Lecture 13: Virtual Memory

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Quote of the Day

"A good programmer is someone who always looks both ways before crossing a one-way street."

-- Doug Linder

Chapter 9: Virtual Memory

- Background
- Demand Paging
- Copy-on-Write
- Page Replacement
- Allocation of Frames
- Thrashing
- Memory-Mapped Files
- Allocating Kernel Memory
- Other Considerations
- Operating-System Examples

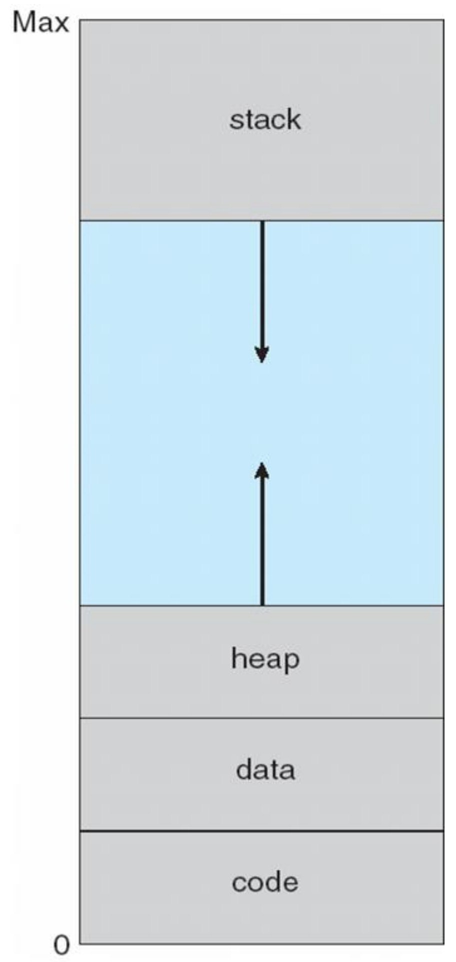
Objectives

- To describe the benefits of a virtual memory system
- To explain the concepts of demand paging, page-replacement algorithms, and allocation of page frames
- To discuss the principle of the working-set model

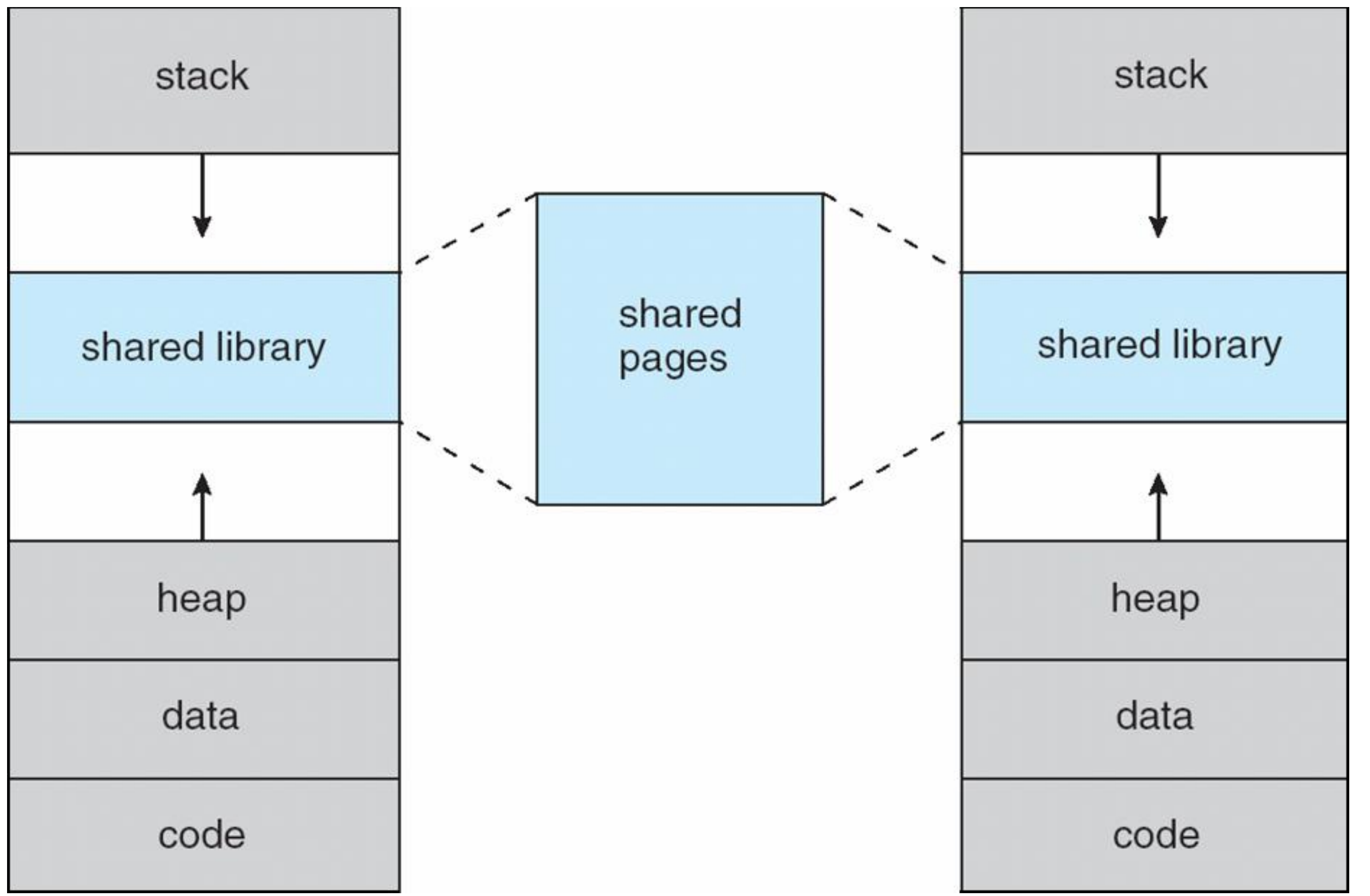
Background

- **Virtual memory** – separation of user logical memory from physical memory.
  - Only part of the program needs to be in memory for execution
  - Logical address space can therefore be much larger than physical address space
  - Allows address spaces to be shared by several processes
  - Allows for more efficient process creation
- Virtual memory can be implemented via:
  - Demand paging
  - Demand segmentation

