Final Review 03

Operating Systems

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08: Deadlock

The Deadlock Problem

- **Deadlock**: a set of blocked processes each holding a resource and waiting to acquire a resource held by another process in the set
- Examples:
  - a system has 2 disk drives, P_1 and P_2 each hold one disk drive and each needs another one
  - semaphores A and B, initialized to 1

P_1	P_2
wait (A);	wait(B)
wait (B);	wait(A)

Deadlock in program

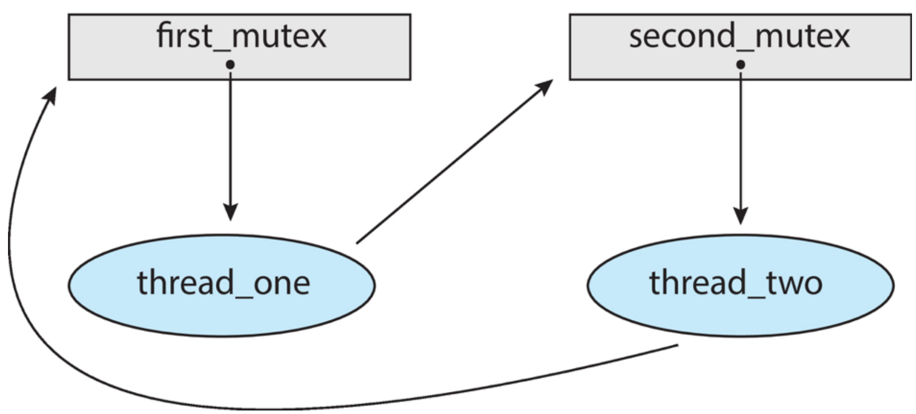
- Two mutex locks are created an initialized:

```
pthread_mutex_t first_mutex;
pthread_mutex_t second_mutex;

pthread_mutex_init(&first_mutex,NULL);
pthread_mutex_init(&second_mutex,NULL);
```

```
/* thread_one runs in this function */
void *do_work_one(void *param)
{
   pthread_mutex_lock(&first_mutex);
   pthread_mutex_lock(&second_mutex);
   /**
    * Do some work
    */
   pthread_mutex_unlock(&second_mutex);
   pthread_mutex_unlock(&first_mutex);

   pthread_exit(0);
}

/* thread_two runs in this function */
void *do_work_two(void *param)
{
   pthread_mutex_lock(&second_mutex);
   pthread_mutex_lock(&first_mutex);
   /**
    * Do some work
    */
   pthread_mutex_unlock(&first_mutex);
   pthread_mutex_unlock(&second_mutex);

   pthread_exit(0);
}
```

Deadlock in program

- Deadlock is possible if thread 1 acquires **first_mutex** and thread 2 acquires **second_mutex**. Thread 1 then waits for **second_mutex** and thread 2 waits for **first_mutex**.
- Can be illustrated with a **resource allocation graph**:



Four Conditions of Deadlock

- **Mutual exclusion**: only one process at a time can use a resource
- **Hold and wait**: a process holding at least one resource is waiting to acquire additional resources held by other processes
- **No preemption**: a resource can be released only voluntarily by the process holding it, after it has completed its task
- **Circular wait**: there exists a set of waiting processes $\{P_0, P_1, \ldots, P_n\}$
  - P_0 is waiting for a resource that is held by P_1
  - P_1 is waiting for a resource that is held by P_2 …
  - P_{n-1} is waiting for a resource that is held by P_n
  - P_n is waiting for a resource that is held by P_0

How to Handle Deadlocks

- How?
  - **Prevention: that the possibility of deadlock is excluded!!!**
  - **Avoidance**
  - **Deadlock detection and recovery**
  - **Ignore the problem** and pretend deadlocks never occur in the system

Deadlock Prevention

- How to prevent **mutual exclusion**
  - not required for sharable resources
  - must hold for non-sharable resources
- How to prevent **hold and wait**
  - whenever a process requests a resource, it doesn't hold any other resources
    - require process to request ***all*** its resources before it begins execution
    - allow process to request resources only when the process has none
  - low resource utilization; starvation possible

Deadlock Prevention

- How to handle **no preemption**
  - if a process requests a resource not available
    - release all resources currently being held
    - preempted resources are added to the list of resources it waits for
    - process will be restarted only when it can get all waiting resources
- How to handle **circular wait**
  - impose a total ordering of all resource types
  - require that each process requests resources in an increasing order
  - Many operating systems adopt this strategy for some locks.

