Lecture 9
Demand Paging

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Demand Paging Mechanisms

How To Go Beyond Physical Memory?

- How to support large address space?
  - 64-bit machine supports up to 4EB address space
  - Applications may use more space than available in physical memory

现代 64 位机器支持极大的地址空间（理论上可达 4EB），但物理内存（RAM）通常只有 16GB 或 32GB

- Solution: stash away portions of address spaces that aren't currently in use
  - in the next-level of storage (e.g., hard disk drive)
  - slower but much larger

将当前不使用的地址空间部分“暂存”到下一级存储设备（ 如硬盘 HDD 或固态硬盘 SSD ）中。虽然磁盘比内存慢很多，但容量大且便宜。

An Abstraction of Address Space

- Who is responsible for moving data?
- Application: **memory overlays**

  非常麻烦且容易出错

  - Application in charge of moving data between memory and disk
  - e.g., calling a function needs to make sure the code is in memory!
- OS: **demand paging**
  - OS configures page table entries
  - Virtual page maps to physical memory or files in disk
  - Process sees an abstraction of address space
  - OS determines where the data is stored

OS 配置页表（Page Table），将虚拟页面映射到物理内存或磁盘文件。
对进程来说，它只看到一个连续的、巨大的抽象地址空间，并不关心数据到底在哪。

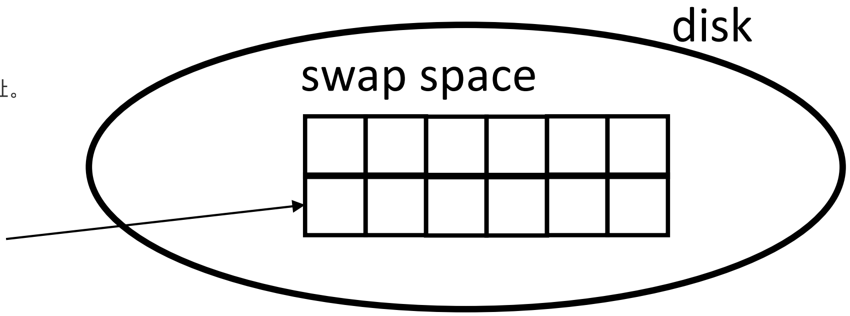
Swap Space

- Swap space is a partition or a file stored on the disk
  - OS swaps pages out of memory to it
  - OS swaps pages from it into memory
- Swap space conceptually divided into page-sized units
  - OS maintains a disk address of each page-sized unit

Swap Out（换出）： 当内存不足时，OS 将不常用的页面从内存移动到 Swap Space。

Swap In（换入）： 当进程需要访问某个在 Swap 中的页面时，OS 将其移回内存。

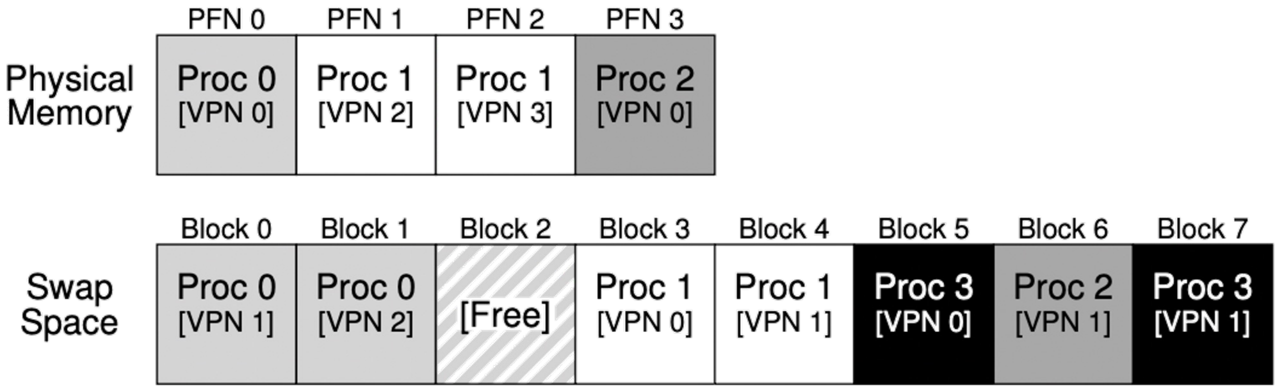
管理： Swap Space 在逻辑上也被切分成一个个“页大小”的单元，OS 会记录每个单元的磁盘地址。



each page-sized unit in
swap space can be
addressed by the OS

Swap Space Example

- 4-page physical memory and an 8-page swap space
  - Proc 0 has three virtual pages
  - Proc 1 has four virtual pages
  - Proc 2 and Proc 3 each has two virtual pages