Virtual-address Space



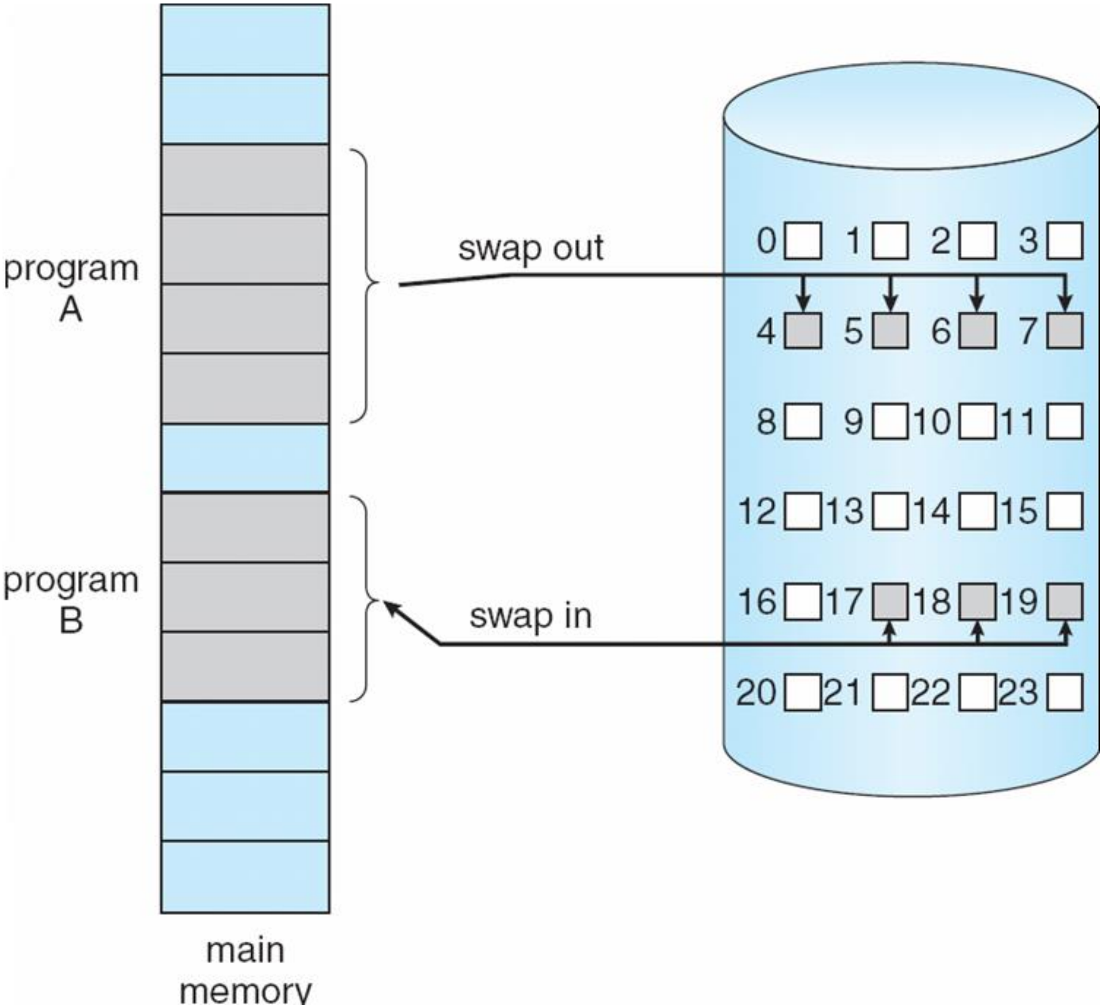
Shared Library Using Virtual Memory



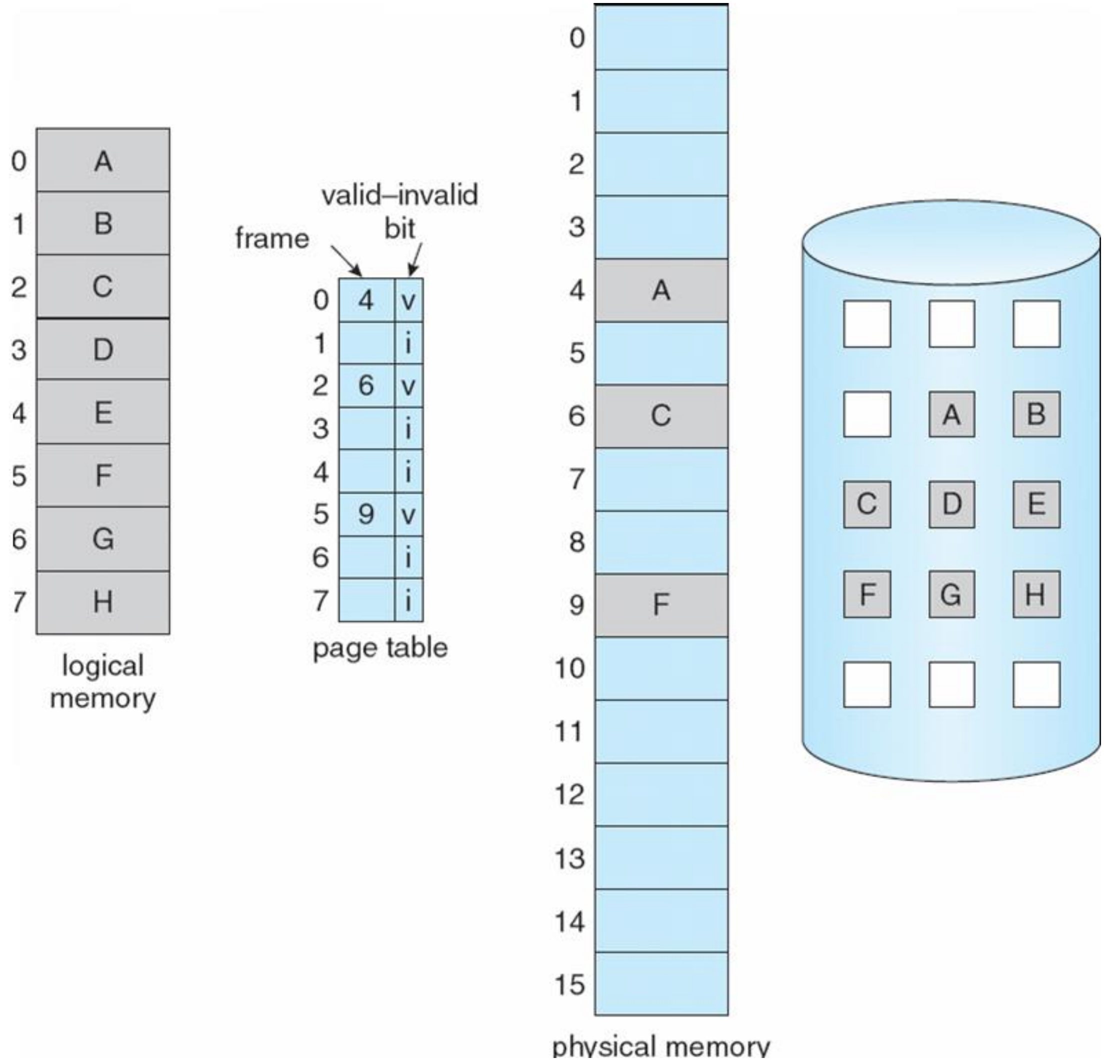
Demand Paging

- Bring a page into memory only when it is needed
  - Less I/O needed
  - Less memory needed
  - Faster response
  - More users
- Page is needed $\Rightarrow$ reference to it
  - Invalid reference $\Rightarrow$ abort
  - Page not in memory $\Rightarrow$ bring page into memory
- **Lazy swapper** – never swaps a page into memory unless page will be needed
  - Swapper that deals with pages is a **pager**

