Operating Systems
[10B. Virtual Memory]

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From Operating System Concepts (10th Edition)

Outline

- Background, Demand Paging, Copy-on-Write
- <u>**Page Replacement**</u>
  - Basic Page Replacement
  - <u>**FIFO Page Replacement**</u>
  - Optimal Page Replacement
  - LRU Page Replacement
  - LRU-Approximation Page Replacement
  - Counting-Based Page Replacement
  - Page-Buffering Algorithms
  - Applications and Page Replacement
- Allocation of Frames, Thrashing, Memory Compression
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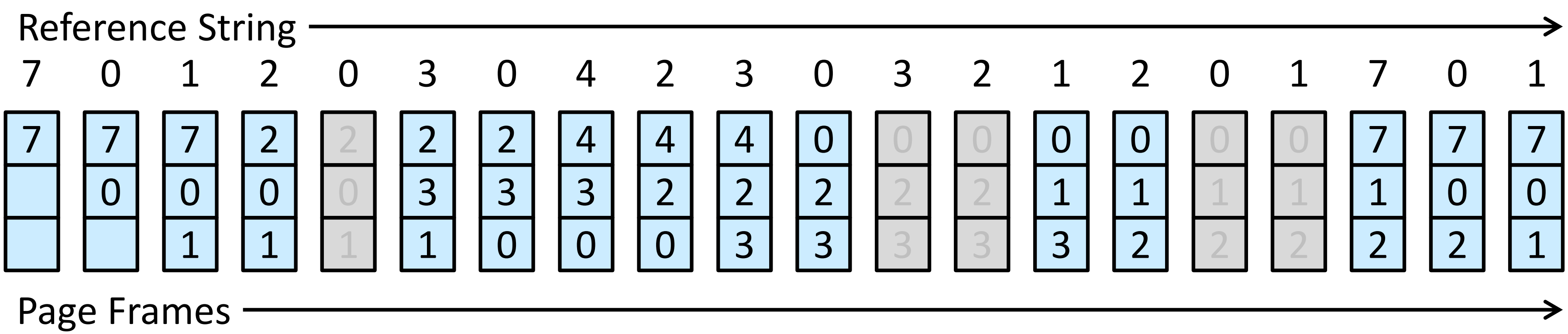
FIFO Page Replacement

- First-in, first-out (FIFO) algorithm
  - Create a FIFO queue to hold all pages in memory
  - Replace a page at the head of the queue
  - Insert a page at the tail of the queue
- 15 page faults in the running example



Belady's Anomaly

- For some page-replacement algorithms, the page-fault rate may increase as the number of allocated frames increases
- Reference string: 1 2 3 4 1 2 5 1 2 3 4 5
  - If # of frames = 1, # of page faults = 12
  - If # of frames = 2, # of page faults = 12
  - If # of frames = 3, # of page faults = 9
    - 1 2 3 4 1 2 5 ☺ ☺ 3 4 ☺
  - If # of frames = 4, # of page faults = 10
    - 1 2 3 4 ☺ ☺ 5 1 2 3 4 5
  - If # of frames ≥ 5, # of page faults = 5
- Giving more memory to a process does not necessarily improve its performance

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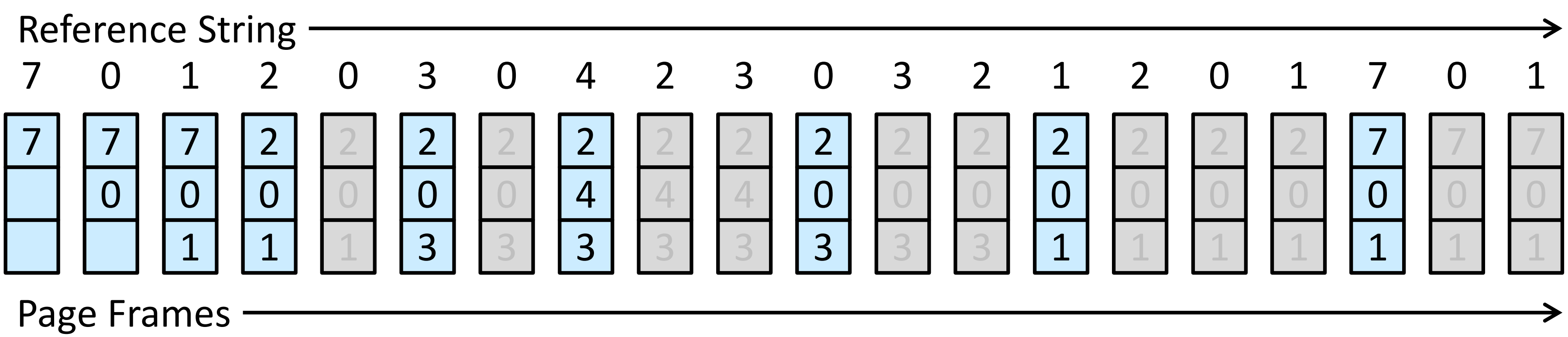
Optimal Page Replacement

