Operating Systems: On-disk paging

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Motivation

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  - No more page can be allocated, so
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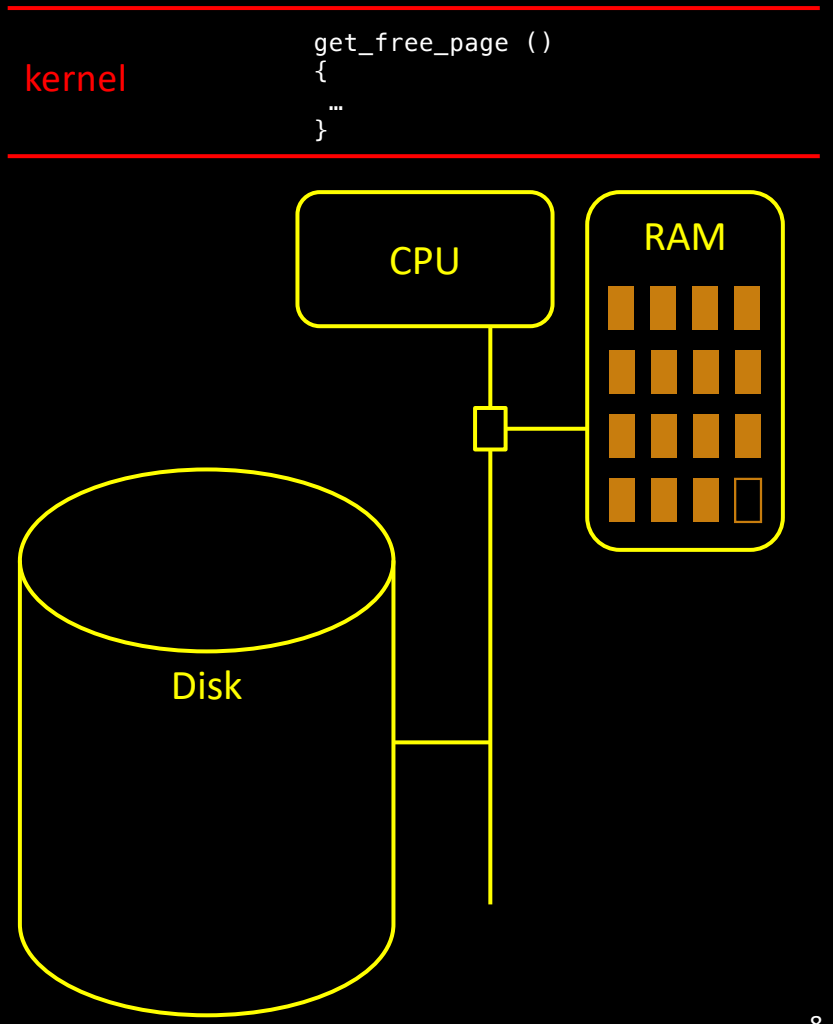
    - Process creation fails
    - Process growth fails
    - Lazy allocation fails
    - Copy-on-Write fails
    - What a mess! 😱
- Disks have a larger capacity
  - We could use disk space as a RAM extension

Motivation

- When the RAM is full, we could satisfy upcoming allocations on disk



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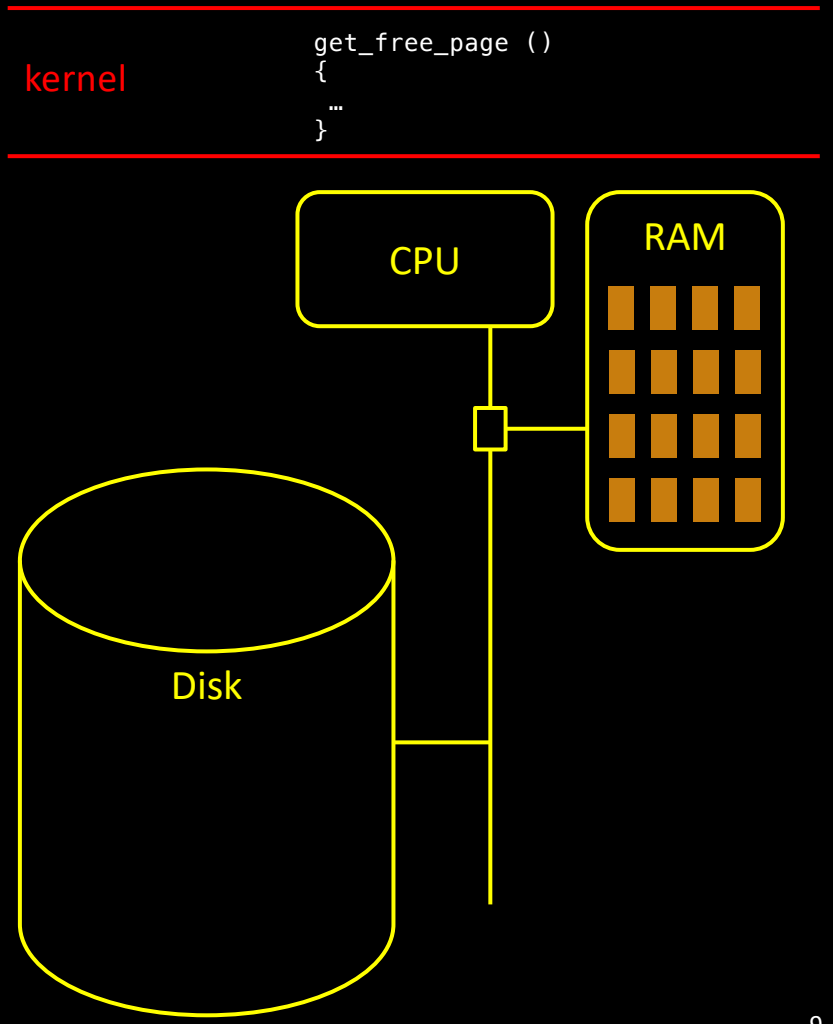

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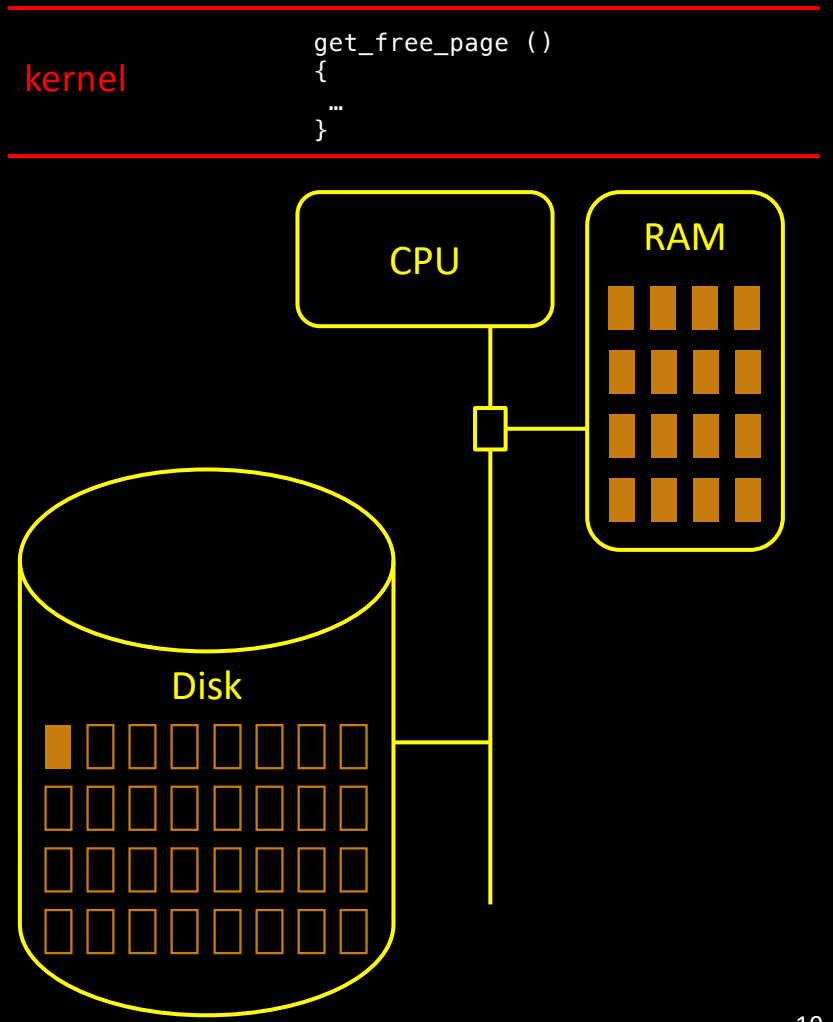

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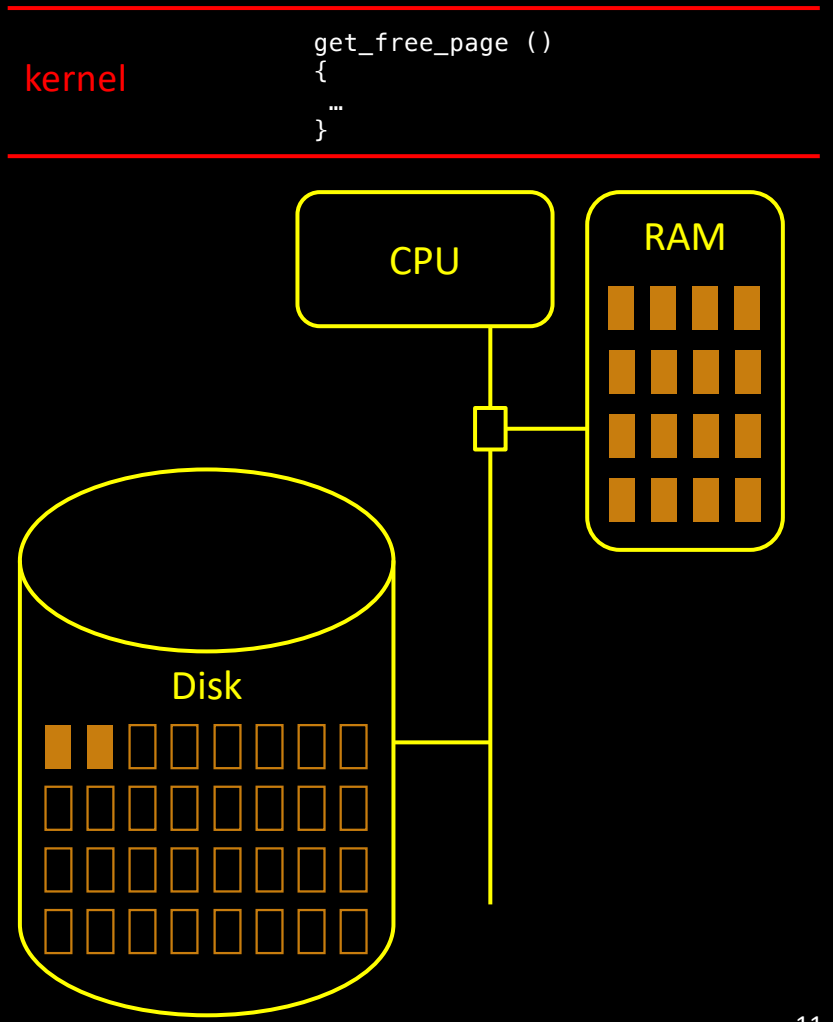
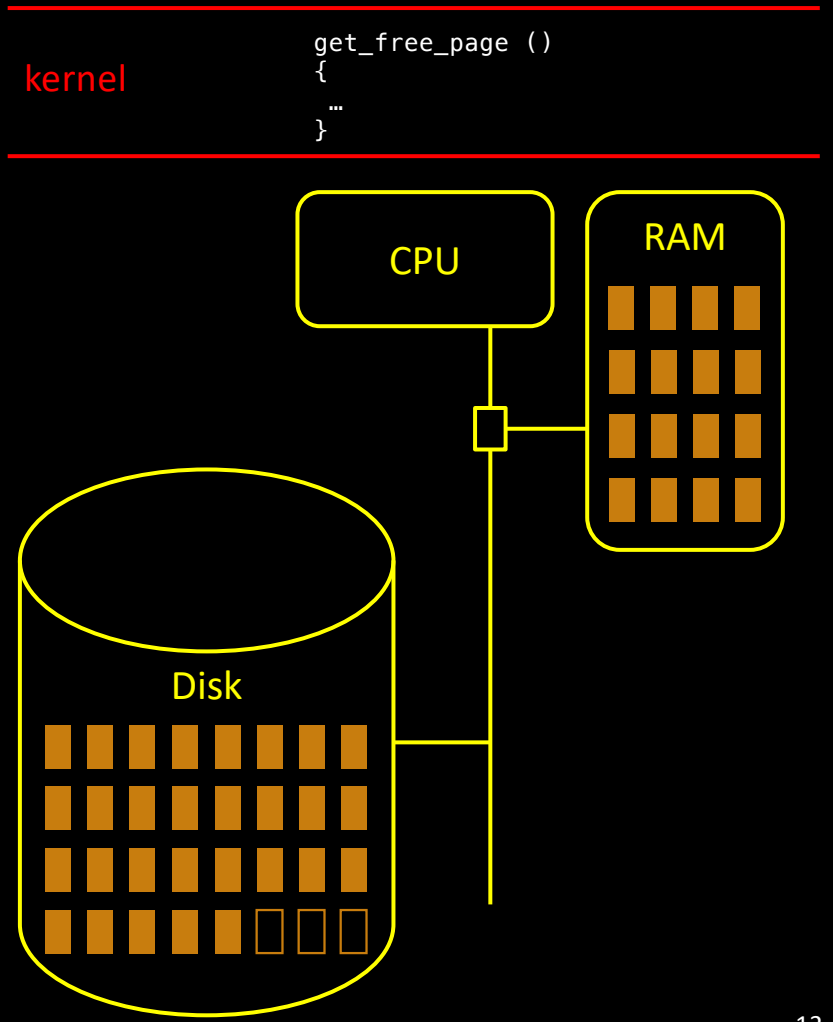


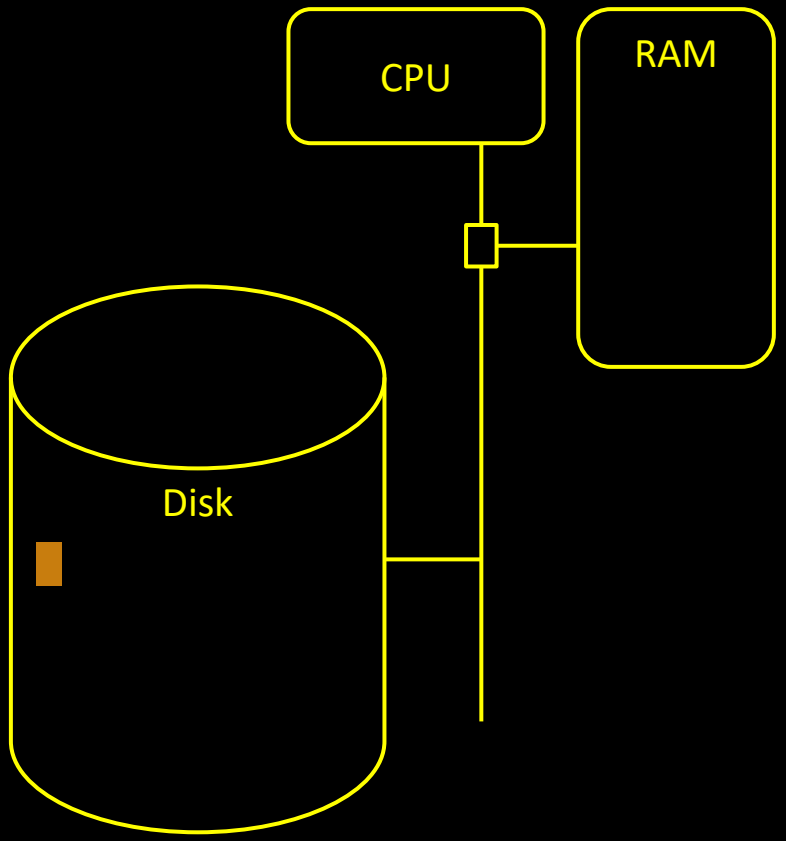
Motivation

- When the RAM is full, we could satisfy upcoming allocations on disk
  - Is it possible for a CPU to access disk storage transparently?
  - Could we choose a smarter RAM/disk distribution?