Transfer of a Paged Memory to Contiguous Disk Space



Page Table When Some Pages Are Not in Main Memory



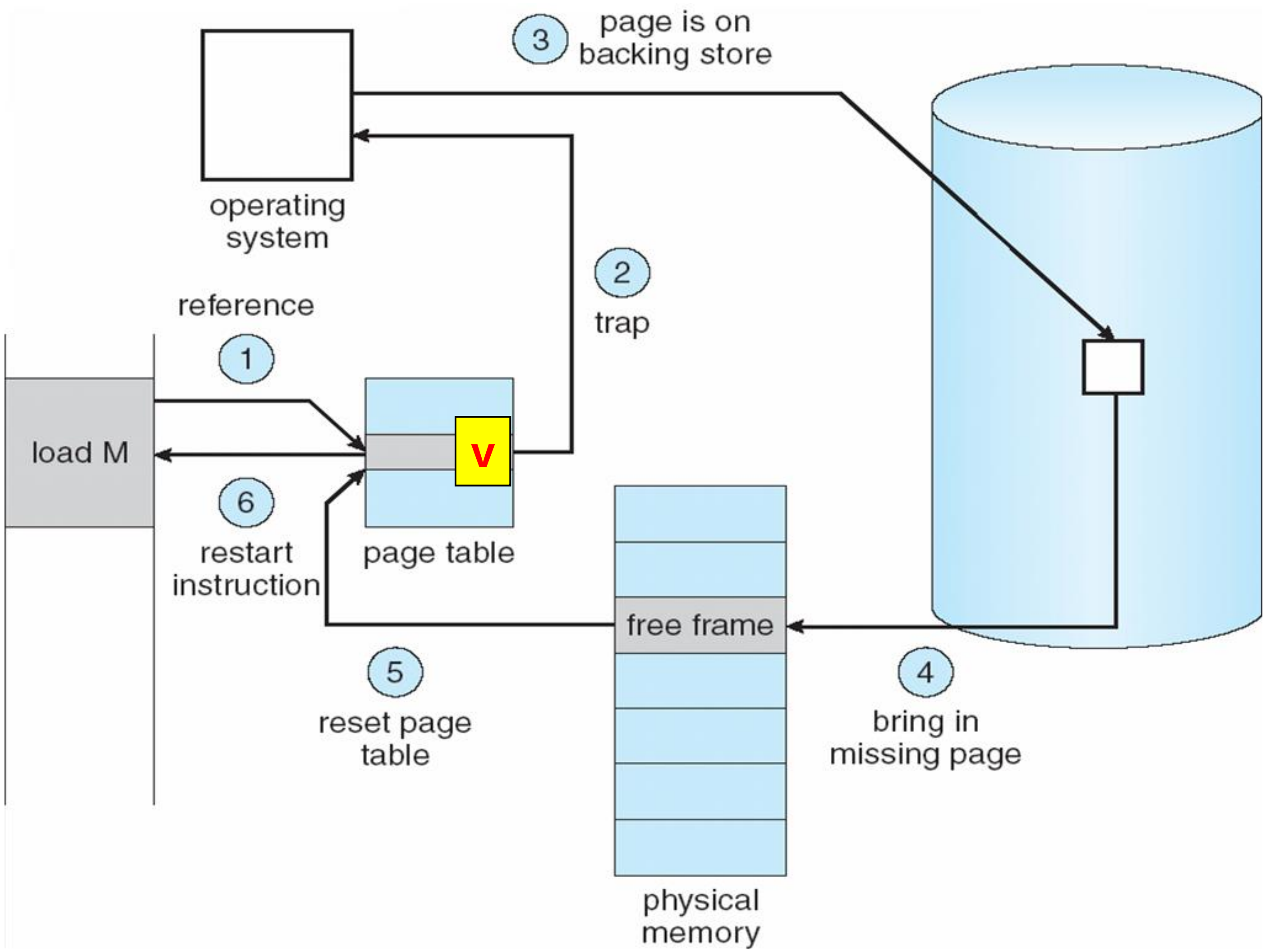
- With each page table entry a valid–invalid bit is associated (**v** ⇒ in-memory, **i** ⇒ not-in-memory)

Page Fault

- If there is a reference to a page, first reference to that page will trap to operating system: **page fault**

1. Operating system looks at page table to decide:
   - Invalid reference $\Rightarrow$ abort
   - Just not in memory
2. Get empty frame
3. Swap page into frame
4. Reset tables
5. Set validation bit = **v**
6. Restart the instruction that caused the page fault

Steps in Handling a Page Fault

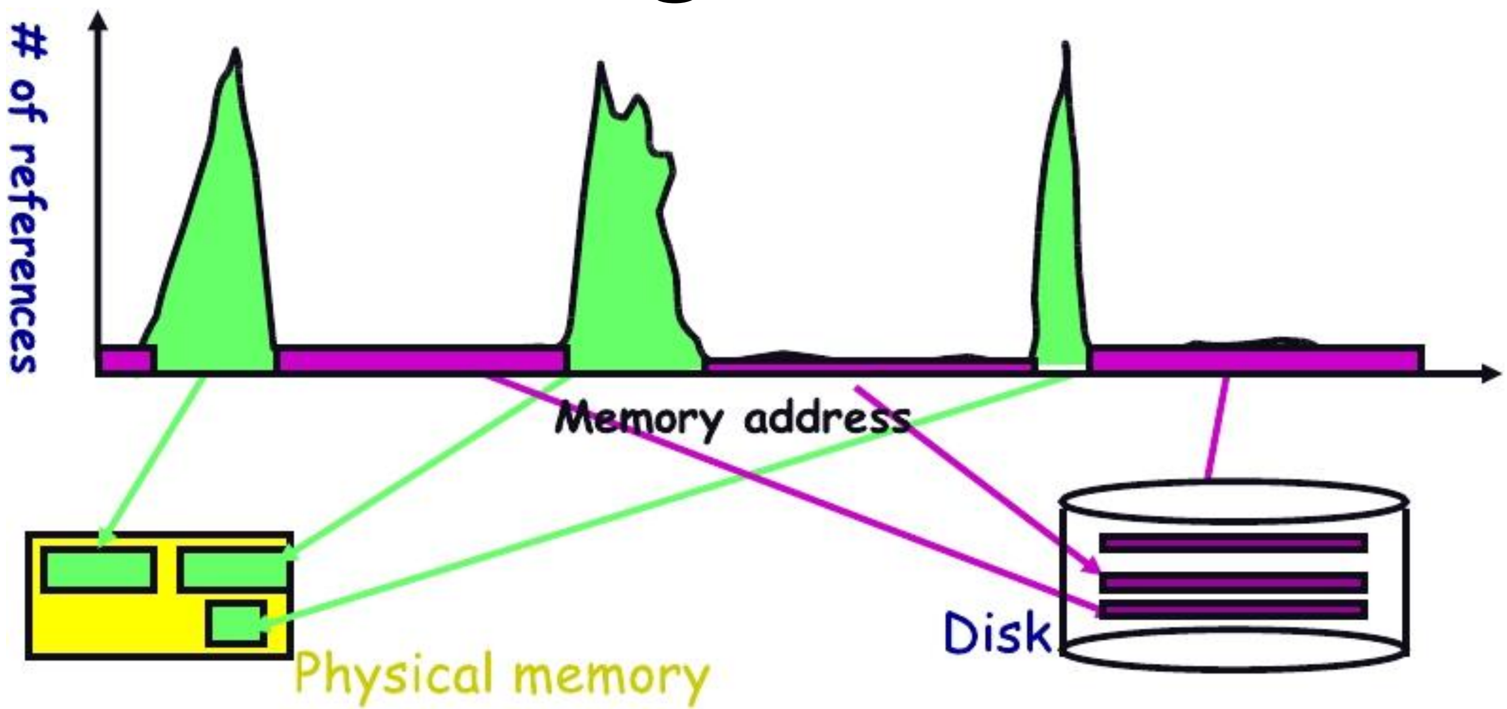


Other Issues – I/O interlock

- **I/O Interlock** – Pages must sometimes be locked into memory

- Consider I/O - Pages that are used for copying a file from a device must be locked from being selected for eviction by a page replacement algorithm