	PFN 0	PFN 1	PFN 2	PFN 3
Physical Memory	Proc 0 [VPN 0]	Proc 1 [VPN 2]	Proc 1 [VPN 3]	Proc 2 [VPN 0]

	Block 0	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Block 7
Swap Space	Proc 0 [VPN 1]	Proc 0 [VPN 2]	[Free]	Proc 1 [VPN 0]	Proc 1 [VPN 1]	Proc 3 [VPN 0]	Proc 2 [VPN 1]	Proc 3 [VPN 1]

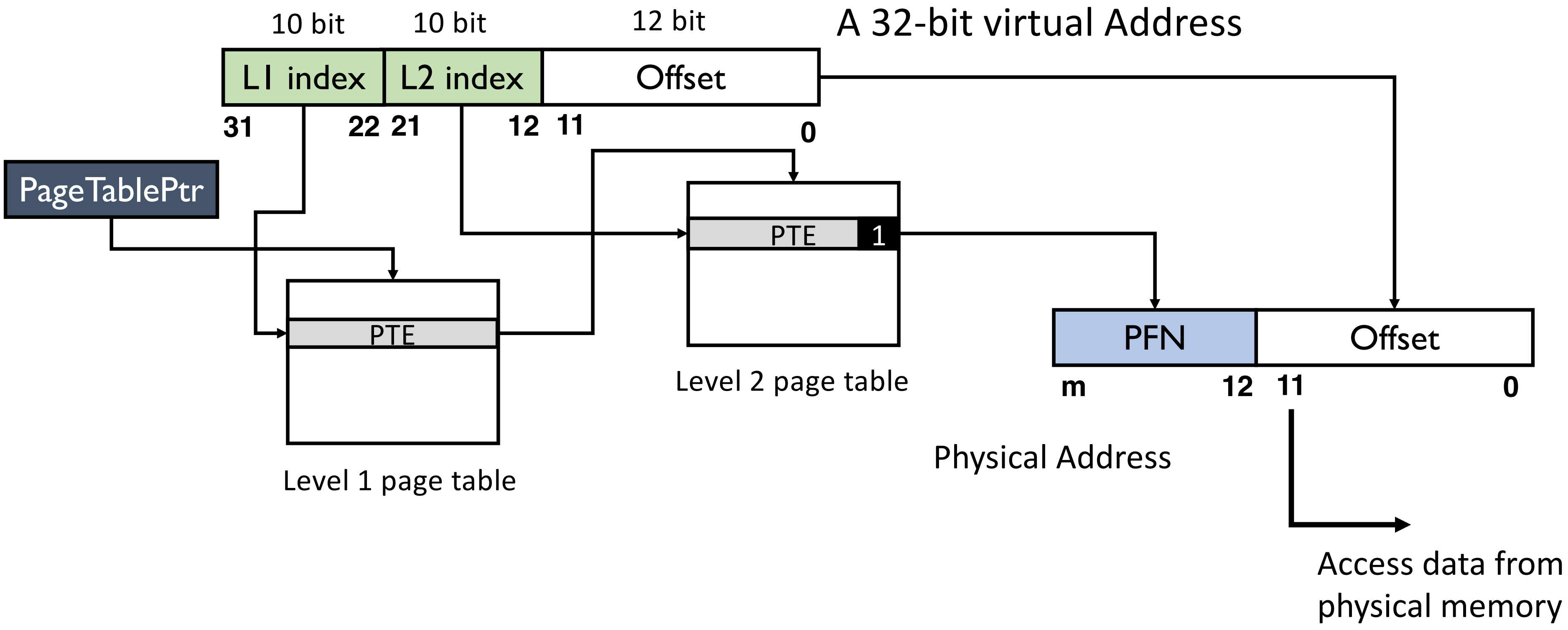
Demand Paging

- Load pages from disk to memory only as they are needed
  - Pages are loaded “on demand”
- Data transferred in the unit of pages
- Two possible on-disk locations
  - Swap space:
    - created by OS for temporary storage of pages on disk
    - e.g., pages for stack and heap
  - Program binary files:
    - The code pages from this binary are only loaded into memory when they are executed
    - Read-only, thus never write back

