Virtual Memory

Operating Systems

Wenbo Shen

Acknowledgement: some pages are based on the slides from Yajin Zhou@ZJU

Review

- Logical vs physical address
- Memory allocation
  - Contiguous allocation: first-, best-, worst-fit
  - Fragmentation: external vs internal
- paging: page number + page offset
  - Hierarchical page table, hashed page table, inverted page table
  - 1-level vs 2-level, why save memory, page table walk
- Swapping
- MMU
  - TLB

Outline

- Demanding paging
- Copy-on-write
- Page replacement algorithm
  - FIFO, optimal, LRU, …
- Allocation of frames
- Thrashing
- Examples

Background

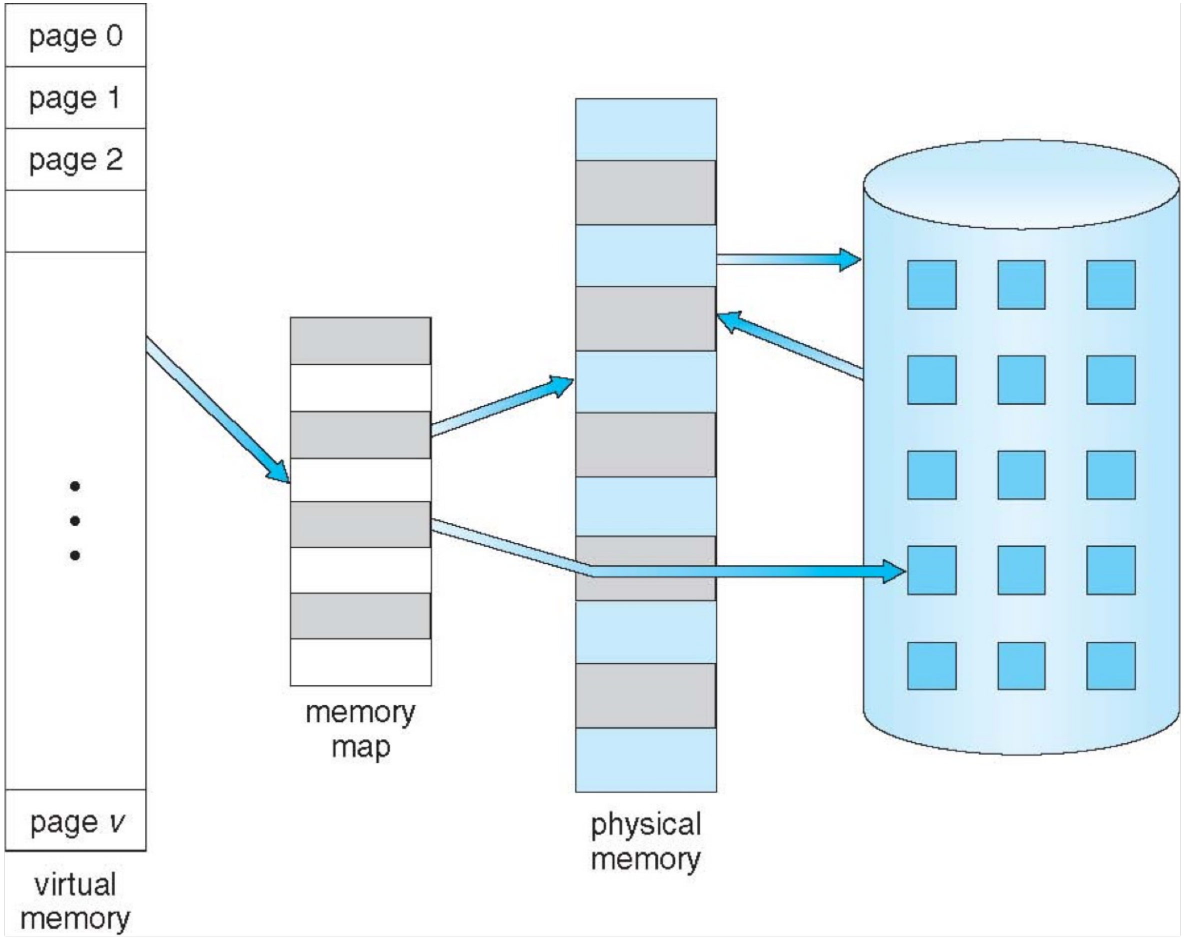
- Code needs to be in memory to execute, but entire program **rarely** needed or used at the same time
  - unused code: error handling code, unusual routines
  - unused data: large data structures
- Consider ability to execute **partially-loaded program**
  - program no longer constrained by limits of physical memory
  - programs could be larger than physical memory

Background

- Virtual memory: separation of **logical memory** from **physical memory**
  - only part of the program needs to be in memory for execution
    - logical address space can be much larger than physical address space
    - more programs can run concurrently
    - less I/O needed to load or swap processes (part of it)
  - allows memory (e.g., shared library) to be shared by several processes
    - better IPC performance
  - allows for more efficient process forking (**copy-on-write**)
- Virtual memory can be implemented via:
  - **Paging**

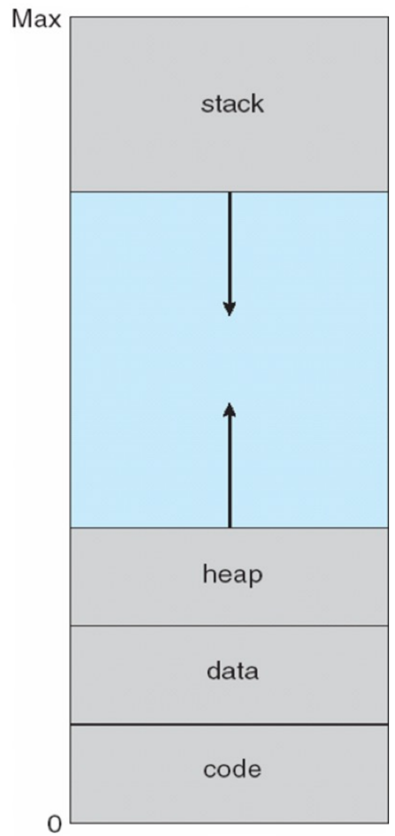
Virtual Memory Larger Than Physical Memory

- Virtual memory is larger than physical memory
  - Virtual memory is just address ranges, all storage is backed by physical memory

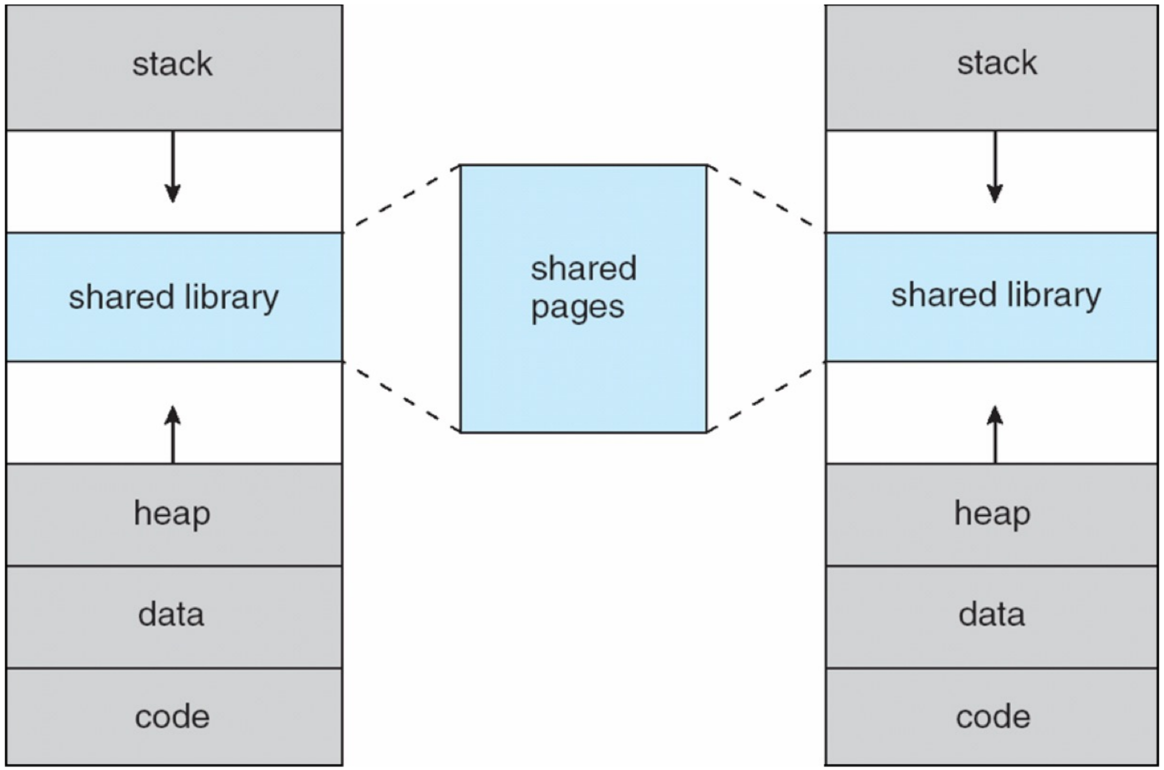


Virtual-address Space

- Usually design virtual address space for stack to start at Max logical address and grow "down" while heap grows "up"
  - Maximizes address space use
  - Unused address space between the two is hole
    - No physical memory needed until heap or stack grows to a given new page
- Enables **sparse** address spaces with holes left for growth, dynamically linked libraries, etc
- System libraries shared via mapping into virtual address space
- Pages can be shared during fork(), speeding process creation: COW



Shared Library Using Virtual Memory



Shared Library Using Virtual Memory

```
wenbo@parallels: ~
wenbo@parallels: ~ 107x30
7ffc75a5f000-7ffc75a80000 rw-p 00000000 00:00 0                          [stack]
7ffc75aa7000-7ffc75aaa000 r--p 00000000 00:00 0                          [vvar]
7ffc75aaa000-7ffc75aac000 r-xp 00000000 00:00 0                          [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0                  [vsyscall]
wenbo@parallels:~$ which cat
/bin/cat
wenbo@parallels:~$ file /bin/cat
/bin/cat: ELF 64-bit LSB shared object, x86-64, version 1 (SYSV), dynamically linked, interpreter /lib64/l,
 for GNU/Linux 3.2.0, BuildID[sha1]=747e524bc20d33ce25ed4aea108e3025e5c3b78f, stripped
wenbo@parallels:~$ cat /proc/self/maps
55b793b79000-55b793b81000 r-xp 00000000 08:01 1048601                    /bin/cat
55b793d80000-55b793d81000 r--p 00007000 08:01 1048601                    /bin/cat
55b793d81000-55b793d82000 rw-p 00008000 08:01 1048601                    /bin/cat
55b794d33000-55b794d54000 rw-p 00000000 00:00 0                          [heap]
7f1974b90000-7f197555f000 r--p 00000000 08:01 662494                     /usr/lib/locale/locale-archive
7f197555f000-7f1975746000 r-xp 00000000 08:01 267596                     /lib/x86_64-linux-gnu/libc-2.27.so
7f1975746000-7f1975946000 ---p 001e7000 08:01 267596                     /lib/x86_64-linux-gnu/libc-2.27.so
7f1975946000-7f197594a000 r--p 001e7000 08:01 267596                     /lib/x86_64-linux-gnu/libc-2.27.so
7f197594a000-7f197594c000 rw-p 001eb000 08:01 267596                     /lib/x86_64-linux-gnu/libc-2.27.so
7f197594c000-7f1975950000 rw-p 00000000 00:00 0
7f1975950000-7f1975977000 r-xp 00000000 08:01 267568                     /lib/x86_64-linux-gnu/ld-2.27.so
7f1975b3c000-7f1975b60000 rw-p 00000000 00:00 0
7f1975b77000-7f1975b78000 r--p 00027000 08:01 267568                     /lib/x86_64-linux-gnu/ld-2.27.so
7f1975b78000-7f1975b79000 rw-p 00028000 08:01 267568                     /lib/x86_64-linux-gnu/ld-2.27.so
7f1975b79000-7f1975b7a000 rw-p 00000000 00:00 0
7ffc73010000-7ffc73031000 rw-p 00000000 00:00 0                          [stack]
7ffc73148000-7ffc7314b000 r--p 00000000 00:00 0                          [vvar]
7ffc7314b000-7ffc7314d000 r-xp 00000000 00:00 0                          [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0                  [vsyscall]
wenbo@parallels:~$
```

Demand Paging

- **Demand paging** brings a page into memory only when it is demanded
  - demand means access (read/write)
  - if page is invalid (error) ➠ abort the operation
  - if page is valid but not in memory ➠ bring it to memory
    - Memory here means physical memory
    - This is called page fault
    - via swapping for swapped pages
    - via mapping for new page
    - no unnecessary I/O, less memory needed, slower response, more apps

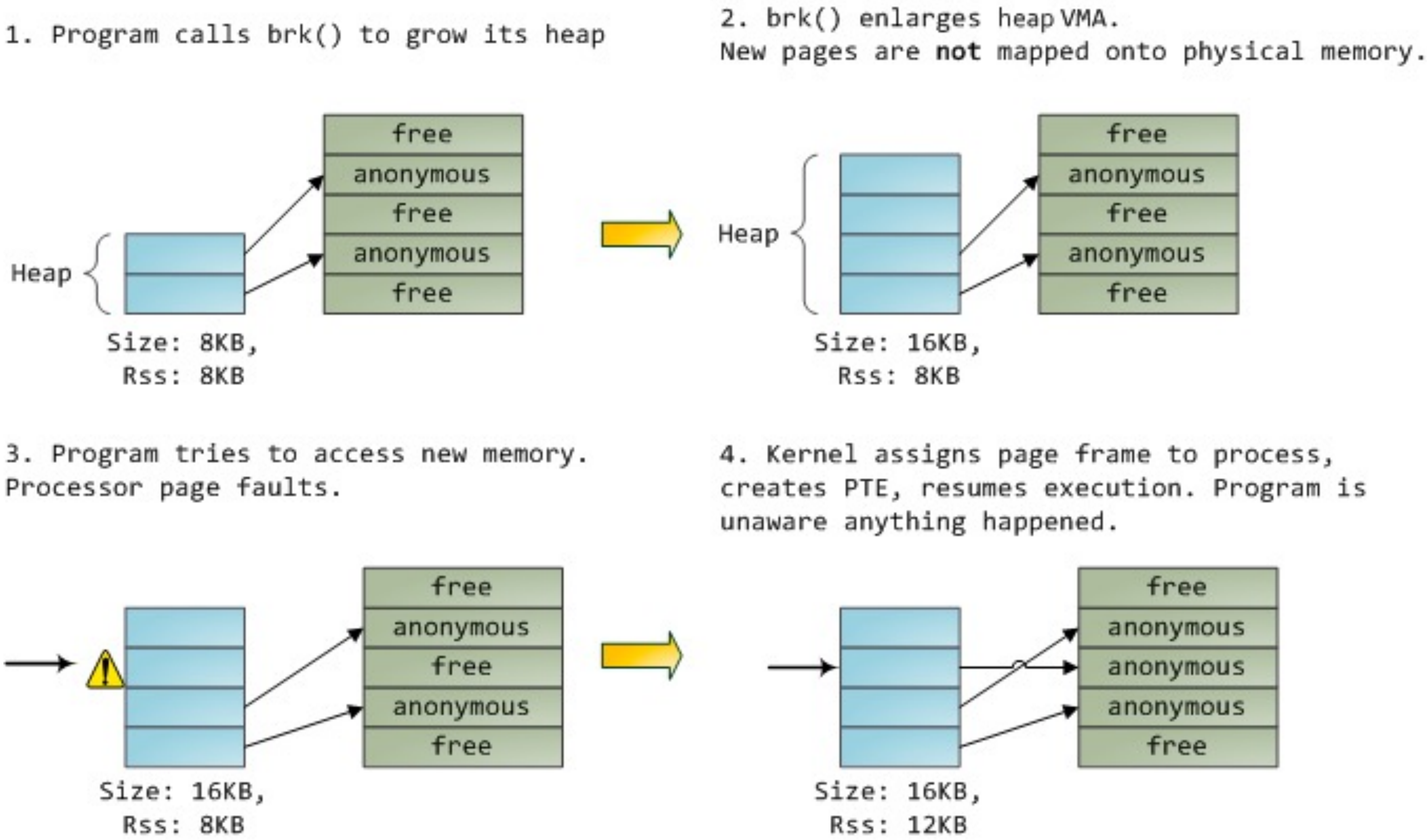
Demand Paging

- Demand paging vs page fault
  - What is the relationship?