Working set model



- **Disk much, much slower than memory**
  - Goal: Run at memory speeds, not disk speeds
- **90/10 rule: 10% of memory gets 90% of memory refs**
  - So, keep that 10% in real memory, the other 90% on disk
  - **How to pick which 10%?**

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?**
  - 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 w. info about page fault**
  - Faulting virtual address (In %cr2 reg on x86—may have seen it if you modified Pintos page_fault and used 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?
- **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
- **Complex instructions must be re-started, too**
  - E.g., x86 move string instructions
  - Specify srd, 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 spatial 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
  - So many OSes zero freed pages while CPU is idle

Selecting physical pages

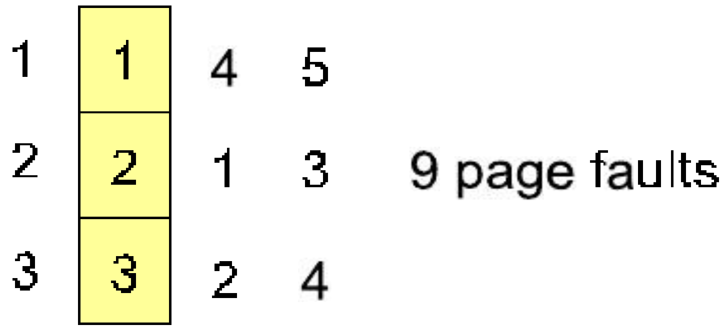
- **May need to eject some pages**
  - More on eviction policy in two slides
- **May also have a choice of physical pages**
- **Direct-mapped physical caches**
  - Virtual → Physical mapping can affect performance
  - Applications can conflict with each other or themselves
  - Scientific applications benefit if consecutive virtual pages do not conflict in the cache
  - Many other applications do better with random mapping

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

Straw man: FIFO eviction

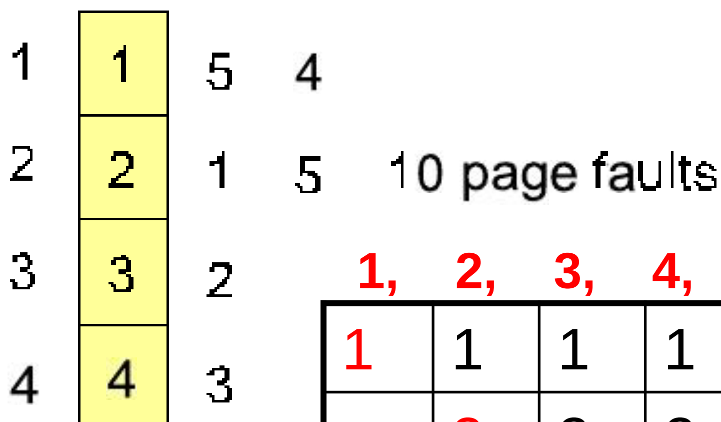
- **Evict oldest fetched page in system**
- **Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5**
- **3 physical pages: 9 page faults**



1,	2,	3,	4,	1,	2,	5,	1,	2,	3,	4,	5
1	1	1	4	4	4	5	5	5	5	5	5
	2	2	2	1	1	1	1	1	3	3	3
		3	3	3	2	2	2	2	1	4	4

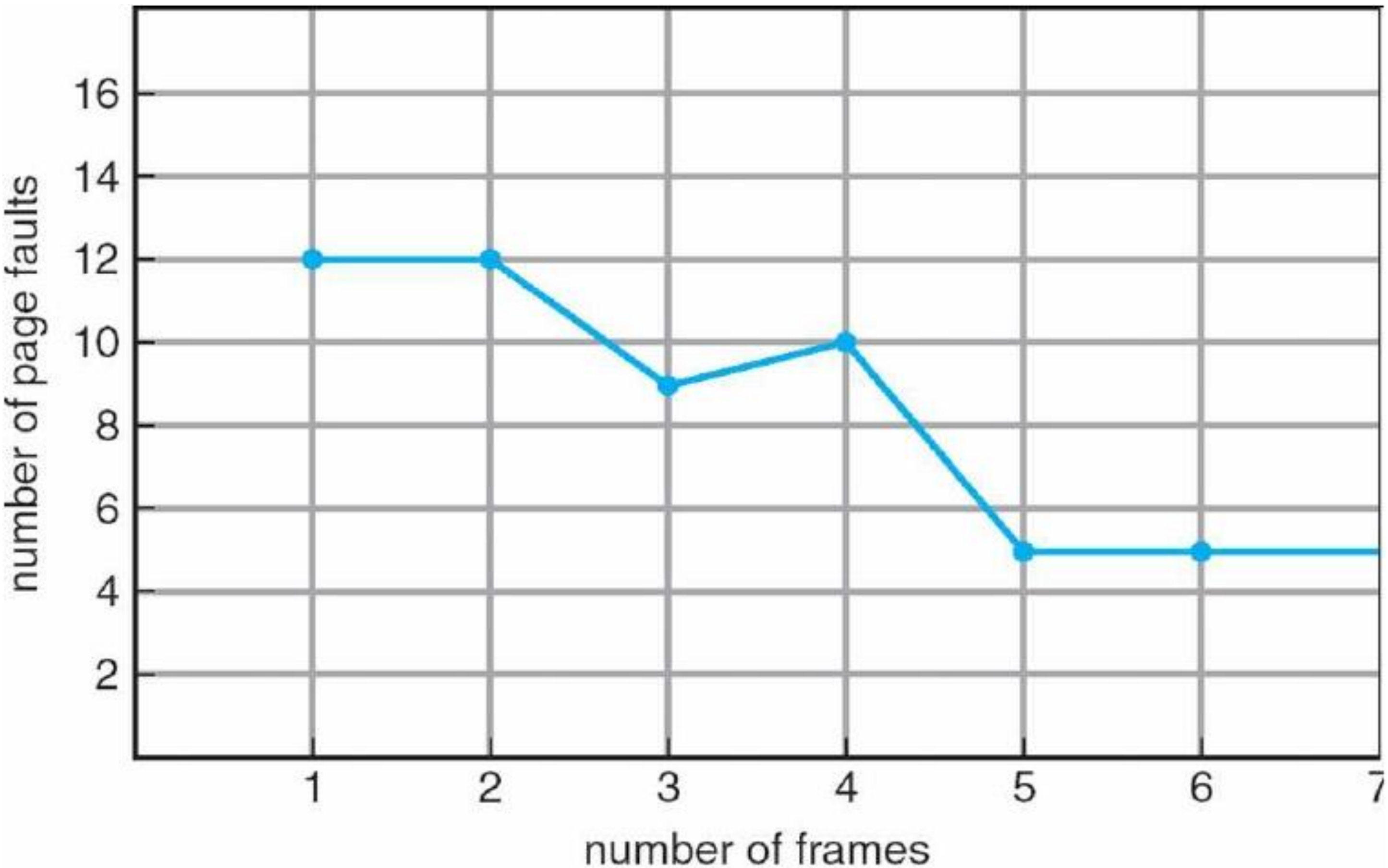
Straw man: FIFO eviction

- 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



1,	2,	3,	4,	1,	2,	5,	1,	2,	3,	4,	5
1	1	1	1	1	1	5	5	5	5	4	4
	2	2	2	2	2	2	1	1	1	1	5
		3	3	3	3	3	3	2	2	2	2
			4	4	4	4	4	4	3	3	3

