Memory Management II
Virtual Memory

COMS W4118

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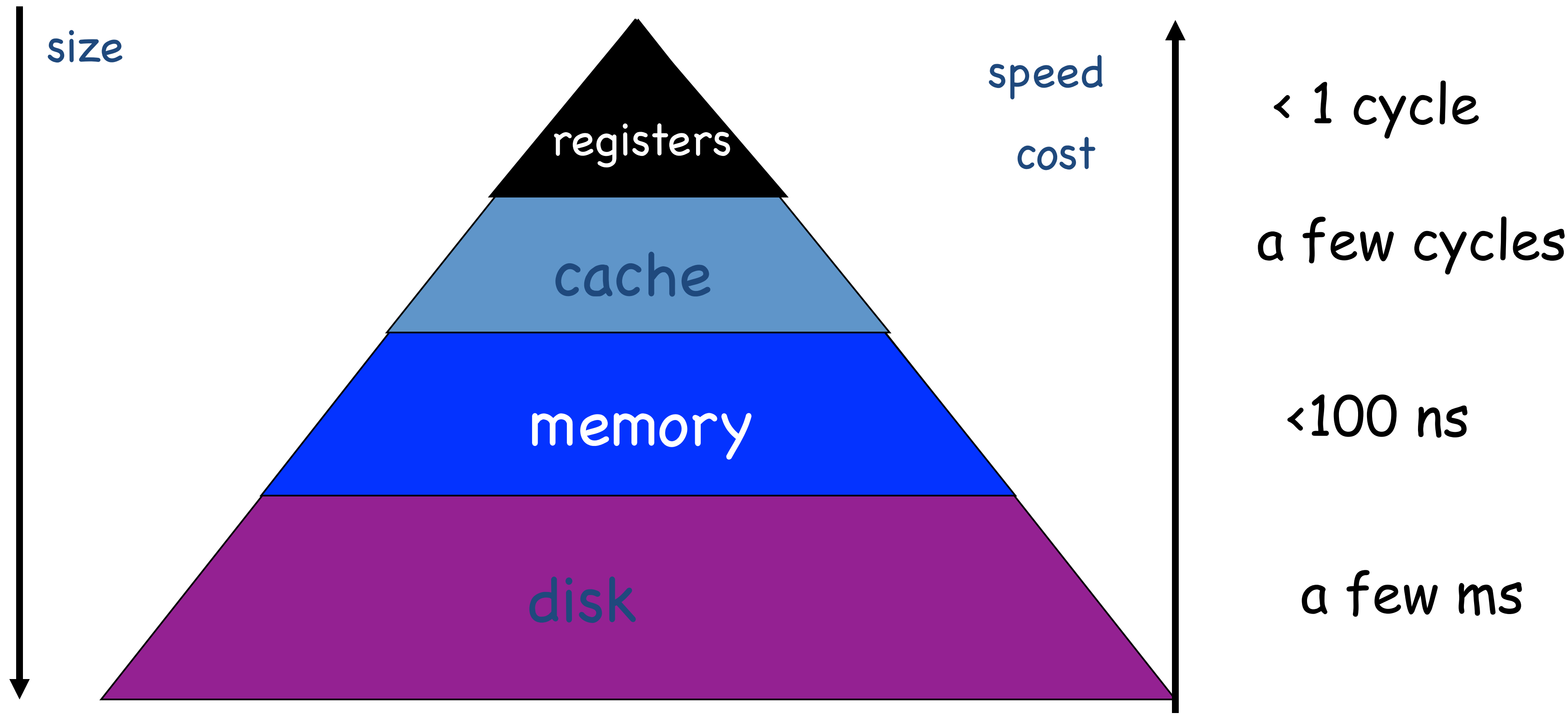
References: Operating Systems Concepts (9e), Linux Kernel Development, previous W4118s