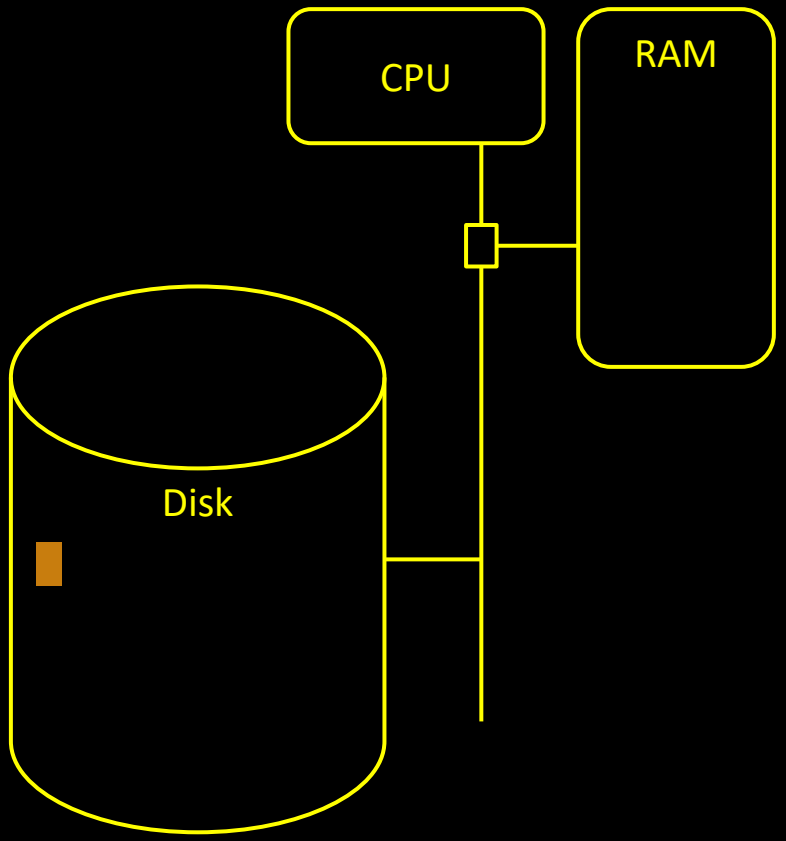
Technical considerations

- Is it possible for a CPU to access disk storage transparently?
  - Devices can be assigned a range of physical addresses on the I/O bus
    - With 39-bit physical addresses, we can not only address RAM, but also any other addressable device
    - A CPU read/write inside this range is redirected to the device
      - Typically used to access device configuration registers
    - This range can be mapped to a process address space
      - Eg. Dolphin “Scalable Coherent Interface” [1992]



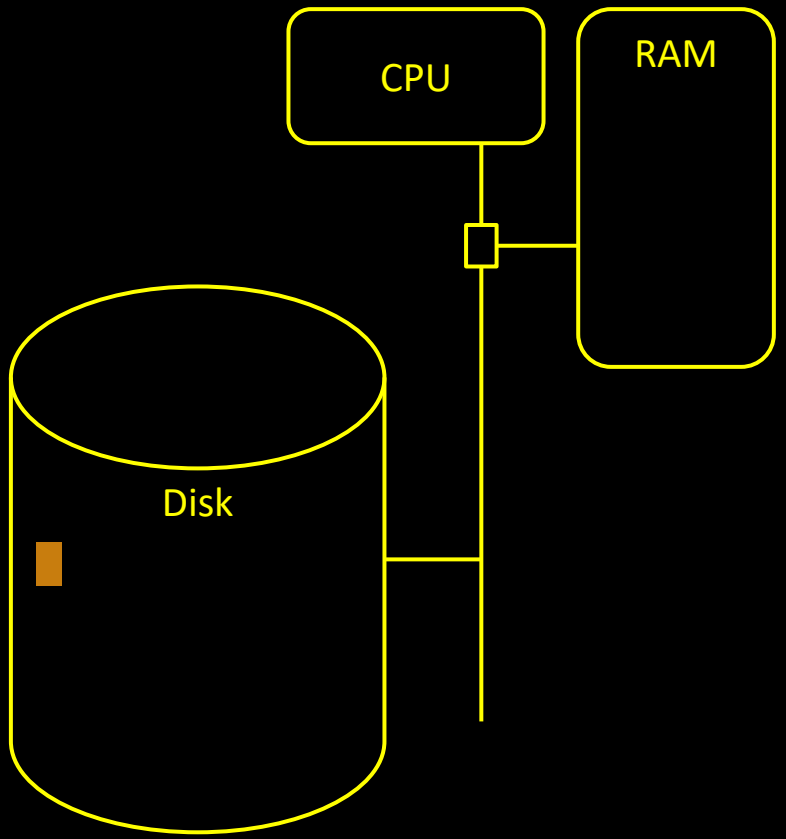
Technical considerations

- Is it possible for a CPU to access disk storage transparently?
  - Yes, in theory, this would be possible… however
    - This would involve sending PCI requests for each individual access
      - Coalescing is possible, but only for small bursts
      - Would lead to poor performance!
  - Disks (either hard drives or SSD) perform block-based transfers
    - E.g. 512B or 1K



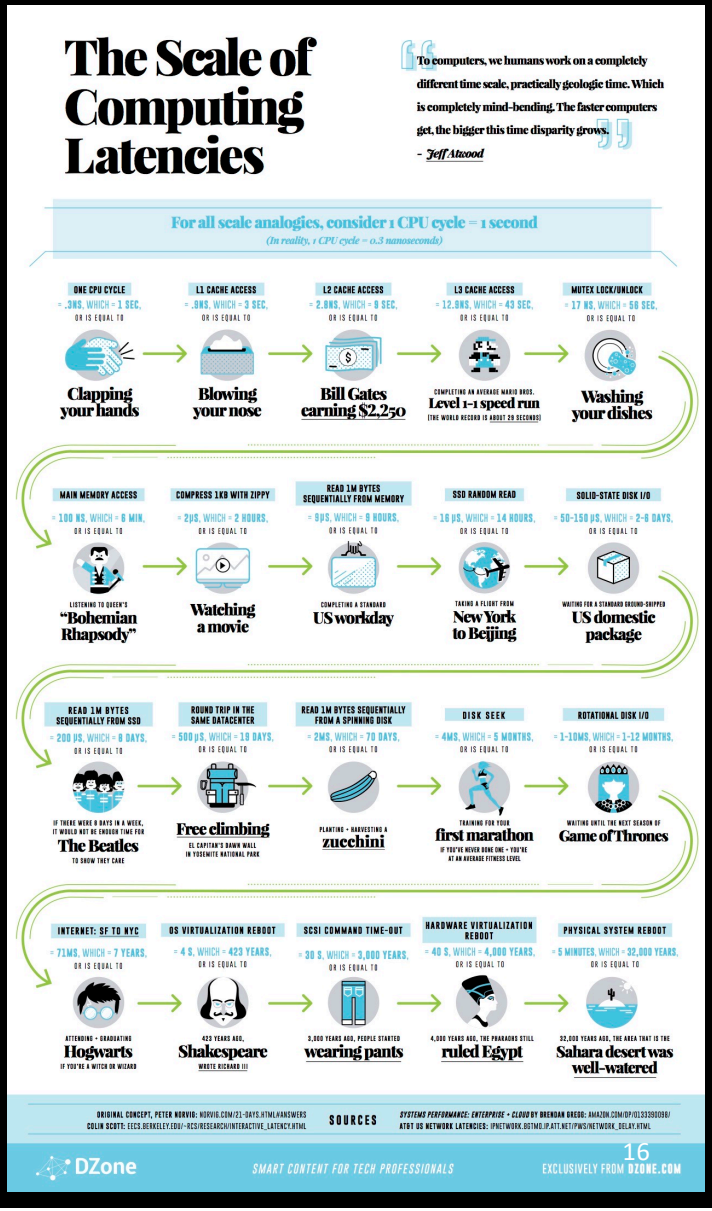
Technical considerations

- Is it possible for a CPU to access disk storage transparently?
  - Even if it was possible
    - Latency would kill us!
      - Accessing a word on a disk is *significantly* slower than accessing a variable in RAM
        - How much slower?



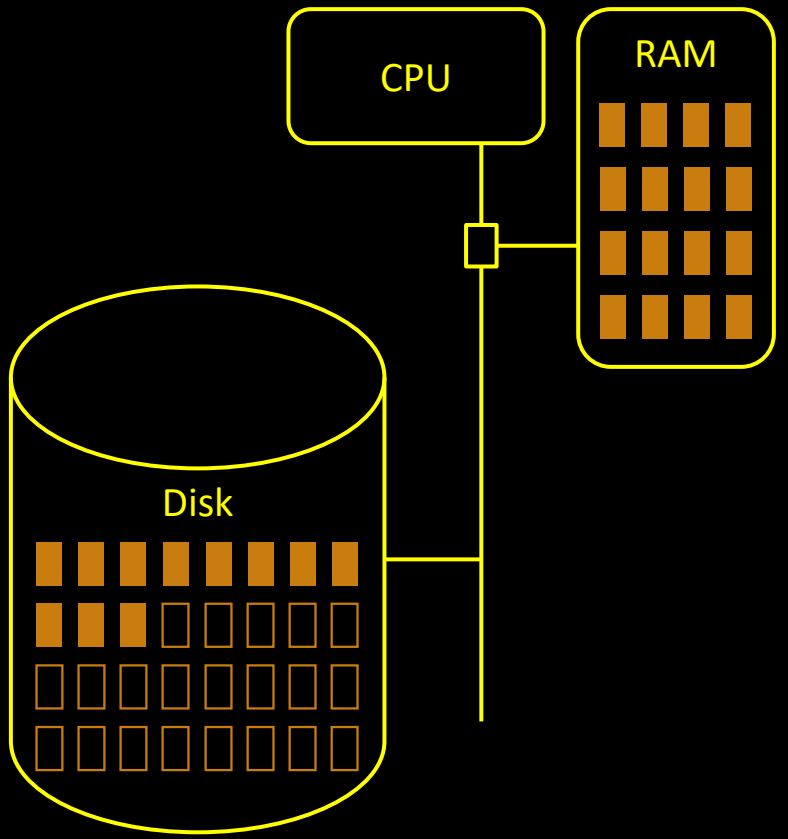
Scale of Computer Latencies

- CPU cycle: 0.3 ns (Core i7 3 GHz)
- L1 cache: 1 ns
- L2 cache: 5 ns
- L3 cache: 20 ns
- RAM: 50 ns
- NVMe SSD: 20 µs
- Sata SSD: 150 µs
- Hard Drive: 3 ms



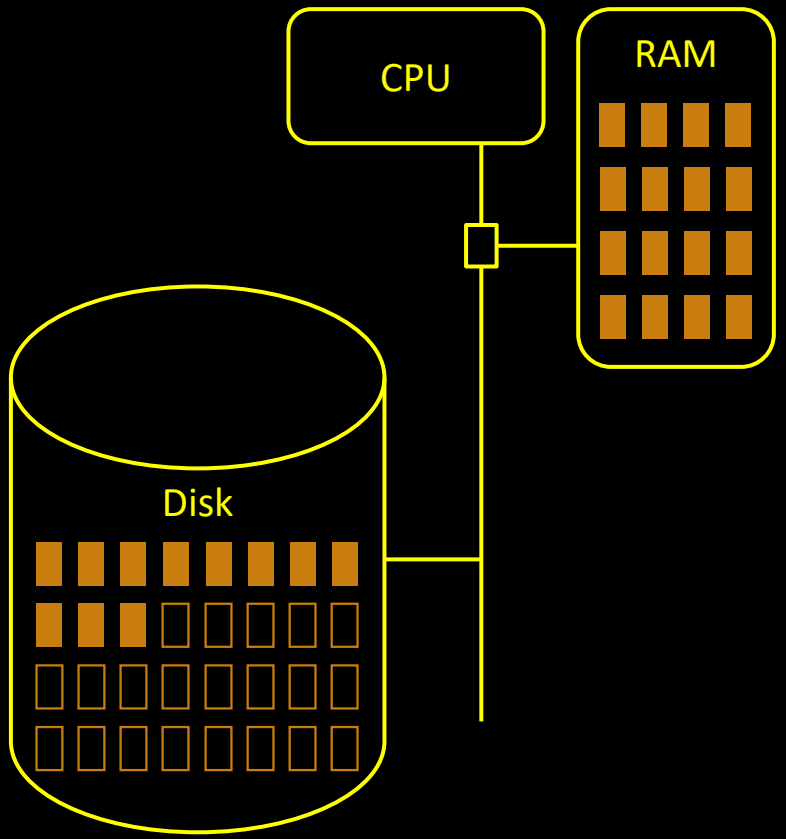
On-disk paging

- As a result, pages stored on disk will become…
  "temporarily unreachable"
  - What does this mean?
    - *Swapped-out* pages must be marked "invalid" in their owner's page table



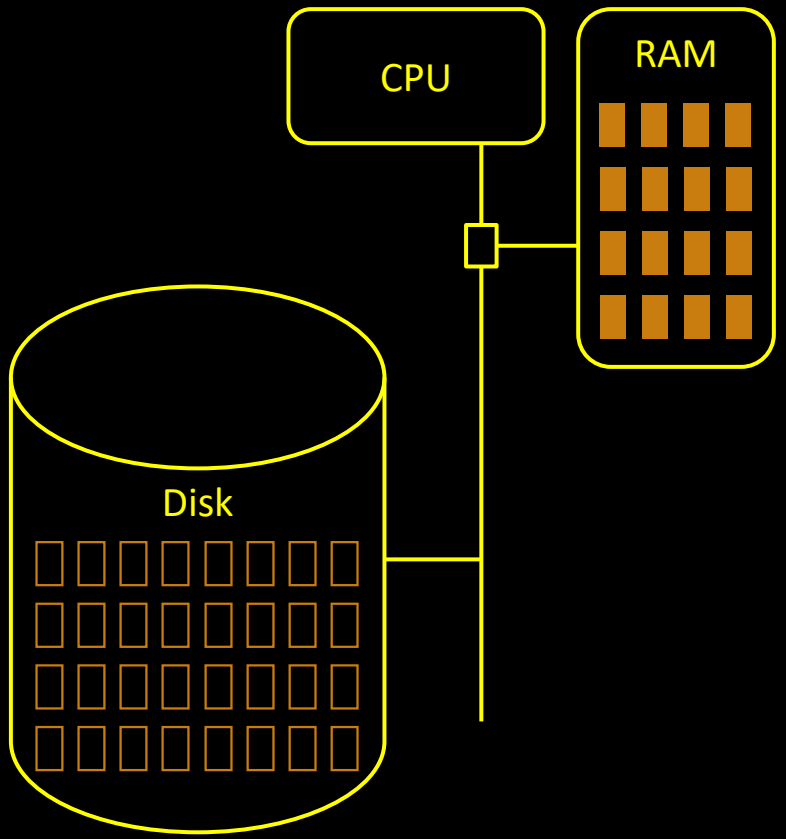
On-disk paging

- As a result, pages stored on disk will become…
  "temporarily unreachable"
  - What does this mean?
    - *Swapped-out* pages must be marked "invalid" in their owner's page table
    - A page fault corresponding to a swapped-out page must bring the page back to memory (swap-in)
      - What if the RAM is still full?
      - What if it happens too frequently?