- What causes page fault？
  - User space program accesses an address
- Which hardware issues page fault?
  - MMU
- Who handles page fault？
  - Operating system

What causes page fault?

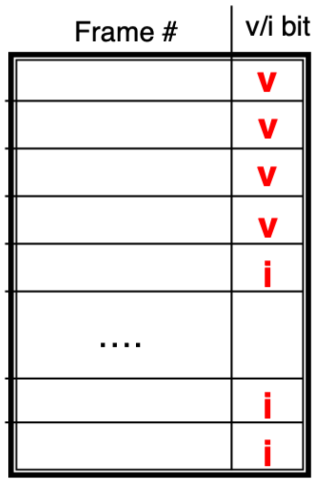
- User space program accesses an address
  - Will kernel code cause page fault?



MMU issues page fault

- How does MMU know the physical frame is not mapped?

- Each page table entry has a valid-invalid (present) bit
  - *v* ➠ frame mapped, *i* ➠ frame not mapped
  - initially, valid-invalid bit is set to *i* on all entries
  - during address translation, if the entry is invalid, it will trigger a **page fault**
- Example of a page table snapshot:

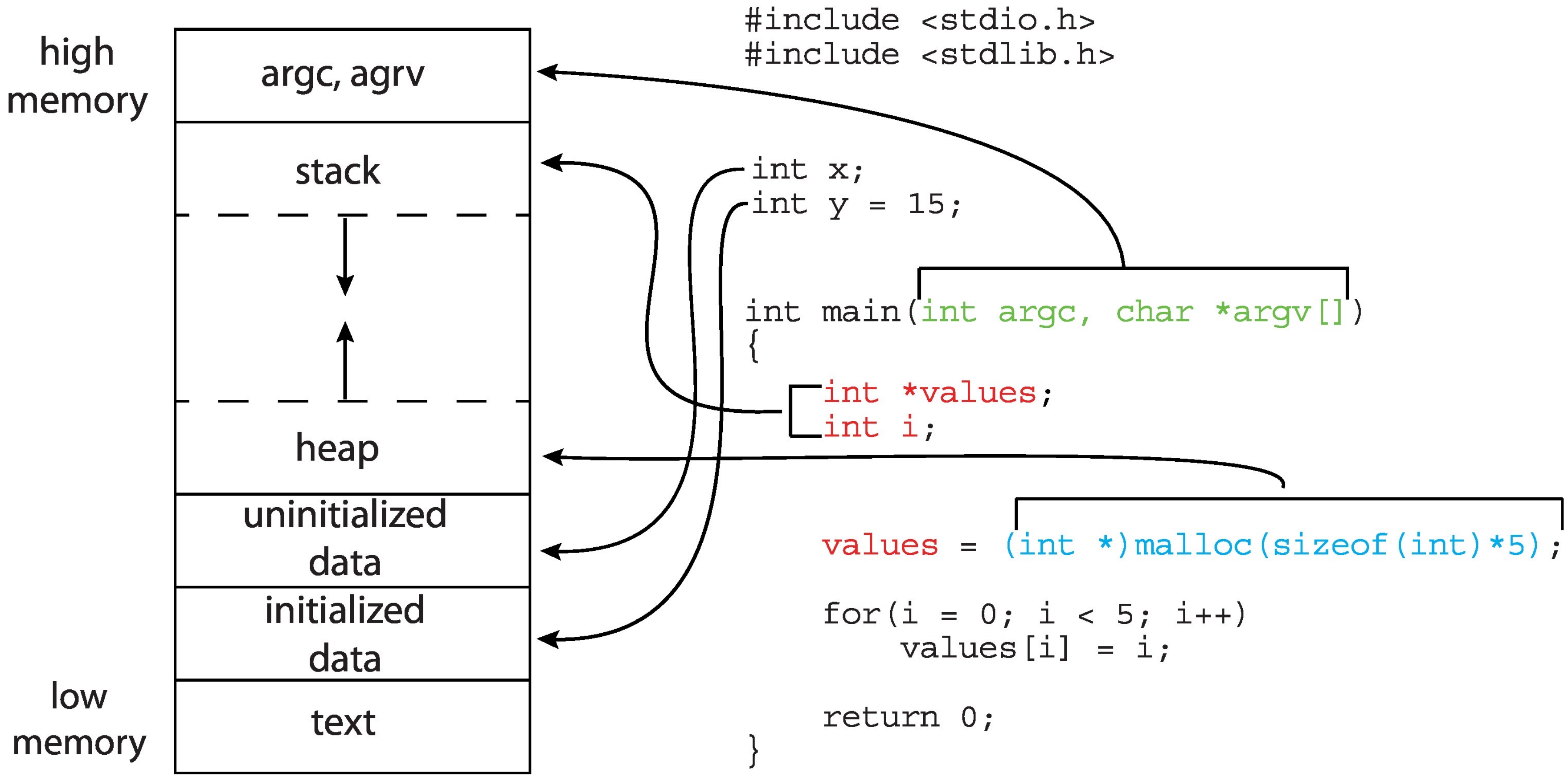


page table

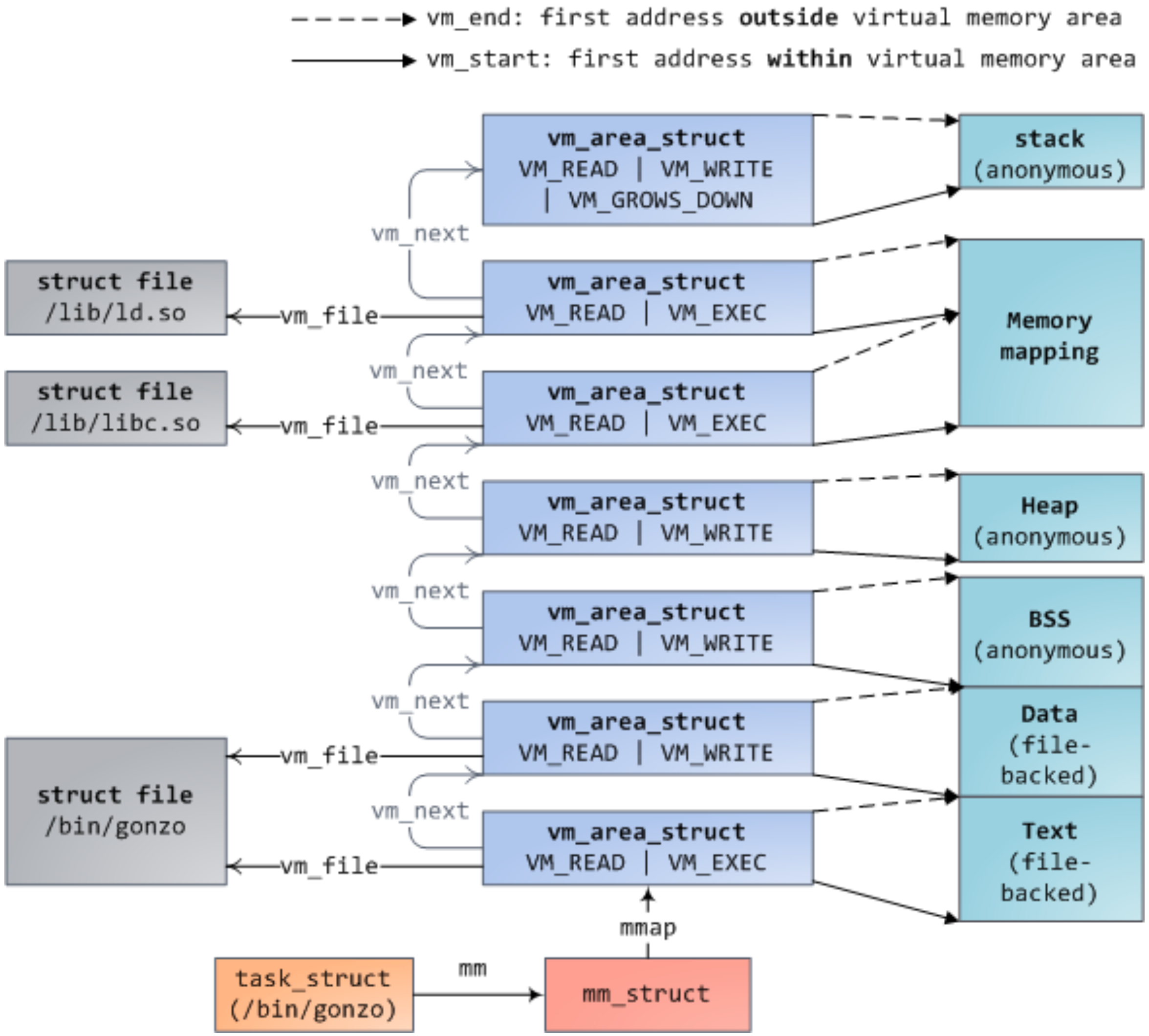
Who handles page fault?

- Linux implementation
  - First check vma to decide fault type
    - Address in vm_area
    - Address out of vm_area
      - Error, abort
  - Then map physical frame

Memory Layout of a C Program



Page Faults

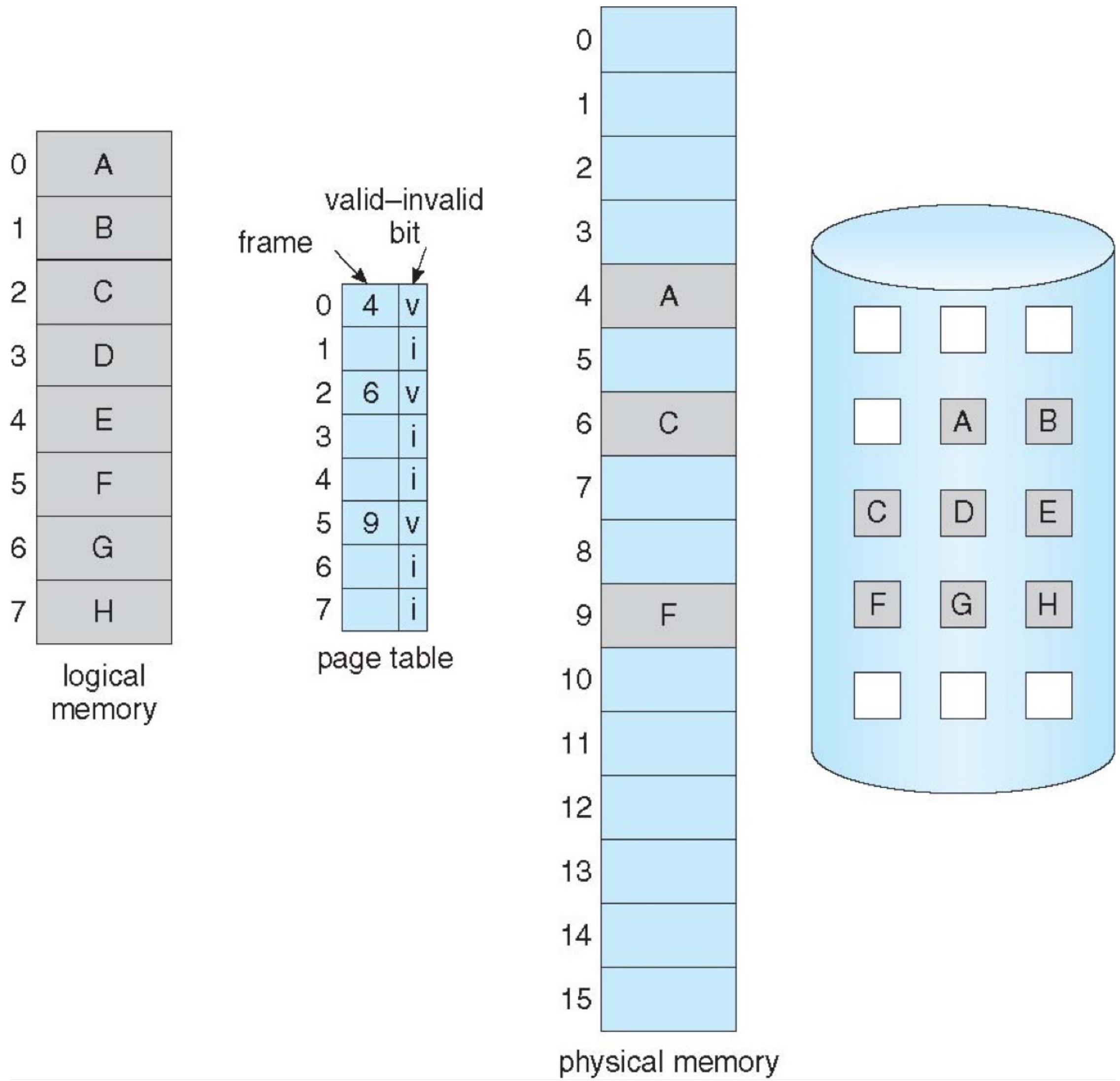



```c
struct vm_area_struct {
        /* The first cache line has the info for VMA tree walking. */

        unsigned long vm_start;         /* Our start address within vm_mm. */
        unsigned long vm_end;           /* The first byte after our end address
                                           within vm_mm. */
```