Background: memory hierarchy

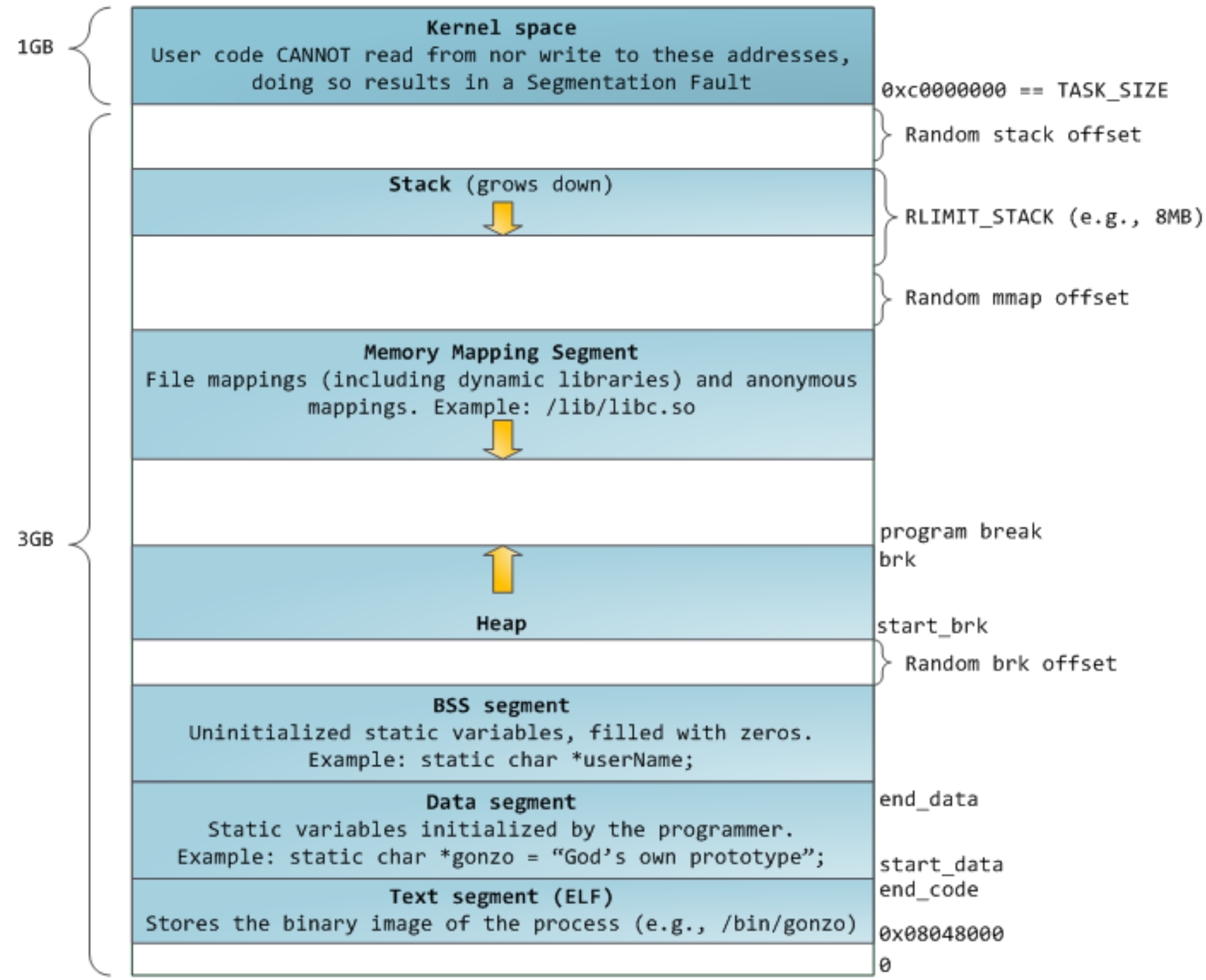
- Levels of memory in computer system



Virtual memory motivation

- Previous approach to memory management
  - Must completely load user process in memory
  - One large AS or too many AS → out of memory
- Observation: locality of reference
  - Temporal: access memory location accessed just now
  - Spatial: access memory location adjacent to locations accessed just now
- Implication: process only needs a small part of address space at any moment!
  - Can load programs faster (don't load everything)
  - Can fit more programs in memory (better utilization)

Linux Address Space Layout

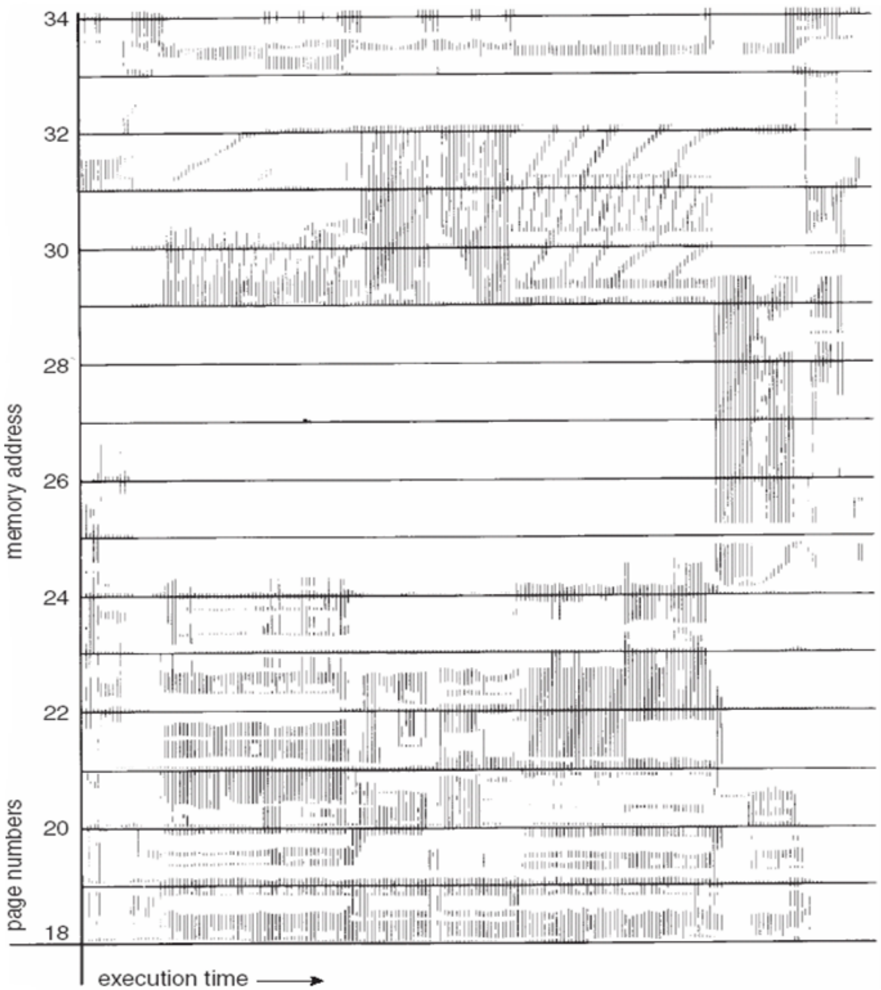


Read: http://duartes.org/gustavo/blog/post/anatomy-of-a-program-in-memory

The Working Set Model

- Working set: set of memory addresses (pages) that the program needs in memory to make progress
  - Often set of pages program accesses in a short period of time
- Why does program need pages in main memory?
  - Instructions can only address main memory and registers
  - Accessed by same instruction
  - Accessed many times
  - Loops access a lot of memory
- Working usually much smaller than full program
  - Program does one thing at a time
  - Code for exception handling rarely accessed
  - Process migrates from one working set to another
  - Working sets may overlap

Locality In A Memory-Reference Pattern



Keeping working sets small

- Small changes to program = big changes to working set
  - Try to preserve locality in high performance code ("cache friendly")
  - Keep accesses related in time also related in space
- Example:
  - int data[1024][1024] of a 2d 1024x1024 byte array
  - Row major: each row is stored in one 4k page

```
Program1: for (j = 0; j <1024; j++)
                    for (i = 0; i < 1024; i++)
                          data[i][j] = 0;
```