Deadlock Avoidance

- **Dead avoidance: require extra information about how resources are to be requested**
  - **Is this requirement practical**?
- Each process declares a **max** number of resources it may need
- Deadlock-avoidance algorithm ensure there can **never be a circular-wait condition**
- Resource-allocation state:
  - the number of **available** and **allocated** resources
  - the **maximum demands** of the processes

Deadlock Avoidance Algorithms

- Single instance of each resource type ➠ use **resource-allocation graph**
- Multiple instances of a resource type ➠ use the **banker's algorithm**

Deadlock Detection

- Allow system to enter deadlock state, but detect and recover from it
- Detection algorithm and recovery scheme

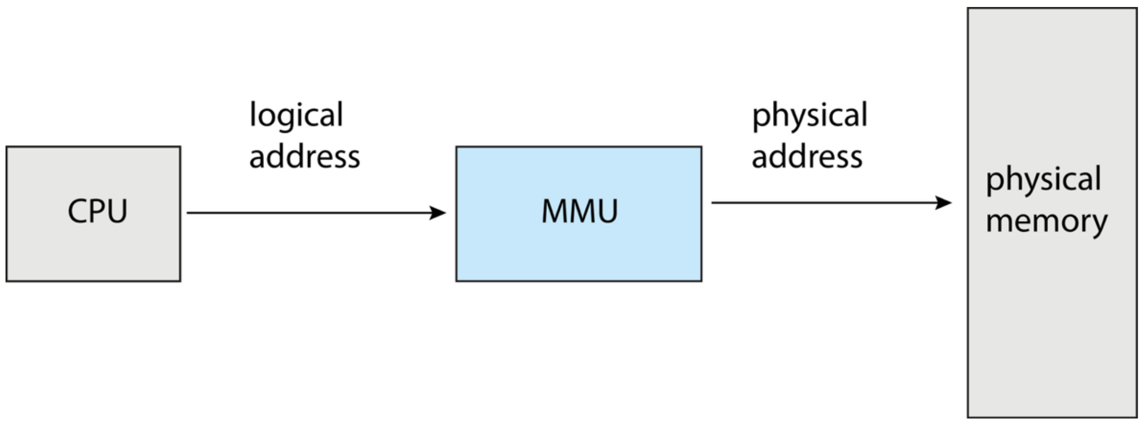
09: Main Memory

Logical vs. Physical Address Space

- The concept of a logical address space that is bound to a **separate physical address** space is central to proper memory management
  - **Logical address** – generated by the CPU; also referred to as virtual address
  - **Physical address** – address seen by the memory unit
- **Logical address space** is the set of all logical addresses generated by a program
- **Physical address space** is the set of all physical addresses generated by a program

Memory-Management Unit (MMU)

- Hardware device that at run time maps virtual to physical address



- Many methods possible, covered in the rest of this chapter

Contiguous Allocation

- Main memory must support both OS and user processes
- Limited resource, must allocate efficiently
- Contiguous allocation is one early method
- Main memory usually into two **partitions**:
  - Resident operating system, usually held in low memory with interrupt vector
  - User processes then held in high memory
  - Each process contained in single contiguous section of memory

Memory Allocation

- How to satisfy a request of size *n* from a list of free memory blocks?
  - **first-fit**: allocate from the first block that is big enough
  - **best-fit**: allocate from the smallest block that is big enough
    - must search entire list, unless ordered by size
    - produces the smallest leftover hole
  - **worst-fit**: allocate from the largest hole
    - must also search entire list
    - produces the largest leftover hole
- **Fragmentation** is big problem for all three methods
  - first-fit and best-fit usually perform better than worst-fit

Fragmentation

- **External fragmentation**
  - unusable memory between allocated memory blocks
    - **total amount** of free memory space **is larger than a request**
    - the request cannot be fulfilled because the free memory is not **contiguous**
  - external fragmentation can be reduced by **compaction**
    - shuffle memory contents to place all free memory in one large block
    - program needs to be **relocatable** at runtime
    - Performance overhead, timing to do this operation
  - Another solution: **paging**
  - 50-percent rule: N allocated blocks, 0.5N will be lost due to fragmentation. 1/3 is unusable!