Belady's Anomaly



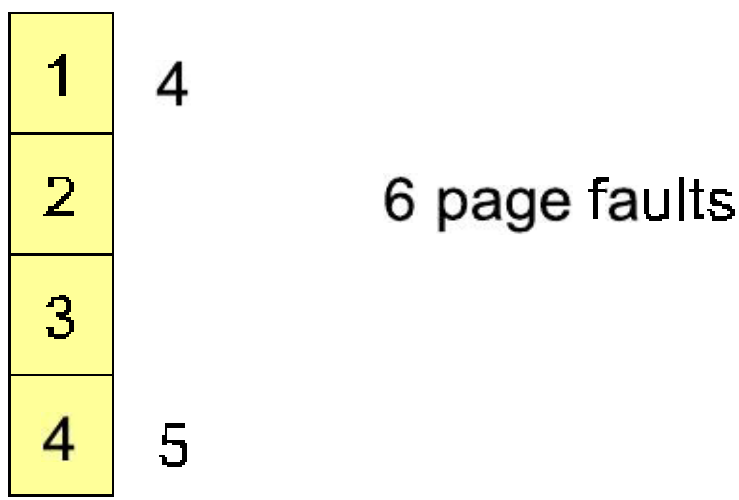
- **More phys. mem. doesn't always mean fewer faults**

Optimal page replacement

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

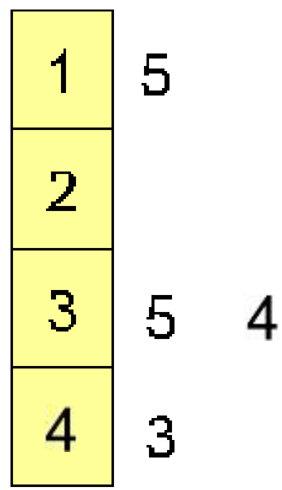
Optimal page replacement

- **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:**



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?**

LRU page replacement

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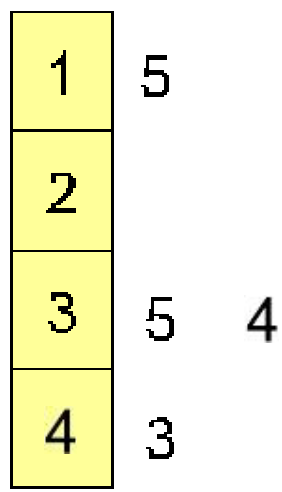

- **Problem 1: Can be pessimal – example?**
  - Looping over memory - circular queue (then want MRU eviction)

LRU page replacement

- **Approximate optimal with least recently used**
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- **Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5**
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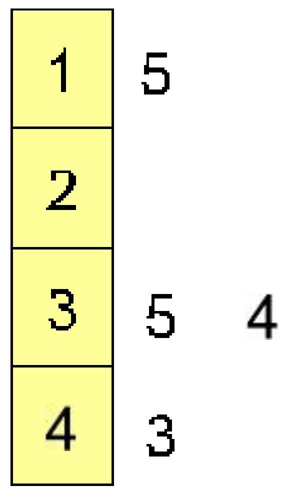


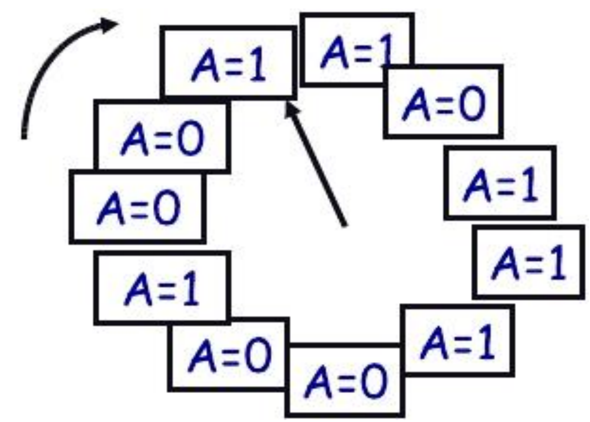
- **Problem 1: Can be pessimal – example?**
- **Problem 2: How to implement?**

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

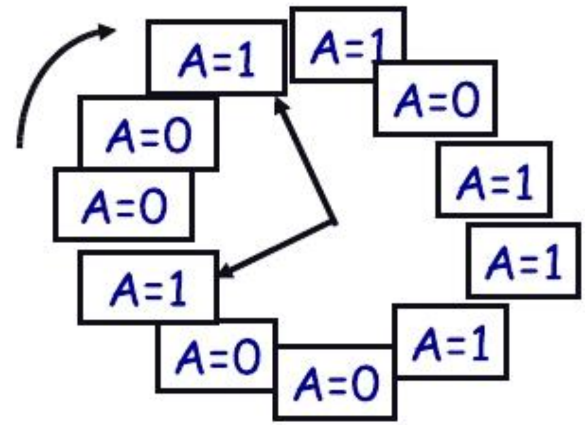
- **Use accessed bit supported by most hardware**
  - E.g., Pentium will write 1 to A bit in PTE on first access
  - Software managed TLBs like MIPS can do the same
- **Do FIFO but skip accessed pages**



- **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 (cont.)

- **Large memory may be a problem**
  - Most pages reference 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