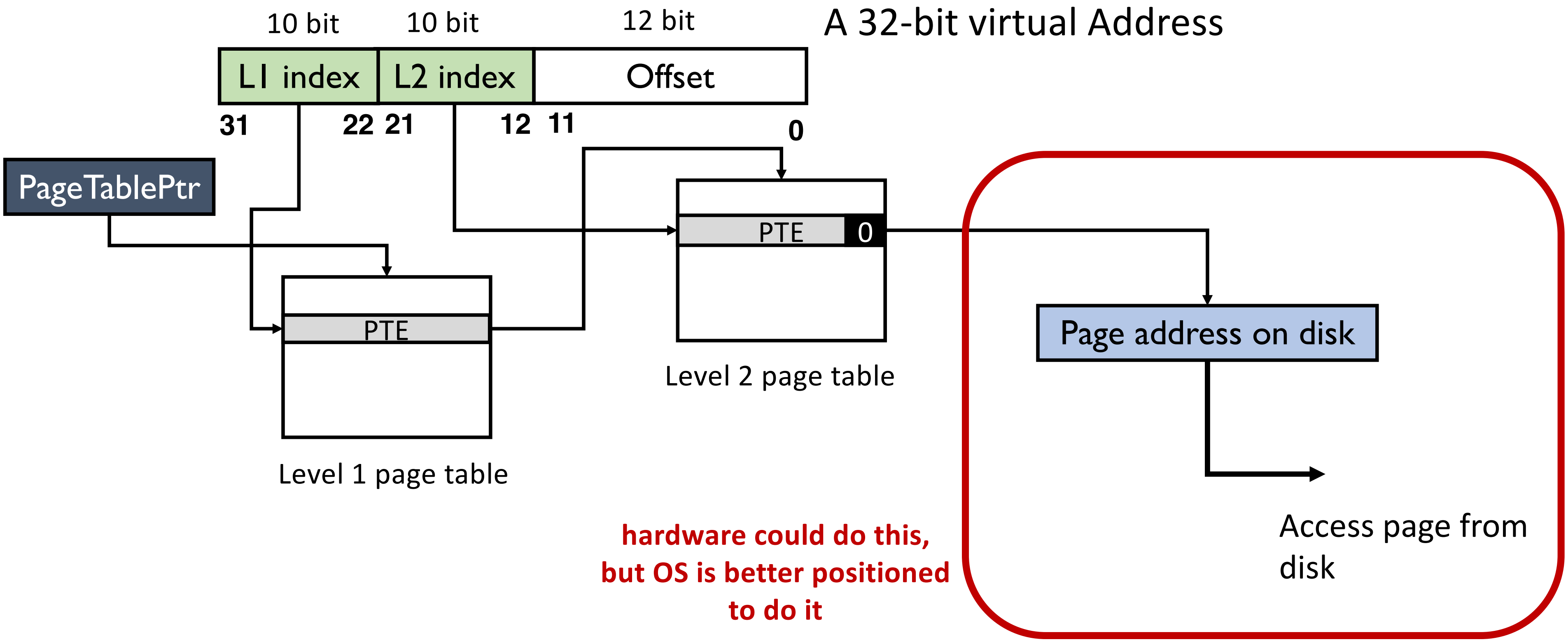
Physical Memory as a Cache

- Physical memory can be regarded as a cache of on-disk swap space
- Block size of the cache?
  - 1 page (4KB)
- Cache organization (direct-mapped, set-associative, fully-associative)?
  - Fully associative: any disk page maps to any page frame
- What is page replacement policy?
  - LRU, Random, FIFO
- What happens on a miss?
  - Go to lower level to fill page (i.e. disk)
- What happens on a write, write-through or write back?
  - write-back: changes are written back to disk when page is evicted

Present Bit


10 bit
10 bit
12 bit
A 32-bit virtual Address
L1 index
L2 index
Offset
31
22
21
12
11
0
PageTablePtr
PTE
1
PTE
Level 2 page table
Level 1 page table
PFN
Offset
m
12
11
0
Physical Address
Access data from physical memory