- Replace the page that will not be used for the longest period of time
  - Guarantee the lowest number of page faults for a fixed reference string
- 9 page faults in the running example



- It requires future knowledge of the reference string
  - The optimal algorithm is used mainly for comparison studies

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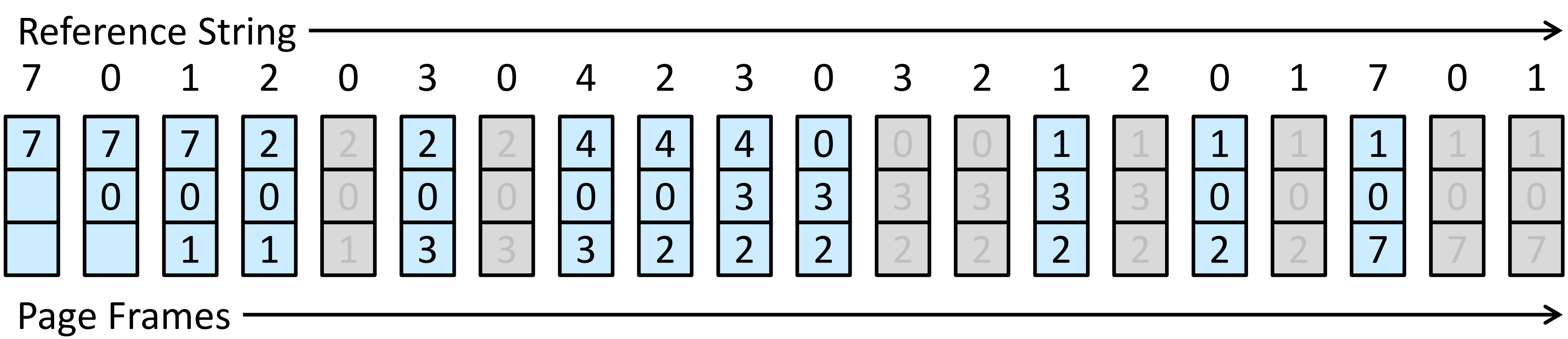
LRU Page Replacement

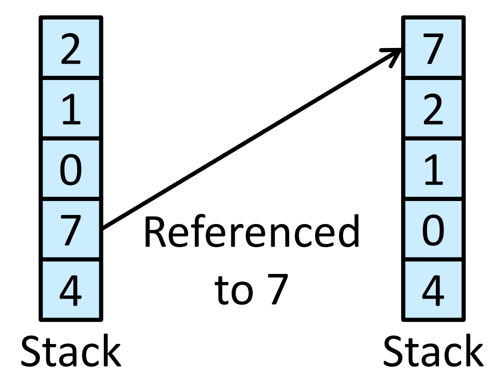
- Least recently used (LRU) algorithm
  - Replace the page that has not been used for the longest period of time
    - Change the optimal page replacement from "looking forward" to "looking backward"
- 12 page faults in the running example



- Often used and considered to be good

Implementing LRU Page Replacement

- **Approach 1: counters**
  - Associate a time-of-use field with each page-table entry
  - Add a logical clock (or counter) to the CPU
  - If a page is referenced, copy the clock register to its time-of-use field
  - Replace the page with the smallest time value
    - Require a search of the page table
- **Approach 2: stack**
  - Keep a stack of page numbers
    - Use a doubly linked list with a head pointer and a tail pointer
  - If a page is referenced, remove it from the stack and put it on the top
    - The least recently used page is always at the bottom
  - Replace the page pointed by the tail pointer
    - No search but a little more expensive update



Stack Algorithms

- The set of pages in memory for n frames is always a subset of the set of pages that would be in memory with (n + 1) frames
  - Optimal page replacement
  - LRU page replacement
- They do not suffer from Belady's anomaly

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LRU-Approximation Page Replacement

- Not many computer systems provide sufficient hardware support for true LRU page replacement
  - The updating of the clock fields or stack must be done for **every** memory reference
- Many systems provide help in the form of a **reference bit**
  - The reference bit (in the page table) of a page is set to 1 by the hardware when the page is referenced
  - We can determine which pages have (or have not) been used after their reference bits are set to 0
    - However, we do not know the order of use
- Examples
  - Additional-reference-bits algorithm
  - Second-chance algorithm
  - Enhanced second-chance algorithm