On-disk paging

- Let's calm down and rewind…
  - When the RAM is full and `get_free_page()` is called
    - The new page is expected to be used… immediately
      - So it must be allocated in RAM



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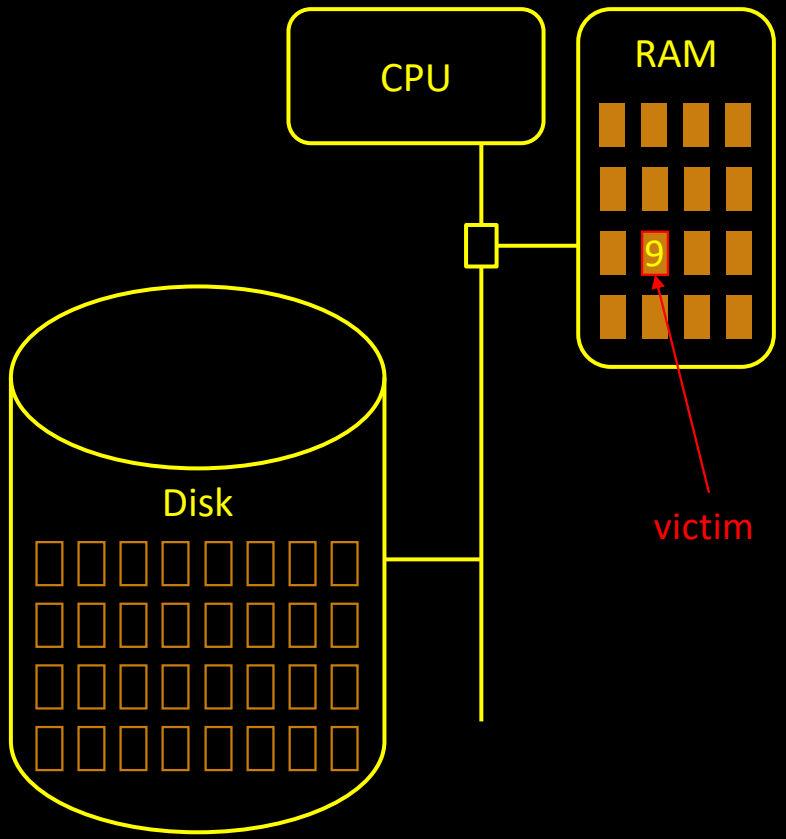

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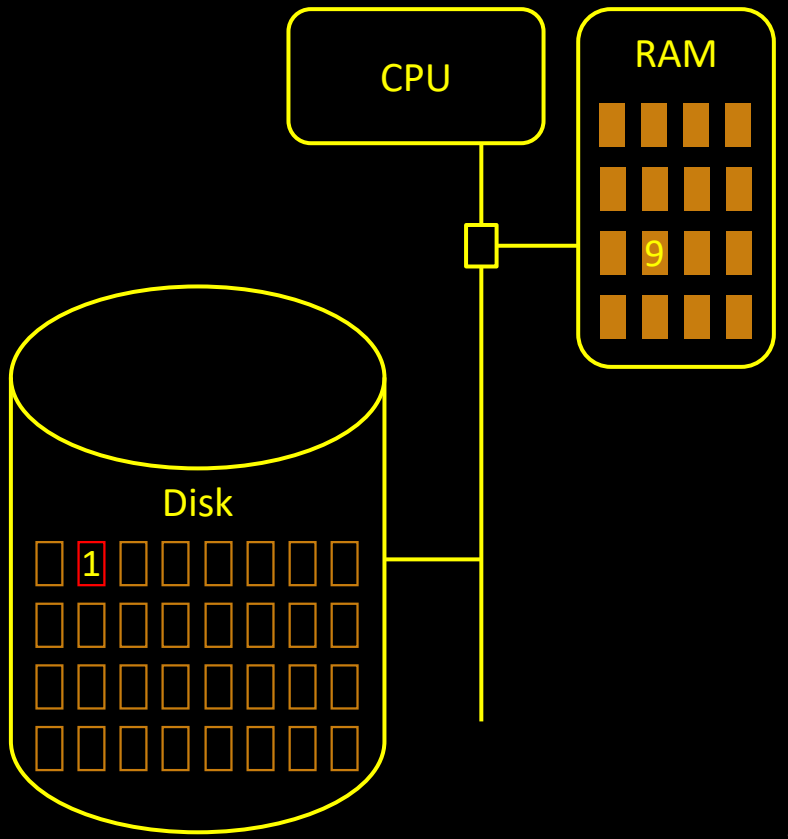

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      - Page is written to disk
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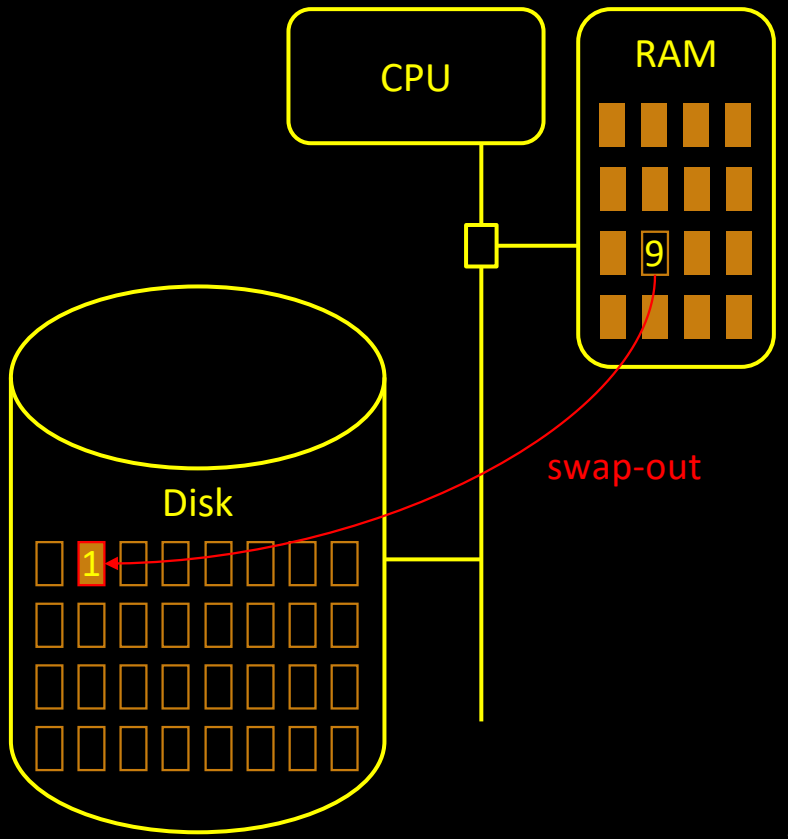

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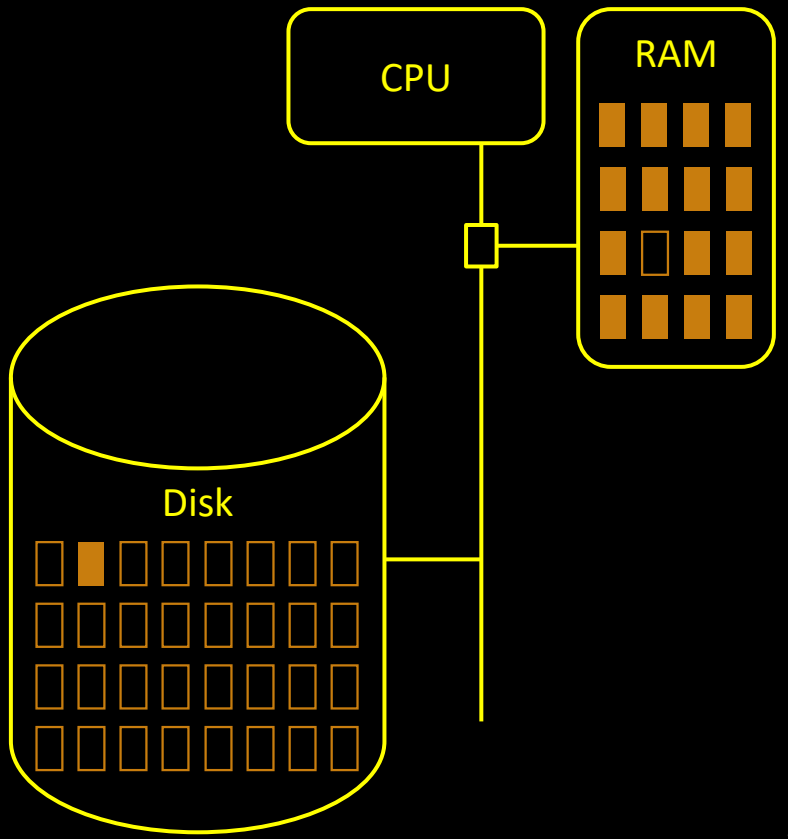
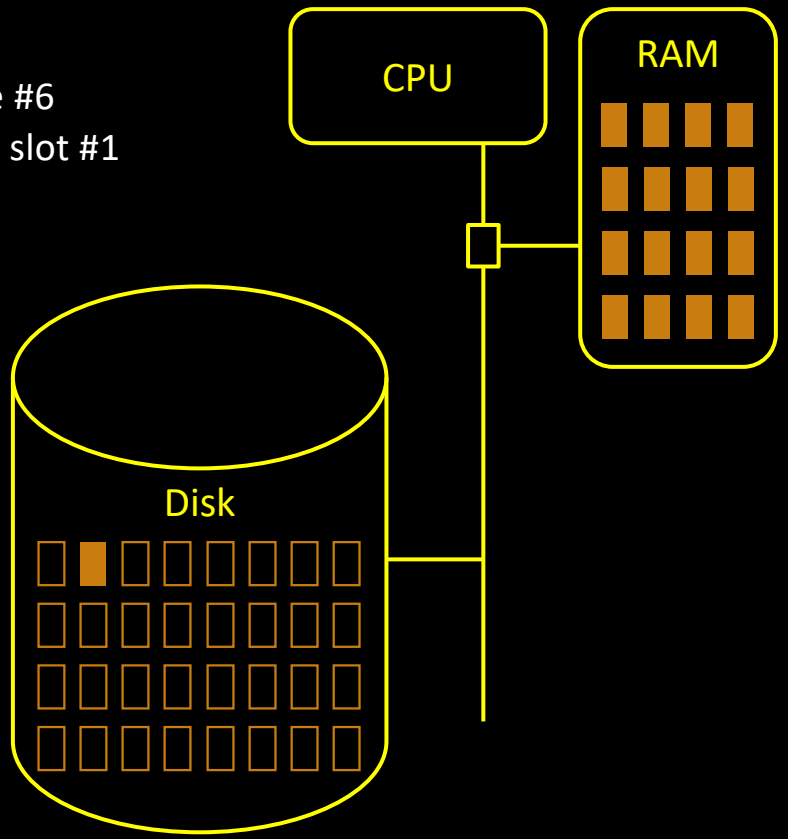


Handling swapped-out pages

	Phys. Page	Valid	R	W	X
0	2	1	1	0	1
1	4	1	1	0	1
2	5	1	1	0	1
3		0			
4	0	1	1	1	0
5		0			
6	9	0			
7		0			
8		0			
9		0			
10		0			
11	11	1	1	1	0
12		0			
13		0			
14		0			

Let's assume virtual page #6
is swapped out and stored in slot #1



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1	4	1	1	0	1
2	5	1	1	0	1
3		0			
4	0	1	1	1	0
5		0			
6	???	0			
7		0			
8		0			
9		0			
10		0			
11	11	1	1	1	0
12		0			
13		0			
14		0			

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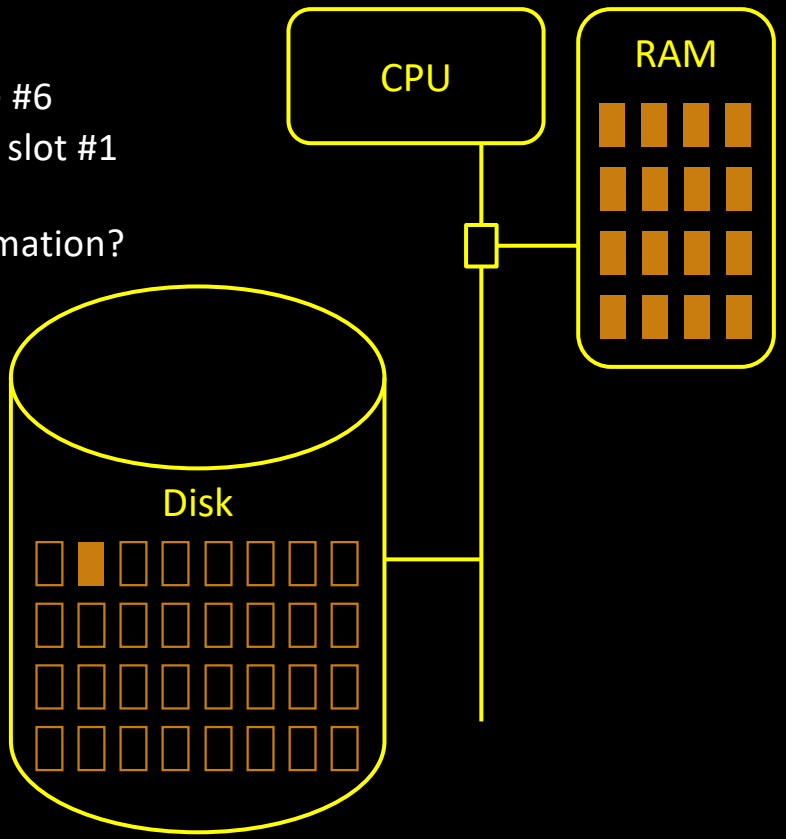
Where do we store this information?