Present Bit



hardware could do this, but OS is better positioned to do it

操作系统读取这个磁盘地址，驱动磁盘控制器，将数据从磁盘（Swap Space 或文件系统）搬运到物理内存的一个空闲页中。

Page Faults

- Present bit = 0 raises a page fault exception
  - OS gets involved in address translation
- Page fault handler
  - (1) Find free page frame in physical memory
  - (2) Fetch page from disk and store it in physical memory
- After page fault
  - Return from page fault exception
  - CPU re-execute the instruction that accesses the virtual memory
  - No more page fault since present bit is set this time
  - TLB entry loaded from PTE

Page Faults (Cont'd)

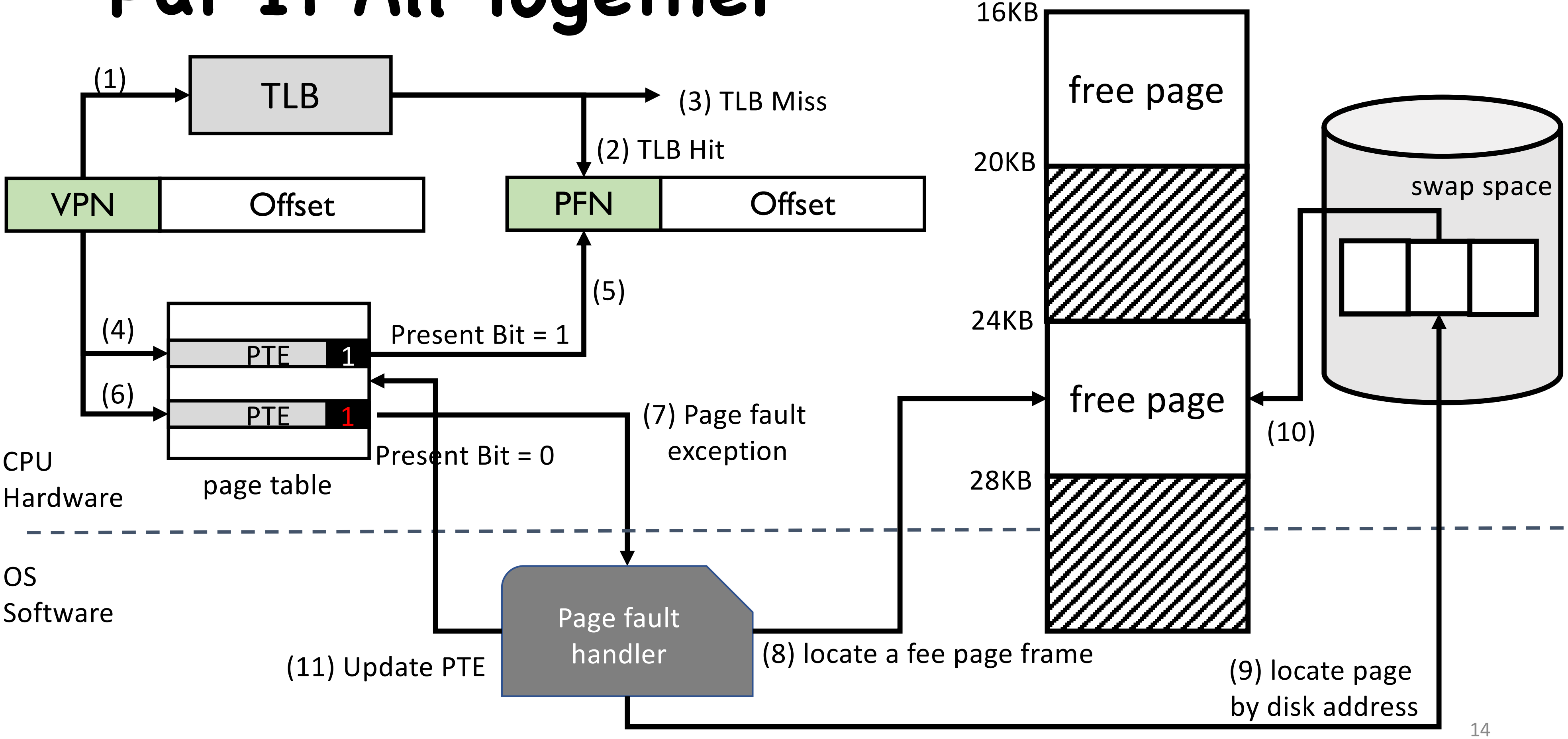
- (1) Find free page frame in physical memory
  - Find one free page frame from a free-page list
  - If no free page, trigger **page replacement** 内存页都满了，需要找到一个内存页清理出去