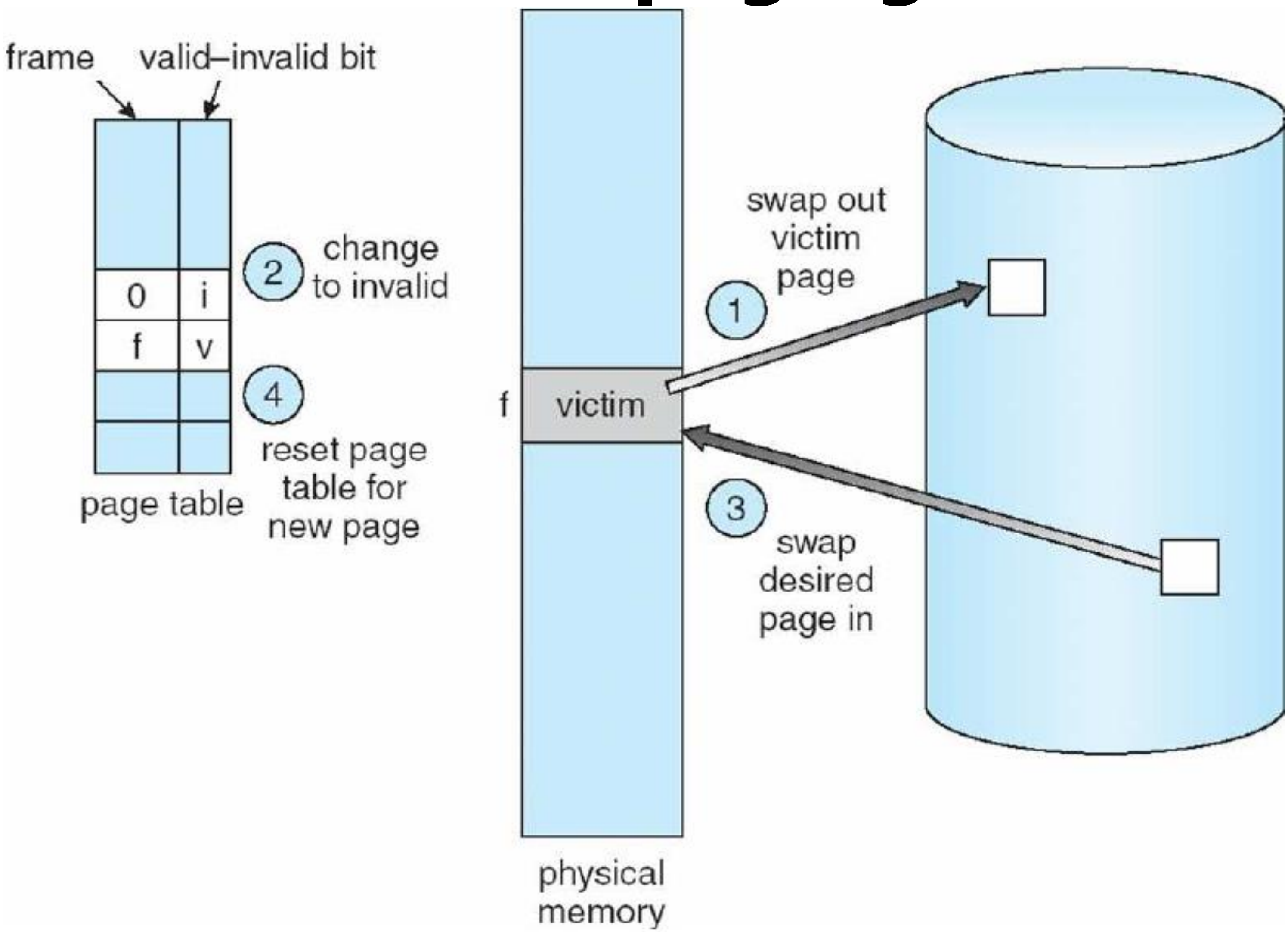


- **Can also take advantage of hardware Dirty bit**
  - Each page can be (Unaccessed, Clean), (Unaccessed, Dirty), (Accessed, Clean), or (Accessed, Dirty)
  - Consider clean pages for eviction before dirty
- **Or use *n*-bit accessed *count* instead just *A* bit**
  - On sweep: $count = (A << (n-1)) \mid (count >> 1)$
  - Evict page with lowest *count*

Other replacement algorithms

- **Random eviction**
  - Dirt simple to implement
  - Not overly horrible (avoids Belady's anomaly & 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**

Naive paging



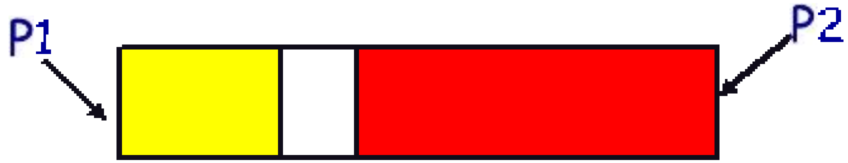
- **Naive page replacement: 2 disk I/Os per page fault**

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 P1 needs 20% of memory and P2 needs 70%:



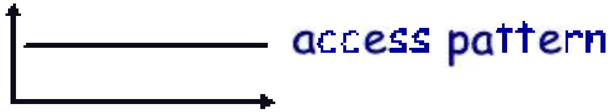
  - Doesn't protect you from memory pigs
    (imagine P2 keeps looping through array that is size of mem)
- **Local allocation isolates processes (or users)**
  - Separately determine how much mem each proc. should have
  - Then use LRU/clock/etc. to determine which pages to evict within each process

Thrashing

- **Thrashing: processes on system require more memory than it 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 have: memory with access time of disk**

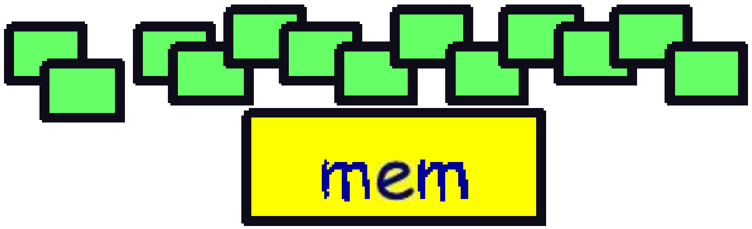
Reasons for thrashing

- **Process doesn't reuse memory, so caching doesn't work (past != future)**



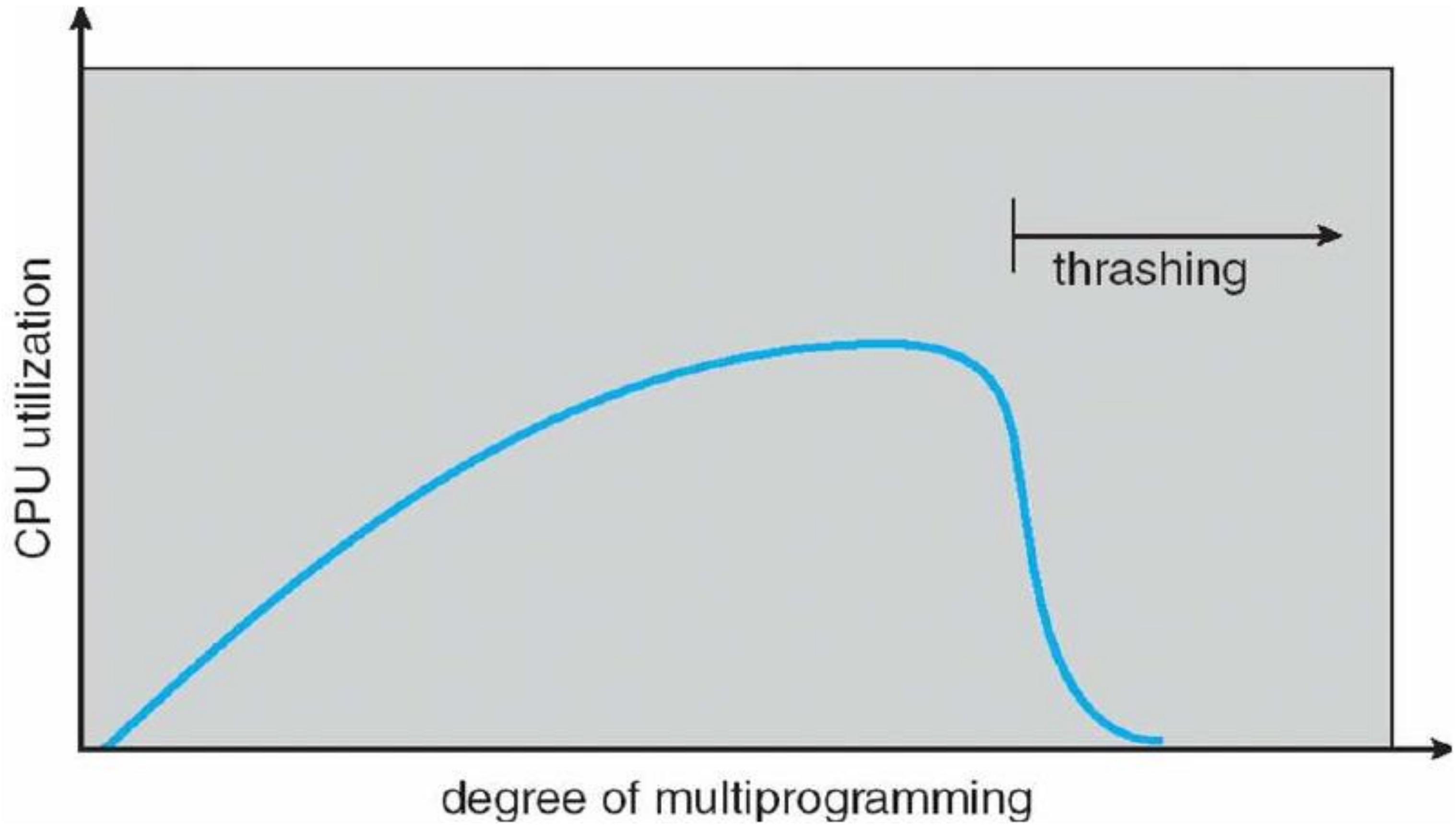
- **Process does reuse memory, but it does not "fit"**