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3		0			
4	0	1	1	1	0
5		0			
6	???	0			
7		0			
8		0			
9		0			
10		0			
11	11	1	1	1	0
12		0			
13		0			
14		0			

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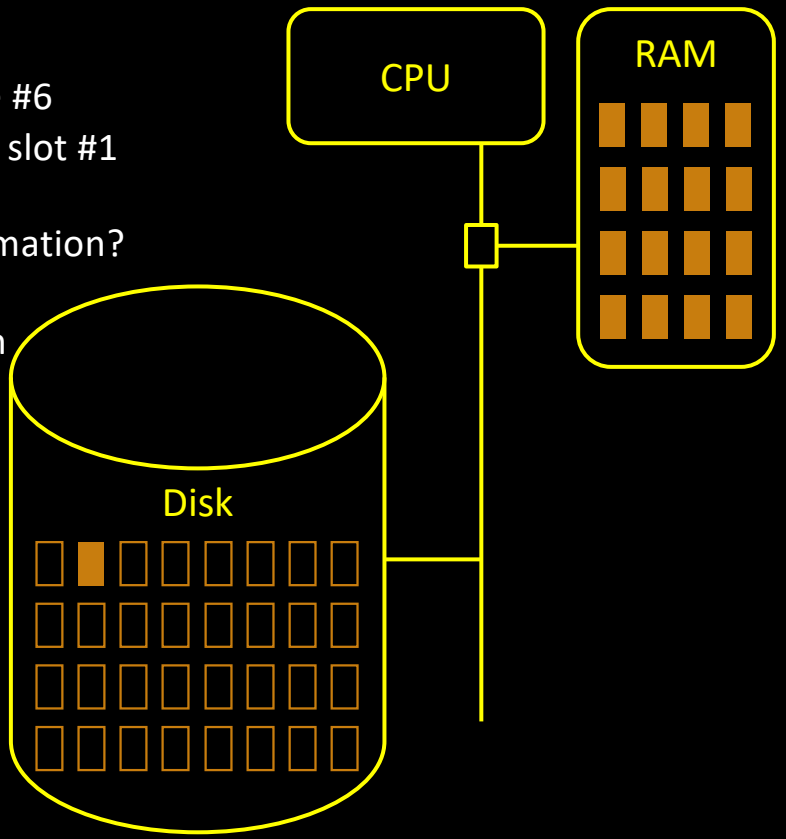
Where do we store this information?

How do we distinguish
swapped-out pages
and
lazily allocated
pages?



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1	4	1	1	0	1
2	5	1	1	0	1
3		0			
4	0	1	1	1	0
5		0			
6	1	0			
7		0			
8		0			
9		0			
10		0			
11	11	1	1	1	0
12		0			
13		0			
14		0			

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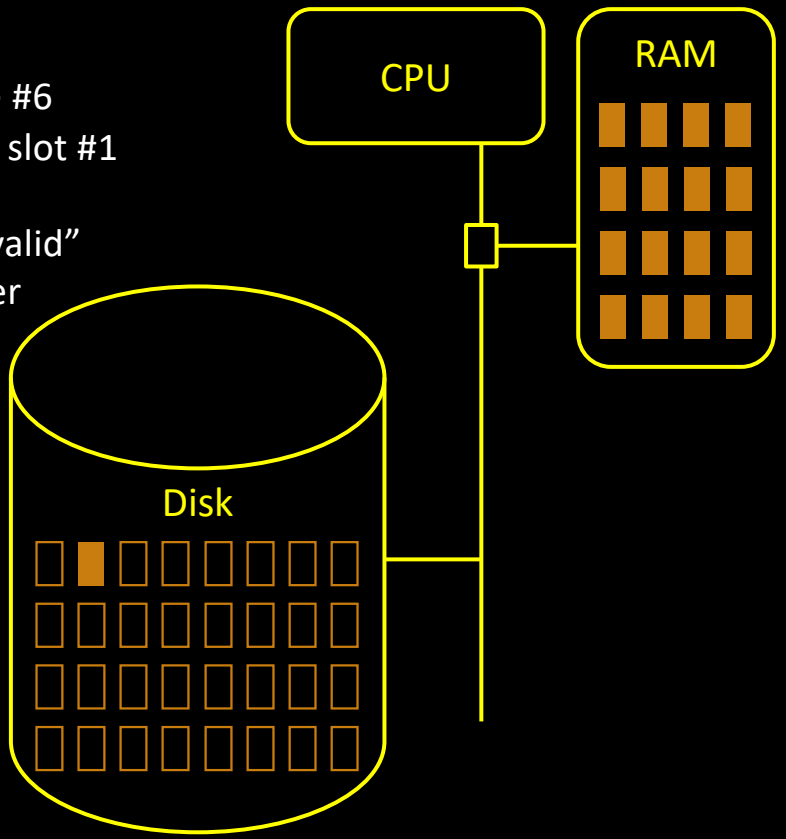
We can use all fields but "valid"
to store the slot number



Handling swapped-out pages

	Phys. Page	Valid	R	W	X
0	2	1	1	0	1
1	4	1	1	0	1
2	5	1	1	0	1
3		0			
4	0	1	1	1	0
5		0			
6	index	0			
7		0			
8		0			
9		0			
10		0			
11	11	1	1	1	0
12		0			
13		0			
14		0			

Let's assume virtual page #6
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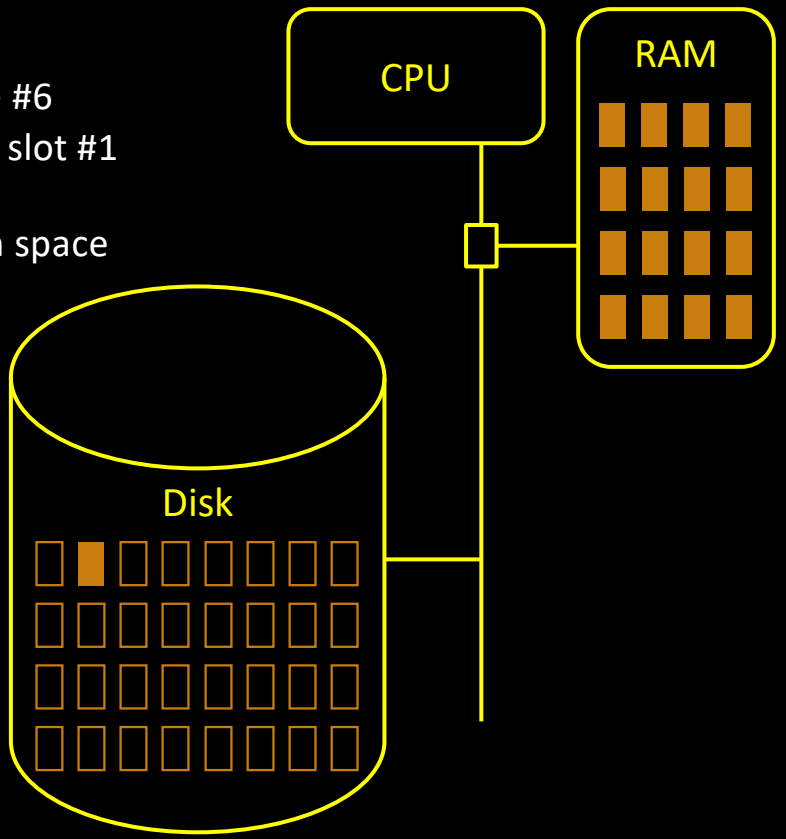
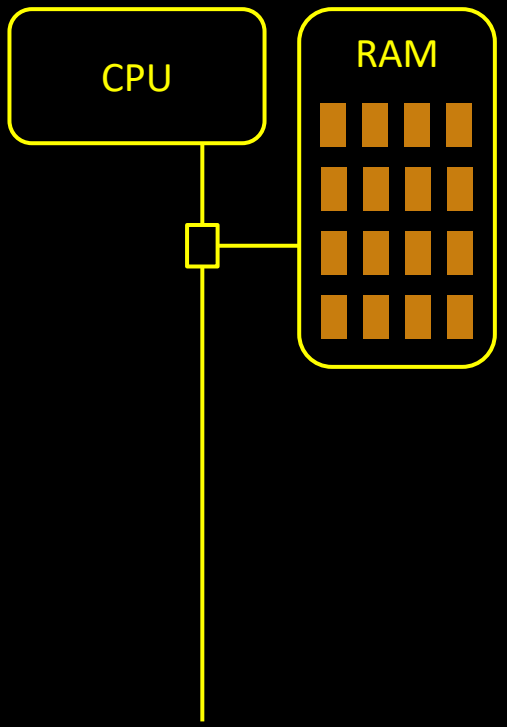
Actually, there is not enough space
to store
<dev, block>

So an index in a
"swap_info" array
is stored



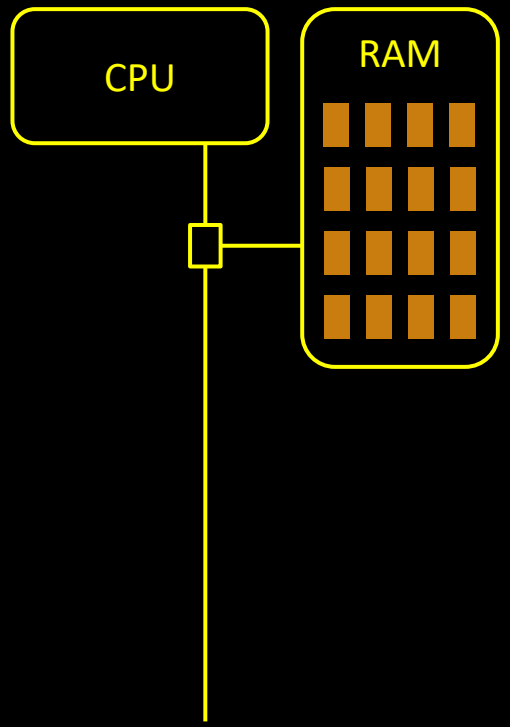
Finding a good victim

- We should choose a page
  - Which has a low probability to be requested again soon
    - Because we don’t have fun swapping pages in & out



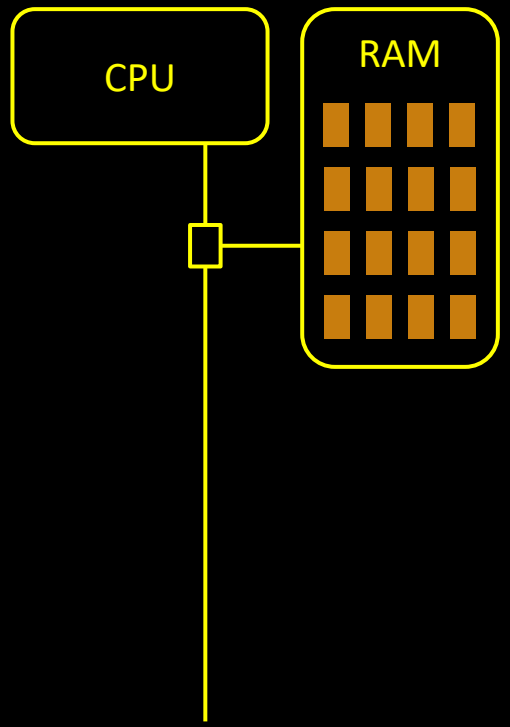
Finding a good victim

- We should choose a page
  - Which has a low probability to be requested again soon
    - Because we don't have fun swapping pages in & out
  - More precisely
    - The optimal algorithm should select the page whose next use will occur farthest in the future
  - Sounds good!
    - But in practice, we have no idea…



Page replacement algorithms

- Simple algorithms are often the best ones



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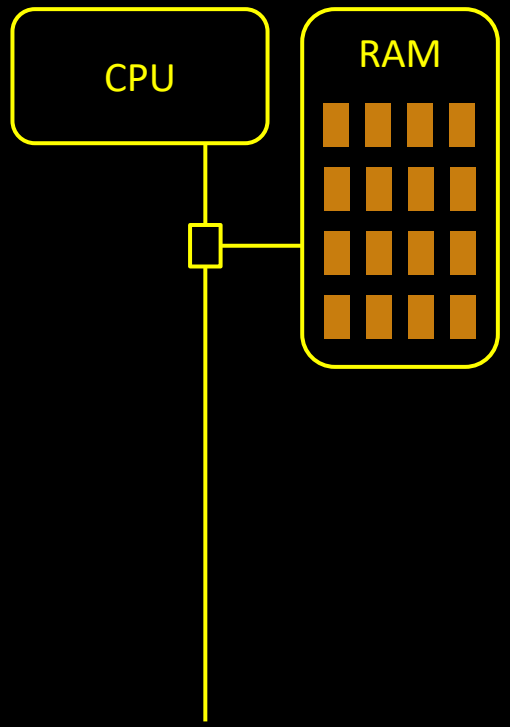
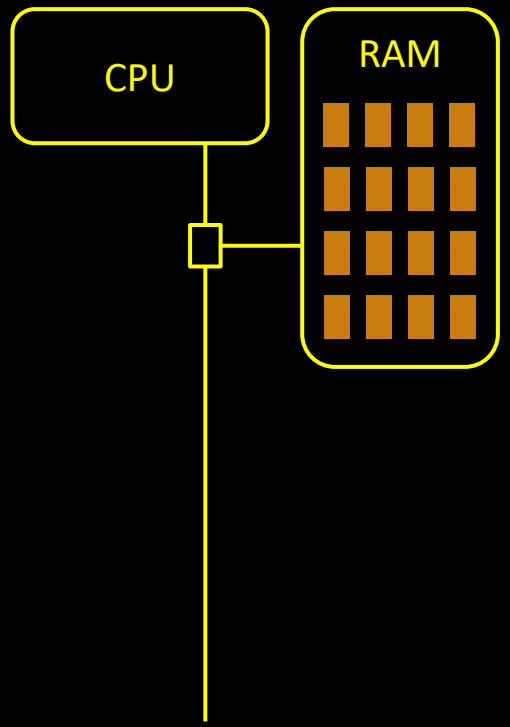
    - The OS keeps the date of ”arrival” of pages in RAM