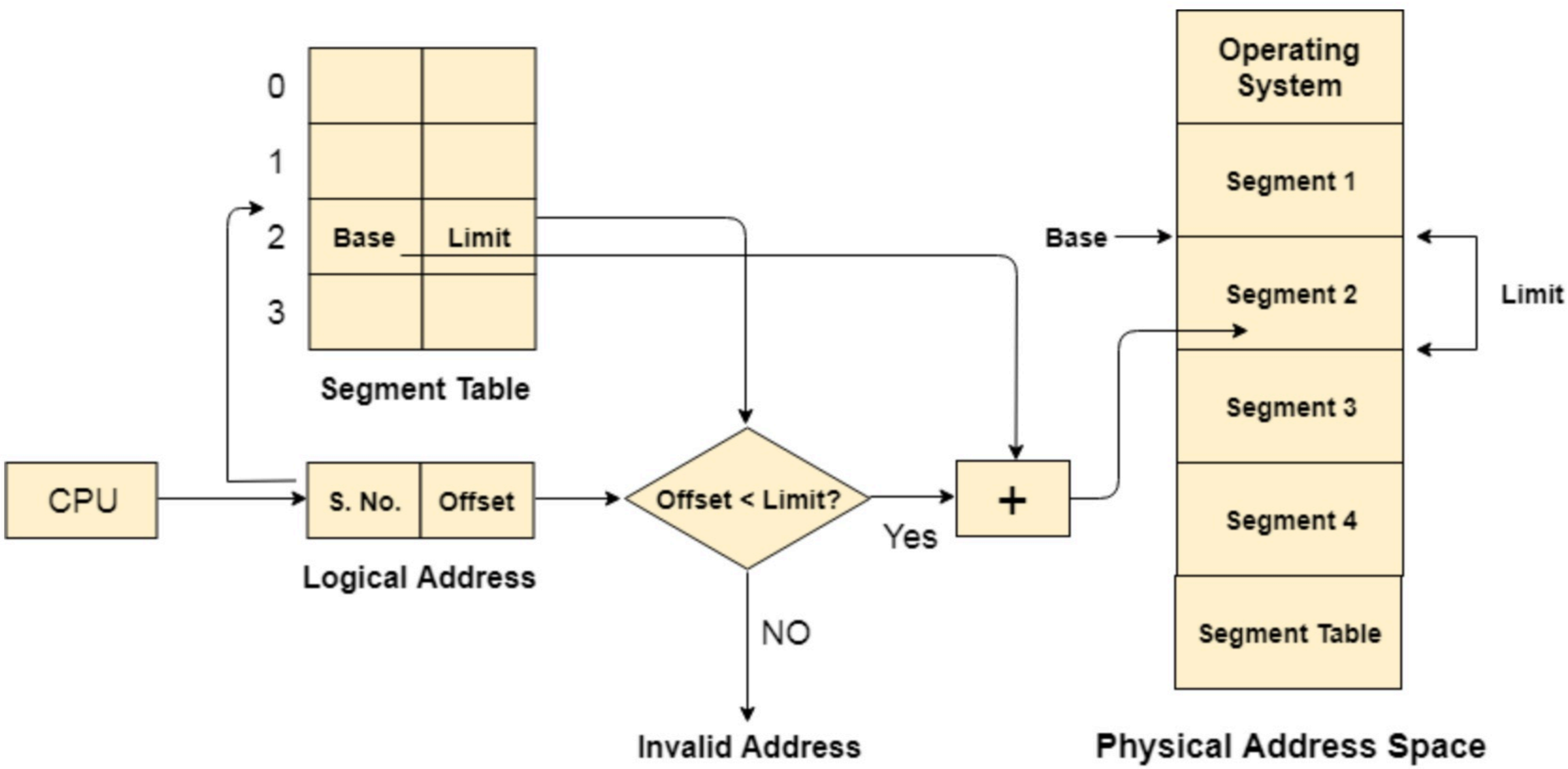
Fragmentation

- **Internal fragmentation**
  - memory allocated may be larger than the requested size
  - this size difference is memory *internal to a partition*, but not being used
  - Example: free space 18464 bytes, request 18462 bytes
- Sophisticated algorithms are designed to avoid fragmentation
  - none of the first-/best-/worst-fit can be considered sophisticated

Segmentation

- Logical address consists of a pair:
  - <segment-number, offset>
- Segment table where each entry has:
  - Base: starting physical address
  - Limit: length of segment

Segment



0
1
2
3
Base
Limit
Segment Table
CPU
S. No.
Offset
Logical Address
Offset < Limit?
Yes
NO
Invalid Address
+
Operating System
Segment 1
Base
Segment 2
Limit
Segment 3
Segment 4
Segment Table
Physical Address Space

Paging

- Physical address space of a process can be **noncontiguous**; process is allocated physical memory whenever the latter is available
    - Avoids **external fragmentation -> avoid for compacting**
    - Avoids problem of varying sized memory chunks
- Basic methods
    - Divide physical memory into fixed-sized blocks called **frames**
        - Size is power of 2, between 512 bytes and 16 Mbytes
    - Divide logical memory into blocks of same size called **pages**
    - Keep track of all free frames
    - To run a program of size **N** pages, need to find **N** free frames and load program
    - Set up a **page table** to translate logical to physical addresses
    - Backing store likewise split into pages
    - **Still have Internal fragmentation**

Paging: Address Translation

- A logical address is divided into:
  - **page number** (p)
    - used as an index into a page table
    - page table entry contains the corresponding **physical** frame number
  - **page offset** (d)
    - offset within the page/frame
    - combined with frame number to get the physical address

page number	page offset
p	*d*
m - n bits	*n bits*

m bit logical address space, *n* bit page size

Effective Access Time

- **Hit ratio** – percentage of times that a page number is found in the TLB
- An 80% hit ratio means that we find the desired page number in the TLB 80% of the time.
- Suppose that 10 nanoseconds to access memory.
  - If we find the desired page in TLB then a mapped-memory access take 10 ns
  - Otherwise we need **two memory access** so it is 20 ns: page table + memory access
- Effective Access Time (EAT)
- EAT = 0.80 x 10 + 0.20 x 20 = 12 nanoseconds
- implying 20% slowdown in access time
- Consider a more realistic hit ratio of 99%,
- EAT = 0.99 x 10 + 0.01 x 20 = 10.1ns
- implying only 1% slowdown in access time.