- **Page Replacement**
  - find a page frame to be replaced
    - Page replacement policy decides which one to replace
  - If page frame to be replaced is dirty, 之前被修改过 write it back to disk
  - Update all PTEs pointing to the page frame
  - Invalidate all TLB entries for these PTEs

Page Faults (Cont'd)

- (2) Fetch page from disk
  - Determine the faulting virtual address from register
  - Locate the disk address of the page in PTE (where PFN should be stored)
    - It is a very natural choice to make use of the space in PTE
  - Issues a request to disk to fetch the page into memory
  - Wait …… (could be a very long time, context switch!)
  - When I/O completes, update page table entry: PFN, present bit

Put It All Together



When to Trigger Page Replacement

- Proactive page replacement usually leads to better performance

  如果每次都要等到内存完全被占满（0 空闲）时才开始置换，那么那个不幸触发缺页的进程会非常痛苦。因为它不仅要等待数据从磁盘读进来（Swap In），还得先等待旧数据写回磁盘（Swap Out）。这会有双倍的延迟。

  - Page replacement even though no one needs free page frames (yet)
  - Always reserve some free page frames in the system
- Swap daemon
  - background process for reclaiming page frames

    当 CPU 比较空闲或者内存紧张时，它就会醒来，检查内存，把那些很久没用的页（LRU）写回到磁盘（Swap Out），然后把物理内存标记为空闲。

  - Low watermark: a threshold to trigger swap deamon
  - High watermark: a threshold to stop reclaiming page frames

Page Replacement Policy

Effective Access Time

- EAT = Hit Rate x Hit Time + Miss Rate x Miss Penalty
- Example:
  - Memory access time = 200 nanoseconds
  - Average page-fault service time = 8 milliseconds
  - Suppose p = Probability of miss, 1-p = Probably of hit
  - Then, we can compute EAT as follows:

$$\boxed{\begin{aligned} EAT &= (1-p) \times 200ns + p \times 8\ ms \\ &= (1-p) \times 200ns + p \times 8{,}000{,}000ns \end{aligned}}$$

Effective Access Time (Cont'd)

$$\boxed{\begin{aligned} EAT &= (1-p) \times 200ns + p \times 8\ ms \\ &= (1-p) \times 200ns + p \times 8{,}000{,}000ns \end{aligned}}$$

- If one access out of 1,000 causes a page fault, then EAT is about 8.2 μs:
  - This is a slowdown by a factor of 40!

- What if we want slowdown by less than 10%?
  - $200ns \times 1.1 < EAT \Rightarrow p < 2.5 \times 10^{-6}$
  - This is about 1 page fault in 400,000!

Types of Cache Misses: Three Cs

- Compulsory Misses:
  - Cold-start miss: pages that have never been fetched into memory before
  - Prefetching: loading them into memory before needed
- Capacity Misses:
  - Not enough memory: must somehow increase available memory size
  - One option: Increase amount of DRAM (not quick fix!)
  - Another option: If multiple processes in memory: adjust percentage of memory allocated to each one!
- Conflict Misses:
  - fully-associative cache (OS page cache) does not have conflict misses

Page Replacement Policies

- Optimal (also called MIN):
  - Replace page that will not be used for the longest time
  - Lead to minimum page faults in theory

- FIFO (First In, First Out)
  - Throw out oldest page first
  - May throw out heavily used pages instead of infrequently used

- RANDOM:
  - Pick random page for every replacement
  - Pretty unpredictable – makes it hard to make real-time guarantees

Replacement Policies (Con't)

- Least Recently Used (LRU):
  - Replace page that has not been used for the longest time
  - **Temporal locality of program**
    - If a page has not been used for a while, it is unlikely to be used in the near future
- Least Frequently Used (LFU)
  - Replace page that has not been accessed many times
  - **Spatial locality of program**
    - if a page has been accessed many times, perhaps it should not be replaced as it clearly has some value.

