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CIS 415:
Operating Systems
Virtual Memory

Spring 2014
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Virtual Memory

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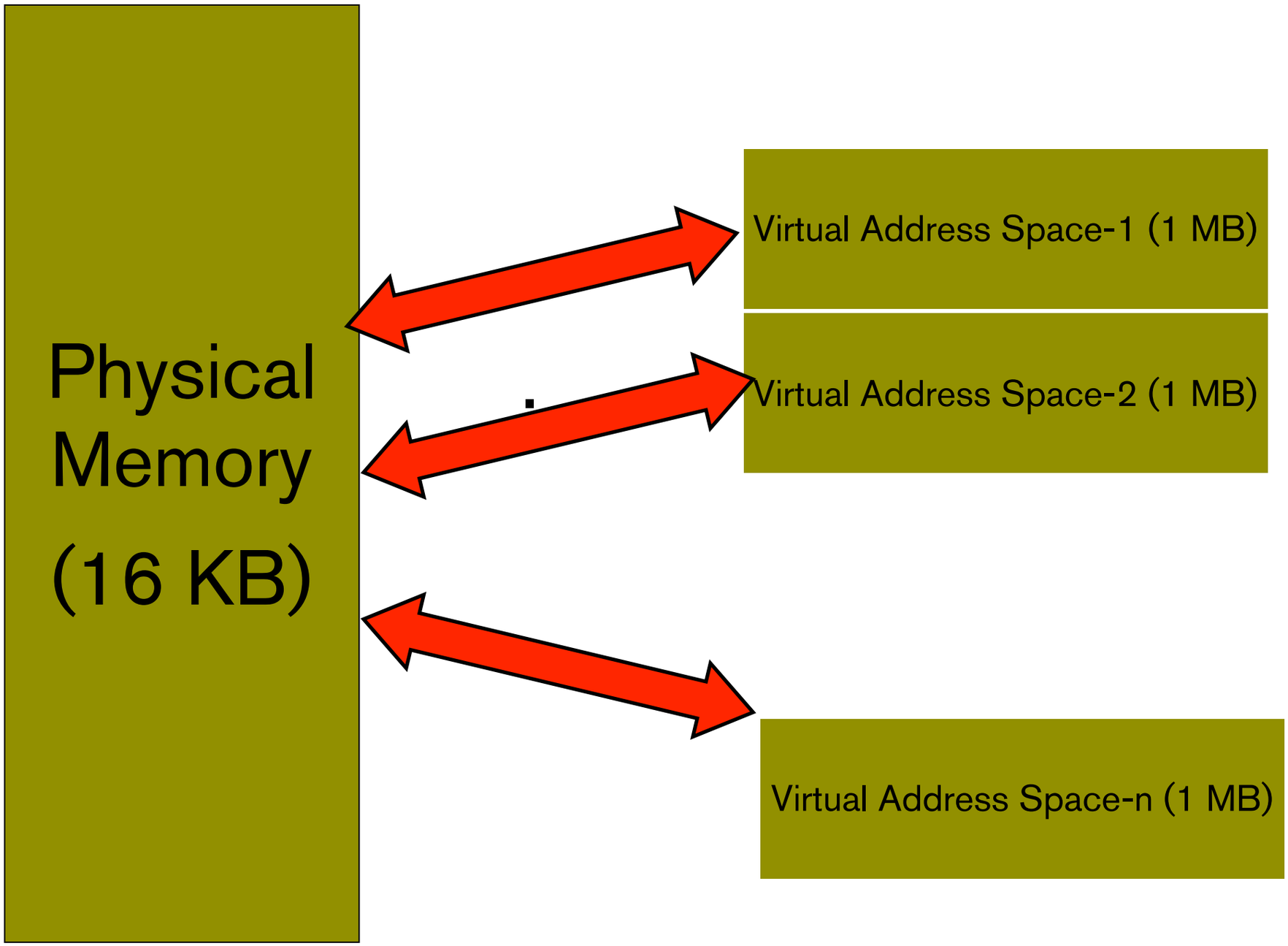
- What if programs require more memory than available physical memory?
  - Use overlays
    - Difficult to program though!
  - Virtual Memory.
    - Supports programs that are larger than available physical memory.
    - Allows several programs to reside in physical memory (or at-least the relevant portions of them).
    - Allows non-contiguous allocation without making programming difficult.