- **Individually, all processes fit and reuse memory, but too many for system**



  - At least this case is possible to address

Multiprogramming & Thrashing

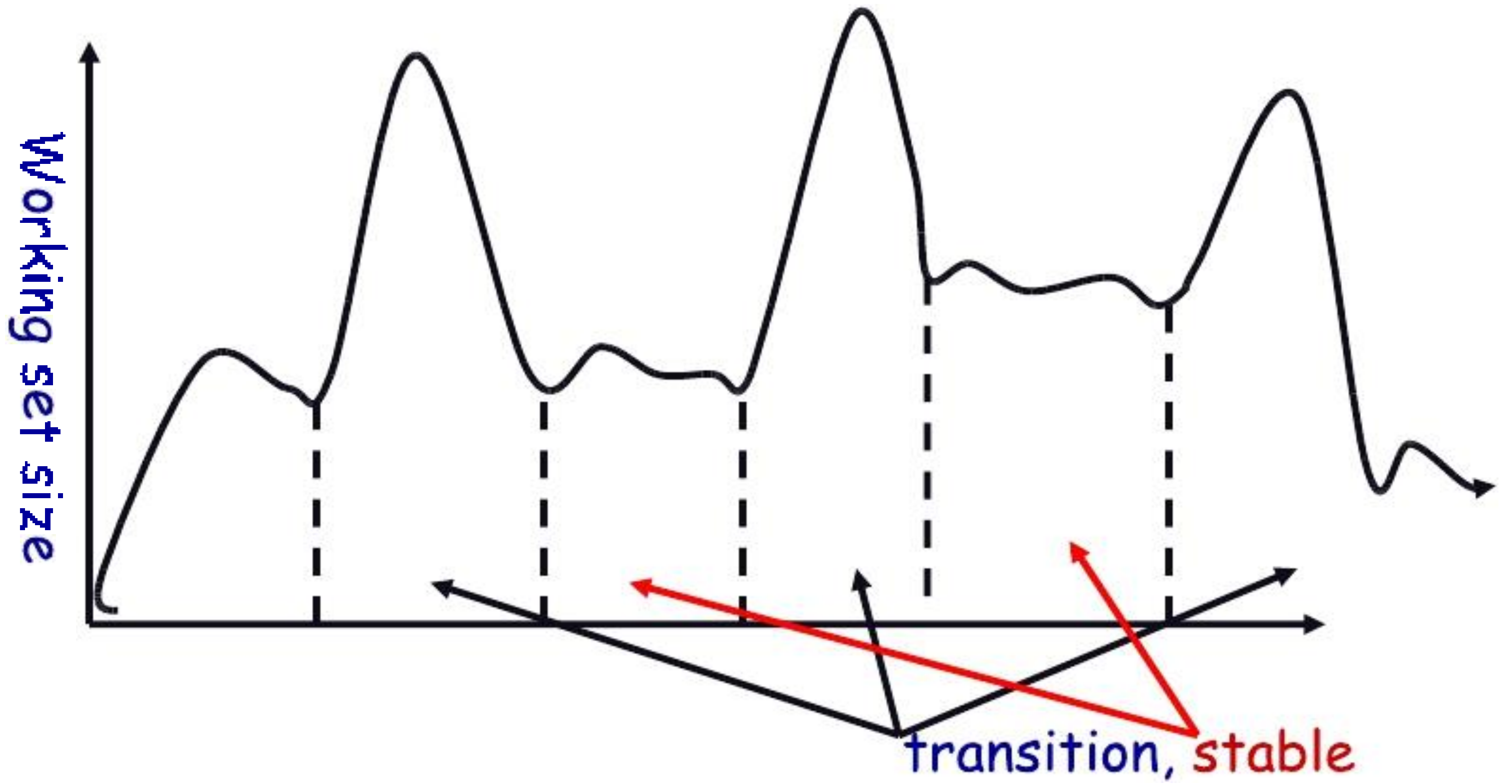


- **Need to shed load when thrashing**

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 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 (PFF)**
  - 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**
  - Balloons during transition

Calculating the working set

- **Working set: all pages proc. will access in next *T* time**
  - Can't calculate without predicting future
- **Approximate by assuming past predicts future**
  - So working set ≈ 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**
  - Moves procs active → 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)