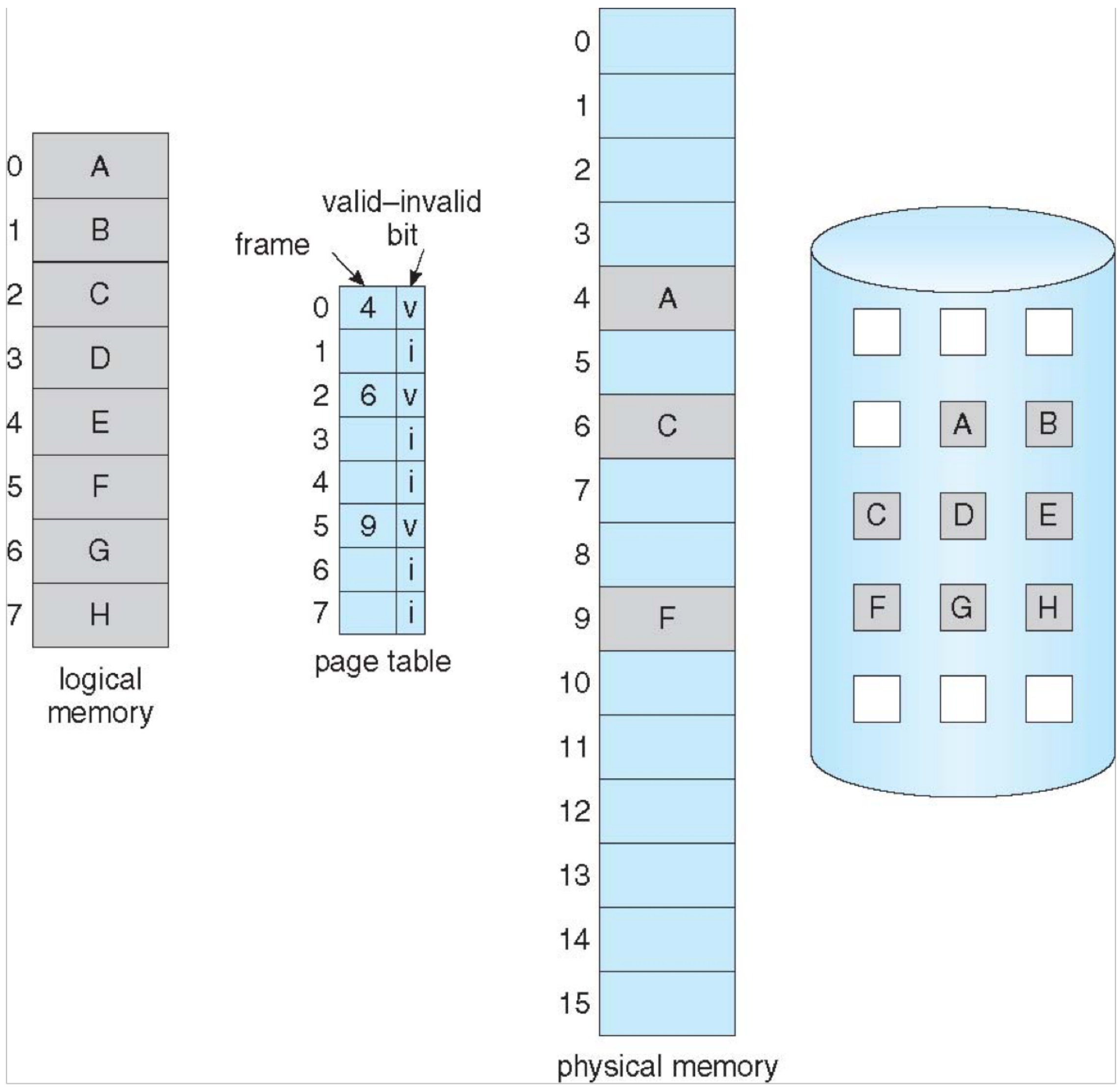
Valid-Invalid Bit

- Each page table entry has a valid–invalid (present) bit
  - *V* ➠ in memory (memory is resident), *I* ➠ not-in-memory
  - 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:

Frame #	v/i bit
	v
	v
	v
	v
	i
....	
	i
	i

page table

Page Table (Some Pages Are Not in Memory)



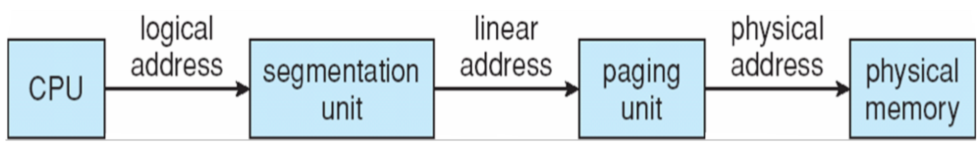
Memory Protection

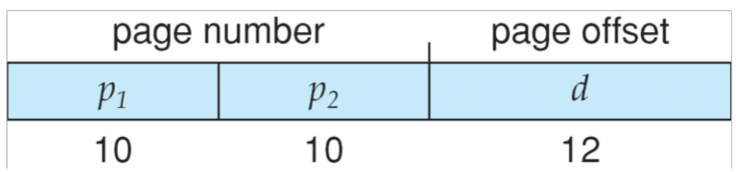
- Accomplished by protection bits with each frame
- Each page table entry has a **present** (aka. valid) bit
  - present: the page has a valid physical frame, thus can be accessed
- Each page table entry contains some protection bits
  - **kernel/user**, **read/write**, **execution**?, **kernel-execution**?
  - why do we need them?
- Any violations of memory protection result in a trap to the kernel

TLB

- TLB and context switch
  - Each process has its own page table
    - switching process needs to switch page table
  - **TLB must be consistent with page table**
    - TLB entries are from page table of current process
    - Option I: Flush TLB at every context switch, **or**,
    - Option II: Tag TLB entries with **address-space identifier** (ASID) that uniquely identifies a process
  - some TLB entries can be **shared** by processes, and fixed in the TLB
    - e.g., TLB entries for the kernel
- TLB and operating system
  - MIPS: OS should deal with TLB miss exception
  - X86: TLB miss is handled by hardware