Working set: 1024x1024 = 4MB

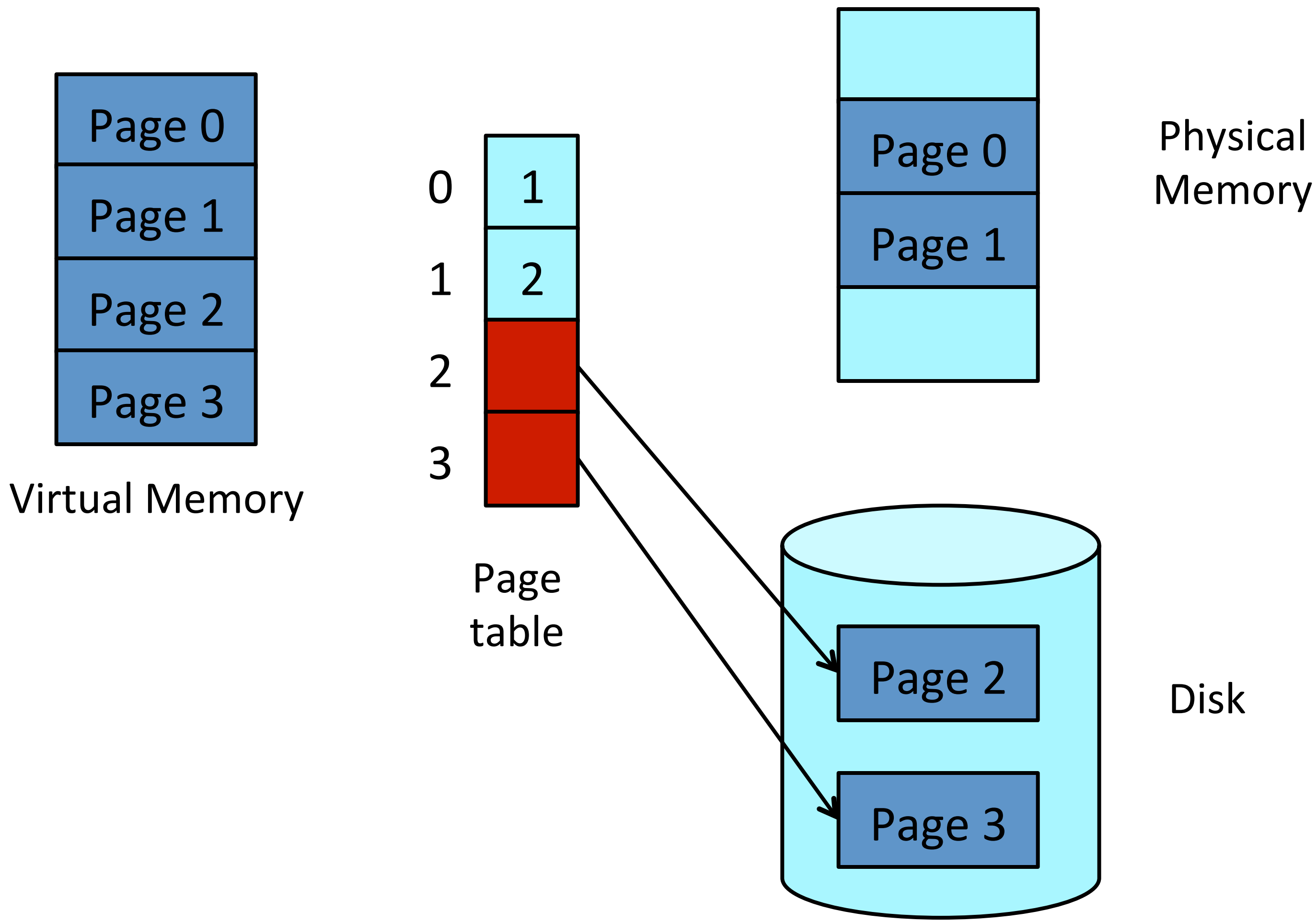
```
Program2: for (i = 0; i < 1024; i++)
                  for (j = 0; j < 1024; j++)
                        data[i][j] = 0;
```

Working set = 1024 = 4KB!

Virtual memory idea

- OS and hardware produce illusion of disk as fast as main memory, or main memory as large as disk
- Process runs when not all pages are loaded in memory
  - Only keep referenced pages in main memory
  - Keep unreferenced pages on slower, cheaper backing store (disk)
  - Bring pages from disk to memory when necessary

Virtual memory illustration



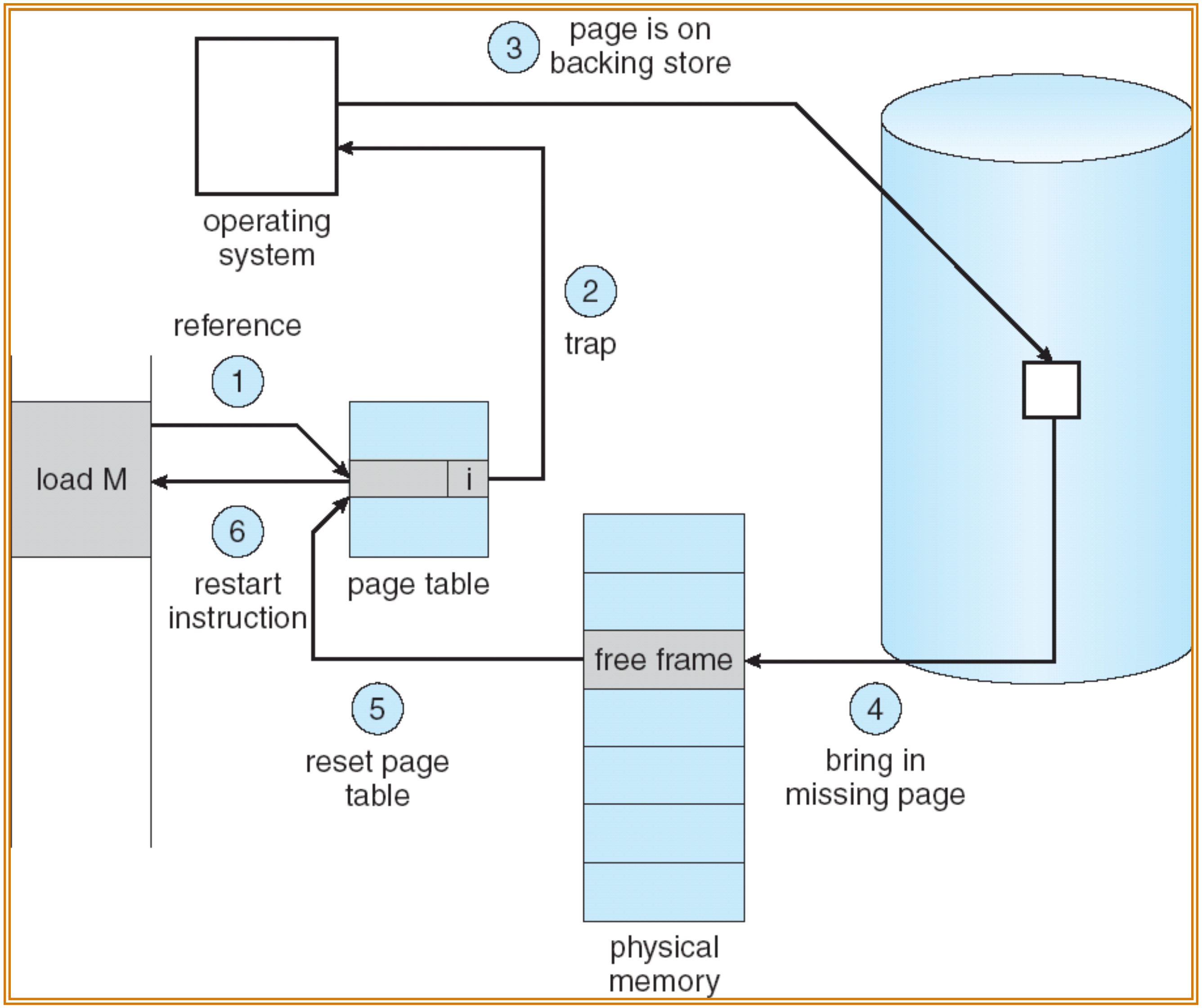
Virtual memory operations

- Detect reference to page on disk
- Recognize disk location of page
- Choose free physical page
  - OS decision: if no free page is available, must replace a physical page
- Bring page from disk into memory
  - OS decision: when to bring page into memory?
- Above steps need hardware and software cooperation