Example


Physical Memory (16 KB)
Virtual Address Space-1 (1 MB)
Virtual Address Space-2 (1 MB)
Virtual Address Space-n (1 MB)

Page Faults

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- If a page table mapping indicates an absence of the page in physical memory, hardware raises a *Page Fault*.
- OS traps this fault and the interrupt handler services the fault by initiating a disk read request.
- Once page is brought in from disk to main memory, page table entry is updated and the process which faulted is restarted.
  - May involve replacing another page and invalidating the corresponding page table entry.

Page Table

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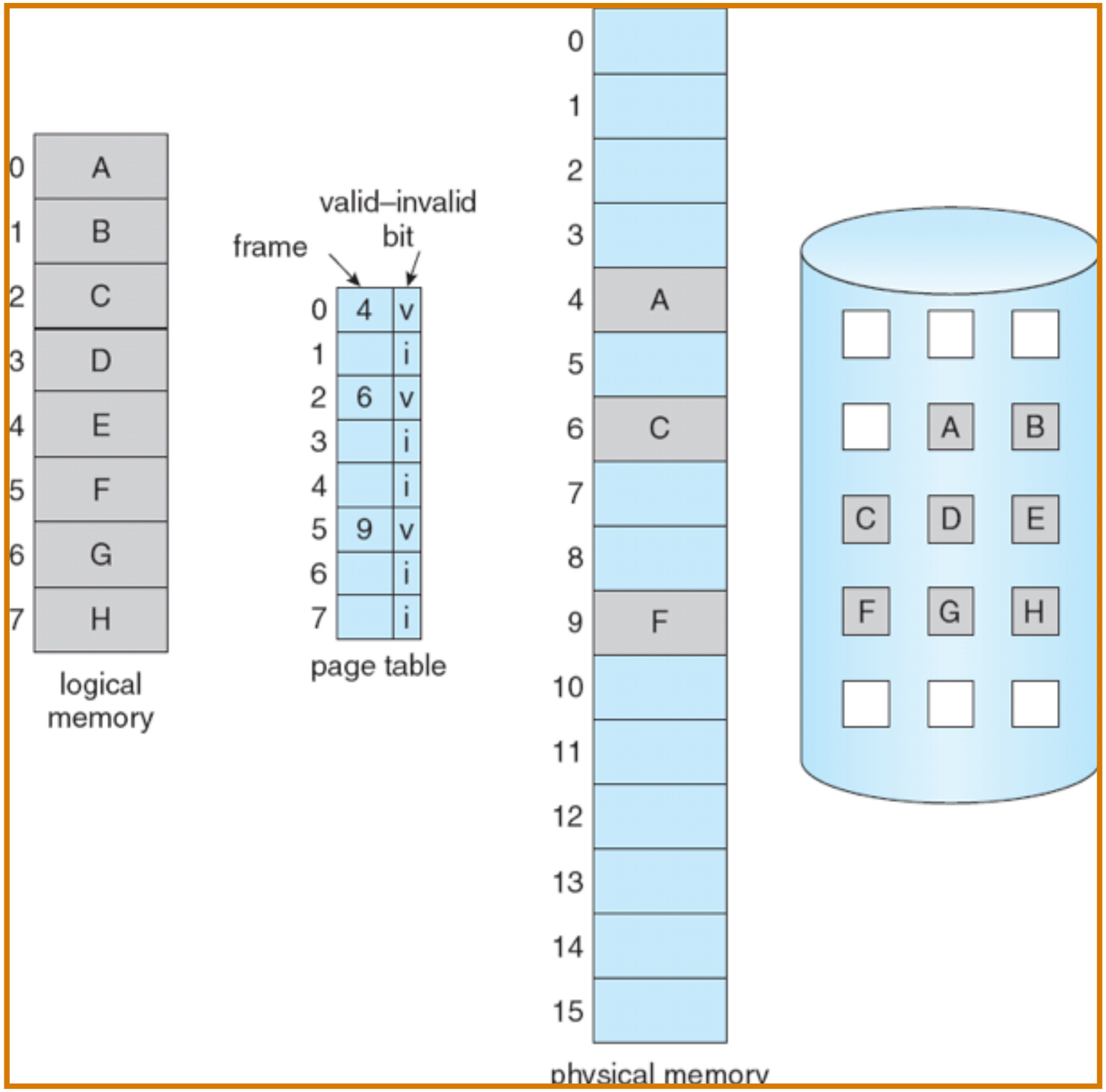
Some pages not in main memory



