algorithms

- **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

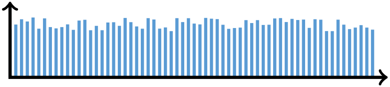
Outline

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**

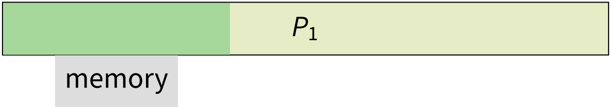
Reasons for thrashing

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

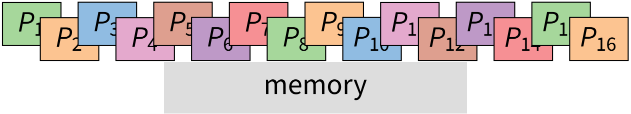


(80/20 rule has broken down)

- **Hot memory does not fit in physical memory**

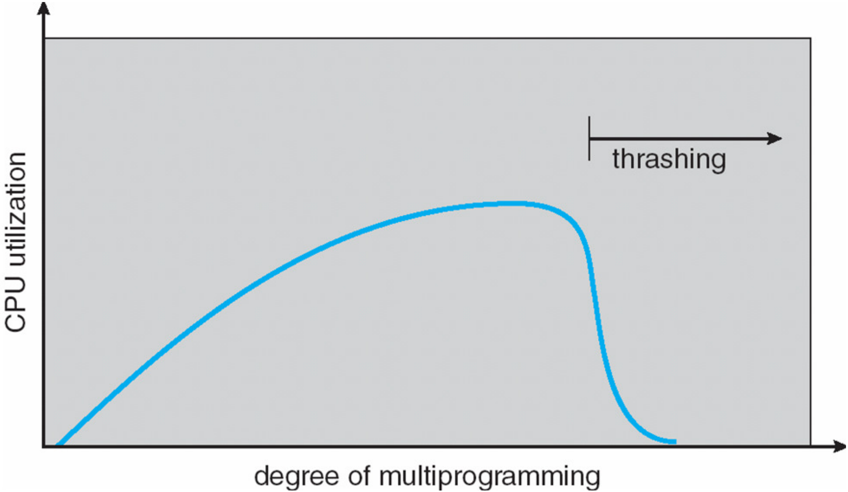


- **Each process fits individually, but too many for system**



  - At least this case is possible to address

Multiprogramming & Thrashing

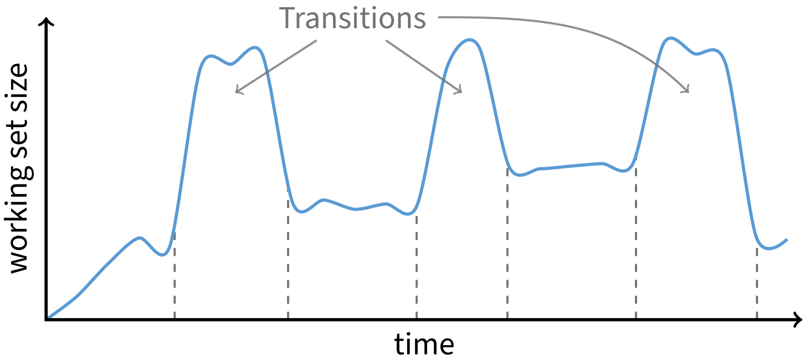


- **Must shed load when thrashing**

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 [recall from lecture 4]**
  - 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)

Outline

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…Why?)

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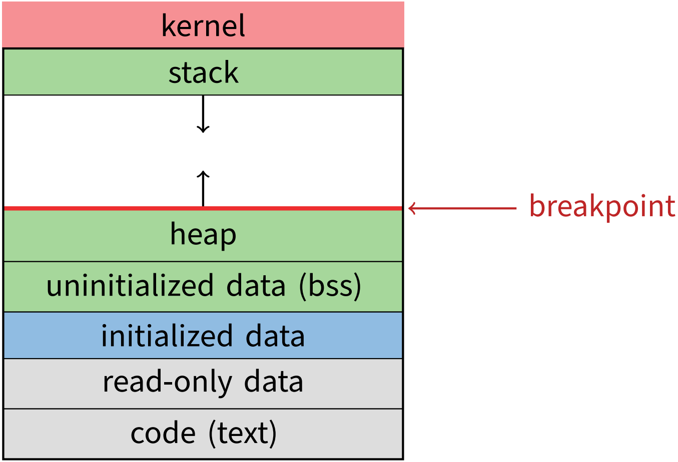
  - Context switch flushes TLB entirely on old x86 machines
    (But not on MIPS. . . Why? MIPS tags TLB entries with PID)

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 → 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

Outline

Recall typical virtual address space

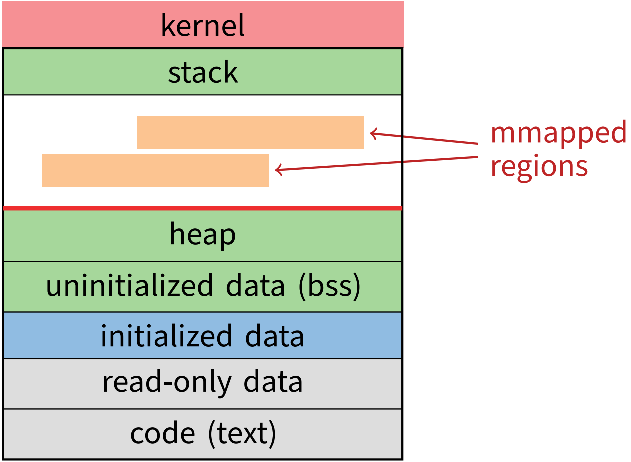


- **Dynamically allocated memory goes in heap**
- **Top of heap called *breakpoint***
  - Addresses between breakpoint and stack all invalid

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 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` **(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

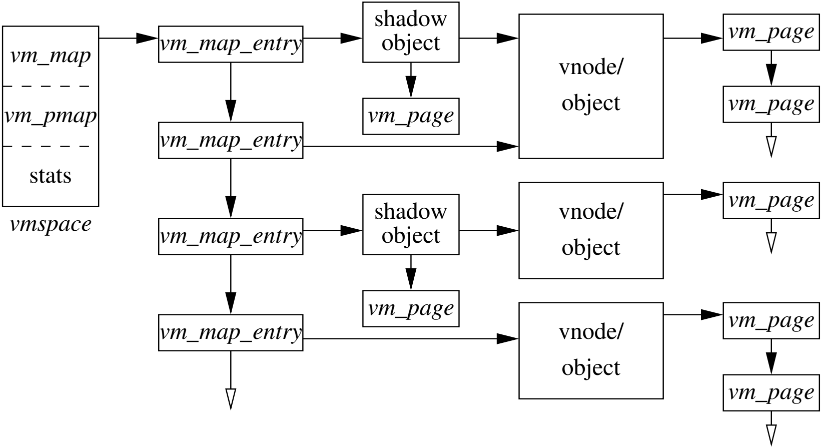
1. Paging
2. Eviction policies
3. Thrashing
4. Details of paging
5. The user-level perspective
6. Case study: 4.4 BSD

4.4 BSD VM system [McKusick][1]

- **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

[1] Use link on searchworks page for access

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)