Detect reference to page on disk and recognize disk location of page

- Overload the present bit of page table entries
- If a page is on disk, clear present bit in corresponding page table entry and store disk location using remaining bits
- Page fault: if bit is cleared then referencing resulting in a trap into OS
- In OS page fault handler, check page table entry to detect if page fault is caused by reference to true invalid page or page on disk

Steps in handling a page fault



Performance of Demand Paging

- Page Fault Rate $0 \le p \le 1$
  - if $p = 0$ no page faults
  - if $p = 1$, every reference is a fault

- Effective Access Time (EAT)

$$
\begin{aligned}
EAT = (1 - p) \times \text{memory access} \\
+ p\,(\text{page fault overhead} \\
+ \text{swap page out} \\
+ \text{swap page in} \\
+ \text{restart overhead})
\end{aligned}
$$

Demand Paging Example

- Disparity in memory and disk access times is huge. E.g.,
  - Memory access time = 200 nanoseconds
  - Average page-fault service time = 8 milliseconds

- EAT = (1 – p) x 200 + p (8 milliseconds)
  = (1 – p x 200 + p x 8,000,000
  = 200 + p x 7,999,800
- If one out of 1,000 accesses faults, then EAT = 8.2 us, or 40x slower!

- If want performance degradation < 10 percent
  - 200 + 7,999,800 x p < 220, or 7,999,800 x p < 20
  - p < .0000025
  - Less than one page fault in every 400,000 memory accesses

OS decisions

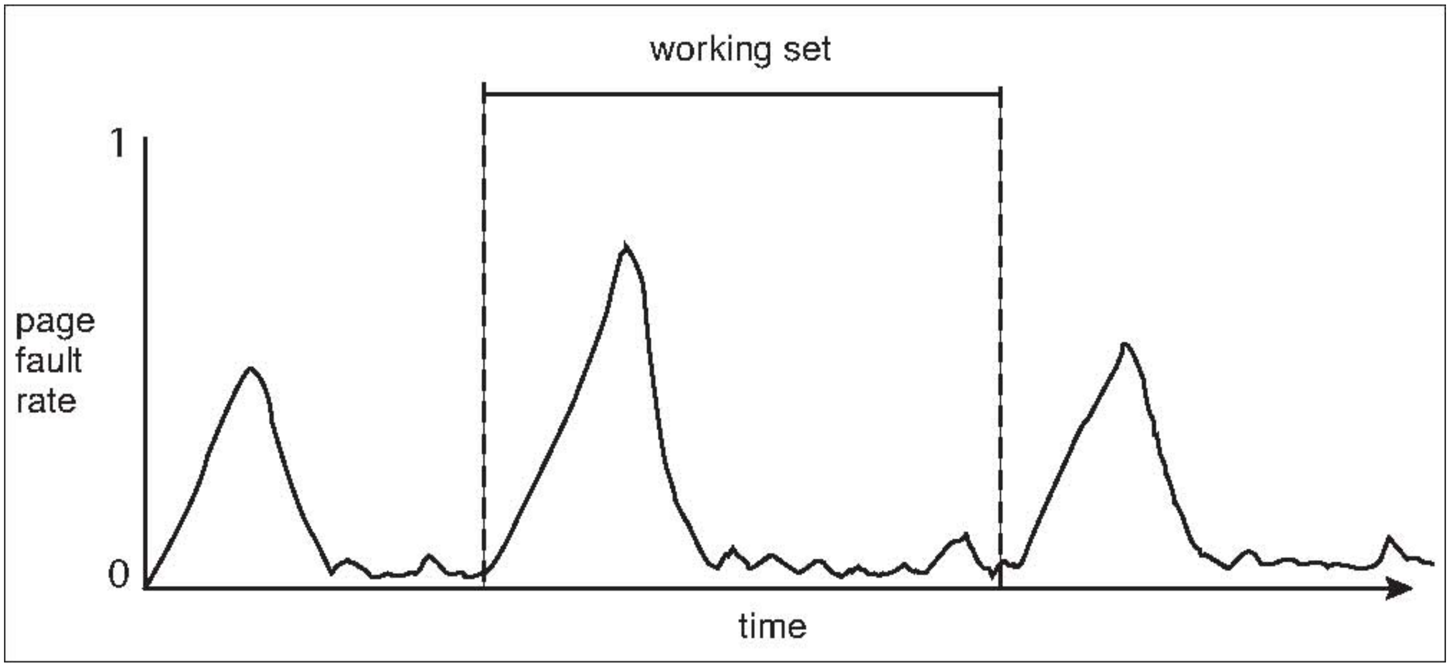
- Page selection
  - When to bring pages from disk to memory?
- Page replacement
  - When no free pages available, must select victim page in memory and throw it out to disk

Page selection algorithms

- Demand paging: load page on page fault
  - Start up process with no pages loaded
  - Wait until a page absolutely must be in memory
- Request paging: user specifies which pages are needed
  - Requires users to manage memory by hand
  - Users do not always know best
  - OS trusts users (e.g., one user can use up all memory)
- Prepaging: load page before it is referenced
  - When one page is referenced, bring in next one
  - Do not work well for all workloads
    - Difficult to predict future