Page Fault

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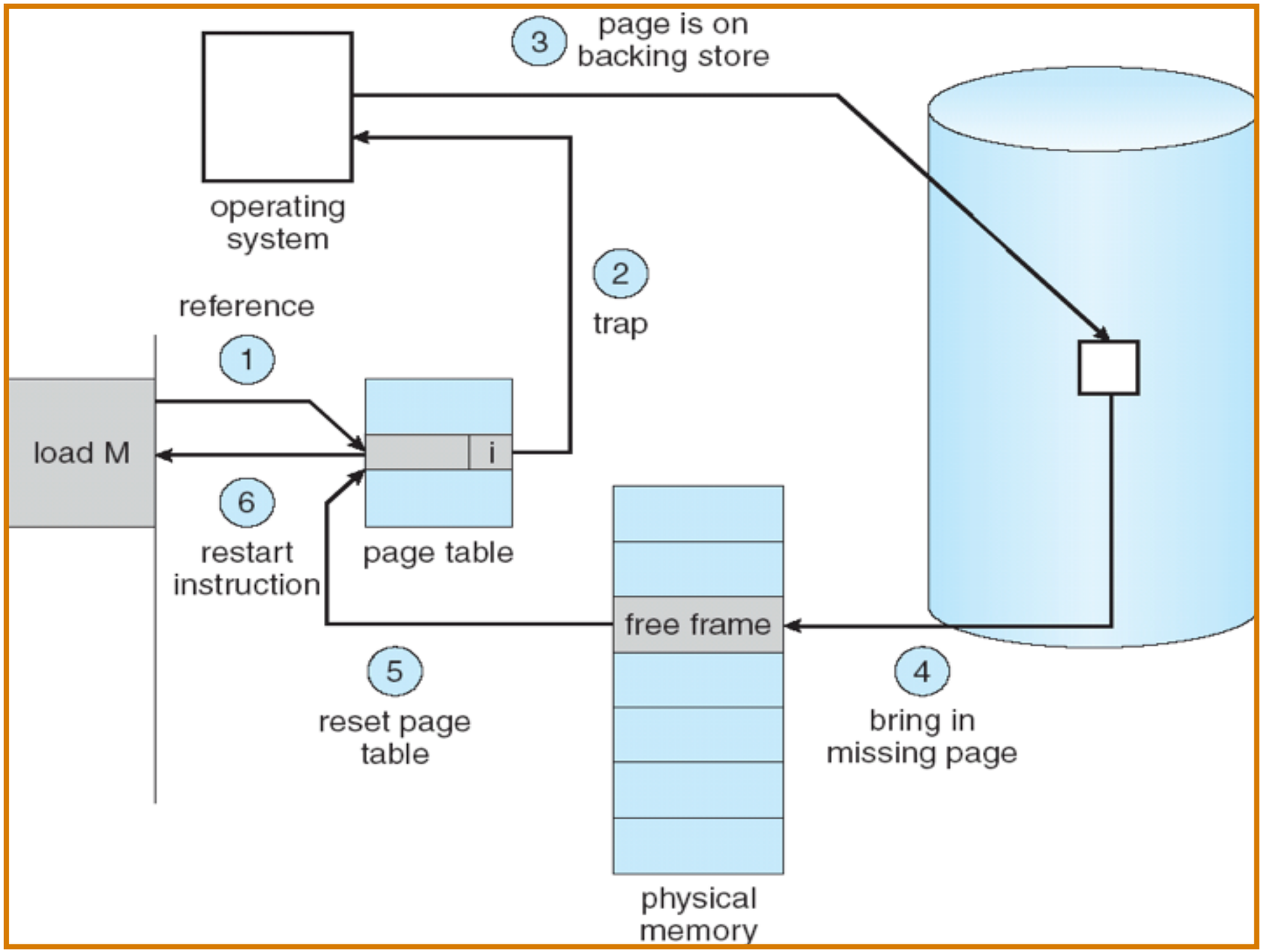
- If there is a reference to a page, first reference to that page will trap to operating system:
  - page fault
- Operating system looks at another table to decide:
  - Invalid reference -- abort
  - Just not in memory
- Get empty frame
- Swap page into frame
- Reset tables
- Set validation bit = v
- Restart the instruction that caused the page fault