Additional-Reference-Bits Algorithm

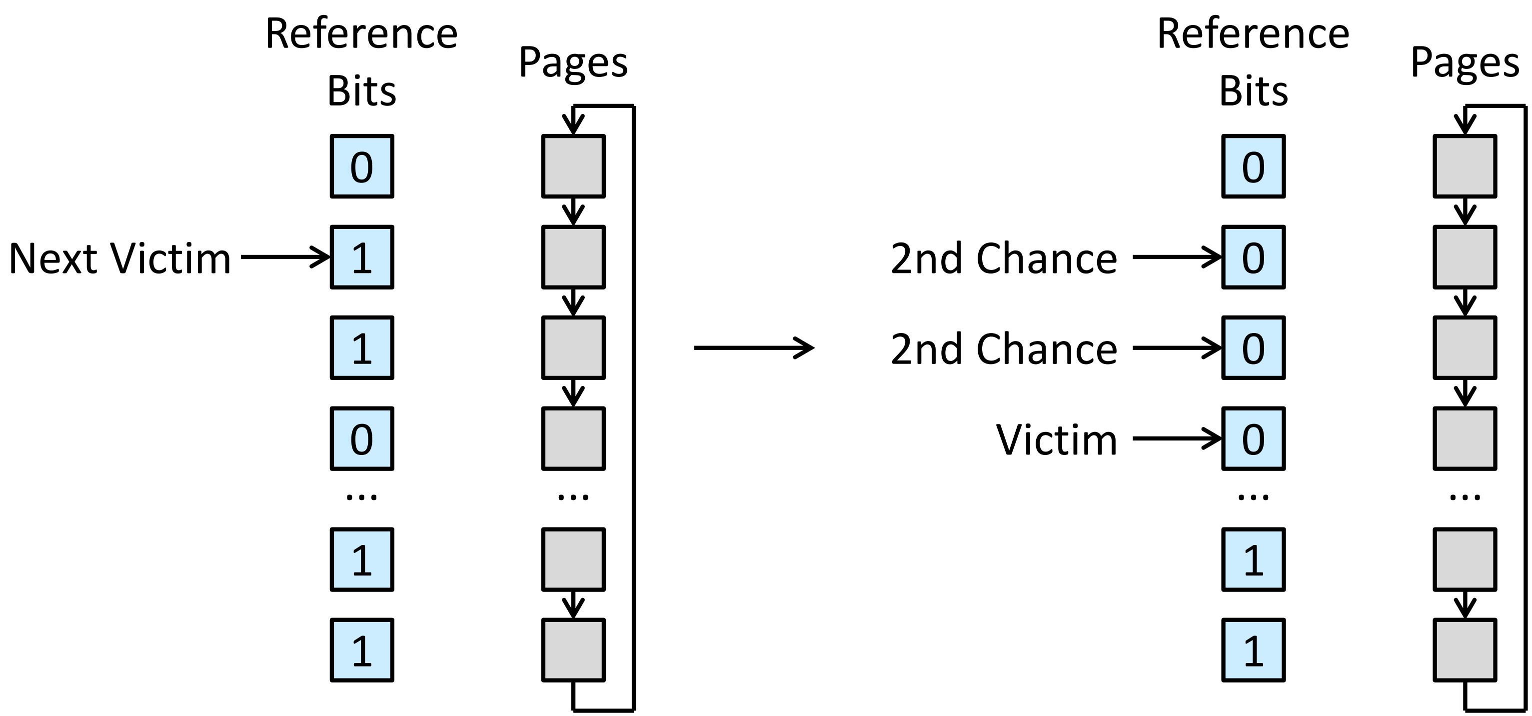
- Gain additional ordering information by recording the reference bits at shift registers at regular intervals
  - At regular intervals (e.g., every 100 milliseconds), a timer interrupt transfers control to the operating system which
    - Shift the reference bit for each page into the high-order bit
    - Shift the other bits right
  - Example: keep an 8-bit byte for each page in a table in memory
    - 00000000 vs. 11111111 vs. 11000100 vs. 01110111
  - The number of bits can be varied
    - In the extreme case, it can be zero, leaving only the reference bit itself (**second-chance page-replacement algorithm**)

Second-Chance Algorithm (1/2)

- A FIFO replacement algorithm with reference bits
- When a page has been selected, inspect its reference bit
  - If it is 0, replace the page
  - If it is 1, give the page a **second chance** and select the next FIFO page
- When a page gets a second chance
  - Its reference bit is cleared to 0
  - Its arrival time is reset to the current time
  - Thus, it will not be replaced until all other pages have been replaced or given second chances
- Note that the reference bit of a page is set to 1 when the page is referenced
  - If a page is used often enough to keep its reference bit set (to 1), it will never be replaced

Second-Chance Algorithm (2/2)

- One way to implement the second-chance algorithm is as a circular queue
  - Sometimes referred to as the **clock** algorithm
- In the worst case, if all bits are set (to 1), the second chance replacement degenerates to FIFO replacement



Enhanced Second-Chance Algorithm

- Consider the reference bit and the modify bit (described earlier) as an ordered pair
  - (0, 0): neither recently used nor modified
    - Best page to replace
  - (0, 1): not recently used but modified
    - Not quite as good, because the page will need to be written 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 the page will need to be written out before replacement
- Use the same scheme as in the clock algorithm and examine the class to which that page belongs

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Counting-Based Page Replacement

- Keep a counter of the number of references that have been made to each page
  - The implementation of these algorithms is expensive
  - They do not approximate the optimal replacement well
- **Least frequently used** (LFU) page-replacement algorithm
  - Require that the page with the smallest count be replaced
    - An actively used page should have a large reference count
    - What if a page is used heavily only during the initial phase of a process? Shift the counts right by 1 bit at regular intervals
- **Most frequently used** (MFU) page-replacement algorithm
  - Require that the page with the largest count be replaced
    - The page with the smallest count was probably just brought in and has yet to be used