Page replacement algorithms

- Simple algorithms are often the best ones
  - How about using FIFO?
    - The OS keeps the date of ”arrival” of pages in RAM
  - Unfortunately, the FIFO replacement strategy has a severe flaw
    - FIFO does not belong to the class of Stack-based 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”*



Belady's anomaly with FIFO

- Belady, *An anomaly in space-time characteristics of certain programs running in a paging machine*, Communications of the ACM, 1969.
- Let us consider the following series of page reclaims
  - 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- It can be shown that this reference list causes more page faults with a 4-frame RAM than with a 3-frame one…
  - The more RAM you have, the worser it behaves ☹

Belady's anomaly with FIFO

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

Belady’s anomaly with FIFO

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

Belady's anomaly with FIFO

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

Belady's anomaly with FIFO

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

Belady's anomaly with FIFO

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

Belady's anomaly with FIFO

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

Belady's anomaly with FIFO

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

Belady's anomaly with FIFO

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

Belady's anomaly with FIFO

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

Belady's anomaly with FIFO

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

Belady's anomaly with FIFO

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

Belady's anomaly with FIFO

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

Belady's anomaly with FIFO

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

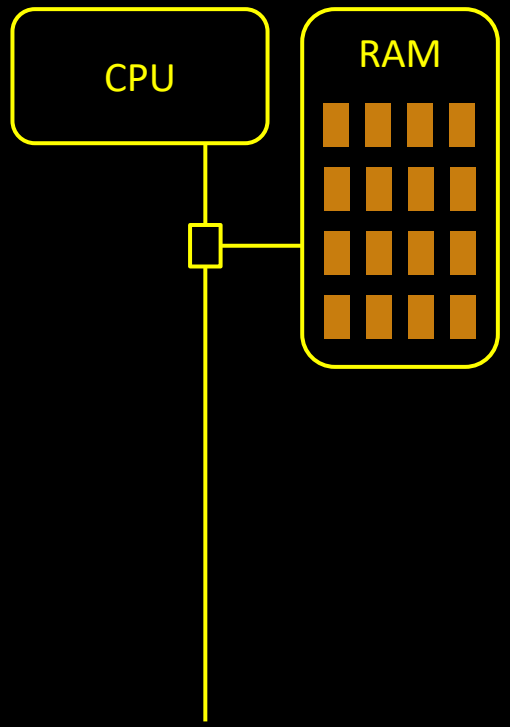
Belady's anomaly with FIFO

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

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

Page replacement algorithms

- So we'd better stick to stack-based algorithms such as
  - LFU (Least Frequently Used)
  - LRU (Least Recently Used)
- How to count the number of accesses to each page?
  - Do we really want to use NFU?
- How to store the last access time of each page?



Page replacement algorithms

- Only one hardware component can do it: the MMU
- When a virtual page is accessed, the MMU sets the corresponding accessed bit in the page table
  - It is up to the kernel to periodically test and reset this bit…

	Phys. Page	Valid	R	W	X	Accessed
0	2	1				0
1	4	1				0
2	5	1				0
3		0				
4	0	1				0
5		0				
6		0				
7		0				
8		0				
9		0				
10		0				
11	10	1				0
12		0				
13		0				
14		0				

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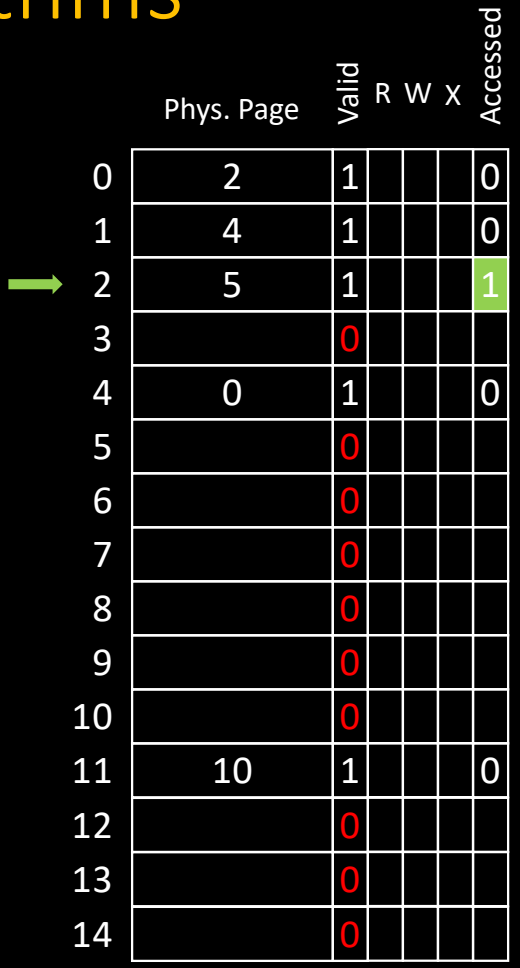
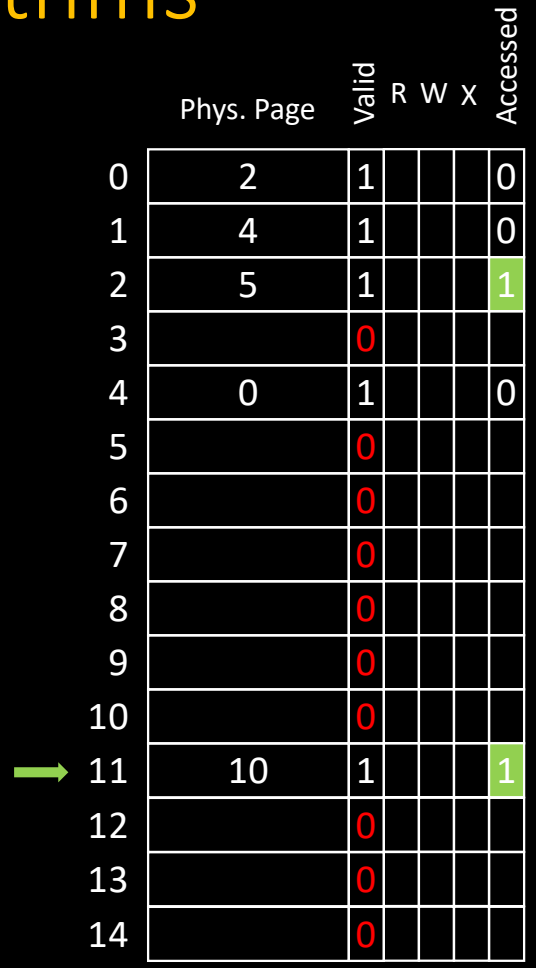


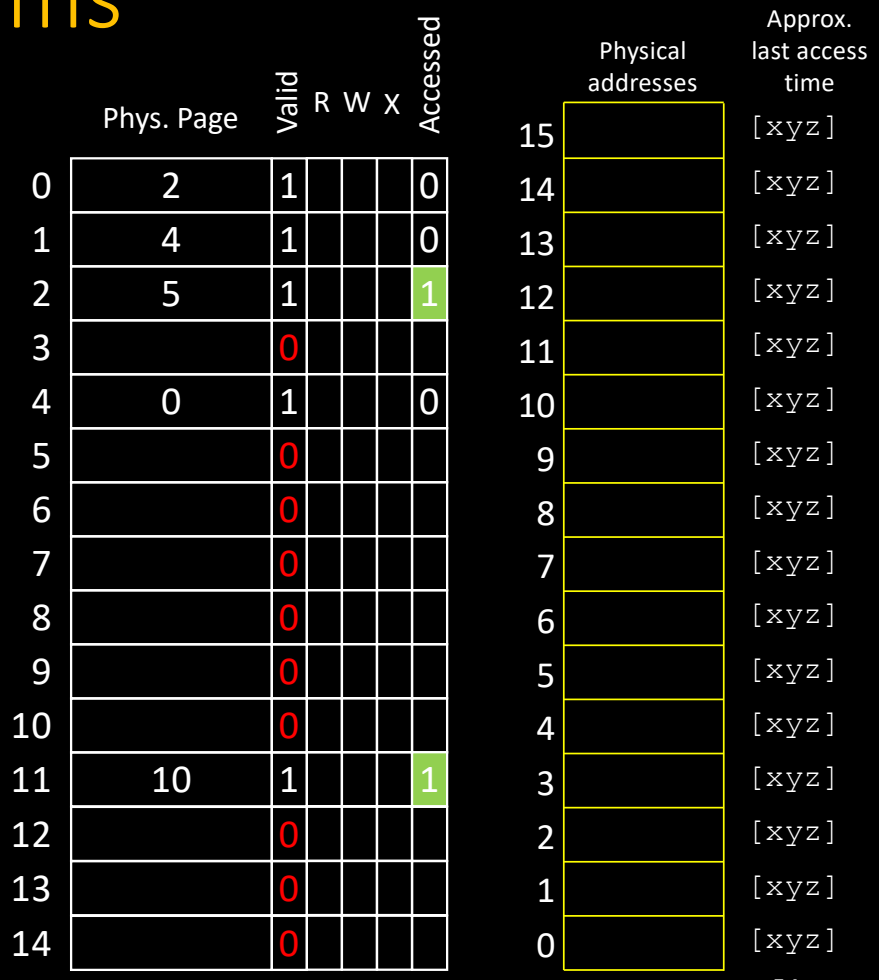
Page replacement algorithms

- Only one hardware component can do it: the MMU
- When a virtual page is accessed, the MMU sets the corresponding accessed bit in the page table
  - It is up to the kernel to periodically test and reset this bit…



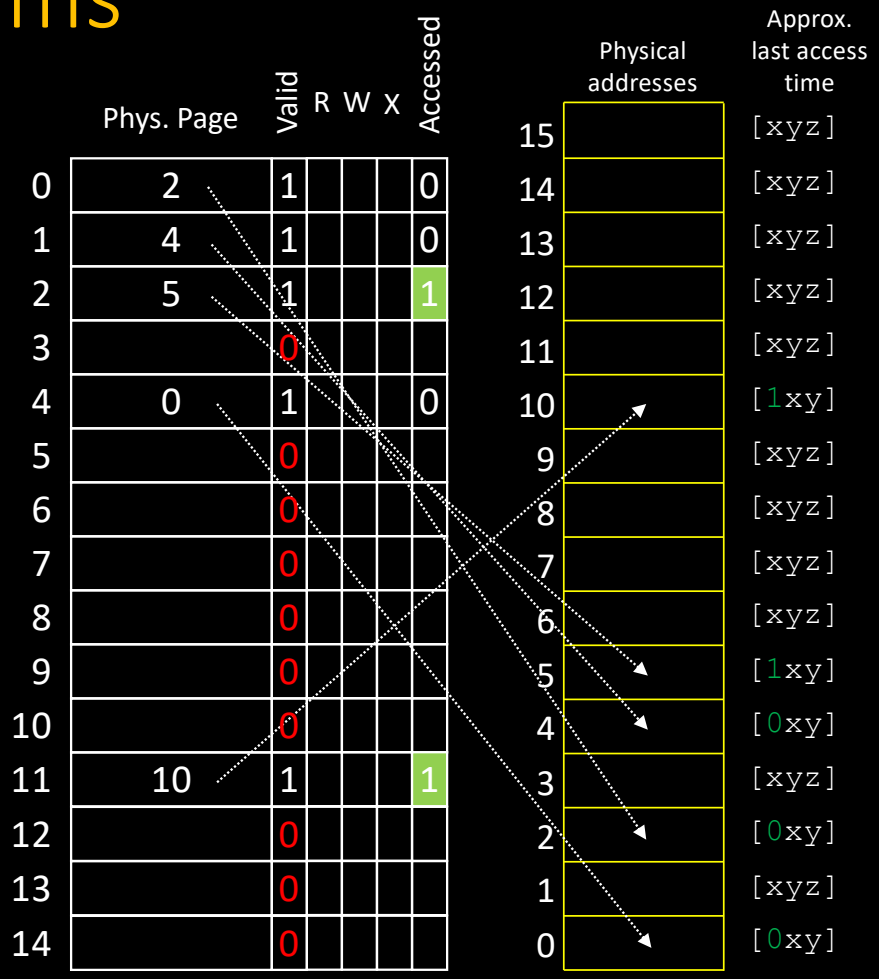
Page replacement algorithms

- Periodically, the kernel can walk through the page table and read (& reset) the accessed bit for each page
  - Sampling
    - Information = “was this page accessed during the last period”?



Page replacement algorithms

- Periodically, the kernel can walk through the page table and read (& reset) the accessed bit for each page
  - Sampling
    - Information = “was this page accessed during the last period”?
  - Aging
    - Kernel can maintain an approximation of last access time per physical page



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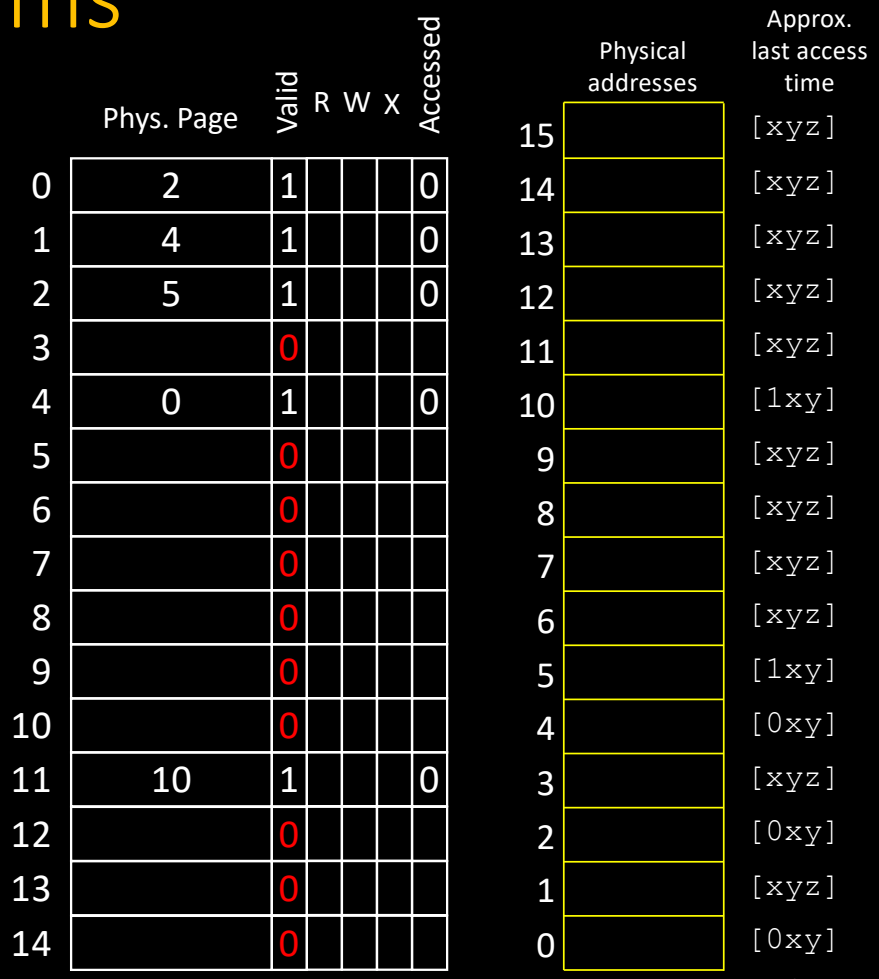