Example: Optimal (MIN)

- Suppose we have 3 page frames, 4 virtual pages, and following reference string:
  - A B C A B D A D B C B

Ref: Page:	A	B	C	A	B	D	A	D	B	C	B
1	A									C	
2		B									
3			C			D					

- MIN: 5 faults
  - Where will D be brought in? Look for page not referenced farthest in future

Example: FIFO

- Suppose we have 3 page frames, 4 virtual pages, and following reference string:
  - A B C A B D A D B C B

Ref: Page:	A	B	C	A	B	D	A	D	B	C	B
1	A					D				C	
2		B					A				
3			C						B		

- FIFO: 7 faults
- When referencing D, replacing A is bad choice, since need A again right away

Example: LRU

- Suppose we have 3 page frames, 4 virtual pages, and following reference string:
  - A B C A B D A D B C B

Ref: Page:	A	B	C	A	B	D	A	D	B	C	B
1	A	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	C	🟦
2		B	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪
3			C	🟦	🟦	D	🟨	🟨	🟨	🟨	🟨

- LRU performs the same as Optimal

Is LRU Always Close to Optimal?

- Consider the following reference string: A B C D A B C D A B C D
- LRU performs as follows (the same as FIFO):

Ref: Page:	A	B	C	D	A	B	C	D	A	B	C	D
1	A			D			C			B		
2		B			A			D			C	
3			C			B			A			D

Is LRU Always Close to Optimal? (Cont'd)

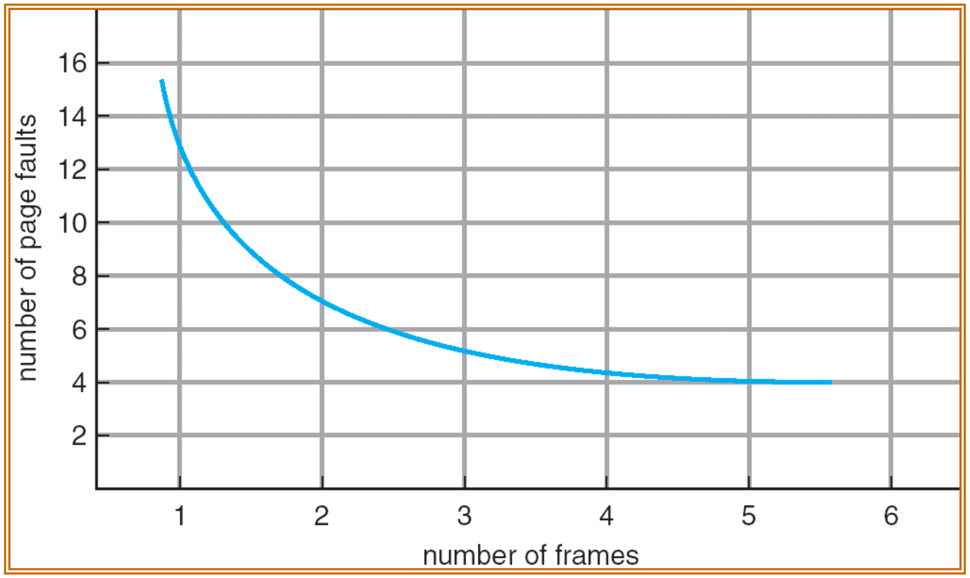
- Consider the following: A B C D A B C D A B C D
- MIN performs better:

Ref: Page:	A	B	C	D	A	B	C	D	A	B	C	D
1	A									B		
2		B					C					
3			C	D								

Bélády's Anomaly

- One desirable property: When you add memory the miss rate drops
  - Yes for LRU and MIN
  - Not necessarily for FIFO!

- Bélády's anomaly
  - For FIFO, more page frames may lead to more page faults!