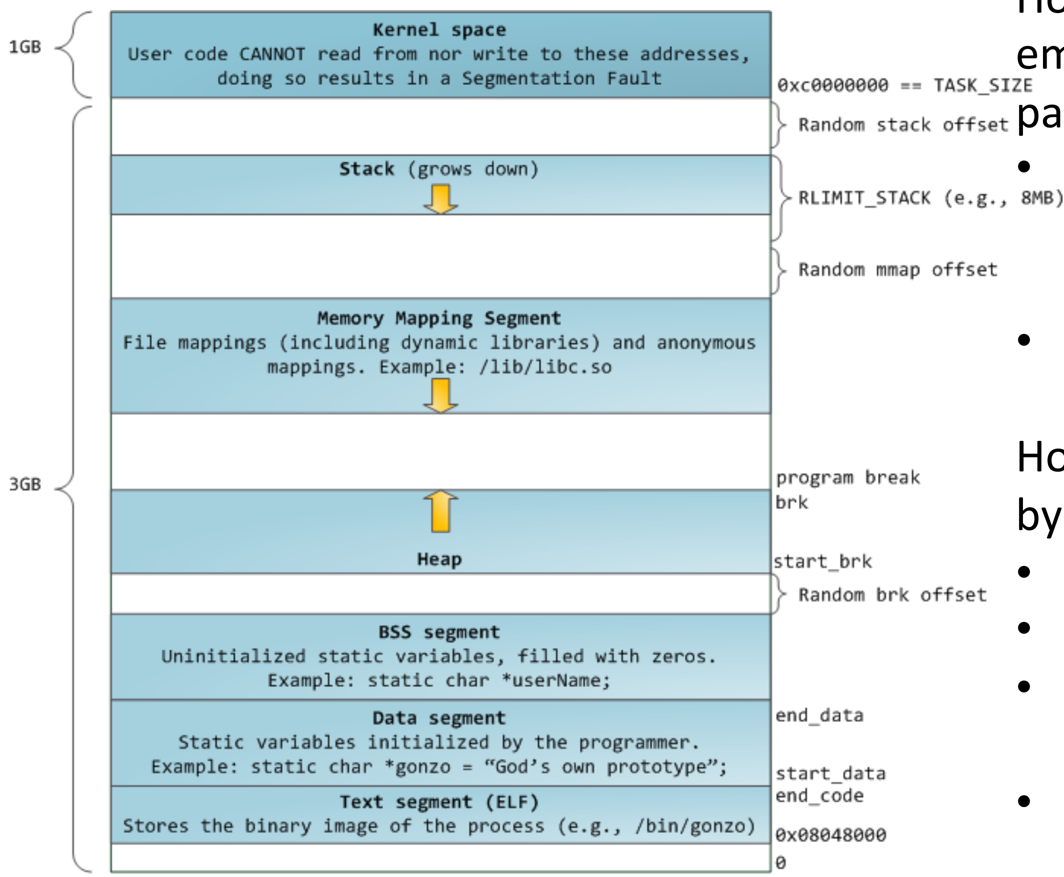
Working Sets and Page Fault Rates

- With pure demand paging



- Prepaging tries to smooth out bursts by predicting and fetching in the previous valley

Virtual Memory Gotchas



How to differentiate between access to empty regions vs. access to a not present page?

- Linux, keep a separate data structure to represent valid regions. Called vma (vm_area_struct)
- Could also use PTE bit

How to swap out a shared page mapped by multiple AS?

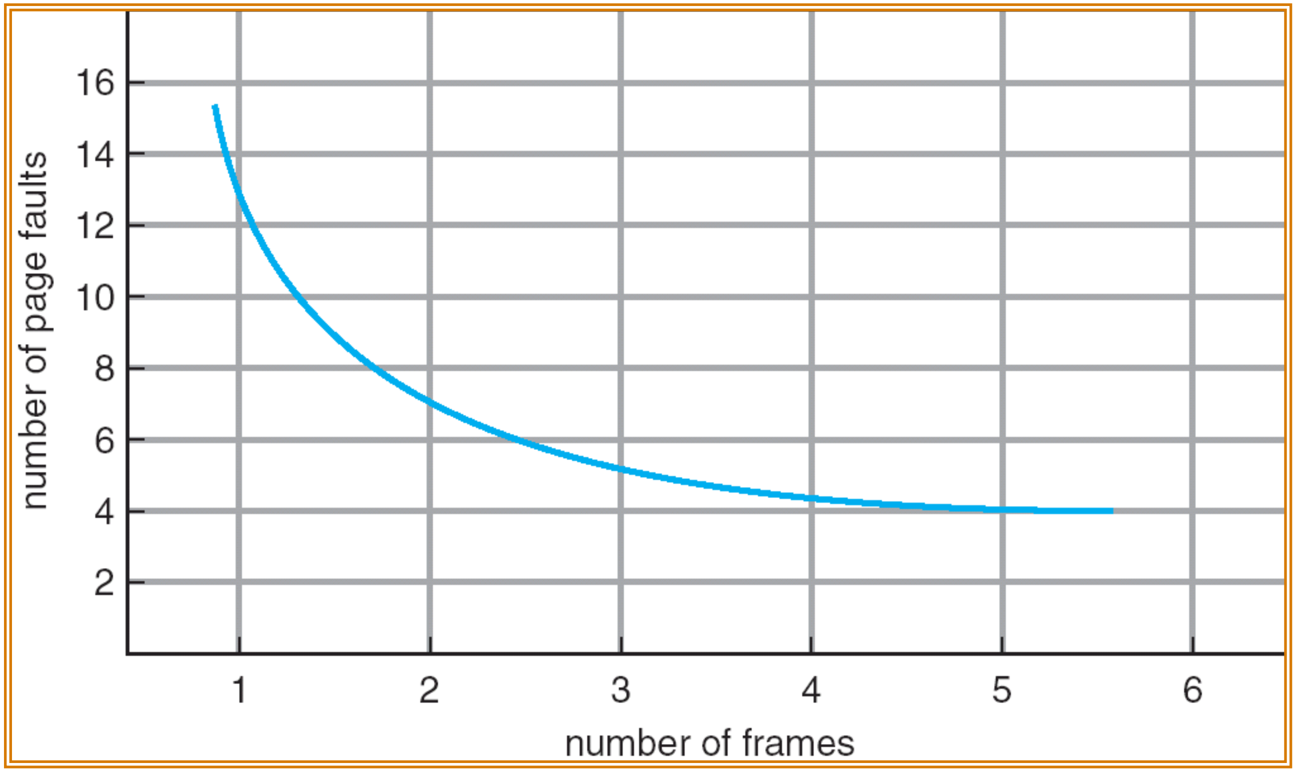
- Disable swapping (pin)
- Maintain reverse mapping
- Physical page to AS that maps the physical page
- Linux maintains rmap between vmas

Ref: http://duartes.org/gustavo/blog/post/anatomy-of-a-program-in-memory

Page replacement algorithms

- Optimal: throw out page that won't be used for longest time in future
- Random: throw out a random page
- FIFO: throw out page that was loaded in first
- LRU: throw out page that hasn't been used in longest time

Ideal curve of # of page faults v.s. # of physical pages



Evaluating page replacement algorithms

- Goal: fewest number of page faults
- A method: run algorithm on a particular string of memory references (reference string) and computing the number of page faults on that string
- In all our examples, the reference string is

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

Optimal algorithm

- Throw out page that won’t be used for longest time in future

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

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

6 page faults

Problem: difficult to predict future!

First-In-First-Out (FIFO) algorithm

- Throw out page that was loaded in first

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

10 page faults

Problem: ignores access patterns

FIFO algorithm (cont.)

- Results with 3 physical pages

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	2	4	4

9 page faults

Problem: fewer physical pages → fewer faults!
belady anomaly

Least-Recently-Used (LRU) algorithm

- Throw out page that hasn't been used in longest time. Can use FIFO to break ties

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

8 page faults

Advantage: with locality, LRU approximates Optimal

Implementing LRU: hardware

- A counter for each page
- Every time page is referenced, save system clock into the counter of the page
- Page replacement: scan through pages to find the one with the oldest clock
- Problem: have to search all pages/counters!