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Page-Buffering Algorithms

- Keep a pool of free frames
  - When a page fault occurs, a victim frame is chosen as before
  - The desired page is read into a free frame from the pool before the victim is written out
    - Restart the process as soon as possible
- Maintain a list of modified pages
  - When the paging device is idle, a modified page is selected and written to secondary storage, and its modify bit is then reset
    - Increase the probability that a page will be clean
- Keep a pool of free frames but remember which page was in each frame
  - When a page fault occurs, check whether the desired page is in the free-frame pool
    - If not, select a free frame and read into it

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Applications and Page Replacement

- Applications accessing data through the operating system's virtual memory may perform worse
  - Some applications understand their memory use and storage use better than an operating system
    - Examples: database, data warehouses
  - Twice the memory is being used for a set of I/O
    - Both the operating system and the application are buffering I/O
- Some operating systems provide a **raw disk**
  - A large sequential array of logical blocks, without any file-system data structure
    - Bypass all the file-system services, such as file I/O demand paging, file locking, prefetching, space allocation, file names, and directories

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Recap: Two Major Problems

- Covered: page-replacement algorithm
  - Select the frames that are to be replaced
- **Frame-allocation algorithm**
  - Decide how many frames to allocate to each process

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Minimum Number of Frames

- Must allocate at least a minimum number of frames
  - Performance: as the number of frames allocated to each process decreases, the page-fault rate increases
  - Instruction restart: we must hold all the different pages that any single instruction can reference
- The minimum number is defined by the computer architecture
  - Example: six frames for an instruction
    - The move instruction for a given architecture itself straddles two frames
    - Each of its two operands is an indirect reference (e.g., via a page table)
  - Example: what if the move instruction allows data to move only from register to register and between registers and memory?
- The maximum number is defined by the amount of available physical memory

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Allocation Algorithms

- Equal allocation (ignoring frames needed by OS now)
  - Example: split 93 frames among 5 processes
    - Give each process 18 frames
    - Leave 3 frames as a free-frame buffer pool
- Proportional allocation
  - Allocate available memory to each process according to its size
  - Adjust to meet the minimum number of frames
  - Example: split 62 frames among 2 processes with 10 and 127 pages
    - 10 / (10 + 127) * 62 ~= 4 (frames)
    - 127 / (10 + 127) * 62 ~= 57 (frames)
  - Variation
    - The ratio of frames depends not on the relative sizes but rather on the priorities (or on a combination of size and priority)

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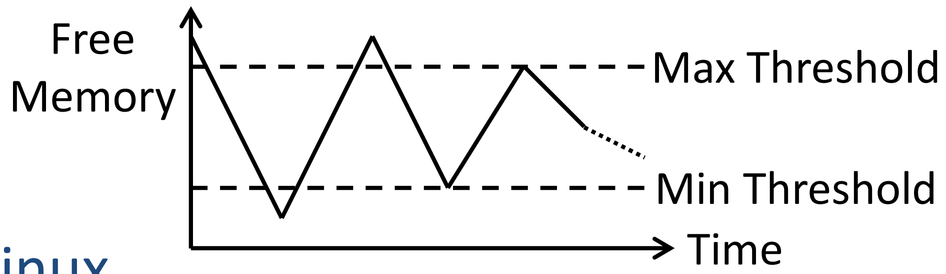
Global versus Local Allocation

- Global replacement
  - A process selects a replacement frame from the set of all frames, and thus it can take a frame from another
    - Greater system throughput
- Local replacement
  - A process selects from only its own set of allocated frames
    - More consistent per-process performance
- Global replacement is the more commonly used method

Reclaiming Pages

- A global page-replacement policy: keep the amount of free memory above a minimum threshold
  - When it drops below the threshold, a kernel routine is triggered that begins reclaiming pages from all processes in the system
    - Such kernel routines are often known as **reapers**
  - When the amount of free memory reaches a maximum threshold, the reaper routine is suspended



- It may adopt any page-replacement algorithm
- A more extreme example in Linux
  - If the amount of free memory is very low, a routine, **out-of-memory** (OOM) killer, selects a process to terminate by OOM scores

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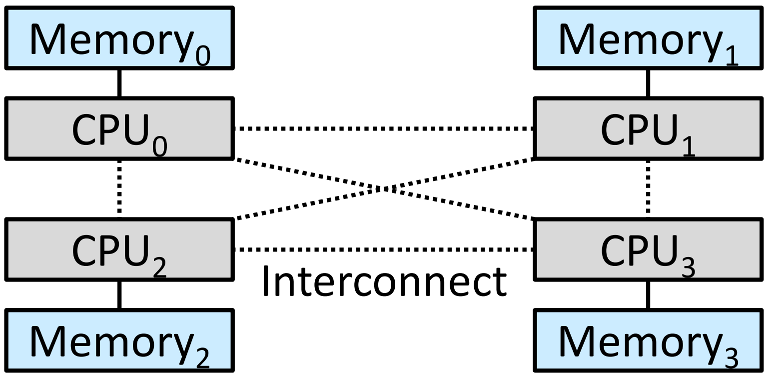
Non-Uniform Memory Access (NUMA)