Bélády's Anomaly Example

- Page replacement with 3 page frames

Ref: Page:	A	B	C	D	A	B	E	A	B	C	D	E
1	A			D			E					
2		B			A					C		
3			C			B					D	

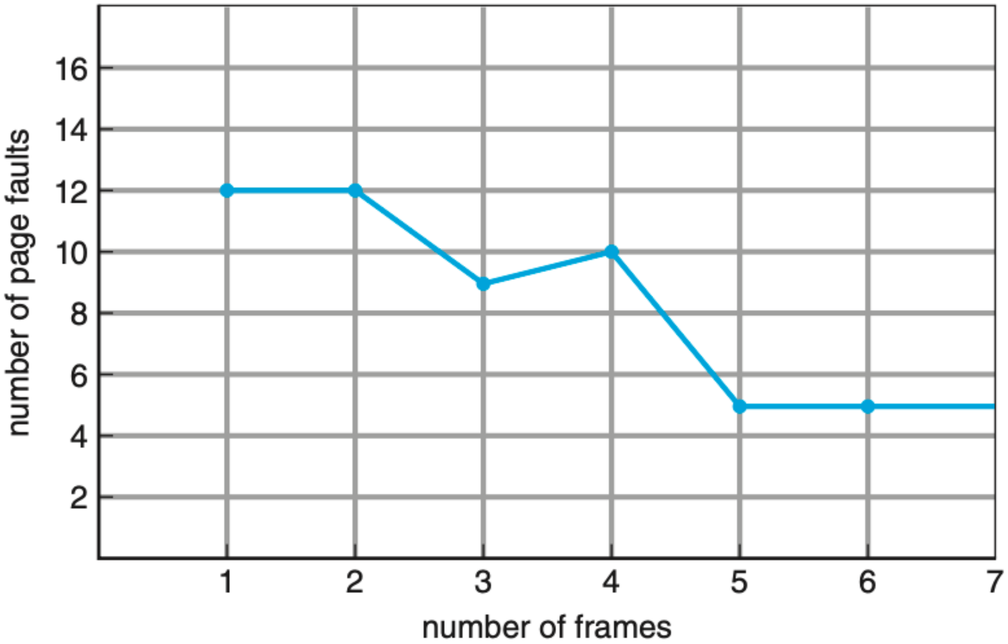
- Page replacement with 4 page frames

Ref: Page:	A	B	C	D	A	B	E	A	B	C	D	E
1	A						E				D	
2		B						A				E
3			C						B			
4				D						C		

Page Fault Curve

- Page fault curve for FIFO on reference string
  - 7 0 1 2 0 3 0 4 2 3 0 3 2 1 2 0 1 7 0 1

How do you plot a chart like this?



LRU Implementation

- Hardware support is necessary
    - Update a data structure in OS upon every memory access
    - E.g., a timestamp counter for each page frame
- Overhead
    - One additional memory write for each memory access
        - TLB hit does not save the extra memory access
    - Scan the entire memory to find the LRU one
        - 4GB physical memory has 1 million page frames
        - sorting is time consuming

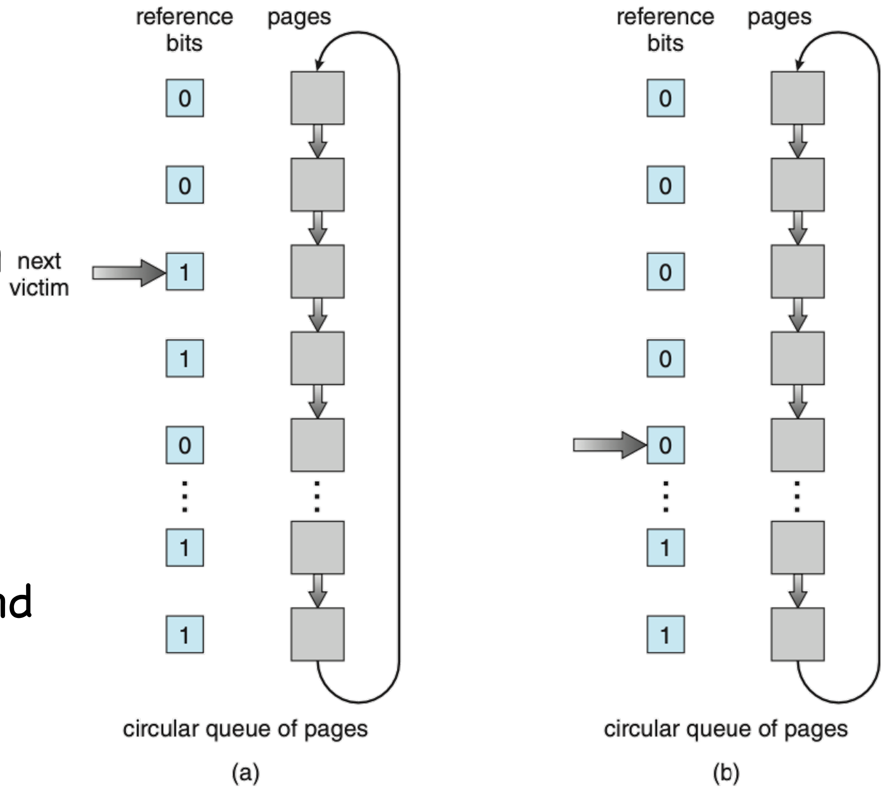
LRU Approximation with Reference Bit

- Reference bit
  - One reference bit per page frame
  - All bits are cleared to 0 initially
  - The first time a page is referenced, the reference bit is set **by CPU**
    - Can be integrated with page table walk
  - The order of page accesses approximated by two clusters: **used** and **unused** pages