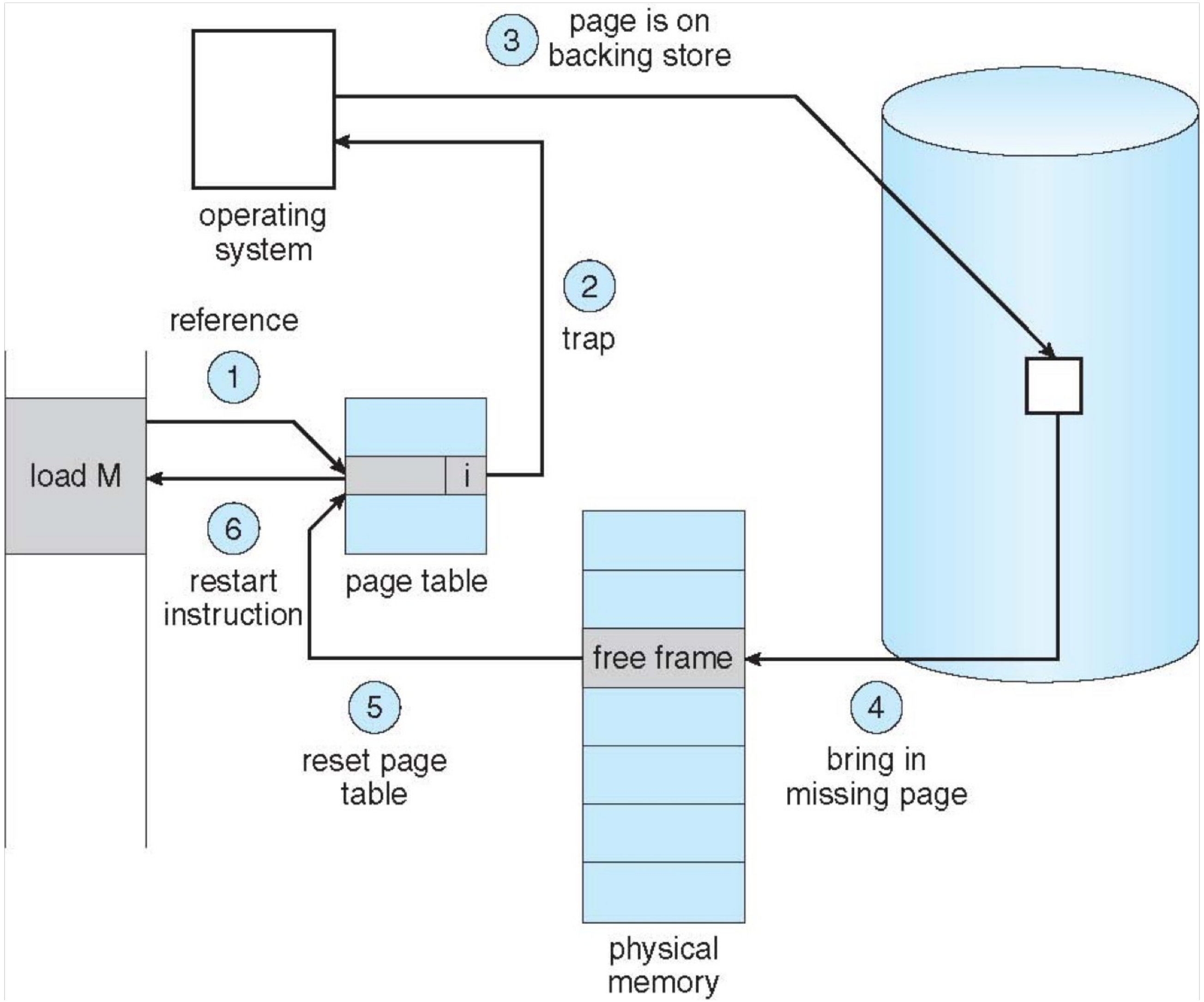
Page Table (Mem pages are not all in memory)

- Executable file



Page Fault Handling

- Page fault for code



Page Fault

- First reference to a non-present page will trap to kernel: **page fault**
- Operating system looks at memory mapping to decide:
  - **invalid reference** ➠ deliver an exception to the process
    - Via check vma in Linux
  - **valid but not in physical memory** ➠ bring in
    - get an empty physical frame
    - bring page into frame via disk operation
    - set page table entry to indicate the page is now in memory
    - restart the instruction that caused the page fault

Page Fault - swapper

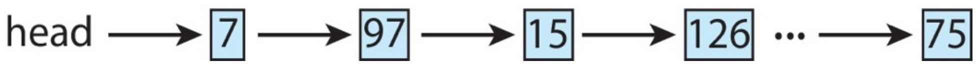
- **Lazy swapper**: never **swaps a page in** memory unless it will be needed
  - the swapper that deals with pages is also caller a pager
- **Pre-Paging**: pre-page all or some of pages a process will need, before they are referenced
  - it can reduce the number of page faults during execution
  - if pre-paged pages **are unused**, I/O and memory was wasted
    - although it reduces page faults, total I/O# likely is higher

Page Fault

- Extreme case: start process with no frames in memory (aka. **pure demand paging**)
  - OS sets instruction pointer to first instruction of process
    - invalid page ➠ page fault
  - every page is paged in on first access
    - **program locality** reduces the overhead
  - an instruction could access multiple pages ➠ multiple page faults
    - e.g., instruction, data, and page table entries for them
- Demand paging needs hardware support
  - page table entries with **valid / invalid bit**
  - **backing storage** (usually disks)
  - **instruction restart**

Page Fault – Get Free Frame

- When a page fault occurs, the operating system must bring the desired page from secondary storage into main memory.
- Most operating systems maintain a free-frame list -- a pool of free frames for satisfying such requests.



- Operating system typically allocate free frames using a technique known as **zero-fill-on-demand** -- the content of the frames zeroed-out before being allocated.
- When a system starts up, all available memory is placed on the free-frame list.

Stages in Demand Paging - Worse Case

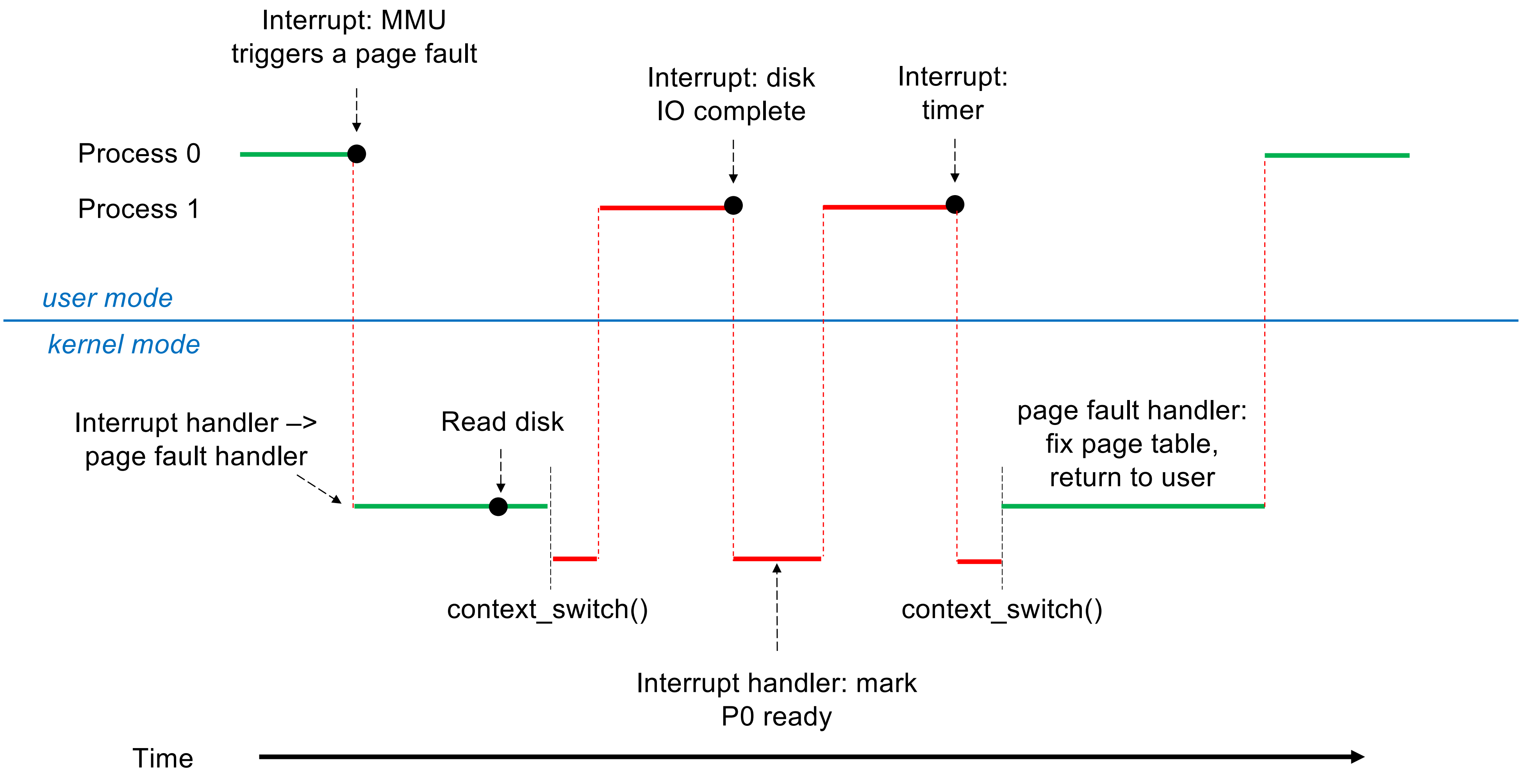
- 1. Trap to the operating system
- 2. Save the user registers and process state
- 3. Determine that the interrupt was a page fault
    - 3.1 Check that the page reference was legal
- 4. Find a free frame
- 5. Determine the location of the page on the disk, issue a read from the disk to the free frame:
    - 5.1 Wait in a queue for this device until the read request is serviced
    - 5.2 Wait for the device seek and/or latency time
    - 5.3 Begin the transfer of the page to a free frame

Stages in Demand Paging – Worse Case

- 6. While waiting, allocate the CPU to other process
- 7. Receive an interrupt from the disk I/O subsystem (I/O completed)
  - 7.1 Determine that the interrupt was from the disk
  - 7.2 Mark page fault process ready
- 8. Wait for the CPU to be allocated to this process again
  - 8.1 Save registers and process state for other process
  - 8.2 Context switch to page fault process
- 9. Correct the page table, mapping new frame
- 10. Return to user: restore the user registers, process state, and new page table, and then resume the interrupted instruction

Stages in Demand Paging - Worse Case

- Assume a page fault happen in Process 0
- While waiting for disk, the CPU is allocated to Process 1



Demand Paging: EAT

- 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):

  $(1 - p)$ x memory access + p x (
  page fault overhead +
  swap page out + swap page in +
  instruction restart overhead)

Demand Paging Example

- Assume memory access time: 200 nanoseconds, average page-fault service time: 8 milliseconds
  - EAT = (1 – p) x 200 + p x (8 milliseconds)

    = (1 – p) x 200 + p x 8,000,000

    = 200 + p x 7,999,800
  - if one out of 1,000 causes a page fault, then EAT = 8.2 microseconds
    - a slowdown by a factor of 41000
      - 8.2 ms / 0.2 us = 41000
  - if want < 10 percent, less than one page fault in every 400,000 accesses

Demand Paging Optimizations

- Swap space I/O faster than file system I/O even if on the same device
  - Swap allocated in larger chunks, less management needed than file system
- Copy entire process image from disk to swap space at process load time
  - Then page in and out of swap space
  - Used in older BSD Unix

Demand Paging Optimizations

- Demand page in from program binary on disk, but **discard** rather than paging out when freeing frame (and reload from disk next time)
  - Following cases still need to **write** to swap space
    - Pages not associated with a file (like stack and heap) – anonymous memory
    - Pages modified in memory but not yet written back to the file system

- Mobile systems
  - Typically don't support swapping
  - Instead, demand page from **file system** and reclaim read-only pages (such as code)

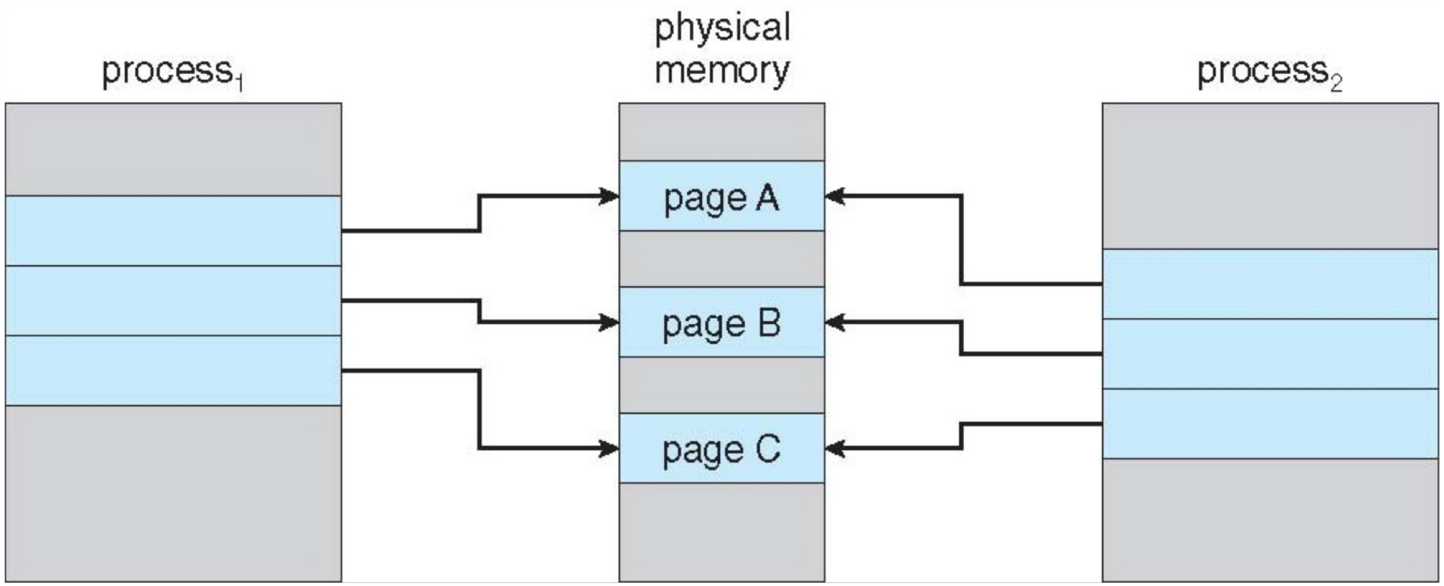
Copy-on-Write

- **Copy-on-write** (COW) allows parent and child processes to initially share the same pages in memory
  - the page is shared as long as no process modifies it
  - if either process modifies a shared page, only then is the page copied