- **Non-uniform memory access** systems with multiple CPUs
  - Not all main memory is created equal (or accessed equally)
- The goal is to have memory frames allocated "as close as possible" to the CPU on which the process is running
- More complicated with threads
  - Linux
    - Migrate threads to the same domain
    - Have a separate free-frame list for each NUMA node



  - Solaris
    - Each **lgroup** (locality groups) gathers together CPUs and memory
    - Each CPU in that group can access any memory in the group within a defined latency interval

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Thrashing

- What if a process does not have the minimum number of frames it needs to support pages in the working set
  - Quickly page-fault
  - Replace a page that will be needed again right away
  - Quickly page-faults again, and again, and again
- A process is **thrashing** if it is spending more time paging than executing
  - Thrashing results in severe performance problems

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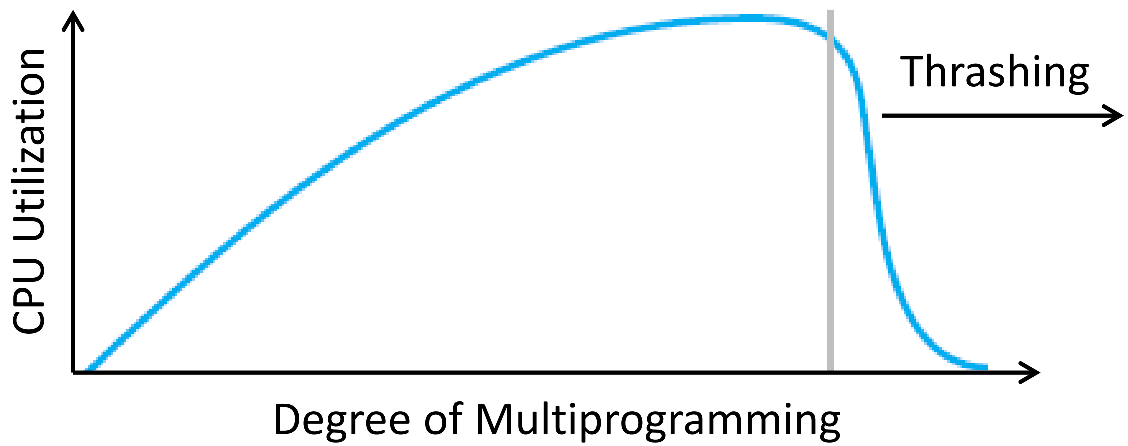
Cause of Thrashing

- A global page-replacement algorithm is used
  - A process needs more frames
  - It faults and takes frames from other processes
  - These processes also fault and take frames from other processes
  - As they queue up for the paging device, the ready queue empties
  - CPU utilization decreases
  - The CPU scheduler increases the degree of multiprogramming ...



Locality Model

- We can limit the effects of thrashing by using a local replacement algorithm (or priority replacement algorithm)
  - The problem is not entirely solved (even if there is no "frame-stealing")
    - Thrashing processes are in the queue for the paging device most of the time
    - The effective access time will increase even for a process that is not thrashing
- **Locality model**
  - As a process executes, it moves from locality to locality
  - A locality is a set of pages that are actively used together
    - Example: the set of pages {18, 19, 20, 21, 22, 23, 24, 29, 30, 33}
    - Example: the set of pages {18, 19, 20, 24, 25, 26, 27, 28, 29, 31, 32, 33}
  - Different localities may overlap
  - If there are not enough frames to accommodate the size of the current locality, the process will thrash

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Working-Set Model (1/2)

- **Working set** (WS): the set of pages in the most recent Δ page references
  - Δ: **working-set window**
    - If Δ is too small, it will not encompass the entire locality
    - If Δ is too large, it may overlap several localities
    - If Δ is infinite, it is the set of pages touched during the process execution
  - Example
    - Page reference: 2 6 1 5 7 7 7 7 5 1 (t_1) 6 2 3 4 1 2 3 4 4 4 3 4 3 4 4 4 (t_2)
    - If $\Delta = 10$, then $WS(t_1) = \{1, 2, 5, 6, 7\}$ and $WS(t_2) = \{3, 4\}$
- D: total demand for frames
  - $D = \Sigma_i$ (working-set size of each process i)
  - If D > the total number of available frames, thrashing will occur

Working-Set Model (2/2)

- This working-set strategy prevents thrashing while keeping the degree of multiprogramming as high as possible
- Difficulty: keeping track of the working set
  - The working-set window is a moving window
  - A page is in the working set if it is referenced anywhere in the window
- Approximation: a timer interrupt and a reference bit
  - Example: Δ = 10,000 references
    - Interrupt every 5,000 references
    - Keep 2 additional bits for each page
    - When the timer interrupts, copy and clear the reference bit for each page
    - Examine the current reference bit and two additional bits
  - Trade-off: interrupt every 1,000 references and keep 10 additional bits