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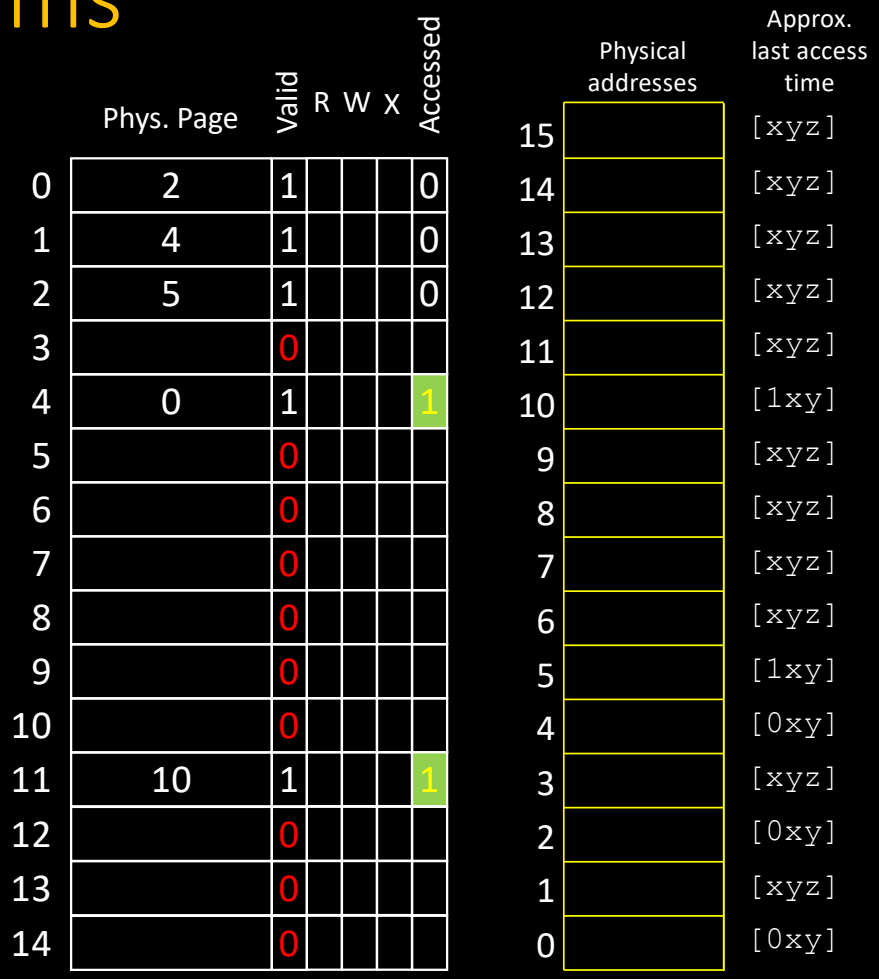

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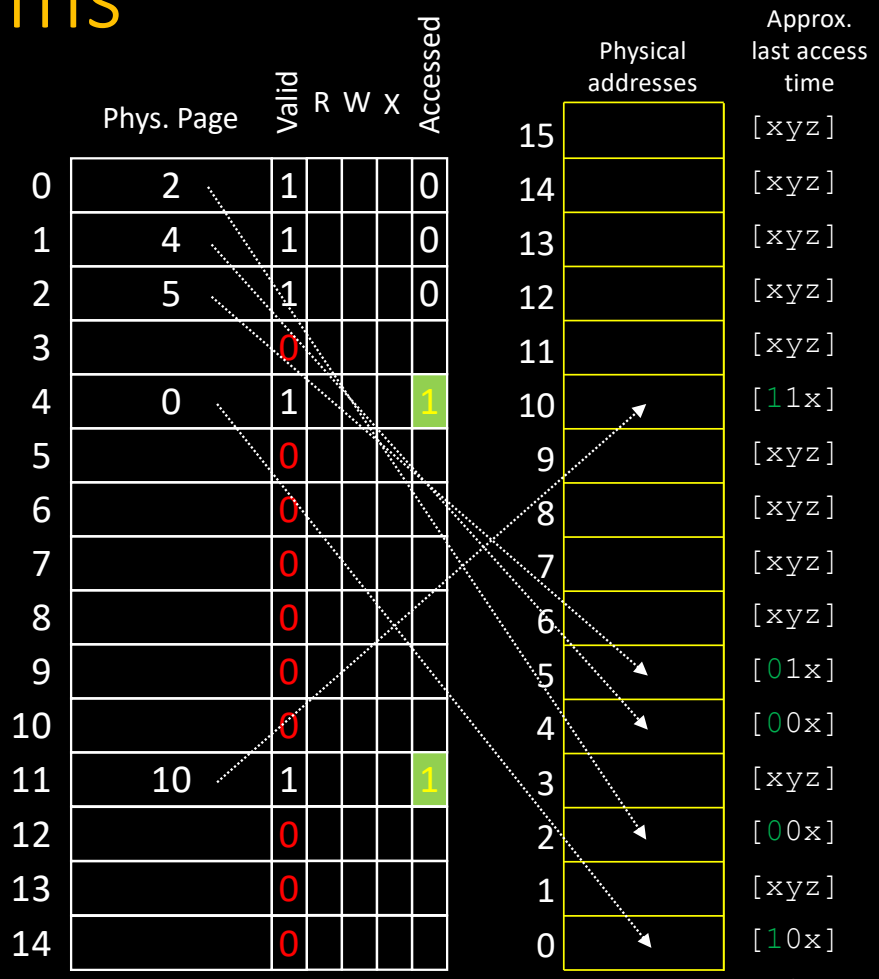
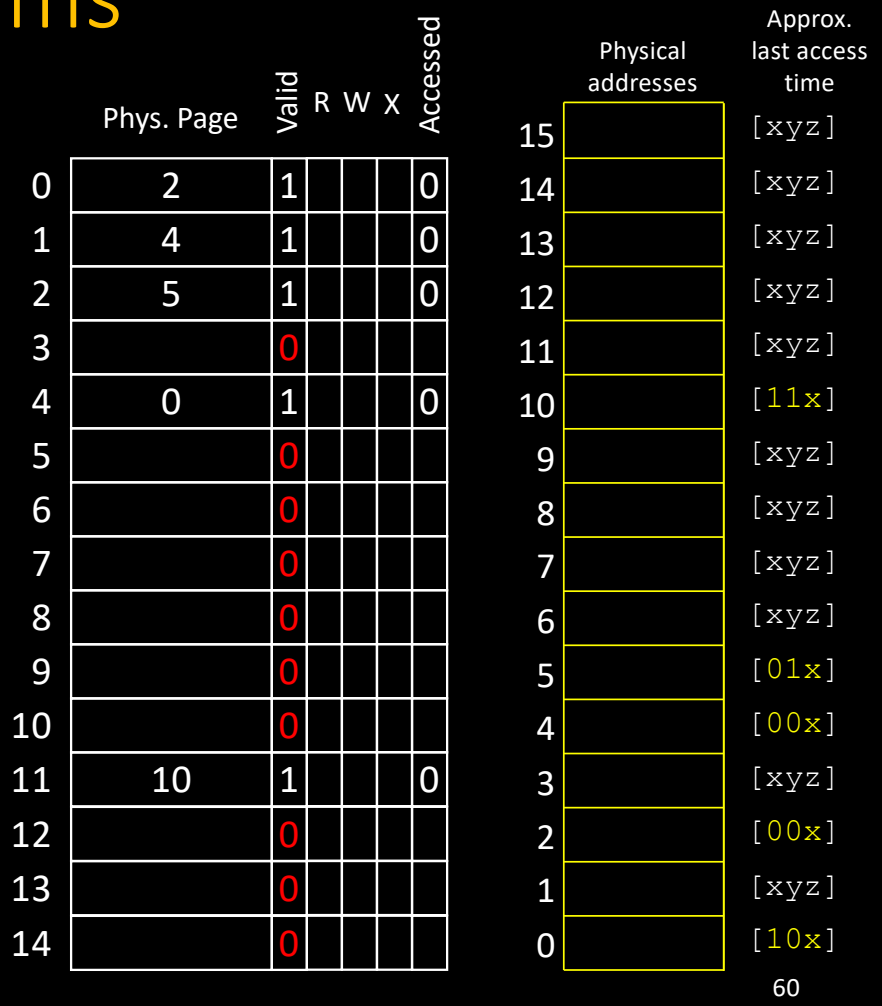


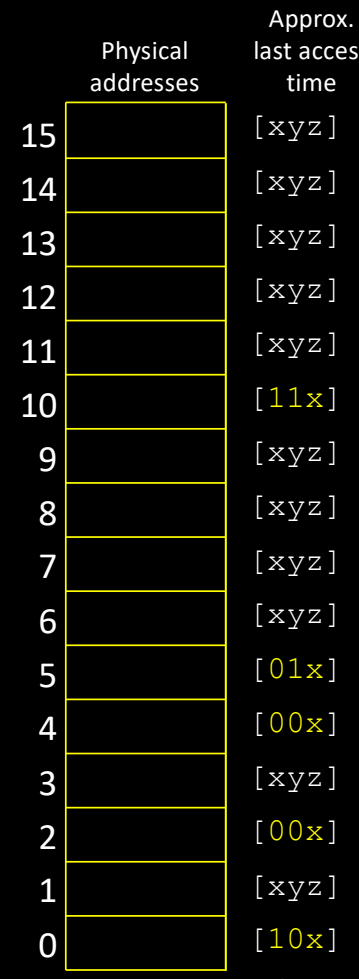
Page replacement algorithms

- Now we have an “approximate last access time” for each physical pages
  - Can be used to implement a pseudo-LRU policy
    - 11x is more ”important” than 10x, which is more important than 01x, etc.
    - E.g. Physical pages 2 and 4 (stamped “00x“) are a good candidates for being evicted from RAM



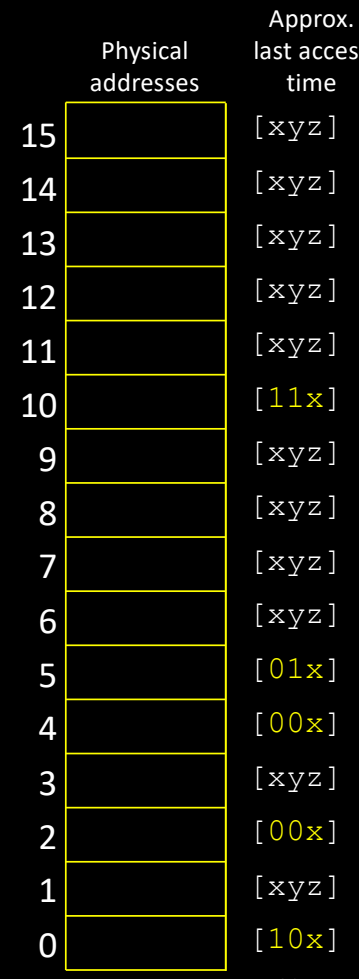
Page replacement algorithms

- Should our algorithm be local or global?
  - Local
    - Search victim among pages from current process
  - Global
    - Inspect all pages before deciding



Page replacement algorithms

- Should our algorithm be local or global?
  - Local
    - Search victim among pages from current process
    - Would tend to keep the number of resident pages constant



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- Should our algorithm be local or global?
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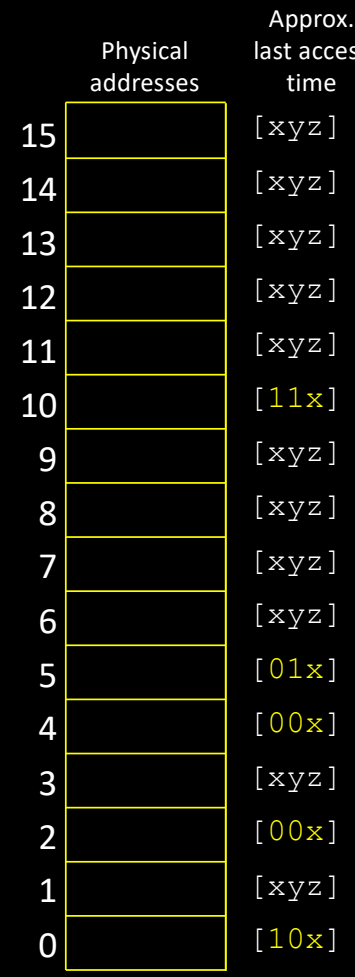
    - Inspect all pages before deciding
    - Treat all processes equally?
      - Or consider evicting pages from the biggest?



Page replacement algorithms

- Should our algorithm be local or global?
  - Global
    - Inspect all pages before deciding
    - Treat all processes equally?
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  - Take from the rich and give to the poor, uh?

Errol Flynn, The Adventures of Robin Hood, 1938.