Handling a Page Fault



Demand Paging Performance

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- Page Fault Rate
  - $0 \leq p \leq 1.0$
  - if $p = 0$, no page faults
  - if $p = 1$, every reference is a fault
- Effective Access Time (EAT)
- EAT = (1 – p) x memory access
  + p x (page fault overhead
    + swap page out
    + swap page in
    + restart overhead)

Demand Paging Example

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- Memory access time = 200 nanoseconds
- Average page-fault service time = 8 milliseconds

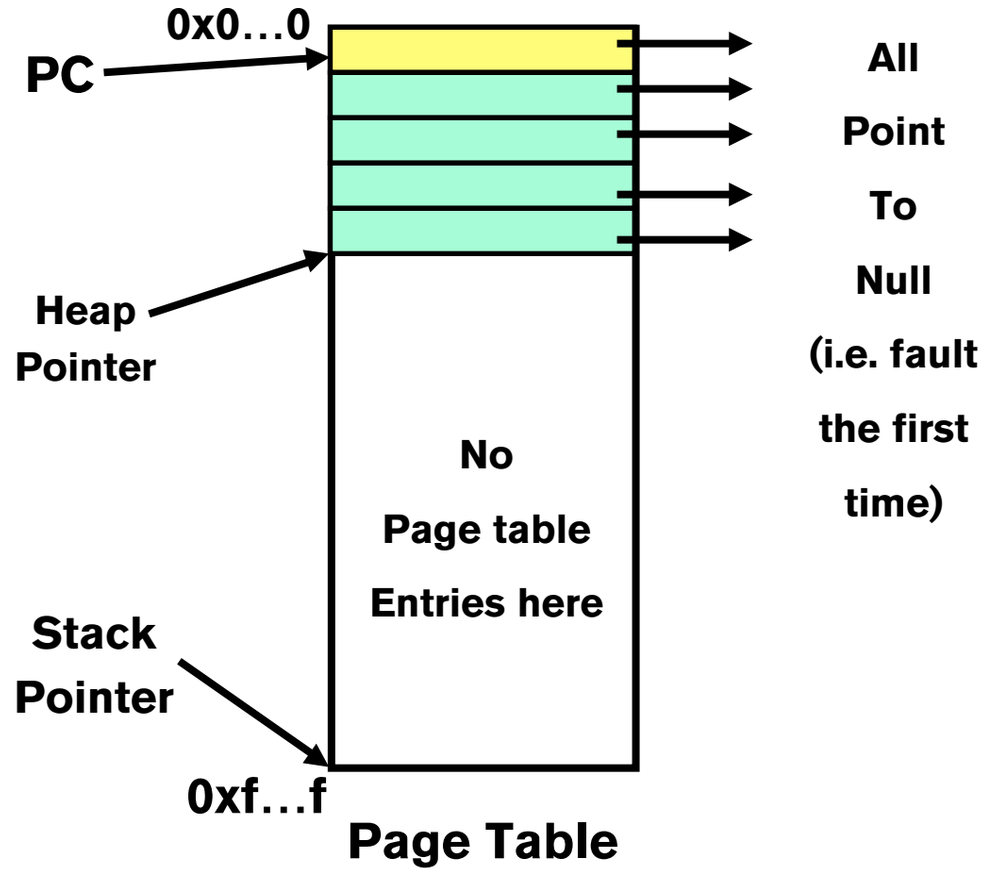
- EAT = (1 – p) x 200 + p (8 milliseconds)
  - = (1 – p x 200 + p x 8,000,000
  - = 200 + p x 7,999,800

- If one access out of 1,000 causes a page fault, then
- EAT = 8.2 microseconds.
- This is a slowdown by a factor of 40!!