- Examples:
  - Clock algorithm (also called second-chance algorithm)
  - Enhanced clock algorithm with dirty bits

Clock Algorithm

- Arrange physical pages in a circular list
- CPU sets reference bit to 1 upon first access
- OS maintains a pointer
  - When a replacement occur, check reference bit of the current page
  - If 1: the page has been accessed recently, clear the bit (set to 0) and move to the next page
  - If 0: the page has not been accessed recently, good candidate for replacement, stop



Clock Algorithm with Dirty Bit

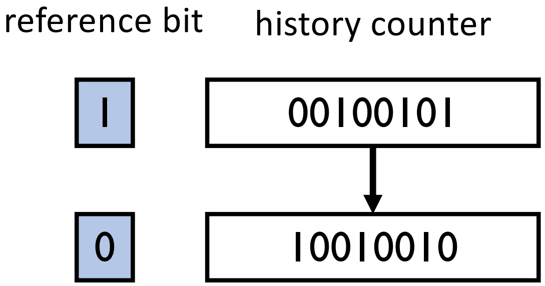
- Enhance clock algorithm with a dirty bit
  - dirty bit = 1: the page has recently been modified
- CPU sets dirty bit to 1 upon **write** access
- When a replacement occurs, OS checks (ref bit, dirty bit), and selects a candidate page in decreasing order
  - (0, 0) neither recently used nor modified — 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 be need to be written out to secondary storage before it can be replaced

LRU Approximation with Reference Bit and Counter

- Each physical page frame is associated with one reference bit and a counter
  - Reference bit indicate recent access
    - set by CPU hardware, cleared by OS
  - Counter records history of accesses
    - Maintained by OS
- Examples
  - Additional-reference-bits algorithm
  - Nth-chance clock algorithm

Additional-reference-bits Algorithm

- 8-bit history register associated with each page frame
- Timer interrupt every 100ms
  - reference bit shifts to highest bit in the history counter
  - other bits shift right and discard the lowest bit
  - 00000000 unused page in 800ms
- Compare history counter as unsigned integer
  - Larger value more recently used
  - 11000100 > 01110111
- Approximate LRU with more bits and more frequent interrupts



Nth-chance Clock Algorithm

- All page frames arranged in a circular list and each page frame is associated with a reference bit and a counter
- CPU hardware sets reference bit upon memory accesses
- OS checks the reference bit of the page pointed to by the clock hand
  - 1 → clear reference bit and the counter
  - 0 → increment counter; if count=N, replace page

- How do we pick N?
  - Large N? Better approximation to LRU
    - If N ~ 1K, really good approximation
  - Small N? More efficient
    - Otherwise might have to look a long way to find free page

Page Frame Allocation

Allocation of Page Frames

- How do we allocate memory among different processes?
  - Does every process get the same fraction of memory? Different fractions?
  - Should we completely swap some processes out of memory?
- Minimum number of pages per process
  - Depends on the computer architecture
  - How many pages would one instruction use at one time
    - x86 only allows data movement between memory and register and no indirect reference
    - needs at least one instruction page, one data page, and some page table pages
- Maximum number of pages per process
  - Depends on available physical memory

Global versus Local Allocation

- Global replacement
  - Process selects replacement frame from all page frames
  - One process can take a frame from another process

- Local replacement
  - Each process selects from only its own set of allocated frames

Allocation Algorithms

- Equal allocation:
  - Every process gets same amount of memory
  - Example: 100 frames, 5 processes → process gets 20 frames
- Proportional allocation
  - Number of page frames proportional to the size of process

    s_i = size of process p_i *and* m = total number of frame

    a_i = allocation for p_i = $m \times \frac{s_i}{\sum s_j}$
- Priority Allocation:
  - Number of page frames proportional to the priority of process
  - Possible behavior: If process p_i generates a page fault, select for replacement a frame from a process with lower priority number

Thrashing

- The memory demands of the set of running processes simply exceeds the available physical memory
- Early OS
  - Working set: the pages used actively of a process
  - Reduce the # of process so their working set fit into memory
- Modern OS
  - Out-of-memory killer when memory is oversubscribed
  - May need a reboot

Thank you!