Page replacement algorithms

- Not so obvious kids…
- Some process may have a lavish lifestyle
  - What we call "*Train de vie luxueux*" in France 🥖🍷💁‍♂️
- They have "just enough money" to be happy

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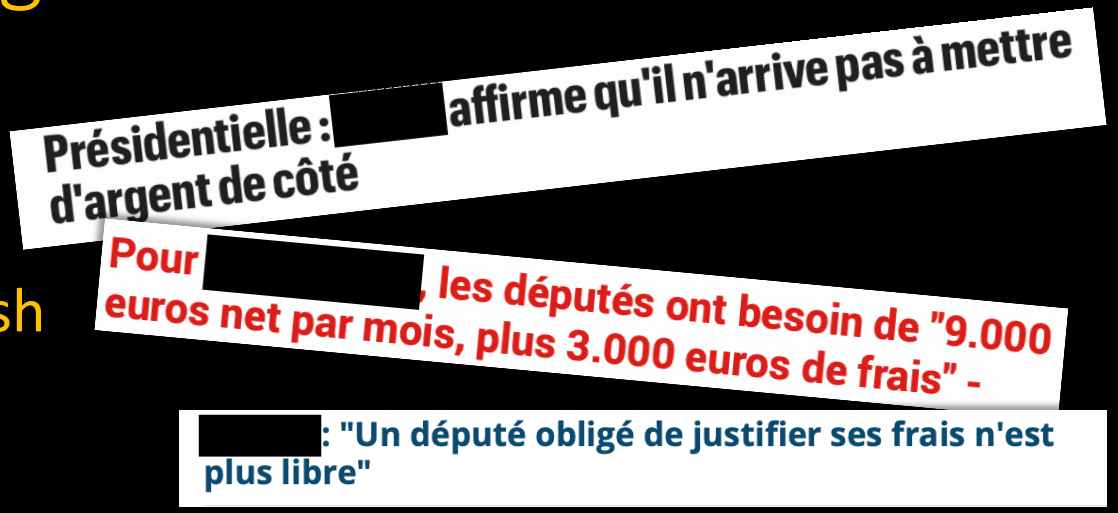

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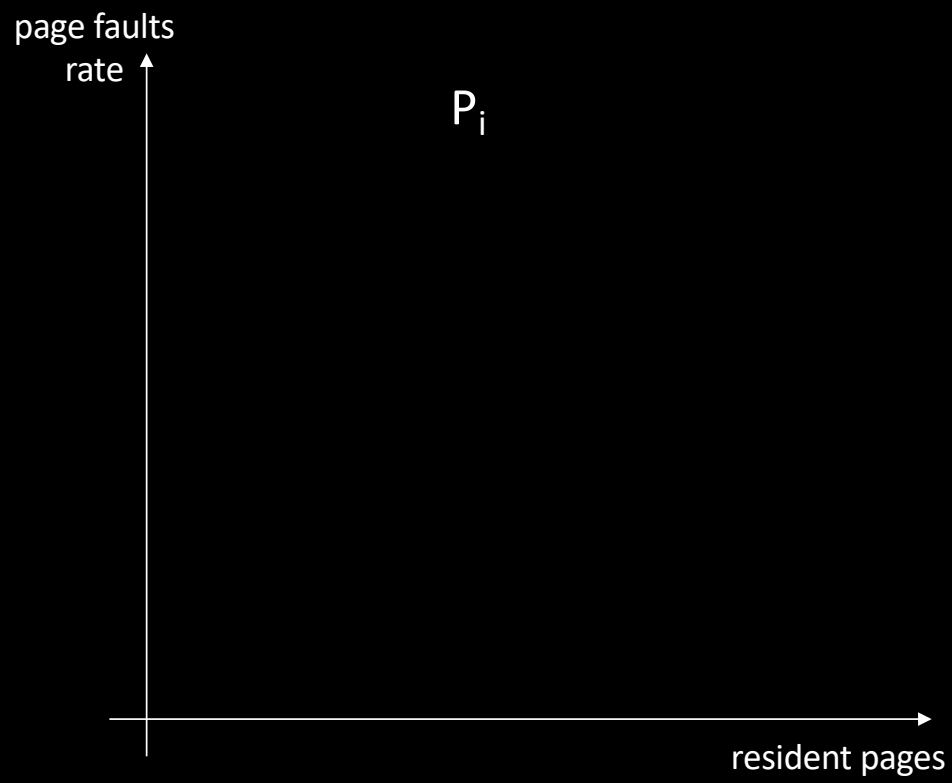
The notion of Working Set

- Can we determine the number of resident pages which will make a process happy?
  - The OS can track the number of page faults per second when
    - 1 resident page is granted
    - 2 resident pages are granted
    - 3 resident pages are granted
    - Etc.



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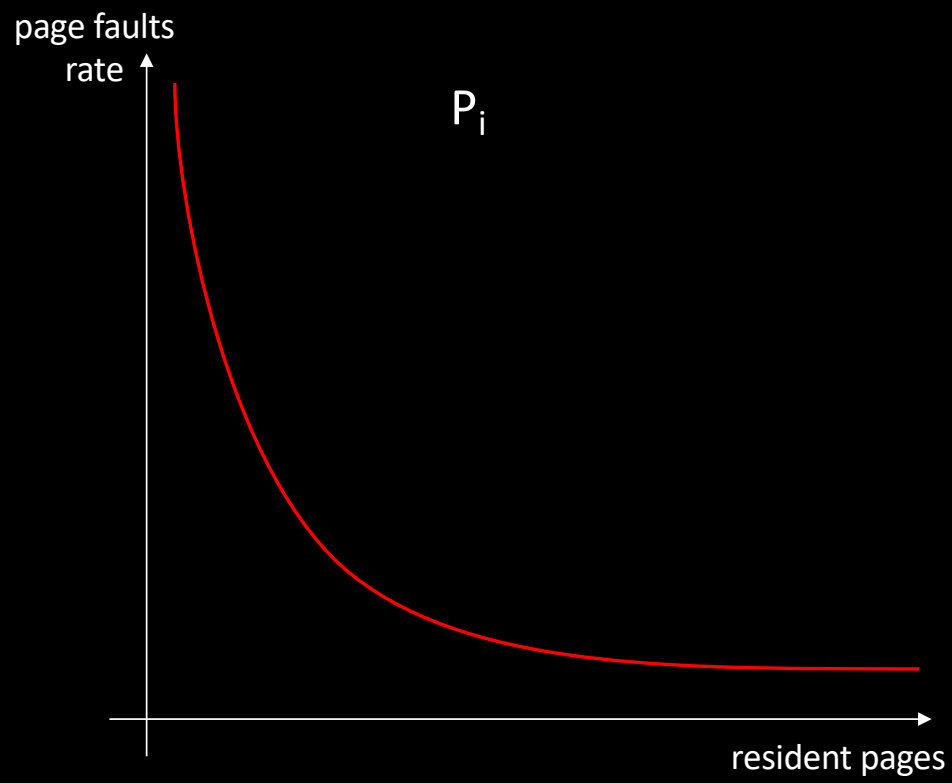

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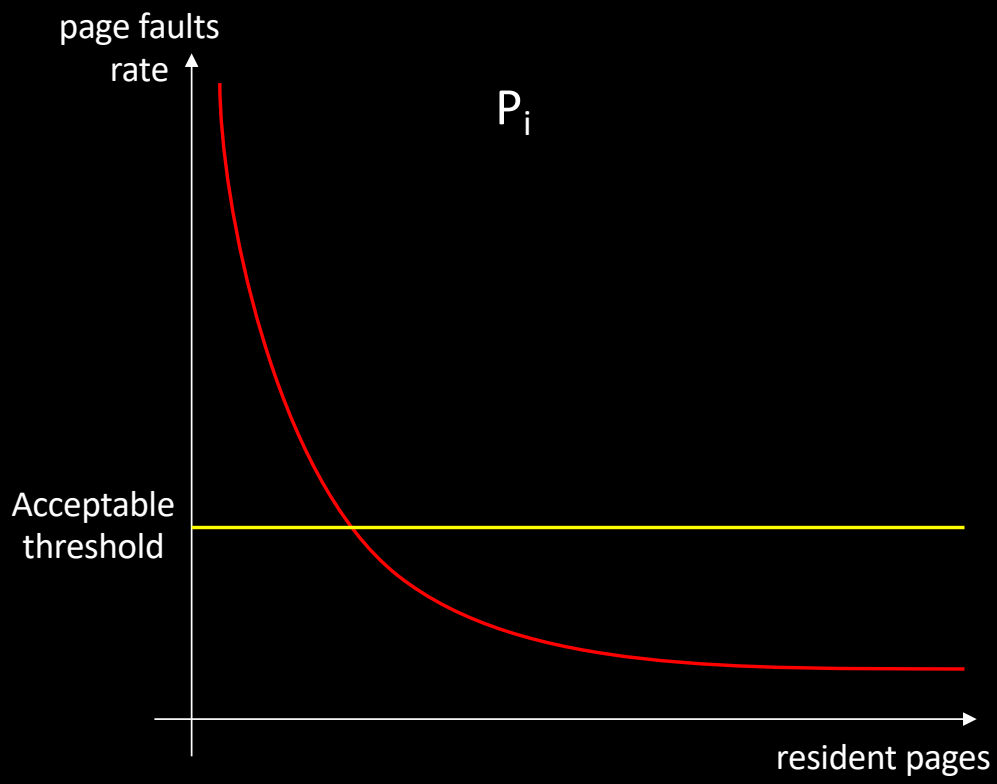
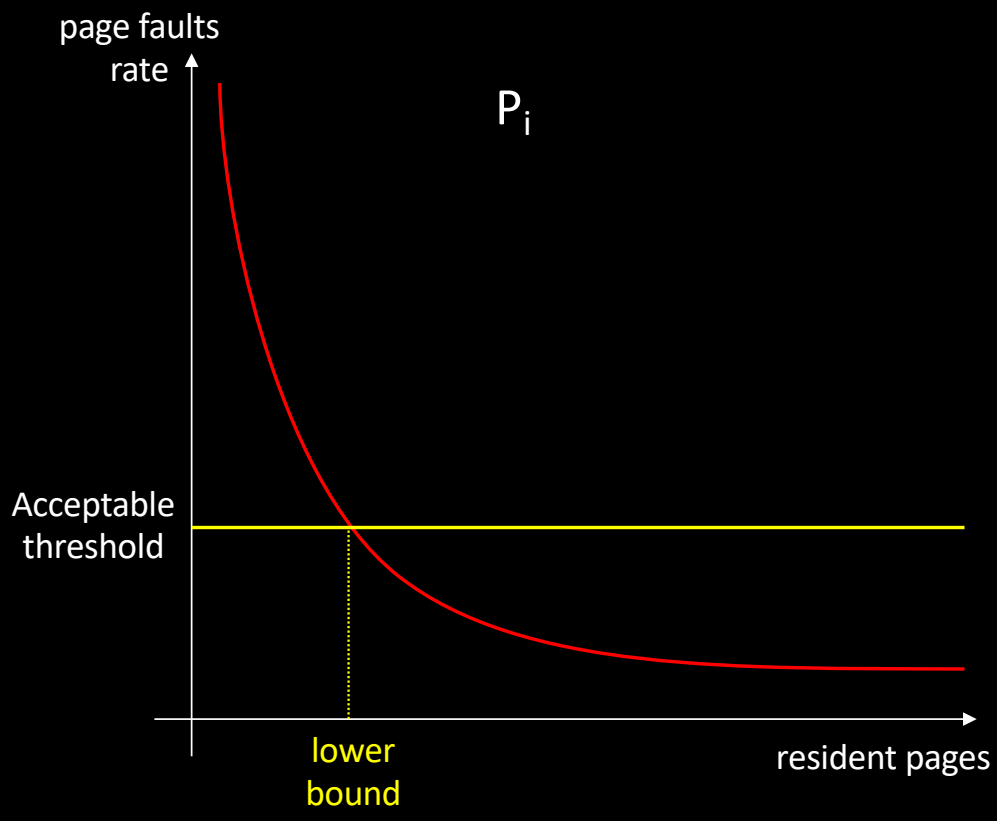


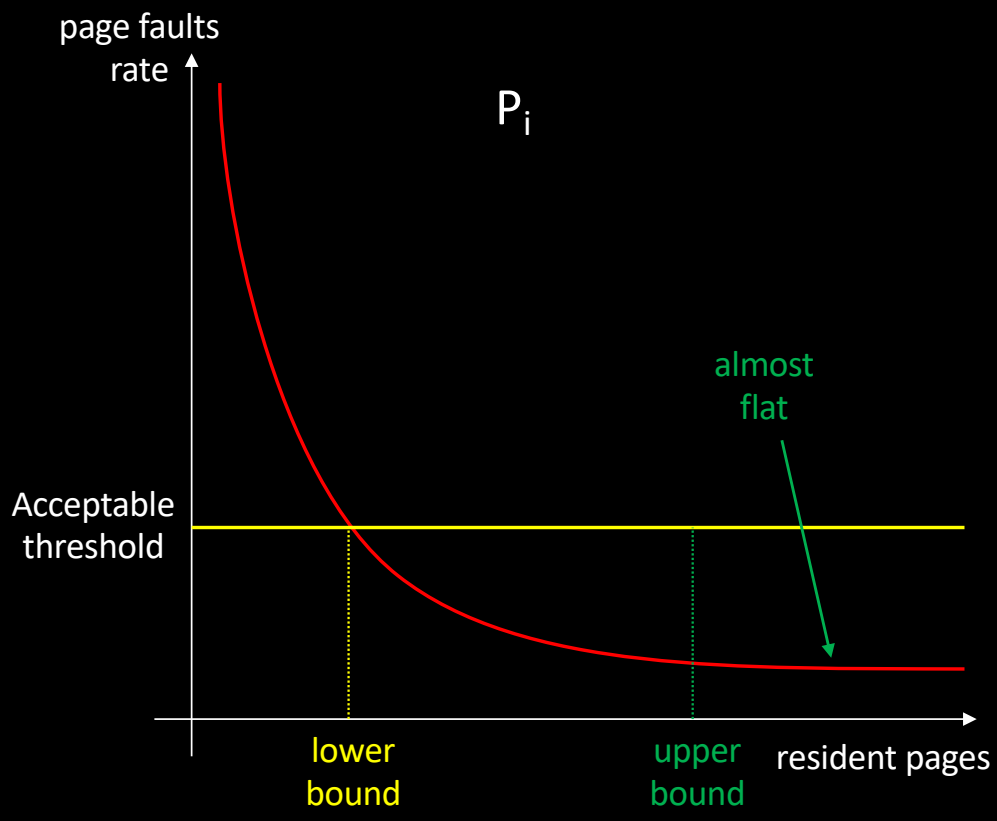
The notion of Working Set

- Can we determine the number of resident pages which will make a process happy?
  - Beyond an “acceptable threshold”, the page fault rate incurs a severe slowdown
    - This gives a lower bound on the number of pages which should stay in RAM for P_i



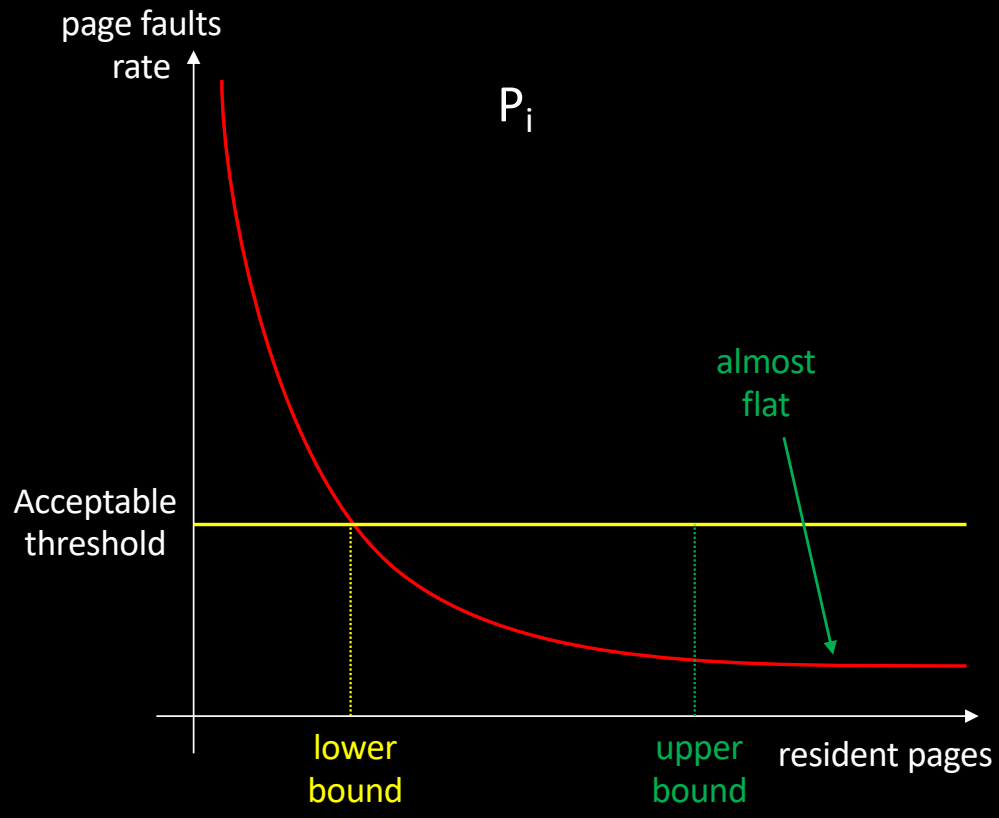
The notion of Working Set

- Can we determine the number of resident pages which will make a process happy?
  - Beyond an upper bound, the page fault rate doesn't decrease any more