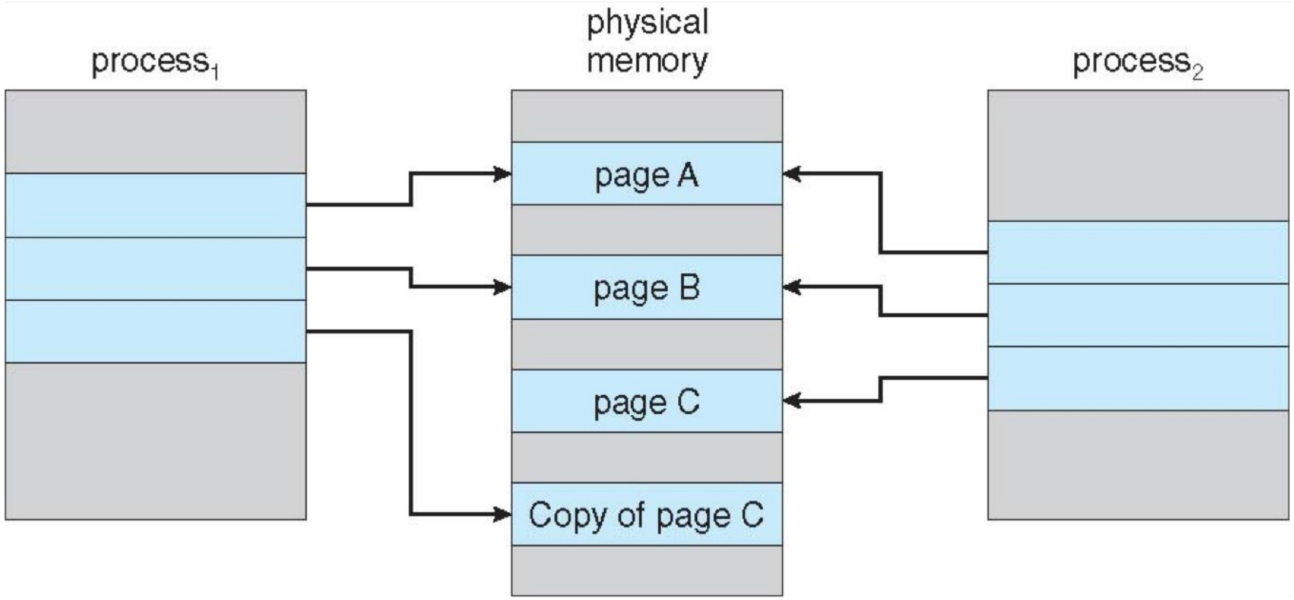
- COW allows more efficient **process creation**
  - no need to copy the parent memory during fork
  - only changed memory will be copied later

- vfork syscall optimizes the case that child calls **exec** immediately after fork
  - parent is suspend until child exits or calls exec
  - child shares the parent resource, including the heap and the stack
    - child cannot return from the function or call exit, should call _exit
  - vfork could be fragile, **it is invented when COW has not been implemented**

Before Process 1 Modifies Page C



After Process 1 Modifies Page C



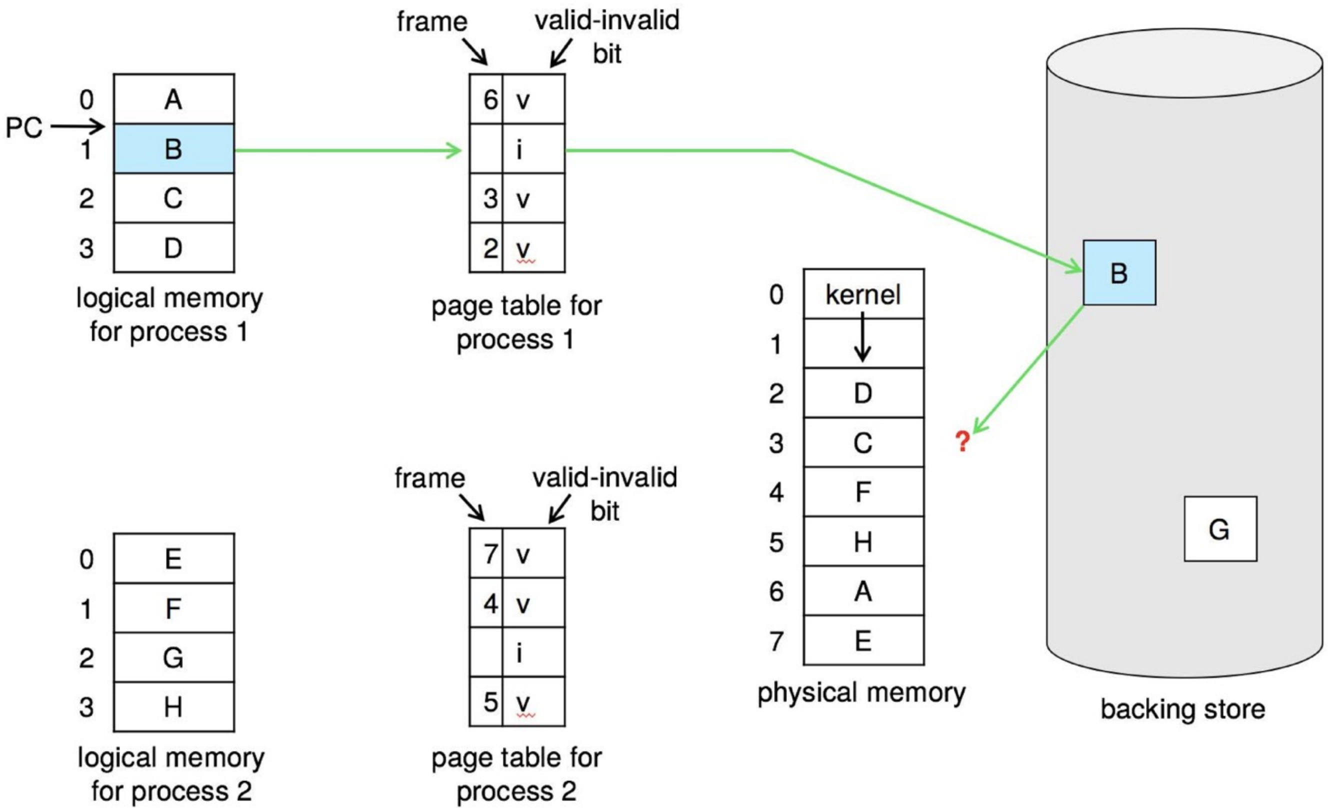
What Happens if There is no Free Frame?

- Used up by process pages
- Also in demand from the kernel, I/O buffers, etc
- How much to allocate to each?
- **Page replacement** – find some page in memory, but not really in use, page it out
    - Algorithm – terminate? swap out? replace the page?
    - Performance – want an algorithm which will result in minimum number of page faults
- Same page may be brought into memory several times

Page Replacement

- Memory is an important resource, system may run out of memory
- To prevent out-of-memory, swap out some pages
  - page replacement usually is a part of the page fault handler
  - policies to select victim page require careful design
    - need to reduce overhead and avoid **thrashing**
  - use modified (dirty) bit to reduce number of pages to swap out
    - only modified pages are written to disk
  - select some processes to kill (last resort)
- **Page replacement completes separation between logical memory and physical memory** – large virtual memory can be provided on a smaller physical memory

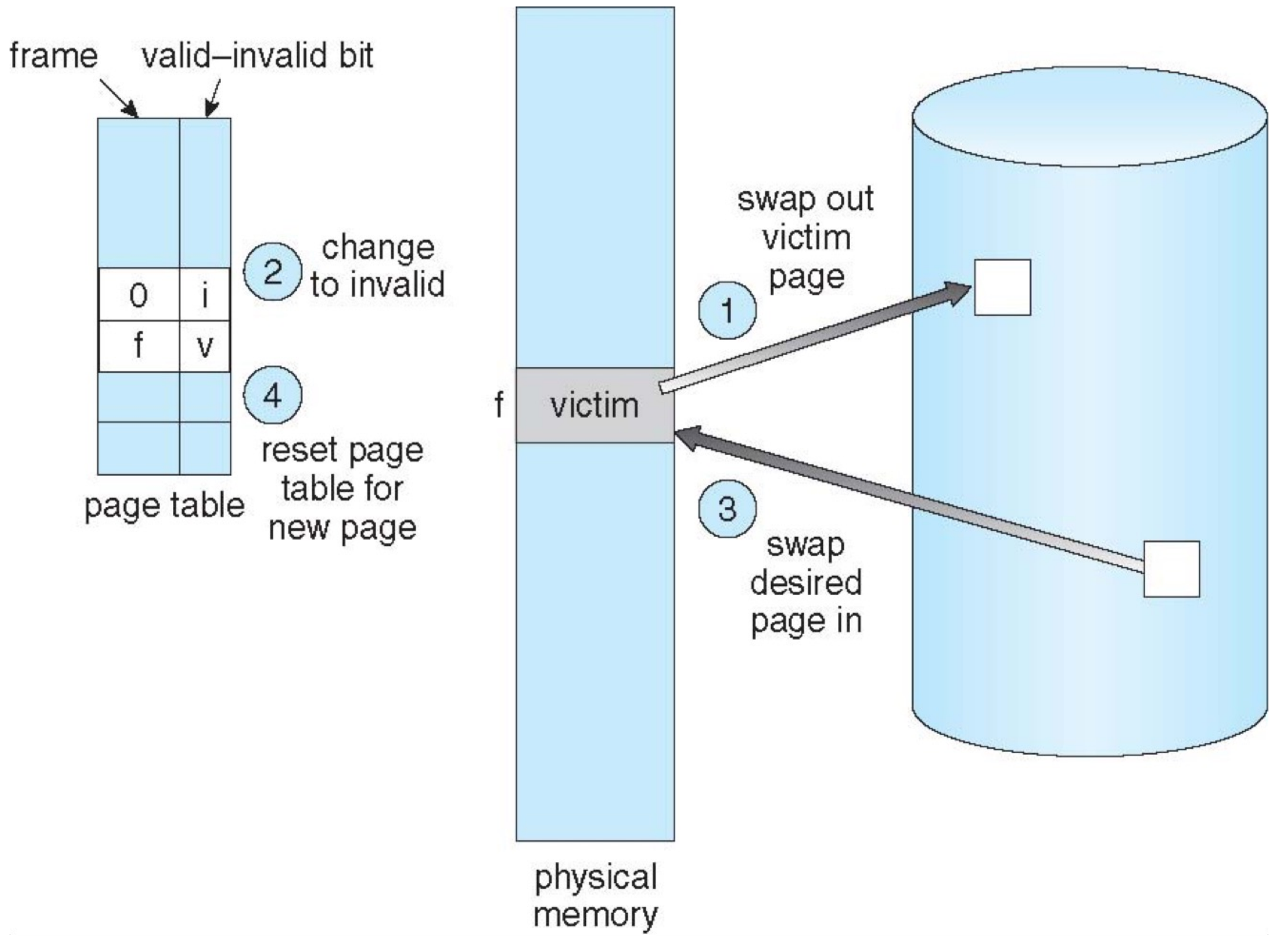
Need For Page Replacement



Page Fault Handler (with Page Replacement)

- To page in a page:
  - find the location of the desired page on disk
  - find a free frame:
    - if there is a free frame, use it
    - if there is none, use a page replacement policy to pick a victim frame, write victim frame to disk if dirty
  - bring the desired page into the free frame; update the page tables
  - restart the instruction that caused the trap
- Note now potentially **2 page I/O** for **one page fault** ➠ increase EAT