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Page-Fault Frequency

- Knowledge of the working set is useful for **prepaging**, but it seems a clumsy way to control thrashing
- The **page-fault frequency** (PFF) takes a more direct approach
  - Control the page-fault rate
    - Establish upper and lower bounds on the desired page-fault rate
    - Allocate a frame to a process if the page-fault rate exceeds the upper bound
    - Remove a frame from a process if the page-fault rate falls below the lower bound

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Current Practice

- Thrashing and the resulting swapping have a high impact on performance
- The best practice is to include enough physical memory to avoid thrashing and swapping
  - Keeping all working sets in memory concurrently, except under extreme conditions, provides the best user experience

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Memory Compression (1/2)

- Compress several frames into a single frame
  - Rather than paging out modified frames to swap space
- Example
  - Before compression
    - Free-frame list: Head → 7 → 2 → 9 → 21 → 27 → 16
    - Modified frame list: Head → 15 → 3 → 35 → 26
  - Frames 15, 3, and 35 are compressed and stored in frame 7
  - After compression
    - Free-frame list: Head → 2 → 9 → 21 → 27 → 16 → 15 → 3 → 35
    - Modified frame list: Head → 26
    - Compressed frame list: Head → 7
  - If one compressed frame is later referenced, a page fault occurs
    - The compressed frame is decompressed, restoring the pages 15, 3, and 35

Memory Compression (2/2)

- Memory compression is an integral part of the memory-management strategy for most mobile operating systems
  - Android and iOS
  - In addition, both Windows 10 and macOS also support it
- Trade-off between
  - The speed of the compression algorithm
  - The amount of reduction that can be achieved (**compression ratio**)

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Allocating Kernel Memory

- Kernel memory is often allocated from a free-memory pool different from the list used for ordinary user-mode processes
- Reasons
  - The kernel requests memory for data structures of varying sizes, some of which are less than a page in size
    - Internal fragmentation
  - Certain hardware devices interact directly with physical memory and consequently require memory residing in physically contiguous pages
    - No benefit of a virtual memory interface

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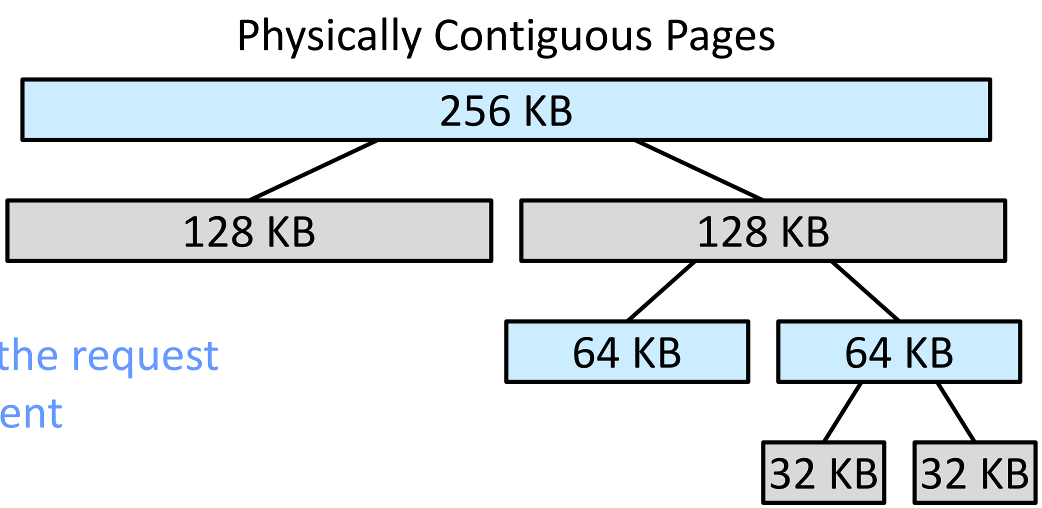
Buddy System

- Allocate memory from a fixed-size segment consisting of physically contiguous pages
  - Memory is allocated from this segment using a **power-of-2 allocator**
  - Example
    - A 256-KB memory segment
    - A 21-KB request from kernel
    - Two **buddies** divided from the segment
    - Buddies further divided until the request is satisfied with a 32-KB segment



  - Advantage
    - Adjacent **buddies** can be combined to form larger segments using **coalescing**
  - Disadvantage
    - Internal fragmentation