Logical to Physical Address Translation in IA-32





10: Virtual Memory

Demand Paging 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

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

Page Fault

- First reference to a non-present page will trap to kernel: page fault, the reasons can be
  - **invalid reference** ➠ deliver an exception to the process
  - **valid but not in memory** ➠ swap in
- get an empty physical frame
- swap 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

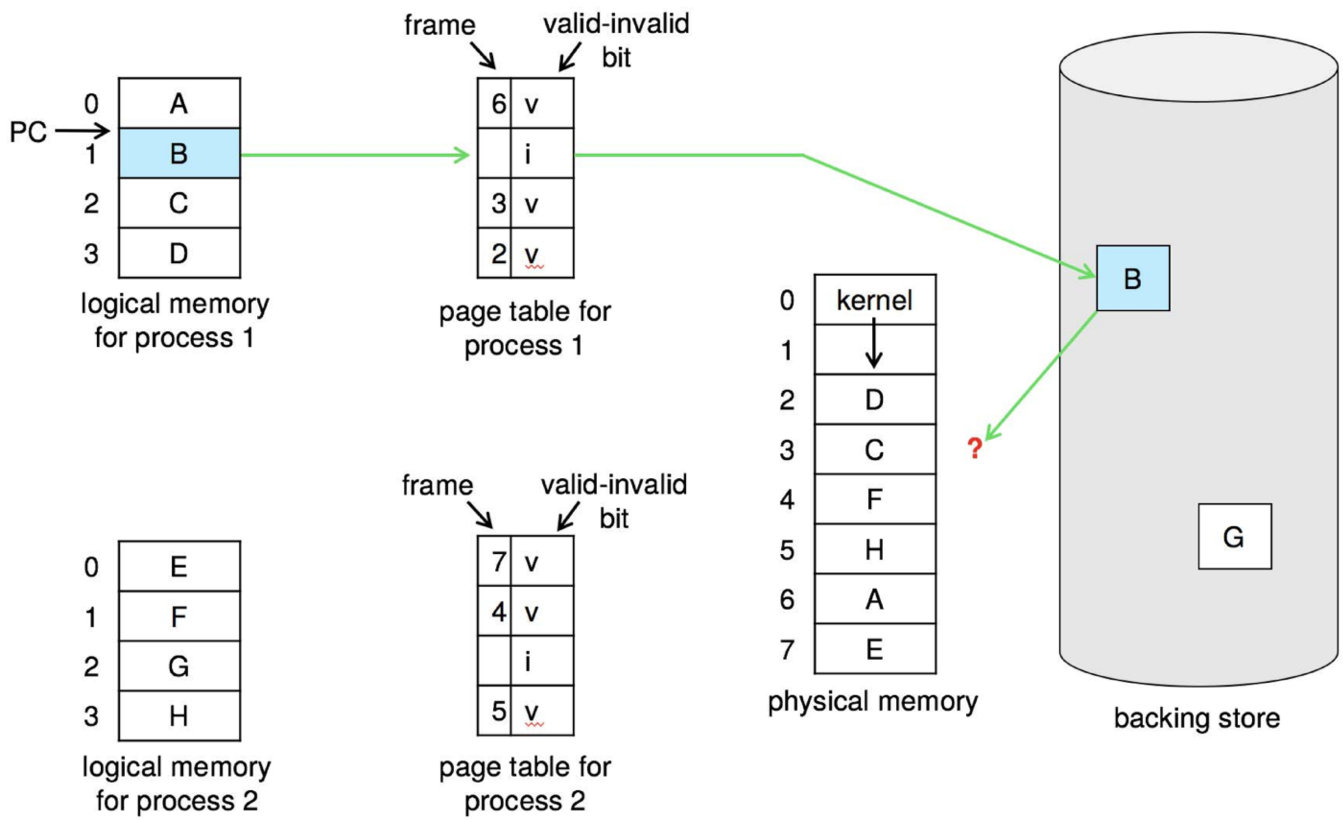
What Happens if There is no Free Frame?