The notion of Working Set

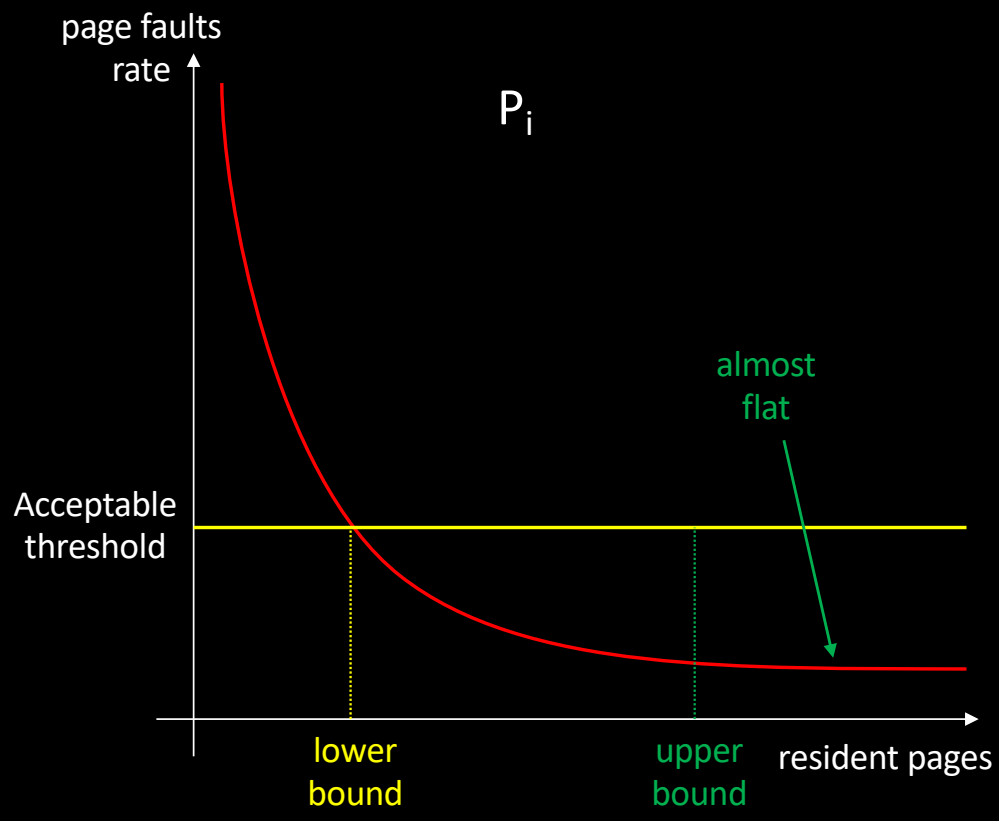
- Keeping the number of resident pages ∈ [lower..upper] is ideal
- When searching for a victim
  - We should consider processes which live far beyond their lower bound
- In practice, modern OSes approximate the WS to
  - "pages which have been accessed during a predefined period"



The notion of Working Set

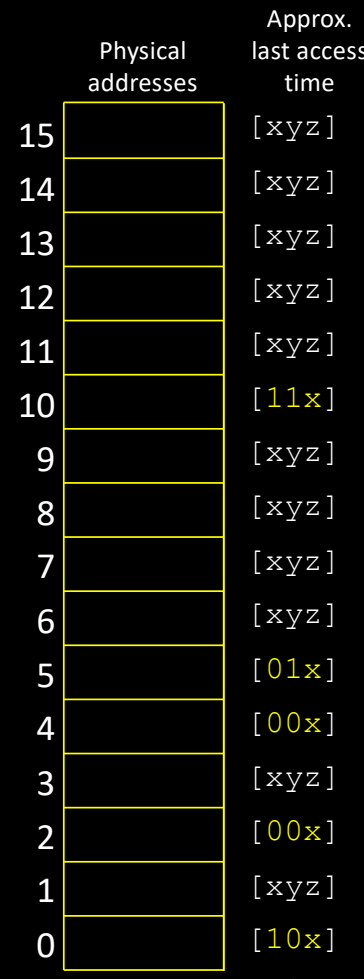
- Keeping the number of resident pages ∈ [lower..upper] is ideal
  - Note that it may be impossible
    - Too many ready processes

    => Trashing
  - Avoiding trashing
    - Gang scheduling
    - Process swapping



Page replacement algorithms

- Recap
  - When RAM is full
    - A victim page must be evicted to satisfy a new allocation
  - The kernel is able to compute an approximation of the last access time for each physical page
    - A page which is not accessed for a long period (taking the virtual time of processes into account) does not belong to a working set
      - Good candidate
      - [see WSClock algorithm]



Page replacement algorithms

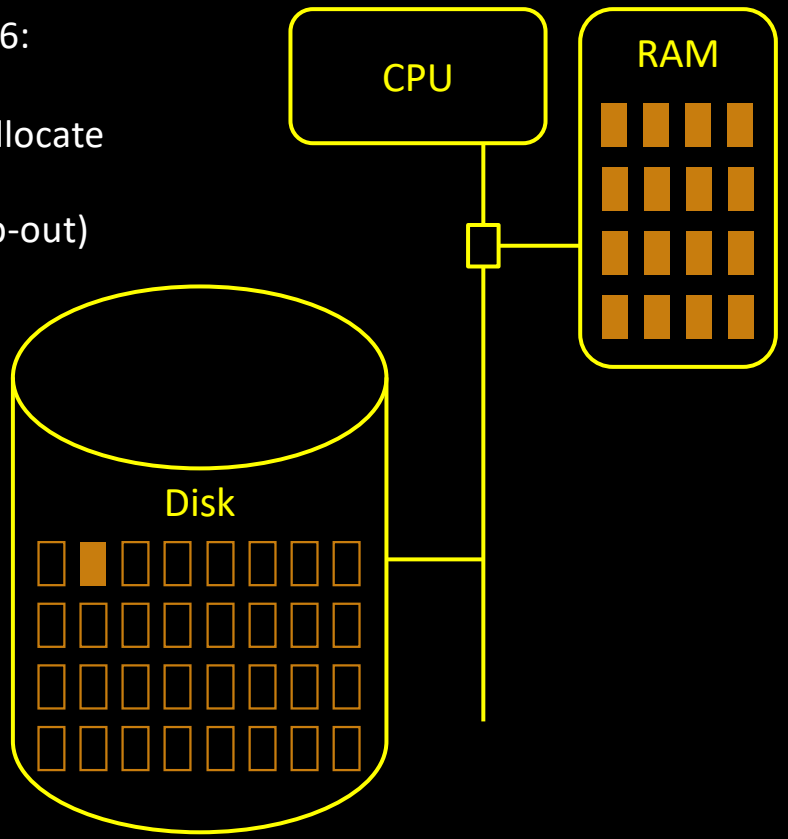
- Side notes
  - How do we find the PTE (*Page Table Entry*) pointing on a physical page?
    - Reverse mapping stored in a structure associated to each physical page
  - How to swap-out shared pages?
    - What if RAM mostly contains shared pages?

Bringing pages back to RAM

	Phys. Page	Valid	R	W	X
0	2	1	1	0	1
1	4	1	1	0	1
2	5	1	1	0	1
3		0			
4	0	1	1	1	0
5		0			
6	1	0			
7		0			
8		0			
9		0			
10		0			
11	11	1	1	1	0
12		0			
13		0			
14		0			

If process accesses virtual page #6:

1. Page fault raised
2. get_free_page() is called to allocate a new physical frame (note: this may trigger a swap-out)
3. Read page from disk (slot #1) and write to new frame
4. Fix page table entry to reference new frame

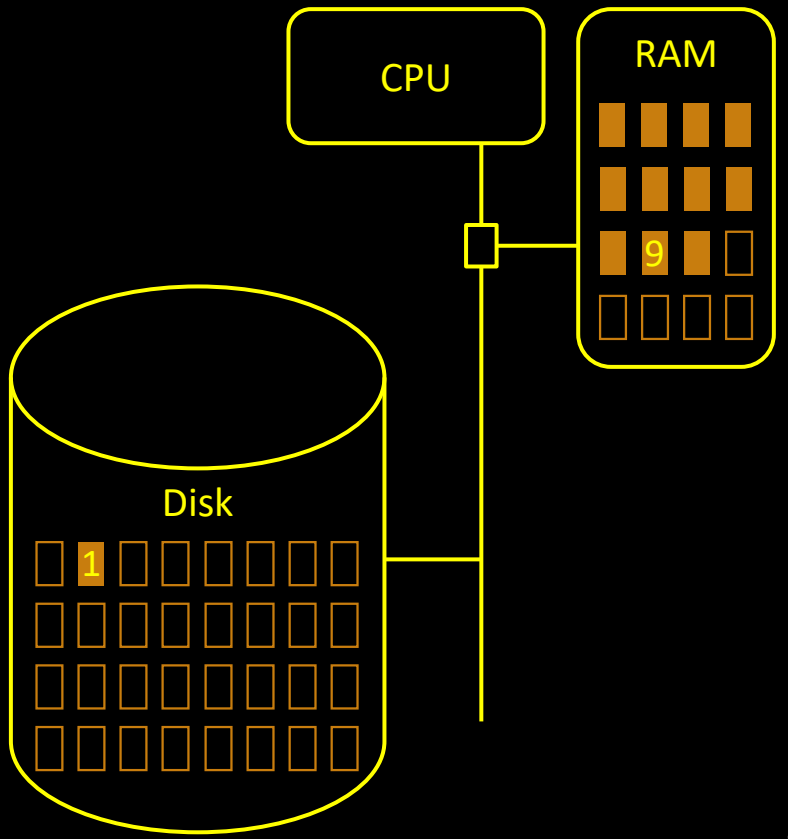


Bringing pages back to RAM

- In the worst case, two I/O operations are involved before the process can resume its execution
  - Too slow!
- Several optimizations can be used
  - Swap-outs can be anticipated
  - Some swap-outs can be avoided

Avoiding Swap-outs

- When a page has already been swapped-out, and is now back to memory
  - The swap slot can be kept as is
  - If the page is not modified until it must be evicted again
    - i.e., the page is “clean”
    - Then no disk write is need
  - If the page was modified in the meantime
    - i.e., the page is ”dirty”
    - Then it must be swapped-out again



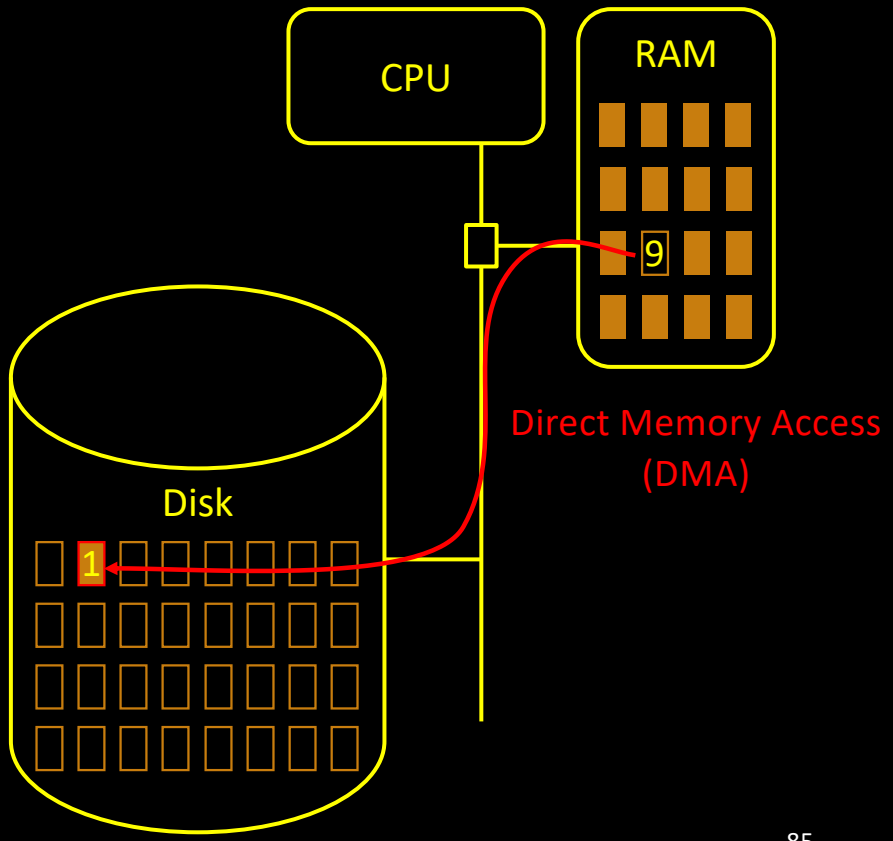
Avoiding Swap-outs

- Detecting if the page was modified could be done by removing the ‘w’ access mode
  - Too expensive
- Page table entries feature a dirty bit
  - Set by MMU on each write access
  - Cleared by OS when page is installed in RAM

	Phys. Page	Valid	R	W	X	Accessed	Dirty
0	2	1				0	0
1	4	1				1	0
2	5	1				1	1
3		0					
4	0	1				0	0
5		0					
6		0					
7		0					
8		0					
9		0					
10		0					
11	10	1				1	0
12		0					
13		0					
14		0					

Anticipating swap-outs

- A kernel DAEMON thread (kswapd) keeps maintaining a threshold of free pages in RAM
  - When the reserve of free pages is too small, the thread frees pages "in the background"
  - Most of the time, get_free_page() finds a free frame immediately!



Additional resources available on http://gforgeron.gitlab.io/se/