In Practice

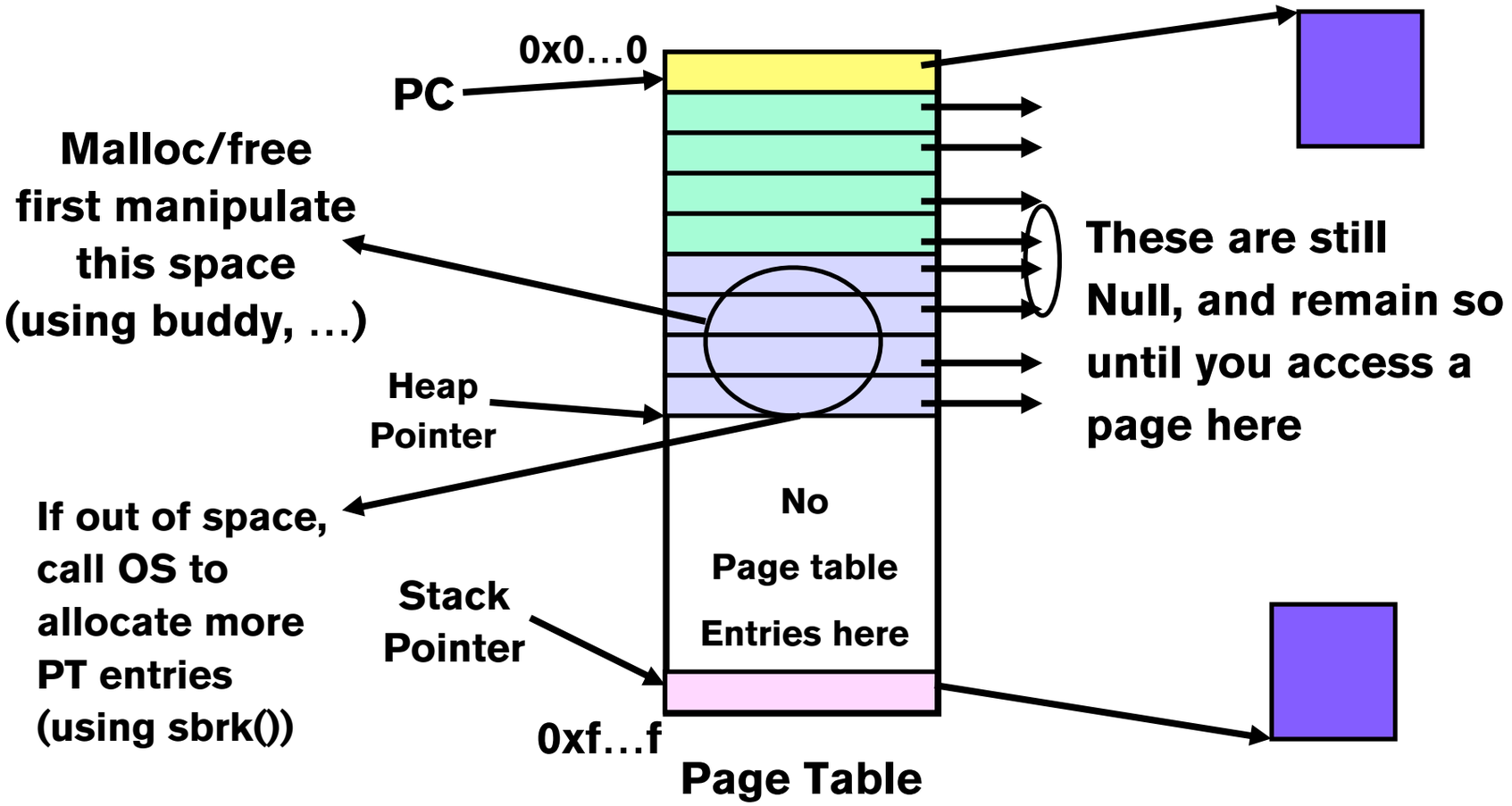

```
int A[2K];
int B[2k];
main() {
    int i, j, p;
    p = malloc(16K);
}
```

VAS before execution



4K page size

After executing malloc



Note: you are not allocating physical memory using malloc()

Page Replacement

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- When bringing in a page, something has to be evicted.

- What should we evict? – page replacement algorithm.

Optimal Page Replacement

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- Why optimal?
  - No other algorithm can have # of page faults lower than this, for a given page reference stream.
- Algorithm:
  - At any point, amongst the given pages in memory, evict the one whose next reference from now is the furthest in the future.