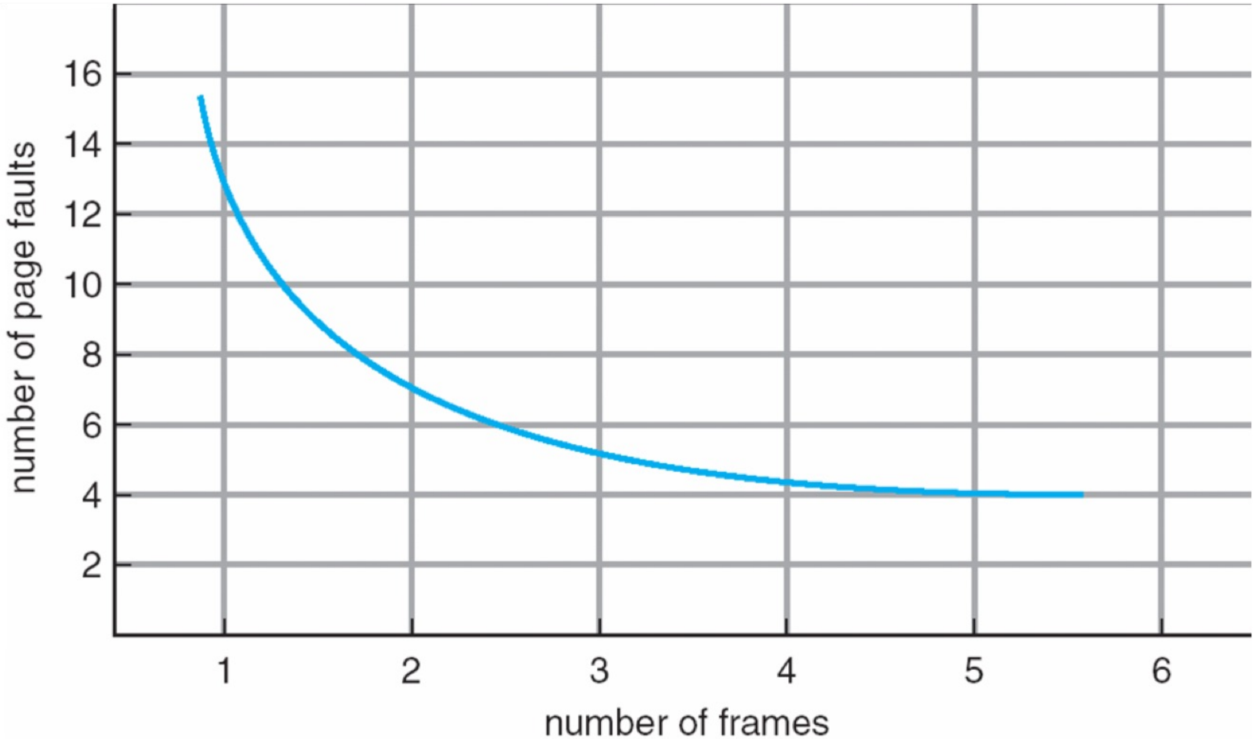
Page Replacement



Page Replacement Algorithms

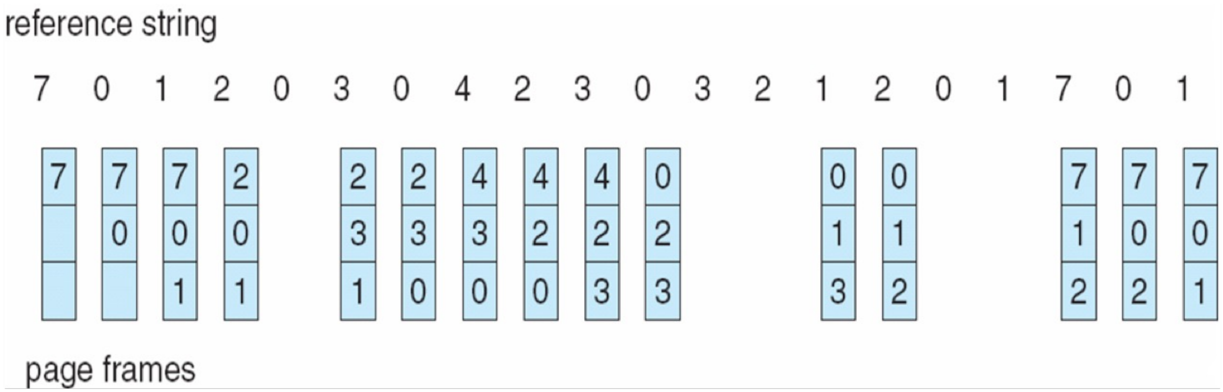
- Page-replacement algorithm should have lowest page-fault rate on both first access and re-access
  - FIFO, optimal, LRU, LFU, MFU…
- To evaluate a page replacement algorithm:
  - run it on a particular string of memory references (reference string)
    - string is just page numbers, not full addresses
  - compute the number of page faults on that string
    - repeated access to the same page does not cause a page fault
  - in all our examples, the reference string is
    7,0,1,2,0,3,0,4,2,3,0,3,0,3,2,1,2,0,1,7,0,1

Page Faults v.s. Number of Frames



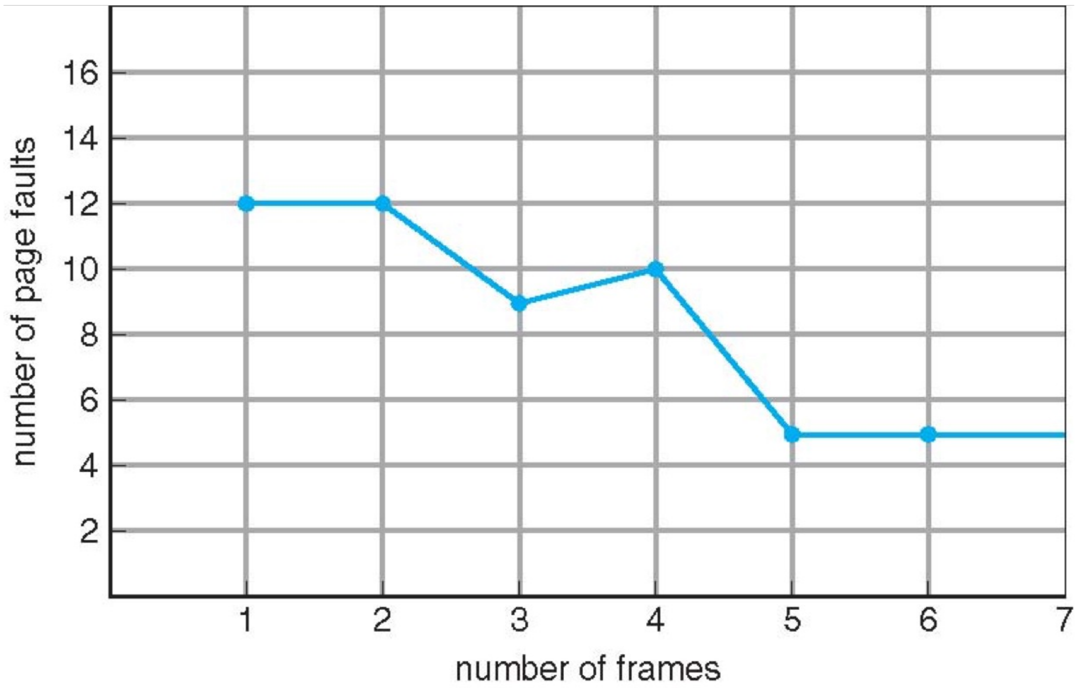
First-In-First-Out (FIFO)

- **FIFO**: replace the first page loaded
  - Similar to sliding a window of n in the reference string
  - Our reference string 7,0,1,2,0,3,0,4,2,3,0,3,0,3,2,1,2,0,1,7,0,1
    - will cause 15 page faults with 3 frames
  - How about reference string of 1,2,3,4,1,2,5,1,2,3,4,5 /w 3 or 4 frames?
- For FIFO, adding **more frames** can cause **more page faults**!
  - **Belady's Anomaly**



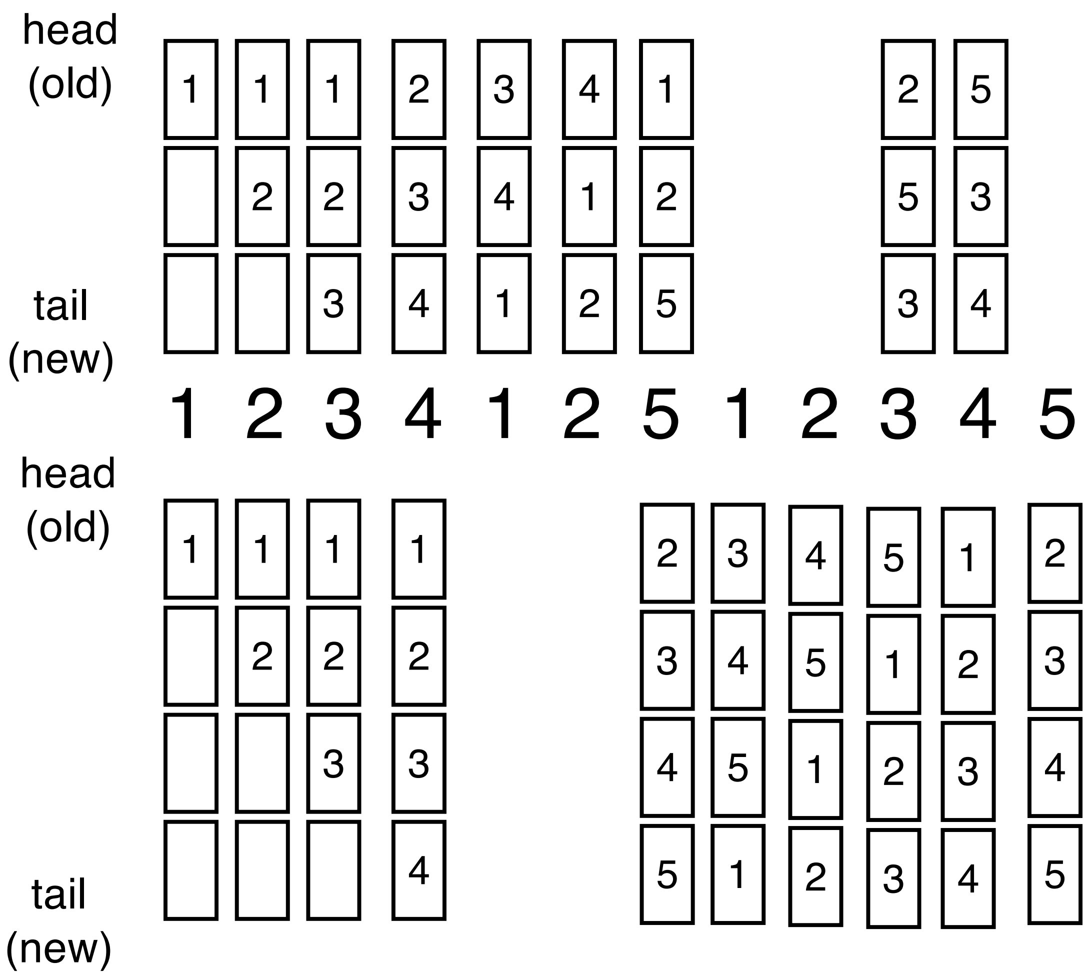
15 page faults

FIFO Illustrating Belady's Anomaly



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

Belady's Anomaly

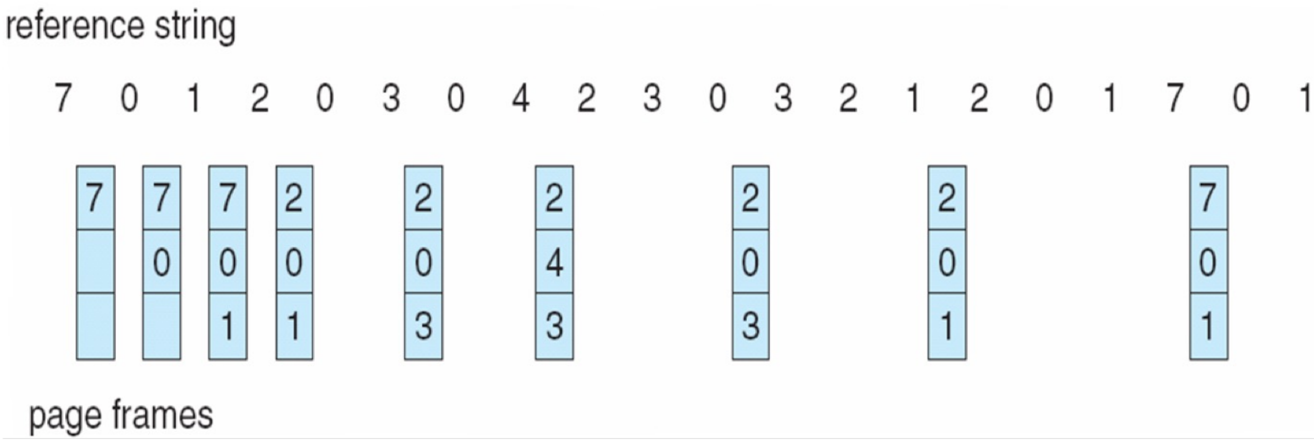


9 page faults

10 page faults!

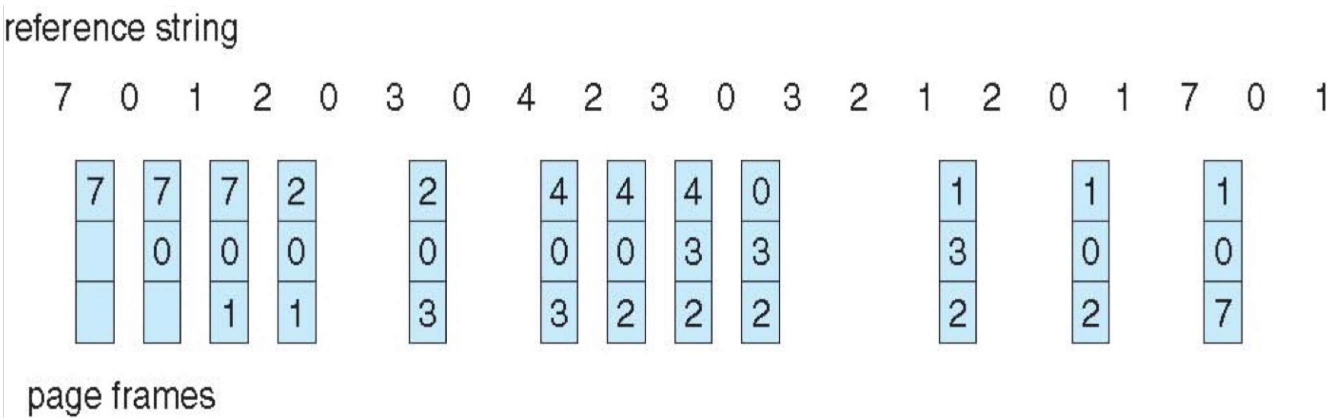
Optimal Algorithm

- **Optimal** : replace page that will not be used for the longest time
  - 9-page-fault is optimal for the example on previous slide
- How do you know which page will not be used for the longest time?
  - can't read the future
  - used for measuring how well your algorithm performs



Least Recently Used (LRU)

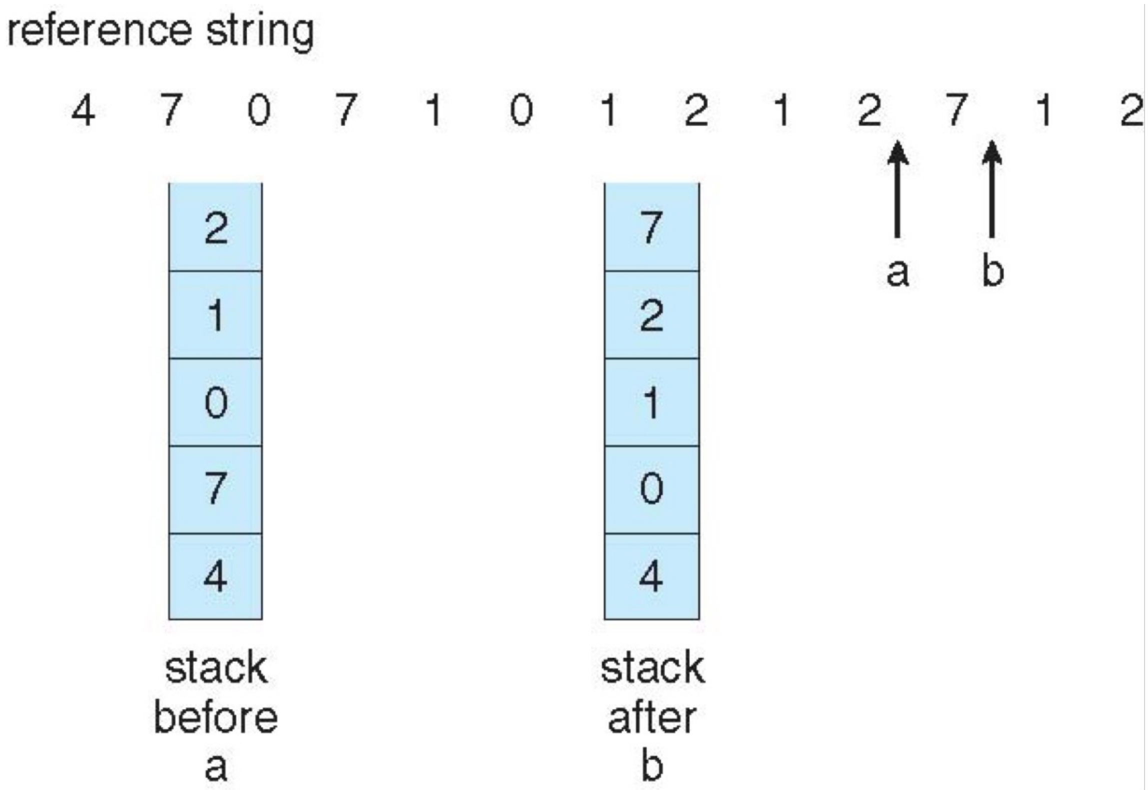
- **LRU** replaces pages that have not been used for the longest time
  - associate time of last use with each page, select pages w/ oldest timestamp
  - generally good algorithm and frequently used
  - 12 faults for our example, better than FIFO but worse than OPT
- LRU and OPT do **NOT** have Belady's Anomaly
- How to implement LRU?
  - **counter-based**
  - **stack-based**