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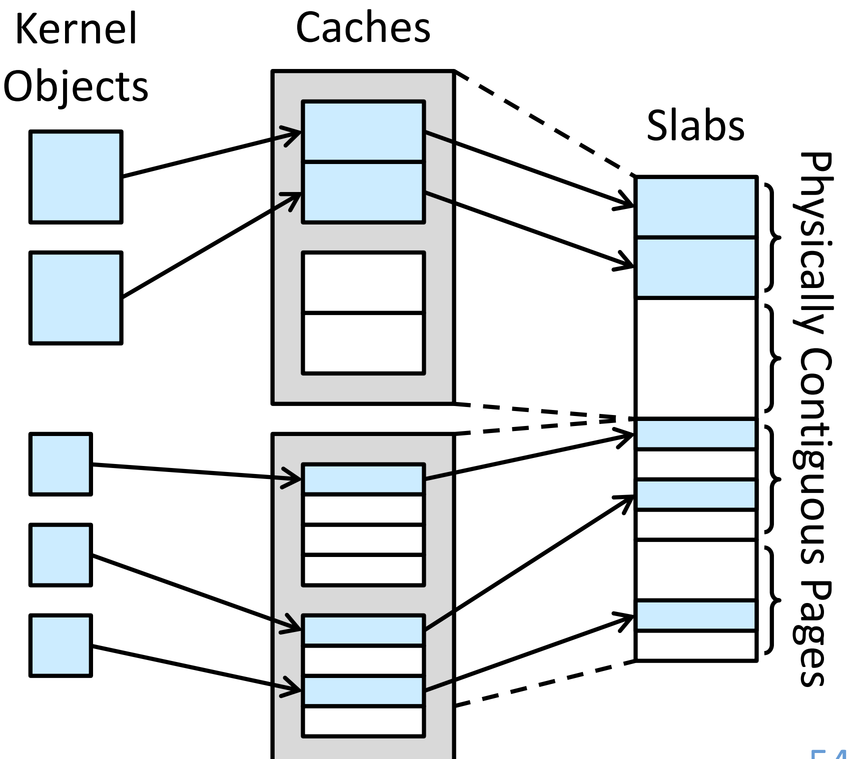
Slab Allocation

- A **slab** is made up of one or more physically contiguous pages
- A **cache** consists of one or more slabs
  - There is a single cache for each unique kernel data structure
    - Examples: process descriptors (process control blocks), file objects, semaphores (Chapter 6)
- Each cache is populated with **objects**
  - Instantiations of the kernel data structure that the cache represents
- The allocator
  - Assign any **free** object from the cache to satisfy a request
  - Mark the object as **used**



Slab Allocation: Benefits

- No memory is wasted due to fragmentation
  - The slab allocator returns the exact amount of memory required to represent an object
    - Each unique kernel data structure has an associated cache
    - Each cache is made up of one or more slabs that are divided into chunks the size of the objects being represented
- Memory requests can be satisfied quickly
  - Objects are quickly allocated from the cache
    - They are created in advance
  - Objects are immediate available for subsequent requests
    - When the kernel has finished with them, they are marked as free and returned to the cache

Slab Allocator in Linux (1/2)

- Example
  - A process descriptor is of the type `struct task_struct`
    - Approximately 1.7 KB of memory
  - The kernel requests memory for a `struct task_struct` object from its cache
  - The cache fulfills the request using a `struct task_struct` object that has been allocated in a slab and marked as free
- Three possible states of a slab
  - Full: all objects are used
  - Empty: all objects are free
    - Second choice
  - Partial: the slab consists of both used and free objects
    - First choice
  - If no empty slab exists, a new slab is allocated and assigned to a cache

Slab Allocator in Linux (2/2)

- The slab allocator first appeared in the Solaris 2.4 kernel
- The Linux kernel adopted the SLAB allocator from Version 2.2
  - Originally used the buddy system
- Recent Linux versions include other kernel memory allocators
  - The SLOB (simple list of blocks) allocator is designed for systems with limited memory, such as embedded systems
    - Three lists of objects: small (<256 bytes), medium (<1,024 bytes), and large (<the size of a page)
  - The SLUB allocator (from Version 2.6.24) reduces much of the overhead required by the SLAB allocator
    - Do not store certain metadata with each slab
    - Do not include the per-CPU queues

Outline

- Background
- Demand Paging
- Copy-on-Write
- Page Replacement
- Allocation of Frames
- Thrashing
- Memory Compression
- Allocating Kernel Memory
- **Other Considerations**
  - Prepaging, Page Size, TLB Reach, Inverted Page Tables, Program Structure, I/O Interlock and Page Locking
- Operating-System Examples

Prepaging

- Bring some (or all) of the pages that will be needed into memory at one time
  - A large number of page faults occur when a process is started
  - Prepaging is an attempt to prevent this high level of initial paging
- The question: whether the cost of using prepaging is less than the cost of servicing the corresponding page faults?
  - Prepaging a file may be more predictable
    - Files are often accessed sequentially
    - The Linux `readahead()` system call prefetches the contents of a file into memory

Page Size

- Page sizes are invariably powers of 2
  - Generally ranging from 4,096 (2^{12}) to 4,194,304 (2^{22}) bytes
- Factors of page size selection
  - Page table size → a larger page is better
  - Internal fragmentation → a smaller page is better
  - I/O time → a larger page is better
  - Resolution and locality → a smaller page is better
  - Number of page faults → a larger page is better
  - Others
- The historical trend is toward larger page sizes
  - Even for mobile systems