An example of OPT

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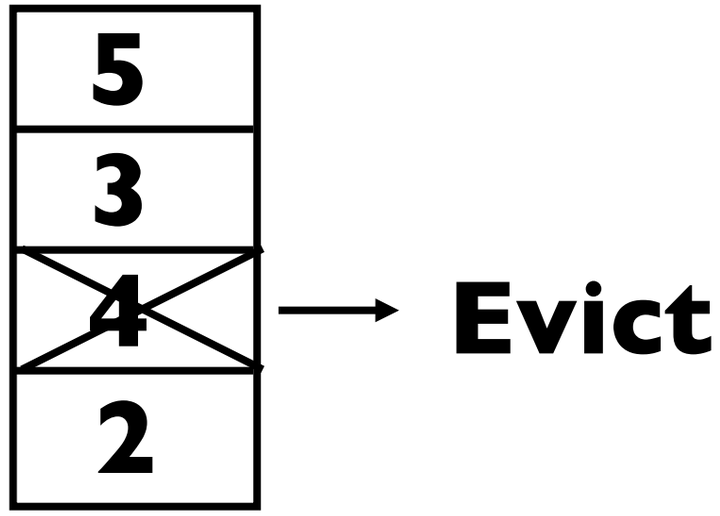
Reference String

..... 7, 5, 3, 3, 5, 2, 4, 4, 3, 2, ...

At this point, what do we replace?

Current Physical Memory



Problem with OPT

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- Not implementable!

- Requires us to know the future.

- But it has the best page fault behavior

- How do we approach OPT?

First-in, First-out (FIFO)

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- Maintain a linked list of pages in the order they were brought into PM.
- On a page fault, evict the one at the head.
- Put the newly brought in page (from disk) at tail of this list.
- Problems:
  - Reference String: 1,2,3,4,1,1,5,1,1,…
  - Page fault at (5) would replace (1) !
  - Need to know what is in recent use!

Not Recently Used

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- Referenced bit set on each Read/write by h/w
- Modified set on each write by h/w
- On startup set both R and M bits to 0.
- Periodically (using clock interrupts) the R bit is cleared.

- On a page fault, examine the state of a page
  - Class 0: R = 0 M = 0
  - Class 1: R = 0 M = 1
  - Class 2: R = 1 M = 0
  - Class 3: R = 1 M = 1

- NRU replaces a page chosen at random from the lowest numbered nonempty class.

Second Chance Replacement

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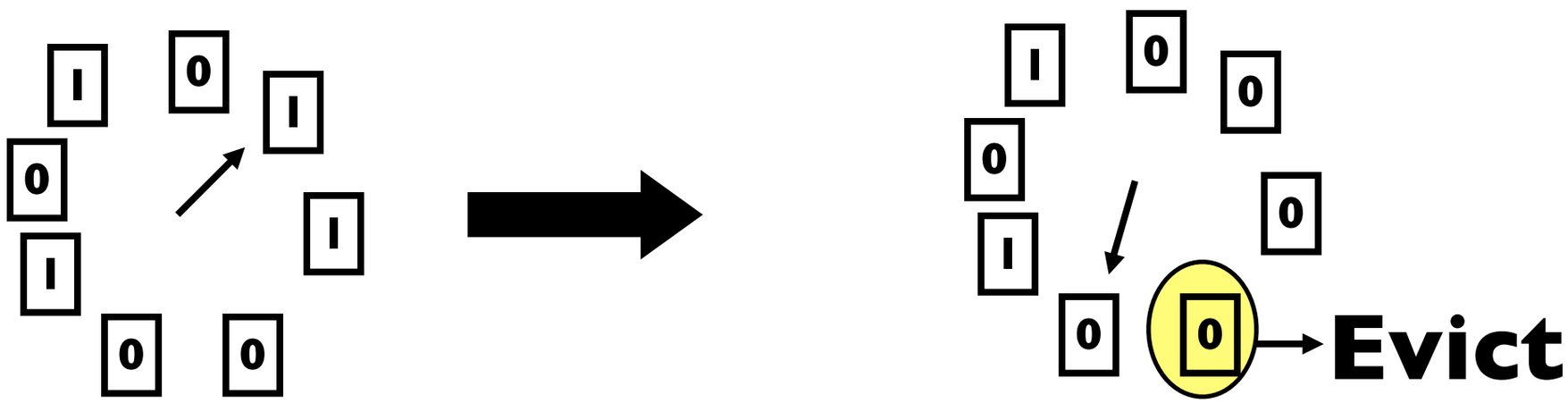
- Aka. clock algorithm (why?)
- Same as FIFO, except you skip over the pages whose reference bit is set, resetting this bit, and moving those pages to end of list.
- Implementation:



Least Recently Used (LRU)

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- Order the list of physical memory pages in decreasing order of recency of usage.
- Replace the page at the tail.
- Problem:
  - This list will need to be updated on each memory reference.
  - Asking the h/w to do this is ridiculous!
- Solution: Approximate LRU

Approximate LRU (counters)

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- Keep a counter for each physical page.
- Initially set to 0.
- At the end of each time interval (interval to be determined), shift the bits right by one position.
- Copy the reference bit to the MSB of counter and reset reference.
- For a page replacement, pick the one with the lowest counter value.
- It is an approximation of LRU because:
  - we do not differentiate between references that occured in the same tick.
  - the history is limited by the size of the counter.

Summary of page replacement algorithms

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- OPT, FIFO, NRU, second-chance/clock, LRU, approximate LRU

- In practice, OSes use second chance/clock or some variations of it.

Belady's Anomaly

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- Normally you expect number of page faults to decrease as you increase physical memory size.

- However, this may not be the case in certain replacement algorithms

Belady's Anomaly

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- FIFO replacement Algorithm
- Reference string:
  - 1 2 3 4 1 2 5 1 2 3 4 5
- 3 physical frames
  - F F F F F F F - - F F -
  - # of faults = 9
- 4 physical frames
  - F F F F - - F F F F F F
  - # of faults = 10

- Algorithms which do NOT suffer from Belady's anomaly are called *stack algorithms*
- E.g. OPT, LRU.

Modeling Paging

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- Paging behavior characterized by
  - Reference string
  - Physical memory size
  - Replacement algorithm

Modeling Paging

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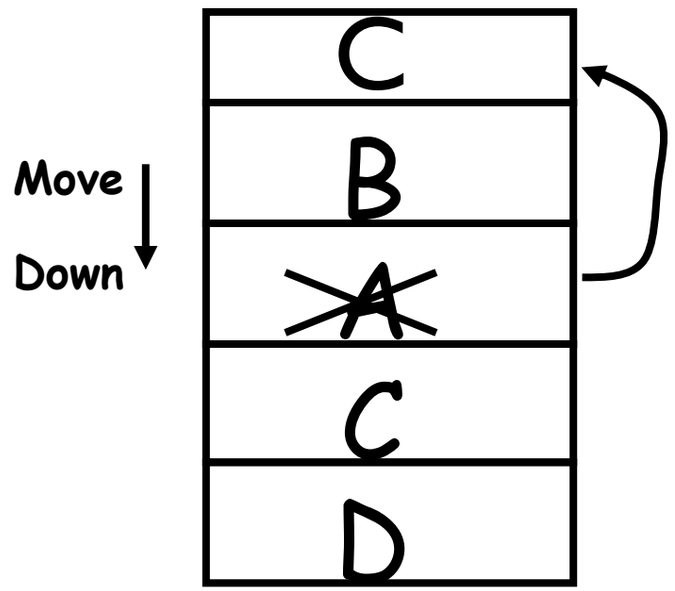
- Visualize it as a stack (say *M*), where a page that is "referenced" is brought to the top of the stack from wherever it is.