- 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

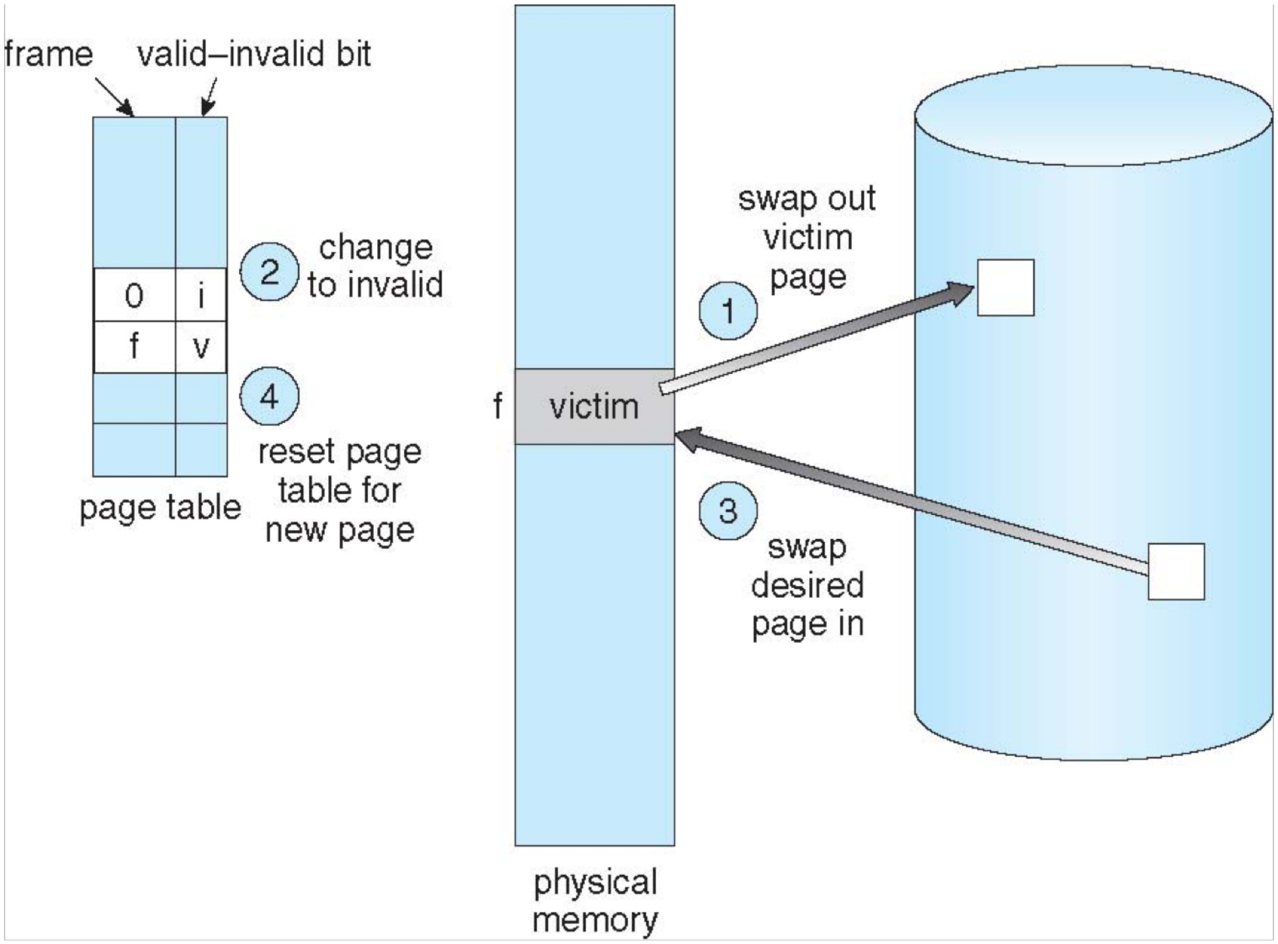
Page Replacement

- 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 Replacement

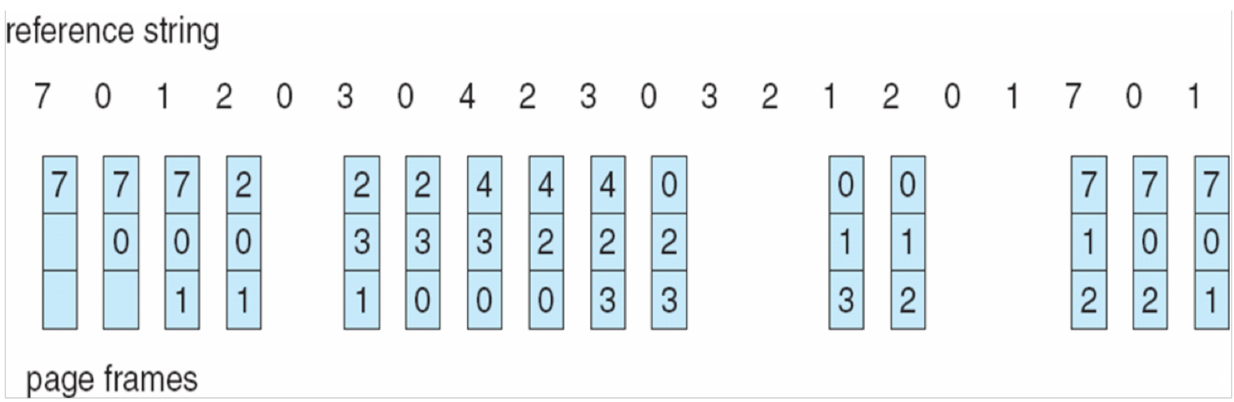


Page Replacement Algorithms

- 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

First-In-First-Out (FIFO)