LRU Implementation

- **Counter-based** implementation
  - every page table entry has a counter
  - every time page is referenced, copy the **clock** into the counter
  - when a page needs to be replaced, search for page with smallest counter
    - min-heap can be used
- **Stack-based** implementation
  - keep a stack of page numbers (in double linked list)
  - when a page is referenced, move it to the top of the stack
  - each update is more expensive, but no need to search for replacement

Stack-based LRU



LRU Approximation Implementation

- Counter-based and stack-based LRU have high performance overhead
- Hardware provides **a reference bit**
- LRU approximation with a **reference bit**
  - associate with each page a reference bit, initially set to 0
  - when page is referenced, set the bit to 1 (done by the hardware)
  - replace any page with reference bit = 0 (if one exists)
    - We do not know the **order**, however

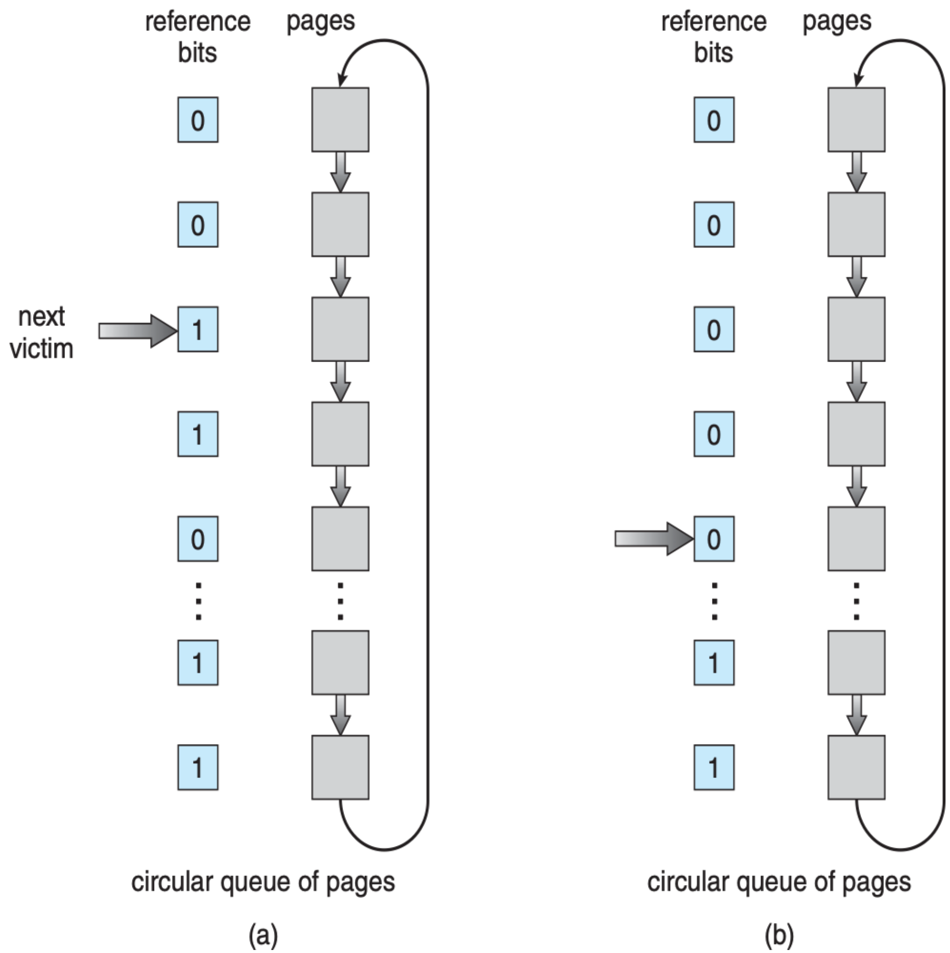
Additional-Reference-Bits Algorithm

- Reordering the bits at regular intervals
  - Suppose we have 8-bits byte for each page
  - During a time interval (100ms), shifts bit rights by 1 bit, sets the high bit if used, and then discards the low-order bits
  - 00000000 => has not been used in 8 time intervals
  - 11111111 => has been used in all time intervals
  - 11000100 vs 01110111 : which one is used more recently?

LRU Implementation

- **Second-chance** algorithm
  - Generally FIFO, plus hardware-provided **reference bit**
  - **Clock** replacement
  - If page to be replaced has
    - Reference bit = 0 -> replace it
    - reference bit = 1 then:
      - set reference bit 0, leave page in memory
      - replace next page, subject to same rules

Second-chance (clock) Page-replacement Algorithm



Enhanced Second-Chance Algorithm

- Improve algorithm by using **reference bit** and modify bit (if available) in concert
- Take ordered pair (reference, modify):
  - (0, 0) neither recently used not modified – best page to replace
  - (0, 1) not recently used but modified – not quite as good, must write out before replacement
  - (1, 0) recently used but clean – probably will be used again soon
  - (1, 1) recently used and modified – probably will be used again soon and need to write out before replacement
- When page replacement called for, use the clock scheme but use the four classes replace page in lowest non-empty class
  - Might need to search circular queue several times

Counting-based Page Replacement

- Keep the number of references made to each page
- **Least Frequently Used (LFU)** replaces page with the smallest counter
  - A page is heavily used during process initialization and then never used
- **Most Frequently Used (MFU)** replaces page with the largest counter
  - based on the argument that page with the smallest count was probably just brought in and has yet to be used
- LFU and MFU are not common

Page-Buffering Algorithms

- **Keep a pool of free frames, always**
  - **frame available when needed**, no need to find at fault time
  - Read page into free frames without waiting for victims to write out
    - Restart as soon as possible
  - When convenient, evict victim
- Possibly, keep list of **modified pages**
  - When disk **idles**, write pages there and set to non-dirty: this page can be replaced **without** writing pages to backing store
- Possibly, keep free frame contents intact and note what is in them - a kind of cache
  - If **referenced again before reused, no need to load contents again from disk**
    - **cache hit**

Applications and Page Replacement

- All of these algorithms have OS guessing about future page access
- Some applications have better knowledge – i.e. databases
- Memory intensive applications can cause **double buffering - a waste of memory**
    - OS keeps copy of page in memory as I/O buffer
    - Application keeps page in memory for its own work
- Operating system can given direct access to the disk, getting out of the way of the applications
    - **Raw disk** mode
- Bypasses buffering, locking, etc

Allocation of Frames

- Each process needs **minimum number** of frames -according to instructions semantics
- Example: IBM 370 – **6 pages to handle SS MOVE** instruction:
  - instruction is 6 bytes, might span 2 pages
  - 2 pages to handle from
  - 2 pages to handle to
- **Maximum** of course is total frames in the system
- Two major allocation schemes for process memory allocation
  - Equal allocation
  - Proportional allocation

Frame Allocation

- Equal allocation
  - For example, if there are 100 frames (after allocating frames for the OS) and 5 processes, give each process 20 frames
  - Keep some as free frame buffer pool
- Proportional allocation
  - Allocate according to the size of process
  - Dynamic as degree of multiprogramming, process sizes change

$$s_i = \text{size of process } p_i$$
$$S = \sum s_i$$
$$m = \text{total number of frames}$$
$$a_i = \text{allocation for } p_i = \frac{s_i}{S} \times m$$

$$m = 62$$
$$s_1 = 10$$
$$s_2 = 127$$
$$a_1 = \frac{10}{137} \times 62 \approx 4$$
$$a_2 = \frac{127}{137} \times 62 \approx 57$$

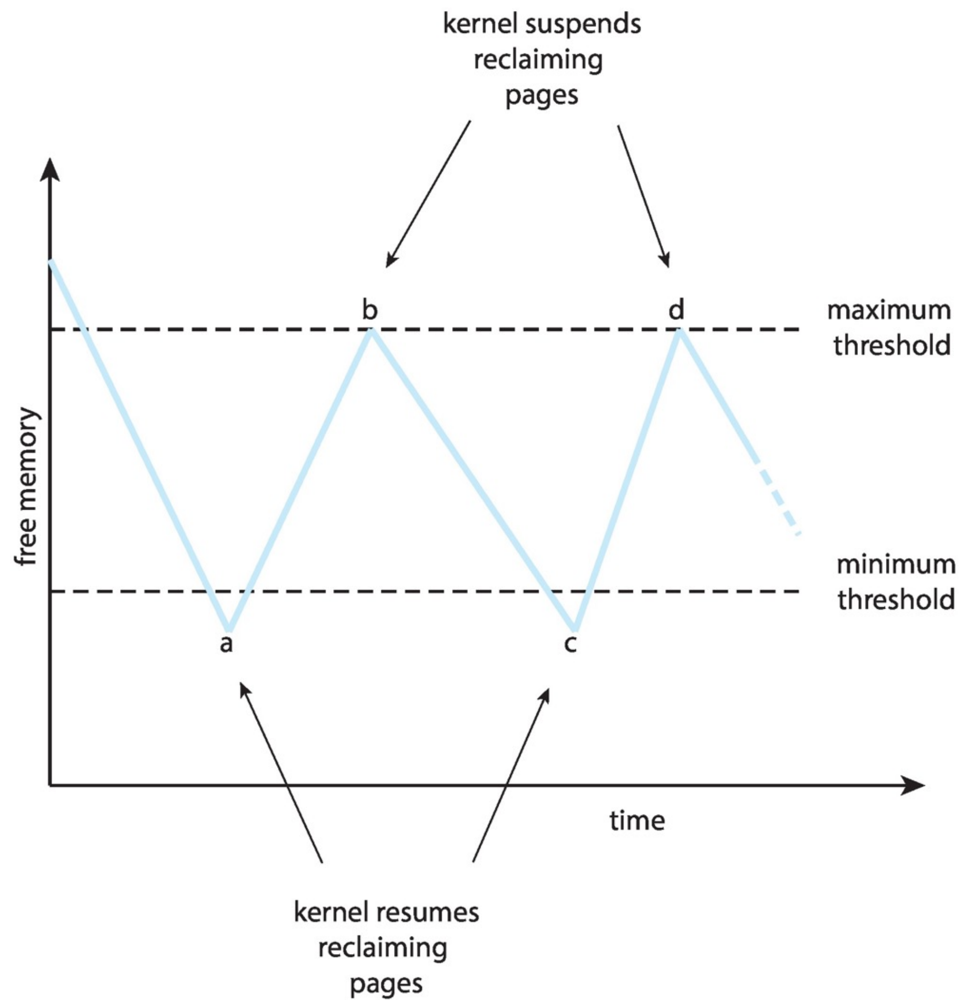
Global vs. Local Allocation

- **Global replacement** – process selects a replacement frame from the set of all frames; one process can take a frame from another
  - But then process execution time can **vary** greatly - depends on others
  - But greater throughput so more common
- **Local replacement** – each process selects from only its own set of allocated frames
  - More consistent per-process performance
  - But possibly underutilized memory

Reclaiming Pages

- A strategy to implement global page-replacement policy
- All memory requests are satisfied from the free-frame list
- Rather than waiting for the list to drop to zero before we begin selecting pages for replacement, page replacement is triggered when the list falls below a **certain threshold.**
- This strategy attempts to ensure **there is always sufficient** free memory to satisfy new requests.

Reclaiming Pages Example



What happens if memory is below the minimum threshold

- Reclaim pages aggressively
  - Kill some processes
    - According to OOM score
    - how likely it is to be terminated in case of low available memory

Major and minor page faults

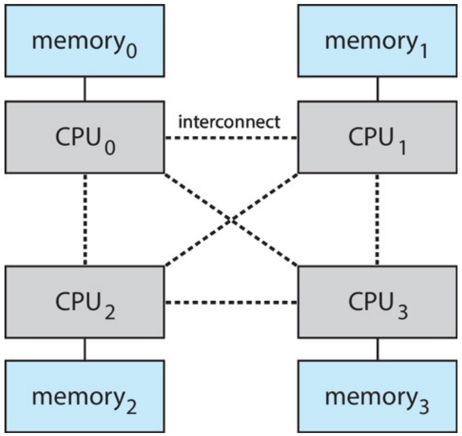
- Major: page is referenced but not in memory
  - Can only be satisfied by disk
  - do_anonymous_page is not major
- Minor: mapping does not exist, but the page is in memory
  - Shared library
  - Reclaimed and not freed yet

```
wenbo@parallels:~$ ps eo min_flt,maj_flt,cmd
 MINFL  MAJFL CMD
   704      1 /usr/lib/gdm3/gdm-x-session --run-script env
 59284     17 /usr/lib/xorg/Xorg vt2 -displayfd 3 -auth /ru
  8439     12 /usr/lib/gnome-session/gnome-session-binary -
 73769     25 /usr/bin/gnome-shell USER=wenbo LC_TIME=zh_CN
  1346      0 ibus-daemon --xim --panel disable USER=wenbo
   376      1 /usr/lib/ibus/ibus-dconf USER=wenbo LC_TIME=z
  1659      0 /usr/lib/ibus/ibus-x11 --kill-daemon USER=wen
```

Thanks to shared libraries!

Non-Uniform Memory Access

- So far all memory accessed equally
- Many systems are NUMA – speed of access to memory varies
  - Consider system boards containing CPUs and memory, interconnected over a system bus
- NUMA multiprocessing architecture



Non-Uniform Memory Access (Cont.)