e.g. A, B, C and D are virtual pages



When C is referenced …

Modeling Paging

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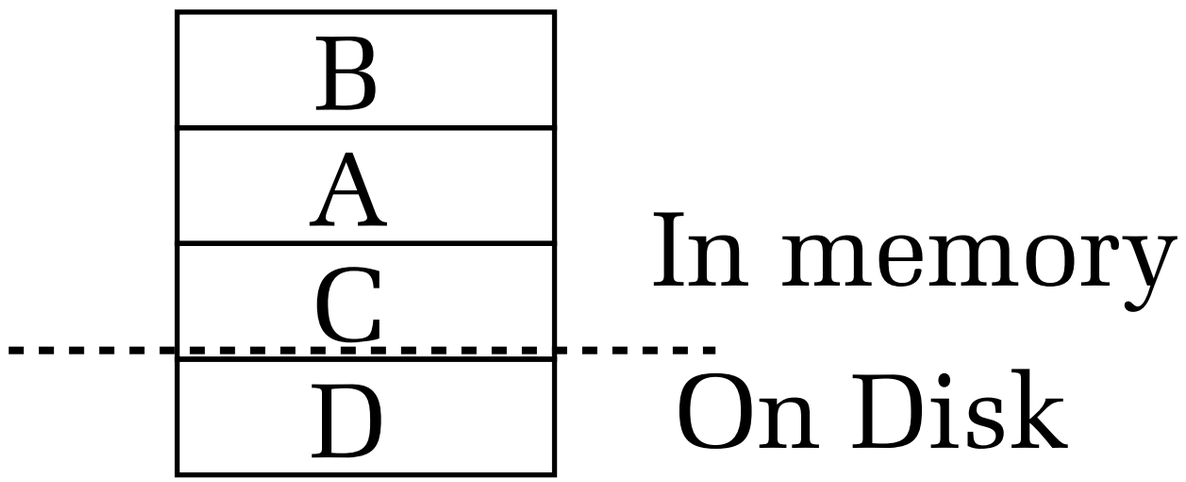
- Whatever is in recent use is on the top of *M*, and the ones that are not in recent use are at the bottom.
- In fact, the top *P* entries of *M* represent the pages in physical memory, where *P* is the # of physical frames.



- Distance String:
  - For each element *r* of reference string *R*, this represents the distance of that element from the top of stack in *M*.

An example of how M changes with 5 virtual pages

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Reference String

A	B	C	D	A	B	E	A	B	C	D	E
A	B	C	D	A	B	E	A	B	C	D	E
	A	B	C	D	A	B	E	A	B	C	D
		A	B	C	D	A	B	E	A	B	C
			A	B	C	D	C	C	D	C	B
						C					A

∞	∞	∞	∞	3	3	∞	2	2	4	4	4

Distance String

Define vector C

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- *C*[*i*] represents the number of times "*i*" appears in the distance string.

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Reference String

A	B	C	D	A	B	E	A	B	C	D	E
A	B	C	D	A	B	E	A	B	C	D	E
	A	B	C	D	A	B	E	A	B	C	D
		A	B	C	D	A	B	E	A	B	C
			A	B	C	D	D	D	F	A	B
						C	C	C	D	E	A

∞ ∞ ∞ ∞ 3 3 ∞ 2 2 4 4 4

Distance String

C vector: C[0]=0, C[1]=0, C[2]=2,

C[3]=2, C[4]=3, C[5] …=0

C[∞]=5

Define Vector F

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- *F*[*j*] is the number of page faults that will occur for the given reference string *R* with "*j*" physical frames.

- *F*[*j*] = *C*[*j*] + *C*[*j*+1] + C[*j*+2] + C[*j*+3] … + C[∞]

- It is now straightforward to prove LRU does not suffer from Belady's anomaly.
  - The *M* vector tracks what is in physical memory in the top *P* slots for LRU.
  - Note that vector *C*[*i*] is independent of physical memory size.
  - When you go from physical memory with *j* frames to (*j*+*x*) frames, note that the number of *C* vector terms in the RHS of equation for *F* decreases => Page faults can only decrease if at all!

$$M(j, R) \subseteq M(j + x, R)$$

Paging Issues

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- Keep the essentials of what you currently need *(working set)* in physical memory.
- When something you need is not in memory, bring it in from disk:
  - On demand (demand-paging)
  - Ahead of need (pre-paging)
- Programs need to exhibit good locality to avoid "thrashing" of pages in memory.
- This usually requires good programming skills!

Fragmentation in paging

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- Note that there is only internal fragmentation, and that too only in the last allocated page.
- Smaller the page, smaller the internal fragmentation.
- However, this reduces spatial locality.

Page size trade-offs

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- Average process size = s bytes
- Page size = p bytes
- Page Table entry = e bytes

$$\text{Overhead} = s * \frac{e}{p} + \frac{p}{2}$$

Summary

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- Page Replacement
  - Virtual memory
  - Page faults
  - Optimal page replacement not achievable
  - Variety of algorithms
  - Anomalies

- Next time: Virtual memory issues