Implementing LRU: software

- A doubly linked list of pages
- Every time page is referenced, move it to the front of the list
- Page replacement: remove the page from back of list
  – Avoid scanning of all pages
- Problem: too expensive
  – Requires 6 pointer updates for each page reference
  – High contention on multiprocessor

LRU: concept vs. reality

- LRU is considered to be a reasonably good algorithm
- Problem is in implementing it efficiently
  - Hardware implementation: counter per page, copied per memory reference, have to search pages on page replacement to find oldest
  - Software implementation: no search, but pointer swap on each memory reference, high contention
- In practice, settle for efficient approximate LRU
  - Find an old page, but not necessarily the oldest
  - LRU is approximation anyway, so approximate more

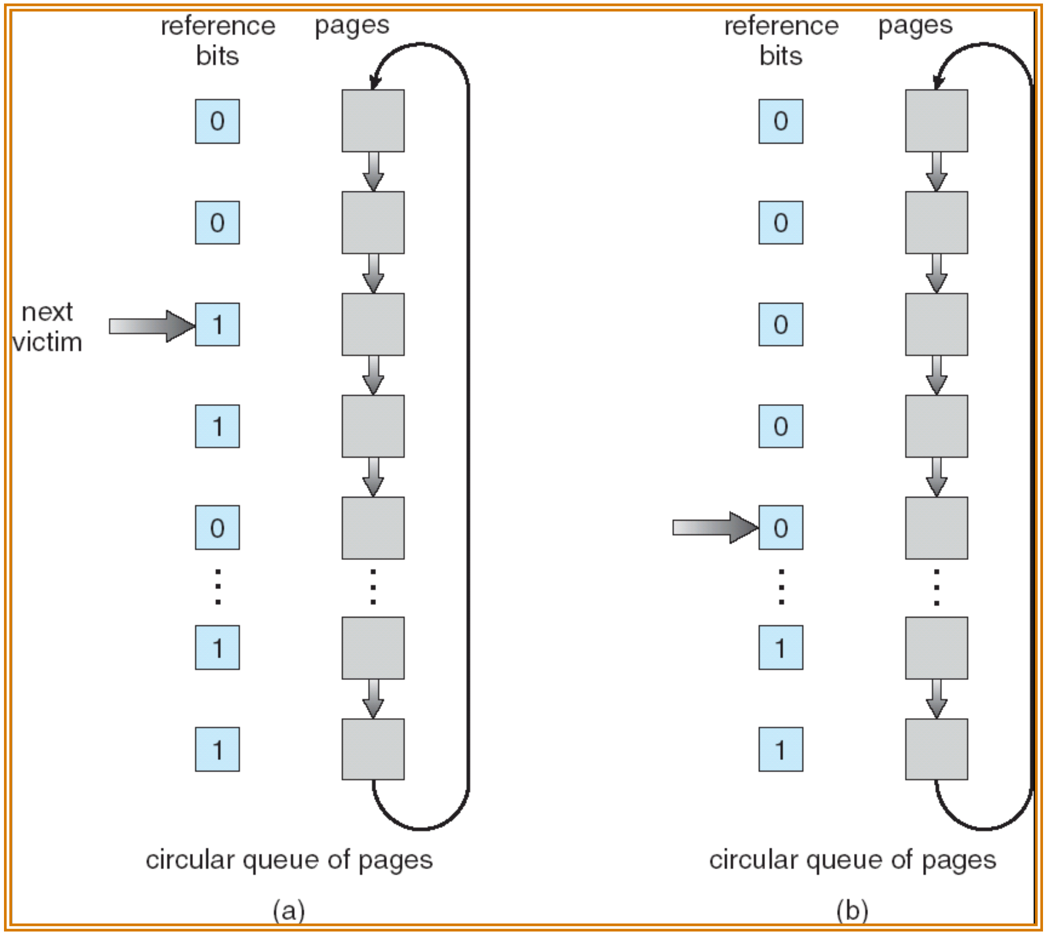
Clock (second-chance) algorithm

- Goal: remove a page that has not been referenced recently
  - good LRU-approximate algorithm
- Idea
  - A reference bit per page
  - Memory reference: hardware sets bit to 1
  - Page replacement: OS finds a page with reference bit cleared
  - OS traverses all pages, clearing bits over time

Clock algorithm implementation

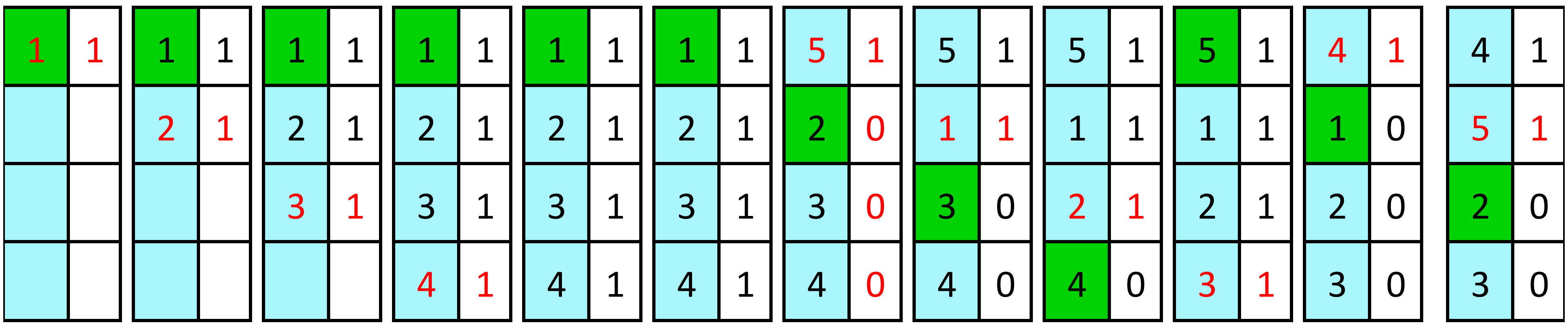
- Combining FIFO with LRU: give the victim page that FIFO selects a second chance
- Keep pages in a circular list = clock
- Pointer to next victim = clock hand
- To replace a page, OS examines the page pointed to by hand
  - If ref bit == 1, clear, advance hand
  - Else return current page as victim

A single step in Clock algorithm



Clock algorithm example

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



10 page faults

Advantage: simple to implement!

Clock algorithm extension

- Problem of clock algorithm: does not differentiate dirty v.s. clean pages
- Dirty page: pages that have been modified and need to be written back to disk
  - More expensive to replace dirty than clean pages
  - One extra disk write (about 5 ms)

Clock algorithm extension (cont.)