- Optimal performance comes from allocating memory "close to" the CPU on which the thread is scheduled
  - And modifying the **scheduler** to schedule the thread on the same system board when possible
  - Linux
    - Kernel maintains scheduling domains: does not allow threads to migrate across domains
    - A separate free-frame list for each NUMA node - allocating memory from the node it is running

Thrashing

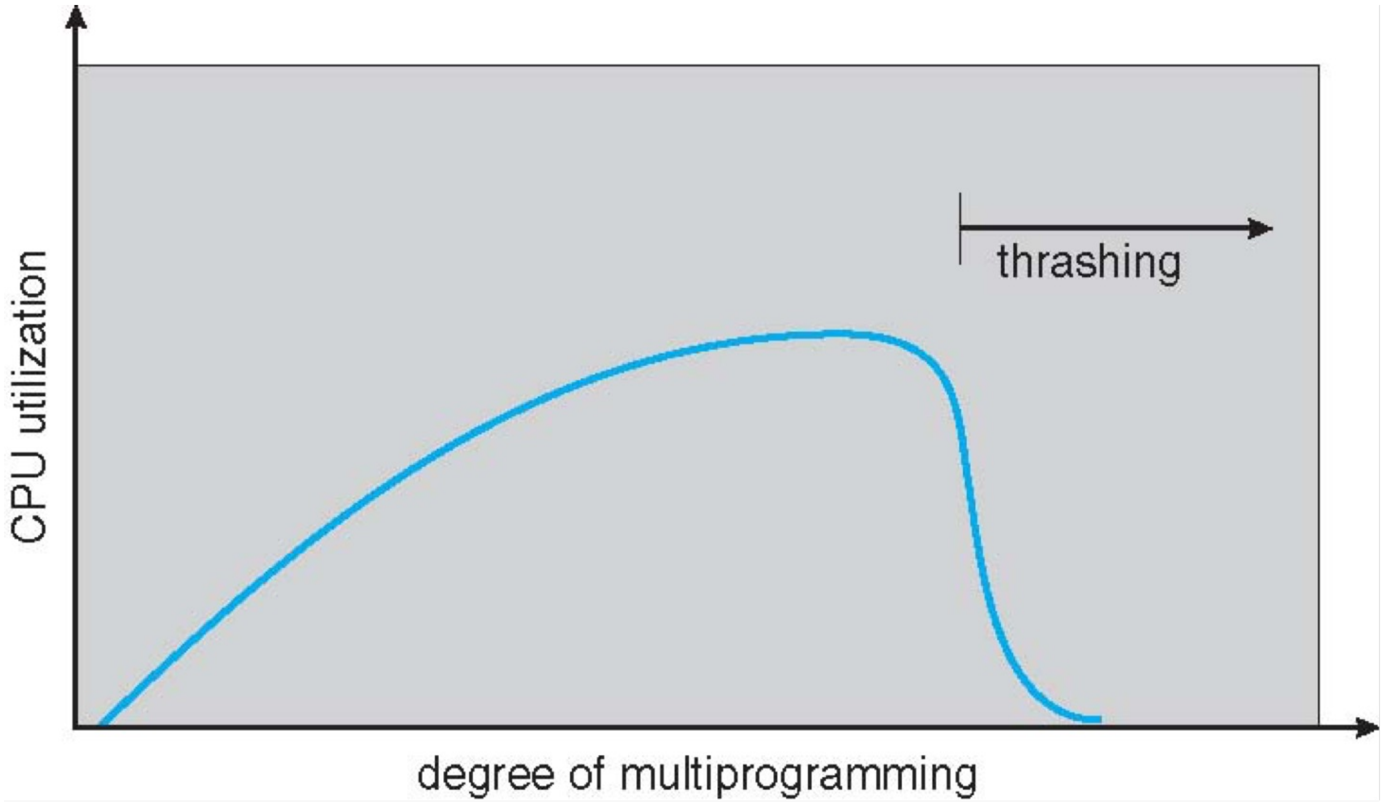
- If a process doesn't have "enough" pages(frames), page-fault rate may be high
  - page fault to get page, replace some existing frame
  - but quickly need replaced frame back
  - this leads to:

    low CPU utilization ➠

    kernel thinks it needs to increase the degree of multiprogramming to maximize CPU utilization ➠

    another process added to the system
- **Thrashing**: a process is busy swapping pages in and out

Thrashing



Demand Paging and Thrashing

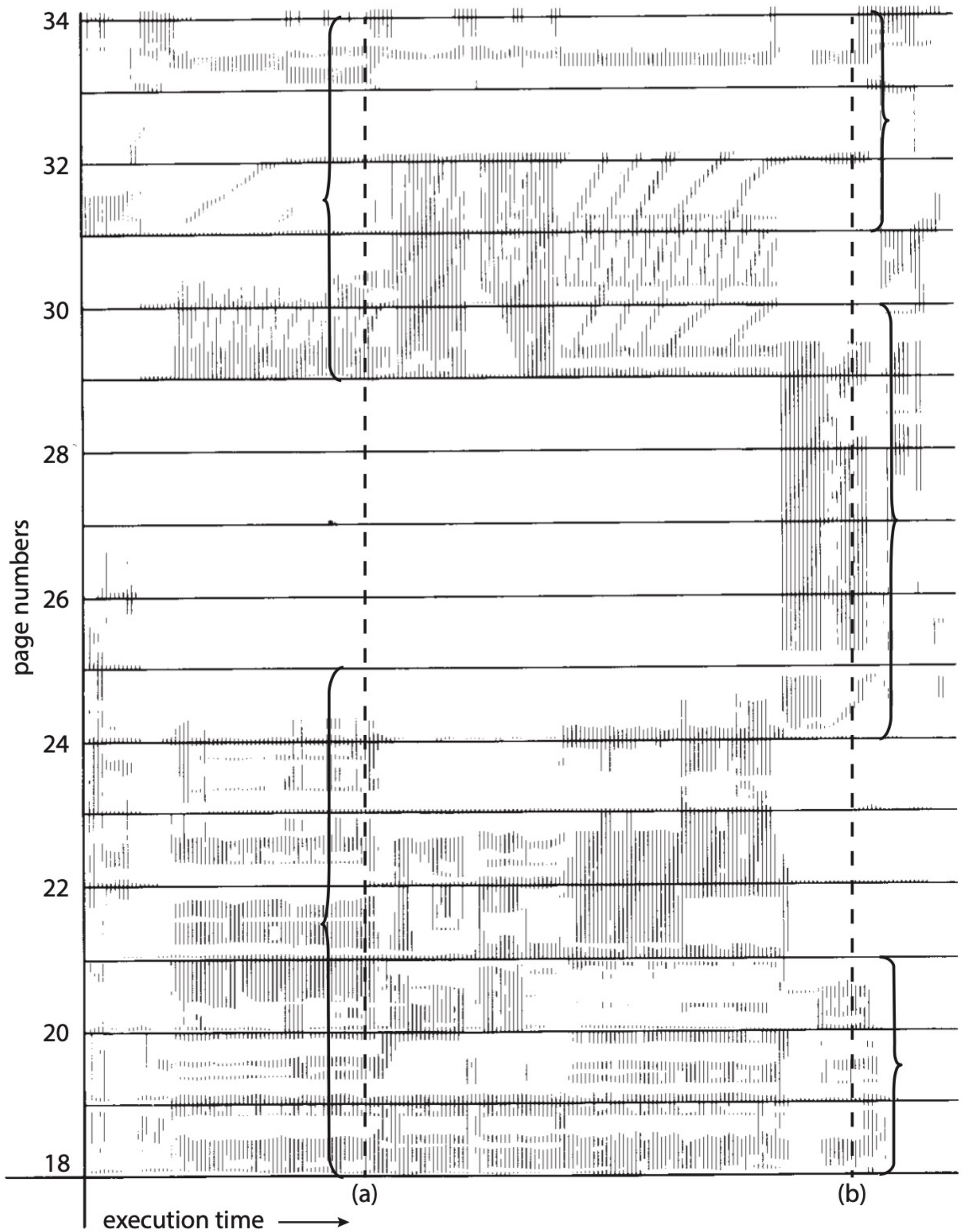
- Why does demand paging work?
  - process memory access has **high locality**
  - process migrates from one locality to another, localities may overlap
- Why does thrashing occur?
  - total memory size < total size of locality

Resolve thrashing - Option I

- Limit thrashing effects by **using local page** replacement
  - One process starts thrashing does not affect others -> it cannot cause other processes thrashing
    - Select swap out page from the same process

Resolve thrashing - Option II

- Provide a process with as many frames as it needs. How?
    - Time (a), the locality is the set of pages {18-24, 29-33}.
    - Time (b), the locality changes to {18-20, 24-29, 31-33}
    - 18, 19, and 20 are part of both localities

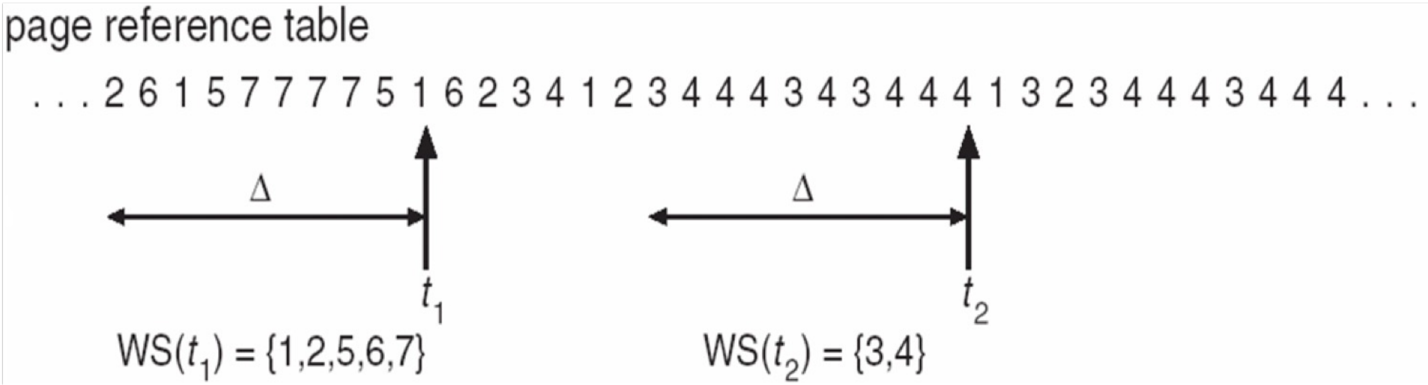


Working-Set Model

- **Working-set window**(Δ): a fixed number of page references
  - if Δ too small ➠ will not include entire locality
  - if Δ too large ➠ will include several localities
  - if Δ = ∞ ➠ will include entire program
- **Working set** of process p_i (WSSi): total number of pages referenced in the most recent Δ (varies in time)
- **Total working sets**: $D = \sum WSS_i$
  - approximation of total locality
  - if D > m ➠ possibility of thrashing
  - to avoid thrashing: if D > m, suspend or swap out some processes

Working-Set Model

- Working-set window Δ = 10

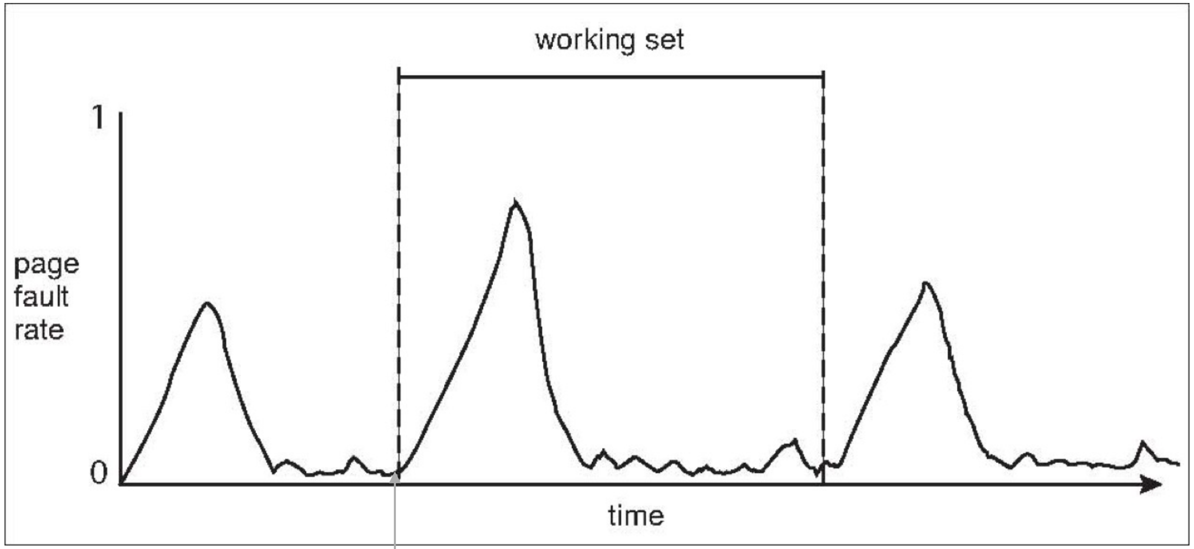


Challenge: Keeping Track of the Working Set

- Approximate with interval timer + a reference bit (in register)
  - The reference bit is set to 1 by hardware when accessing a page
- Example: Δ = 10,000 time units
  - Timer interrupts after every 5000 time units
  - Keep 2 bits in memory for each page
  - Whenever a timer interrupts
    - OS copies the reference bit (to memory bits [0] or [1]) and sets the values of all reference bits to 0
  - If one of the bits in memory = 1 ➠ page in working set
- Why is this not completely accurate?
  - 2 memory bits can only record two interrupts
  - Can not tell **when (in 5000 time unites)** the access occurs
- Improvement = 10 bits and interrupt every **1000** time units

Working Sets and Page Fault Rates

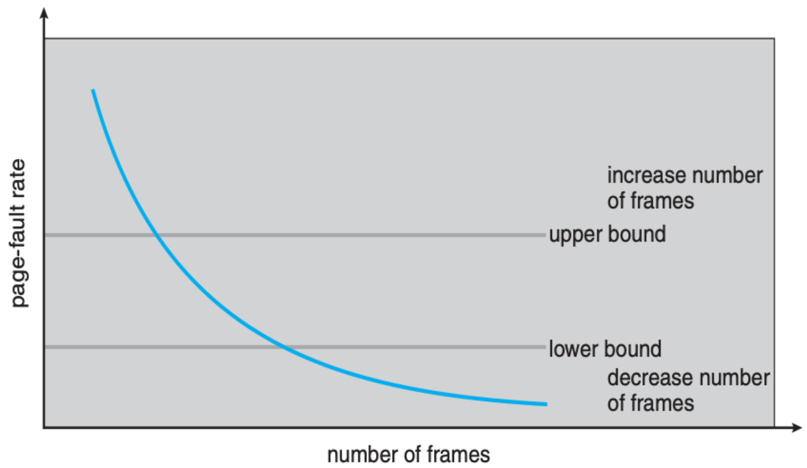
- Assumes there is no thrashing
- Direct relationship between working set of a process and its page-fault rate
- Working set changes over time
- Peaks and valleys over time