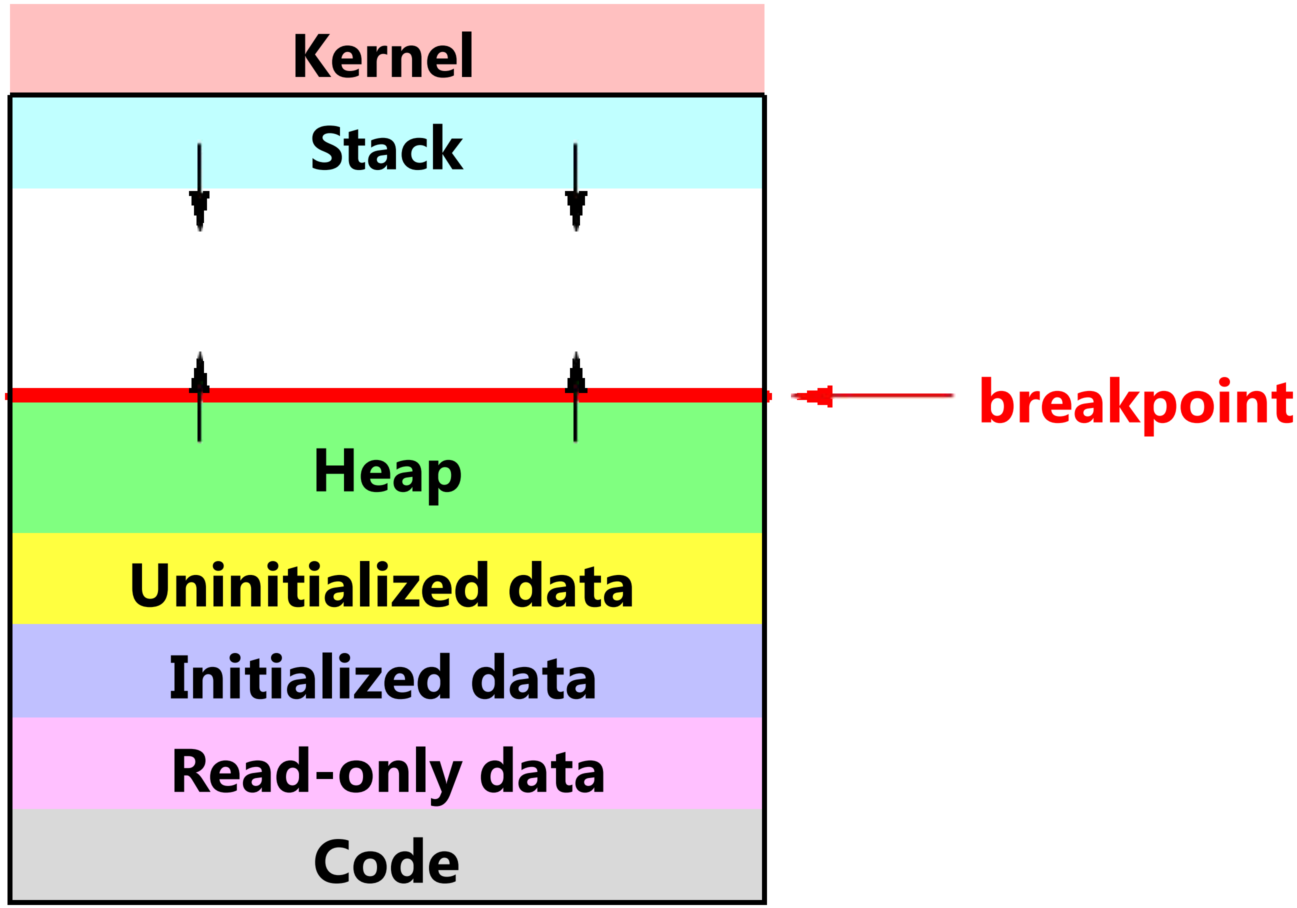
Some complications of paging

- **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 proc. 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

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
- **Solution 1: 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
- **Solution 2: Hashed page tables**
  - Store Virtual → Physical translations in hash table
  - Table size proportional to physical memory
  - Clustering makes this more efficient [Talluri]

Recall typical virtual address space

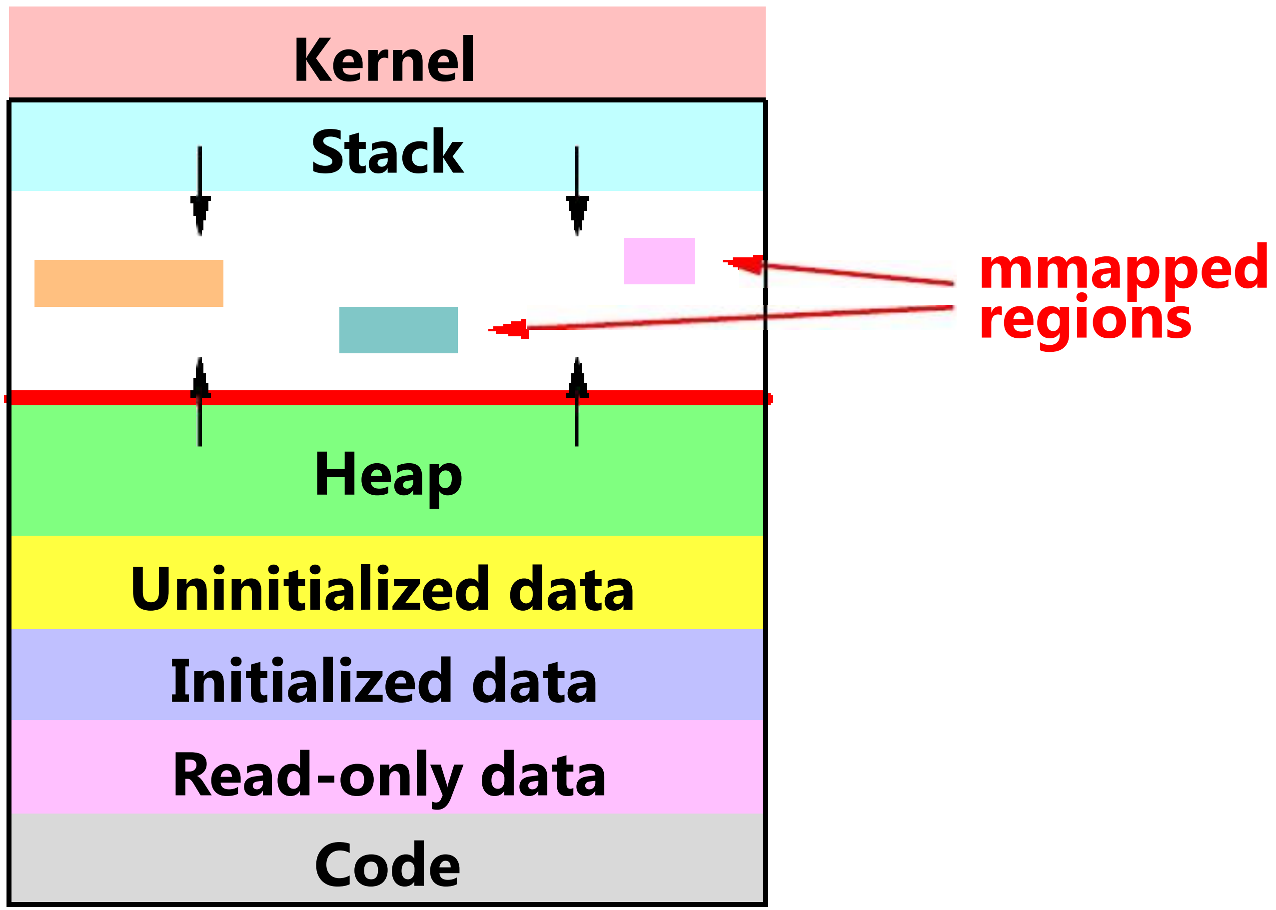


- **Dynamically allocated memory goes in heap**
- **Top of heap called *breakpoint***
  - Addresses between breakpoint and stack all invalid

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
- int mincore(void *addr, size_t len, char *vec)
  - Returns in vec which pages are 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;
};
```

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

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**

Summary

- Read Ch. 1-8
- Processes and Threads (Ch. 4)
- Process Scheduling (Ch. 5)
- Synchronization (Ch. 6)
- Deadlock (Ch. 7)
- Memory Management (Ch. 8)
- Virtual Memory (Ch. 9)
- Project #2 – System Calls and User-Level Processes