- Use dirty bit to give preference to dirty pages
- On page reference
  - Read: hardware sets reference bit
  - Write: hardware sets dirty bit
- Page replacement
  - reference = 0, dirty = 0 → **victim page**
  - reference = 0, dirty = 1 → **skip** (don't change)
  - reference = 1, dirty = 0 → reference = 0, dirty = 0
  - reference = 1, dirty = 1 → reference = 0, dirty = 1
  - advance hand, repeat
  - If no victim page found, run swap daemon to flush unreferenced dirty pages to the disk, repeat

Summary of page replacement algorithms

- Optimal: throw out page that won't be used for longest time in future
  - Best algorithm if we can predict future
  - Good for comparison, but not practical
- Random: throw out a random page
  - Easy to implement
  - Works surprisingly well. Why? Avoid worst case
  - Random
- FIFO: throw out page that was loaded in first
  - Easy to implement
  - Fair: all pages receive equal residency
  - Ignore access pattern
- LRU: throw out page that hasn't been used in longest time
  - Past predicts future
  - With locality: approximates Optimal
  - Simple approximate LRU algorithms exist (Clock)

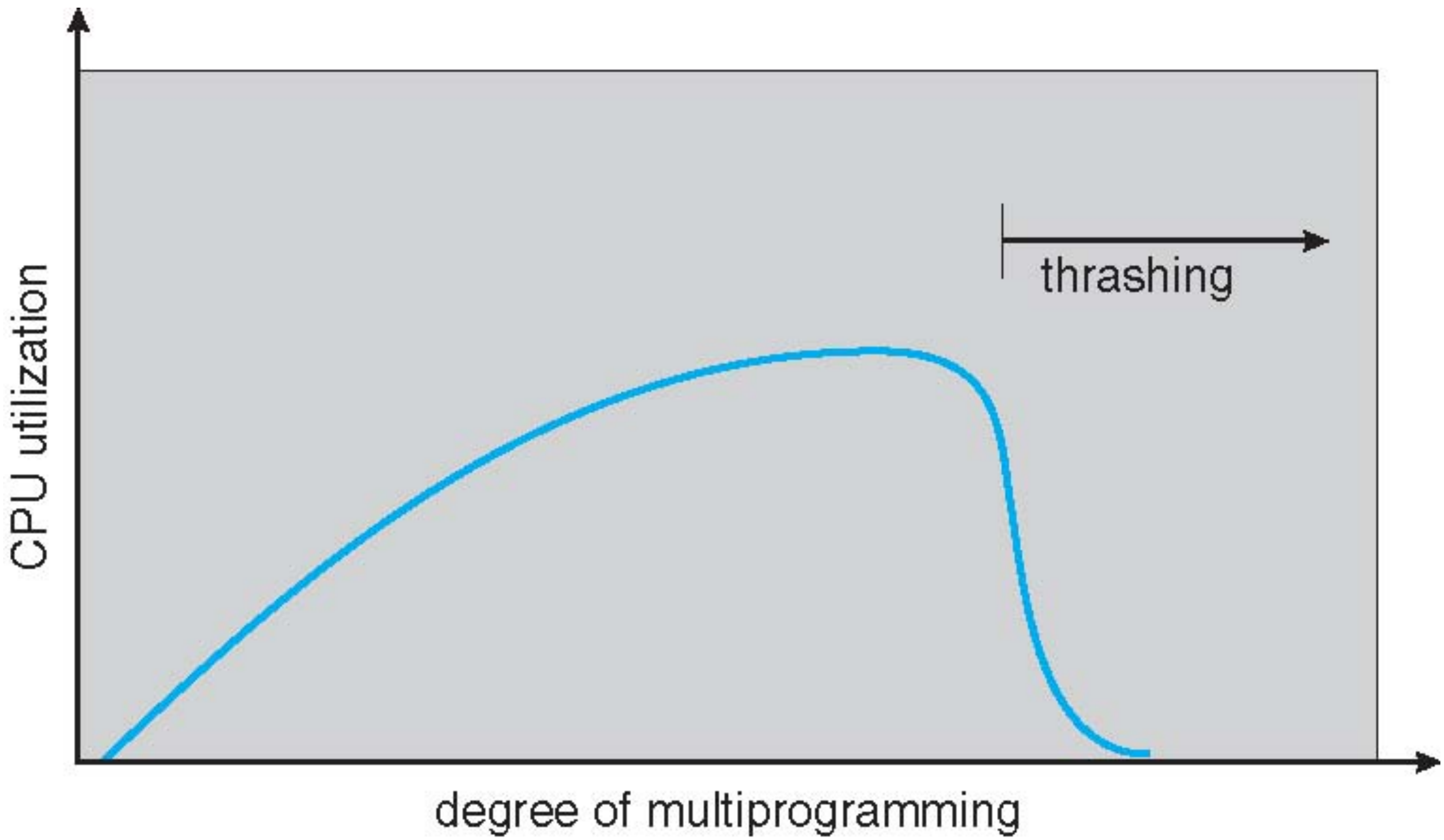
Page-Buffering

- Keep pool of free frames, always
  - Frame always available when needed
  - Read page into free frame
  - Select victim to evict and add to free pool
  - When convenient, evict victim
- Keep list of modified pages
  - When disk idle, write pages there and set to non-dirty
- Note and keep free pool contents intact
  - If referenced again before reused, no need to reload from disk
  - Useful if wrong victim frame was selected

Thrashing

- What if we need more pages regularly than we have?
  - Page fault to get page
  - Replace existing frame
  - But quickly need replaced frame back
- Leads to:
  - High page fault rate
  - Lots of I/O wait
  - Low CPU utilization
  - No useful work done
- **Thrashing** ≡ system busy just swapping pages in and out