Page fault increases due to new locality

Page-Fault Frequency

- More direct approach than WSS
- Establish "acceptable" page-fault frequency (PFF) rate
  - If actual rate too low, process loses frame
  - If actual rate too high, process gains frame
- Need to swap out a process if no free fames are available



Kernel Memory Allocation

- Kernel memory allocation is treated differently from user memory, it is often allocated from a free-memory pool
  - kernel requests memory for structures of varying sizes -> minimize waste due to fragmentation
  - Some kernel memory needs to be **physically contiguous**
    - e.g., for device I/O

Other Considerations

- Prepaging
- Page size
- TLB reach
- Inverted page table
- Program structure
- I/O interlock and page locking

Prepaging

- To reduce the large number of page faults that occurs at process startup
  - Prepage all or some of the pages a process will need, before they are referenced
  - But if prepaged pages are unused, I/O and memory was wasted
- Assume **s** pages are prepaged and a fraction ***a*** of these pages is used
  - Is cost of $s * a$ save pages faults > or < than the cost of prepaging
  - $s * (1 - a)$ unnecessary pages?
  - a near zero -> prepaging loses

Page Size

- Sometimes OS designers have a choice
  - Especially if running on custom-built CPU
- Page size selection must take into consideration:
  - Fragmentation -> small page size
  - Page table size -> large page size
  - Resolution -> small page size
  - I/O overhead -> large page size
  - Number of page faults -> large page size
  - Locality -> small page size
  - TLB size and effectiveness -> large page size
- Always power of 2, usually in the range 2^{12} (4,096 bytes) to 2^{22} (4,194,304 bytes)
- On average, **growing over time**

TLB Reach

- **TLB reach**: the amount of memory accessible from the TLB
  - TLB reach = (TLB size) X (page size)
- Ideally, the working set of each process is stored in the TLB
  - otherwise there is a high degree of TLB misses
- **Increase the page size** to reduce **TLB pressure**
  - it may increase fragmentation as not all applications require large page sizes
  - multiple page sizes allow applications that require larger page sizes to use them without an increase in fragmentation

Other Issues: Program Structure

- Program structure can affect page faults
  - int[128,128] data;
  - Assume page size is 512B; each row is stored in one page;
  - Assume system has less than 127 physical frames
  - Program 1:

```
for (j = 0; j <128; j++)
    for (i = 0; i < 128; i++)
        data[i,j] = 0;
```

128 x 128 = 16,384 page faults

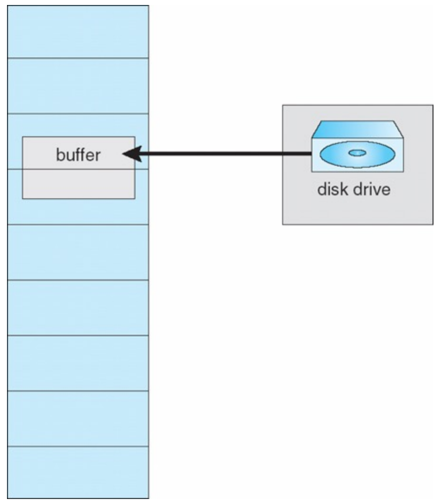
  - Program 2:

```
for (i = 0; i < 128; i++)
    for (j = 0; j < 128; j++)
        data[i,j] = 0;
```

128 page faults

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**



Windows XP

- Uses demand paging with clustering
  - clustering brings in **pages surrounding the faulting page:** locality
- Processes are assigned **working set** minimum and set maximum
  - *wsmin*: minimum number of pages the process is guaranteed to have
  - *wsmax*: a process may be assigned as many pages up to its *wsmax*
- When the amount of free memory in the system falls below a threshold:
  - automatic working set trimming to restore the amount of free memory
  - it removes pages from processes that have more pages than the *wsmin*

Memory management in Linux

- mm_struct
  - https://elixir.bootlin.com/linux/v5.10/source/include/linux/mm_types.h#L388
  - Where is page table?
  - Code walk through

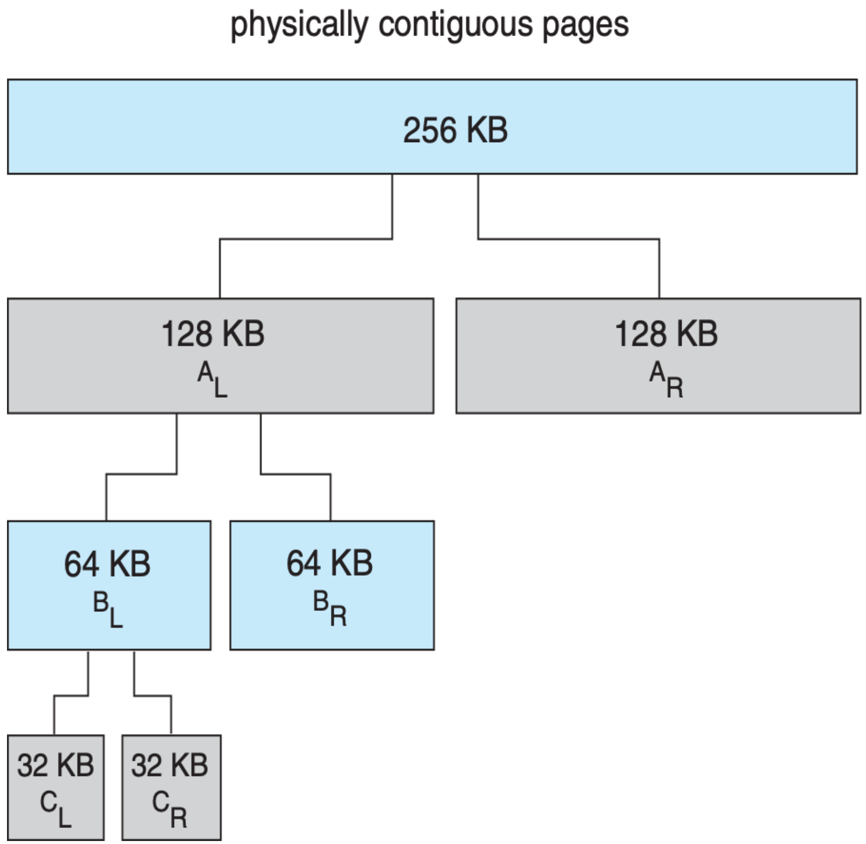
Page fault handling in Linux

- do_page_fault
  - https://elixir.bootlin.com/linux/v5.10/source/arch/riscv/mm/fault.c#L189
  - Code walk through

Linux Buddy System

- Memory allocated using power-of-2 allocator
  - memory is allocated in units of the size of **power of 2**
    - round up a request to the closest allocation unit
    - split the unit into two "**buddies**" until a proper sized chunk is available
  - e.g., assume only 256KB chunk is available, kernel requests 21KB
    - split it into A_l and A_r of 128KB each
    - further split an 128KB chunk into B_l and B_r of 64KB
    - again, split a 64KB chunk into C_l and C_r of 32KB each
    - give one chunk for the request
- advantage: it can quickly merge unused chunks into larger chunk
- disadvantage: **internal fragmentation**
  - 21k request -> 32k segment

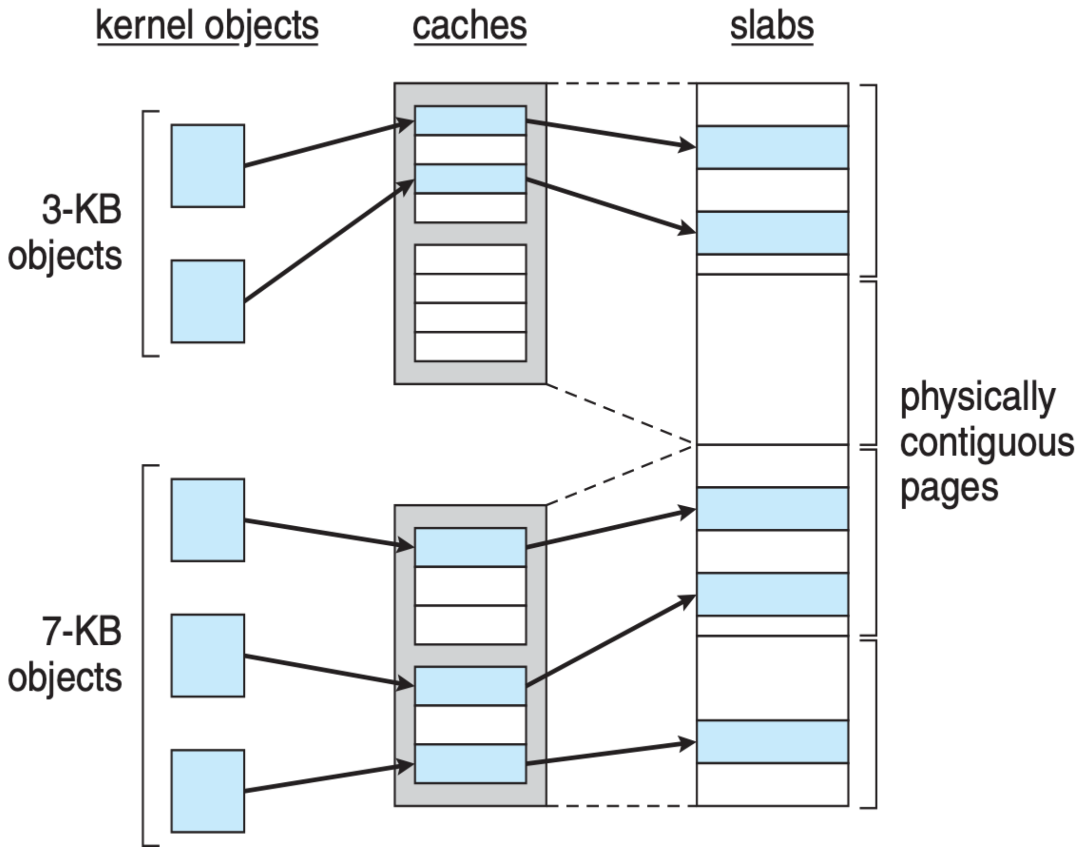
Buddy System Allocator



Slab Allocator

- Slab allocator is a **cache of objects**
  - a **cache** in a slab allocator consists of one or more slabs
  - a slab contains **one or more pages**, divided into **equal-sized objects**
  - kernel uses one cache for each unique kernel data structure
    - when cache created, allocate a slab, divided the slab into free objects
    - objects for the data structure is allocated from free objects in the slab
    - if a slab is full of used objects, next object comes from an empty/new slab
- Benefits: **no fragmentation** and fast memory allocation
  - some of the object fields may be reusable; no need to initialize again

Slab Allocation

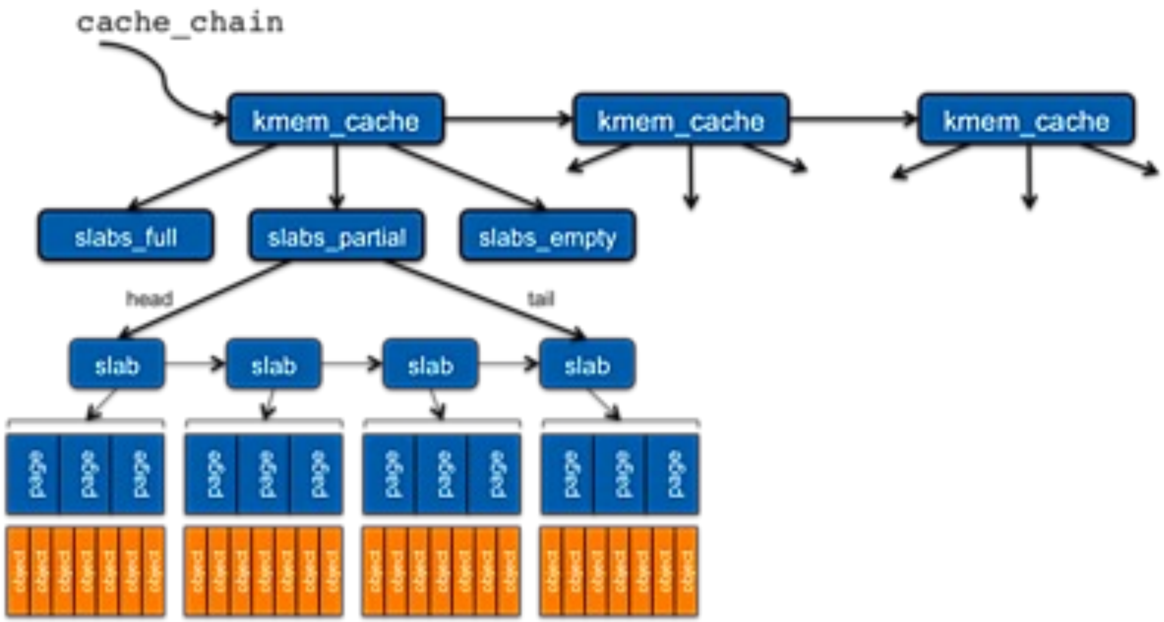


A 12k slab (3 pages) can store 4 3k objects.

Slab Allocator in Linux

- For example process descriptor is of type *struct task_struct*
  - Approx. 1.7KB of memory (some old linux version)
- New task -> allocate new struct from cache
  - Will use existing free *struct task_struct*
- A Slab can be in three possible states
  - **Full** – all used
  - **Empty** – all free
  - **Partial** – mix of free and used
- Upon request, slab allocator
  - Uses free struct in **partial** slab
  - If none, takes one from **empty** slab
  - If no empty slab, create new empty

Slab in Linux



Slab Allocator in Linux (Cont.)

- Slab started in Solaris, now wide-spread for both kernel mode and user memory in various OSes
- Linux 2.2 had SLAB, now has both SLOB and SLUB allocators
  - SLOB for systems with limited memory
    - Simple List of Blocks – maintains 3 list objects for small, medium, large objects
- SLUB is performance-optimized SLAB removes per-CPU queues, metadata stored in page structure

Takeaway

- Page fault
  - Valid virtual address, invalid physical address
- Page replacement
  - FIFO, Optimal, LRU, 2nd chance
- Thrashing and working set
- Buddy system
- slab

Memory management summary

- Partition
- Segmentation
- Paging
  - Page table
  - Demand paging
  - Page replacement
  - Working set
- Linux memory mapping
  - 32-bit
  - 64-bit