TLB Reach

- **Translation look-aside buffer (TLB) reach**
  - The amount of memory accessible from the TLB
  - The number of entries multiplied by the page size
- Ideally, the working set for a process is stored in the TLB
- To increase the TLB reach
  - Increase the number of entries (in the TLB)
    - Still insufficient for storing the working set of a memory-intensive application
  - Increase the page size
    - Increase internal fragmentation for an application that does not require such a large page size
  - Provide multiple page sizes
    - Allow an application to use a large page size without increasing internal fragmentation
    - Require the operating system, rather than hardware, to manage the TLB

Inverted Page Tables

- Do not contain complete information about the logical address space of a process
  - The information is required if a referenced page is not in memory
- An external page table (one per process) must be kept
  - It is like the traditional per-process page table and contains information on where each virtual page is located
  - It does not need to be available quickly, but it may generate another page fault for itself
    - This special case requires careful handling in the kernel and a delay in the page-lookup processing

Program Structure

- `int[128][128] data;`
  - Assume that each row is stored in one page and the array is row major
    - In memory: `data[0][0]`, `data[0][1]`, …, `data[0][127]`, `data[1][0]`, `data[1][1]`, …, `data[127][127]`
- Possible 128 x 128 = 16,384 faults

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

- At most 128 faults

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

- Compiler and loader can have a significant effect on paging

I/O Interlock and Page Locking

- When demand paging is used, we sometimes need to allow some of the pages to be **locked** in memory
- Bad example
  - The page containing the memory buffer of a process is paged out (by another process) during waiting I/O completion
- Solutions
  - Execute I/O to system memory (not user memory)
  - Allow pages to be locked
    - Frequently, some or all of the operating-system kernel is locked into memory
    - User processes may also need to lock pages into memory (e.g., **pinning** of pages by a database process)

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- ❑ Other Considerations
- ❑ **Operating-System Examples**
  - ➢ Linux, Windows, Solaris

Linux

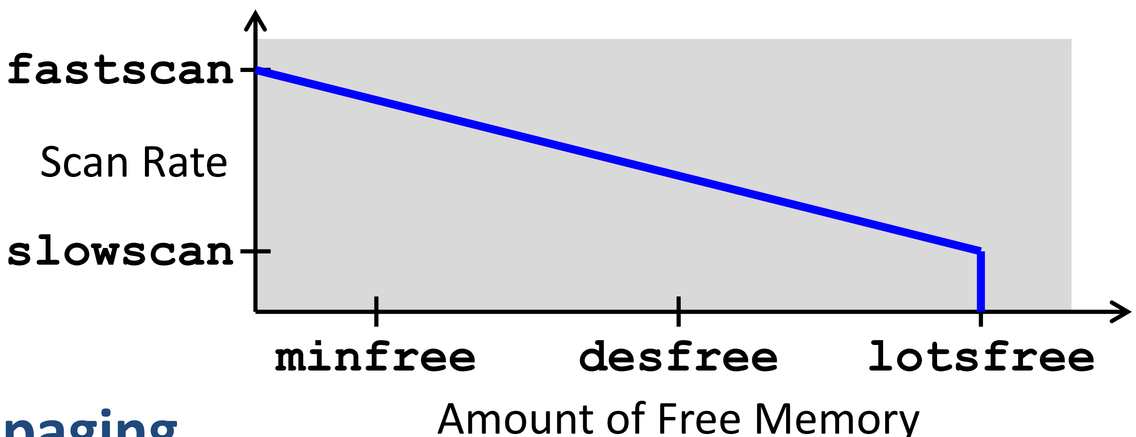
- Manage kernel memory using slab allocation
- Use demand paging
  - Allocate pages from a list of free frames
- Use a global page-replacement policy
  - Similar to the LRU-approximation clock algorithm
- Maintain two types of page lists
  - Active list
    - Contain the pages that are considered in use
  - Inactive list
    - Contain the pages that have not recently been referenced and are eligible to be reclaimed

Windows

- **Clustering** for demand paging
  - Bring in not only the faulting page but also the pages preceding and following the faulting page
- Working-set management
  - **Working-set minimum**: the minimum number of assigned pages
  - **Working-set maximum**: the maximum number of assigned pages
  - May ignore the values unless a process is with **hard working-set limits**
- **Automatic working-set trimming**
  - When the amount of free memory falls below the threshold, use a global replacement tactic to restore it above the threshold

Solaris

- **Pageout** algorithm
  - Use two hands to scan pages
    - The front hand of the clock sets the reference bits of all pages to 0
    - The back hand of the clock appends a page to the free list (if the reference bit is still 0) or writes its contents to secondary storage (otherwise)
  - Control the rate at which pages are scanned



- **Priority paging**
  - Skip pages belonging to libraries that are shared by several processes
  - Distinguish between pages allocated to processes and regular data files

Objectives

- Define virtual memory and describe its benefits
- Illustrate how pages are loaded into memory using demand paging
- Apply the FIFO, optimal, and LRU page-replacement algorithms
- Describe the working set of a process, and explain how it is related to program locality
- Describe how Linux, Windows 10, and Solaris manage virtual memory

Q&A