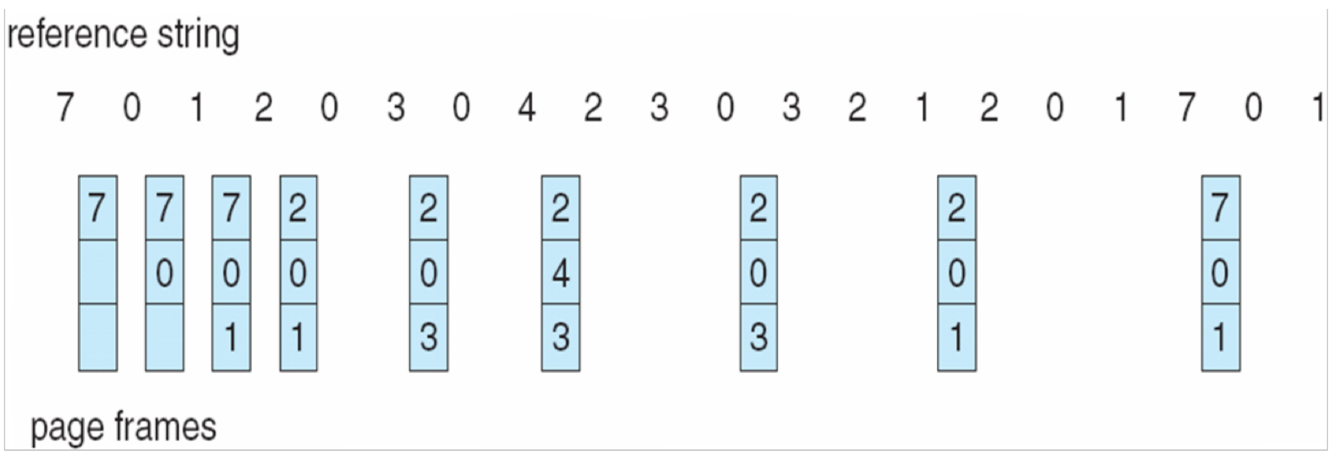
- **FIFO**: replace the first page loaded
  - similar to sliding a window of n in the reference string
  - our reference string will cause 15 page faults with 3 frames
  - how about reference string of 1,2,3,4,1,2,5,1,2,3,4,5 /w 3 or 4 frames?
- For FIFO, adding **more frames** can cause **more page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



15 page faults

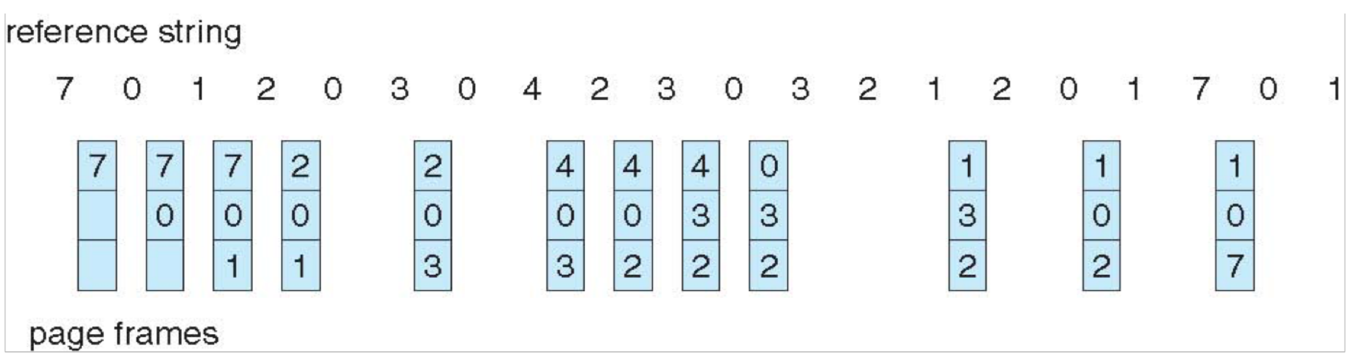
Optimal Algorithm

- **Optimal** : replace page that will not be used for the longest time
  - 9 page fault is optimal for the example on the next 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