Effects of Thrashing



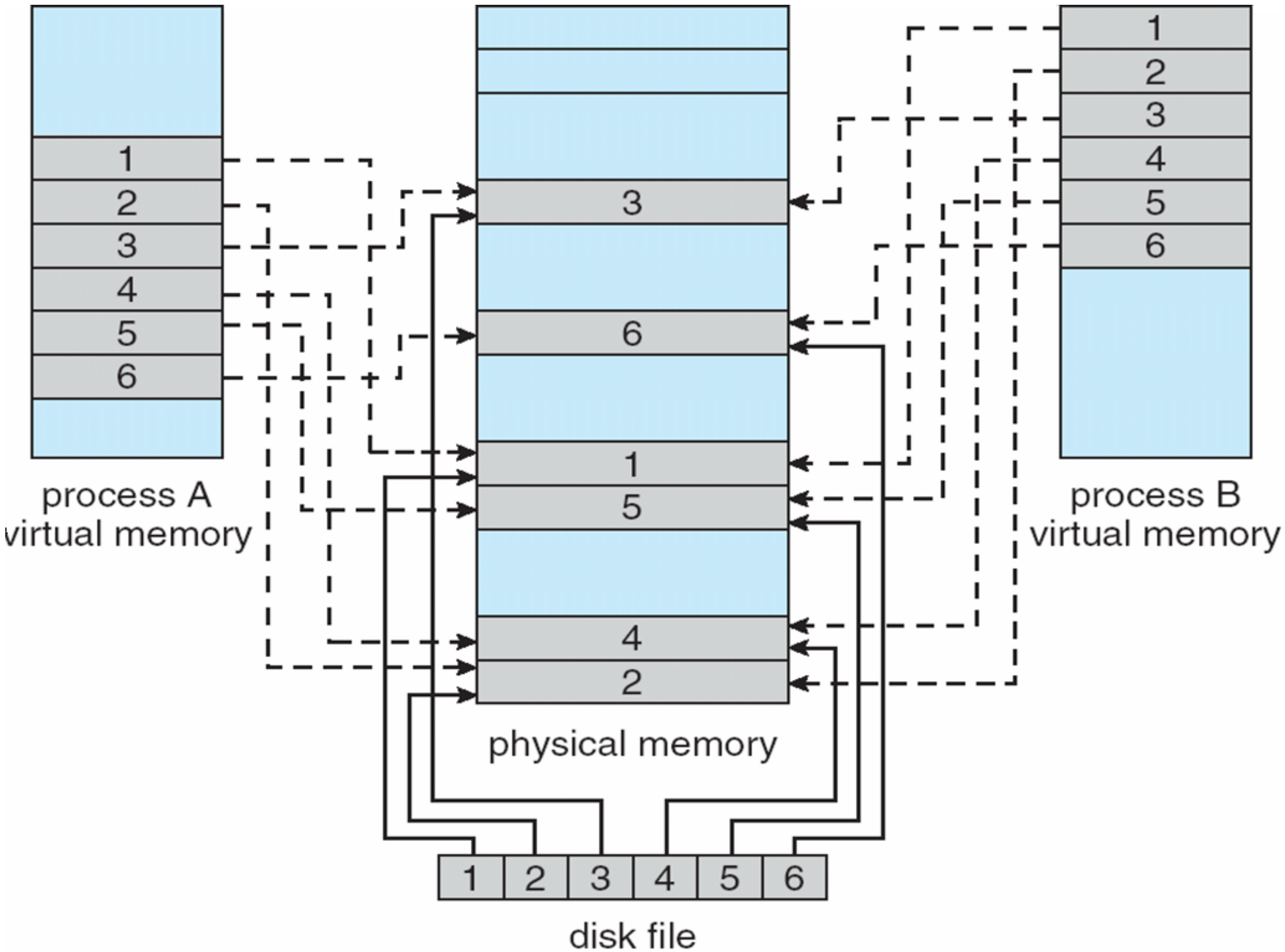
Memory-Mapped Files

- Treat files like memory by **mapping** a disk block to a memory page
  - mmap() syscall maps file into memory region
- File blocks initially loaded using demand paging
  - Page-sized chunk of the file read into physical page
  - Subsequent accesses to chunk treated as ordinary memory accesses
- Lazily flush writes to disk
  - Periodically, e.g., when pager scans for dirty pages
  - At file close() time

Memory-Mapped Files

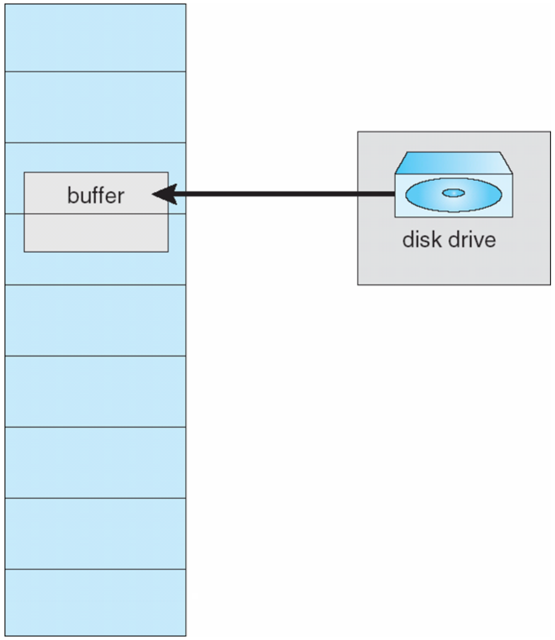
- Benefits of memory mapped files
  - Simplify/speed file access compared to read()/write() syscalls
  - Allows several processes to map same file to facilitate memory sharing (useful for binaries)
- Paging and file I/O often tightly intertwined
  - Swapping can use original file as backing store (if not dirty)
  - COW can be used to quickly create “clone” of file
  - Memory mapped files can be used for shared memory
- Some OSes use mmap internally for all I/O
  - Process still does read() and write()
  - Kernel maps file into kernel address space
  - Copies data to and from kernel space and user space

Memory Mapped Files



Paging (or segmentation) and I/O

- DMA devices directly copy data to memory
  - Does I/O device understand paging?
  - Need IOMMU (newer CPUs)
  - Else, OS must program DMA itself using physical addresses
  - Must do permissions checks
  - Pin pages into memory to prevent swapping out while DMA ongoing



Non-Uniform Memory Access

- So far all memory accessed equally
- NUMA – speed of access to memory varies
  - E.g., many system boards containing CPUs and memory, interconnected over a system bus
  - Memory on same board is "fast", other boards, "slow"
- Allocate memory close to CPU on which thread runs
  - Use processor affinity to keep threads on same CPU
  - E.g.: Solaris "lgroups"
    - Groups of CPU/memory with low latency
    - Scheduler/pager schedule all threads and memory for a process within the lgroup

Current trends in memory management

- Virtual memory is less critical now
  - Personal computer v.s. time-sharing machines
  - Memory is cheap ➔ Larger physical memory
- Virtual to physical translation is still useful
  - "All problems in computer science can be solved using another level of indirection" David Wheeler
- Larger page sizes (even multiple page sizes)
  - Better TLB coverage
  - Smaller page tables, less page to manage
  - Internal fragmentation: not a big problem
- Larger virtual address space
  - 64-bit address space
  - Sparse address spaces
- File I/O using the virtual memory system
  - Memory mapped I/O: mmap()

Backup Slides

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Problem with LRU-based Algorithms

- LRU ignores frequency
  - Intuition: a frequently accessed page is more likely to be accessed in the future than a page accessed just once
  - Problematic workload: scanning large data set
    - 1 2 3 1 2 3 1 2 3 1 2 3 … (pages frequently used)
    - 4 5 6 7 8 9 10 11 12 … (pages used just once)
- Solution: track access frequency
  - Least Frequently Used (LFU) algorithm
    - Expensive
  - Approximate LFU: LRU-2Q

Problem with LRU-based Algorithms (cont.)

- LRU doesnt handle repeated scan well when data set is bigger than memory
  - 4-frame memory with 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5
- Solution: Most Recently Used (MRU) algorithm
  - Replace most recently used pages
  - Best for repeated scans

Virtual memory illustration