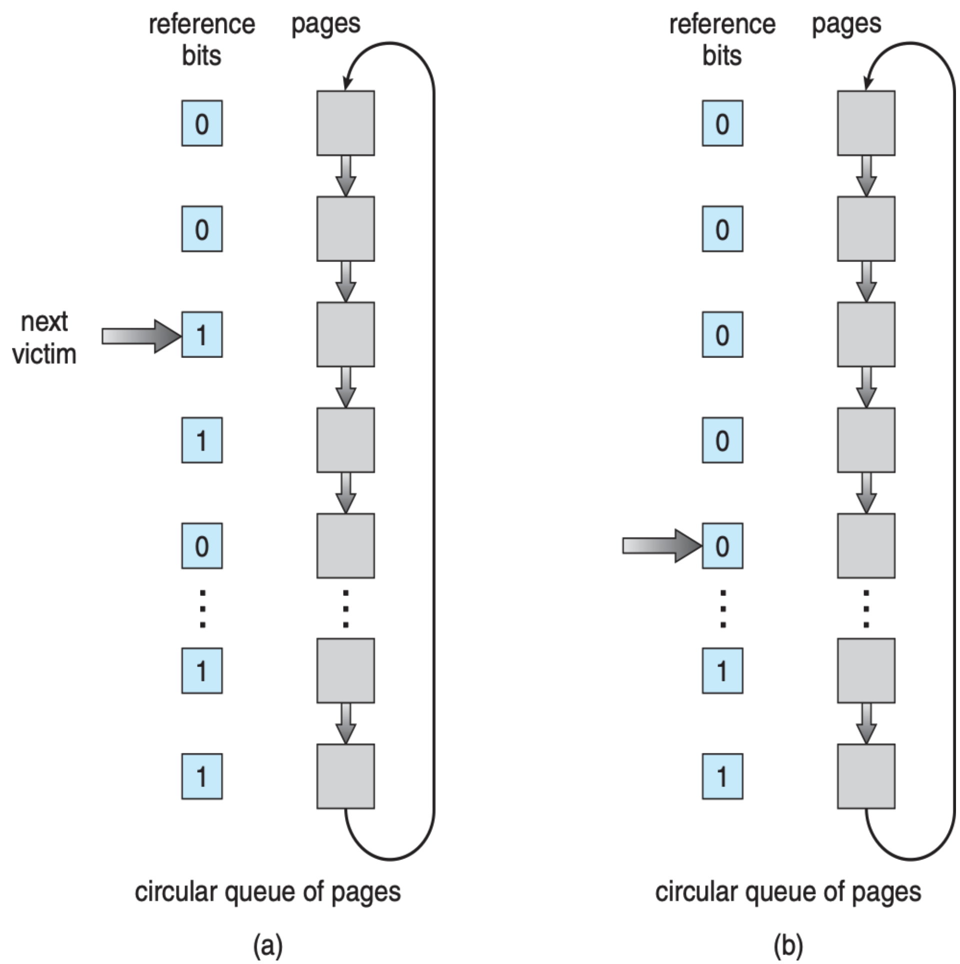
LRU Approximation Implementation

- 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

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



Thrashing

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

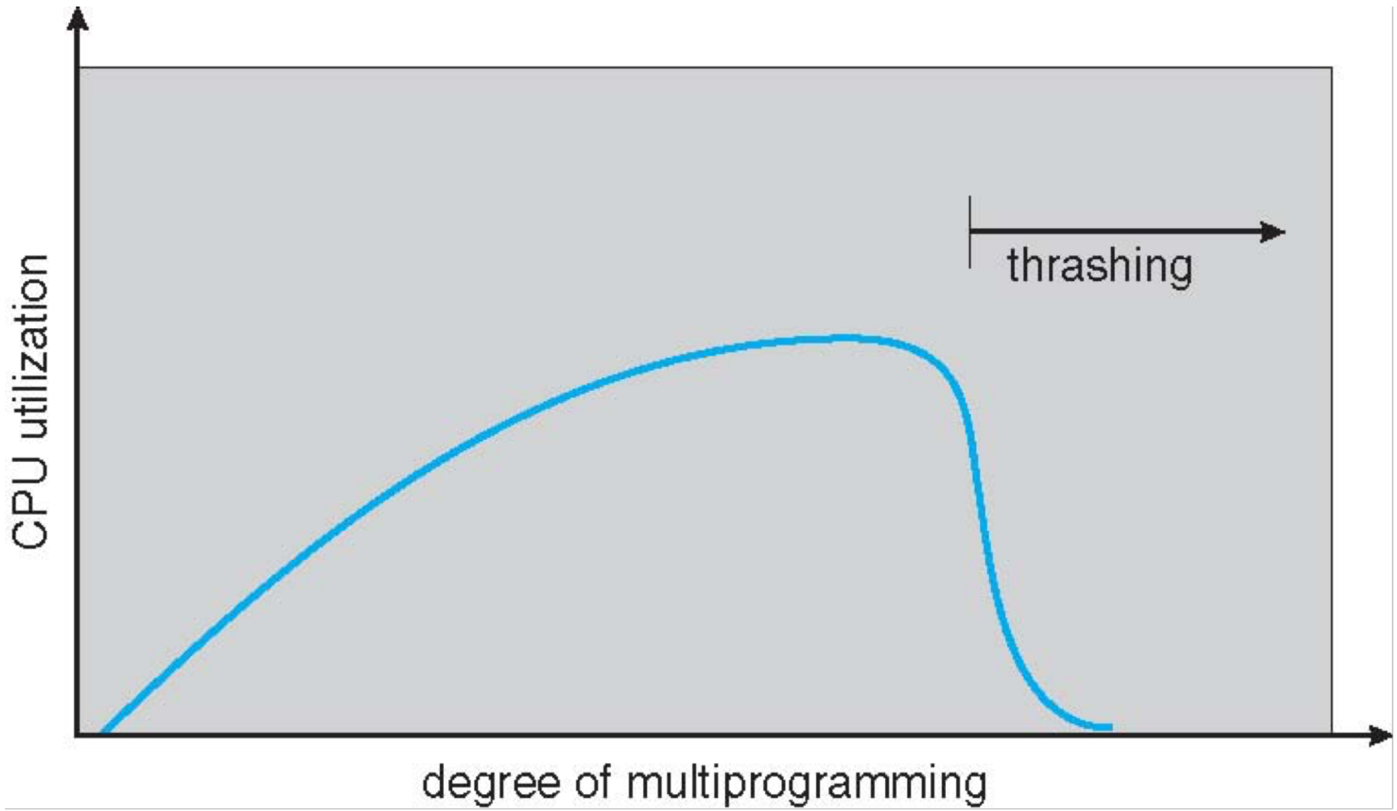
    low CPU utilization ➠

    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 size of locality > total memory size

Takeaway

- The whole slides