Virtual Memory 1

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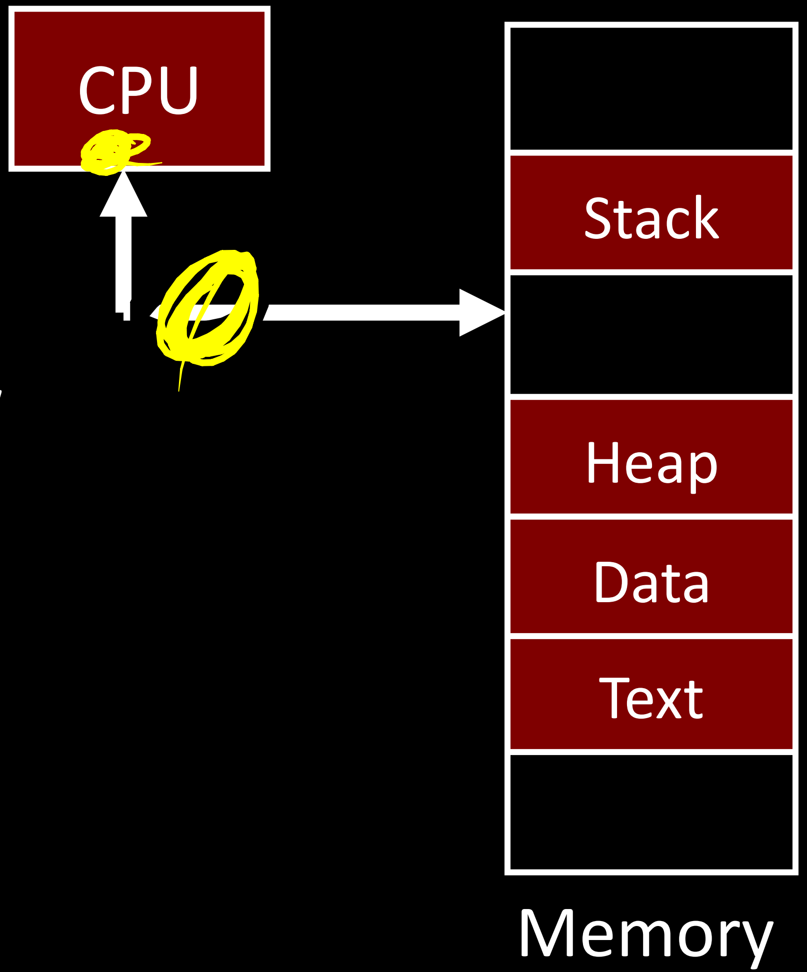
P & H Chapter 5.4 (up to TLBs)

CPU address/data bus...

... routed through caches

... to main memory

- Simple, fast, but...



Q: What happens for LW/SW to an invalid location?

- 0x000000000 (NULL)
- uninitialized pointer

Running multiple processes…

Time-multiplex a single CPU core (multi-tasking)

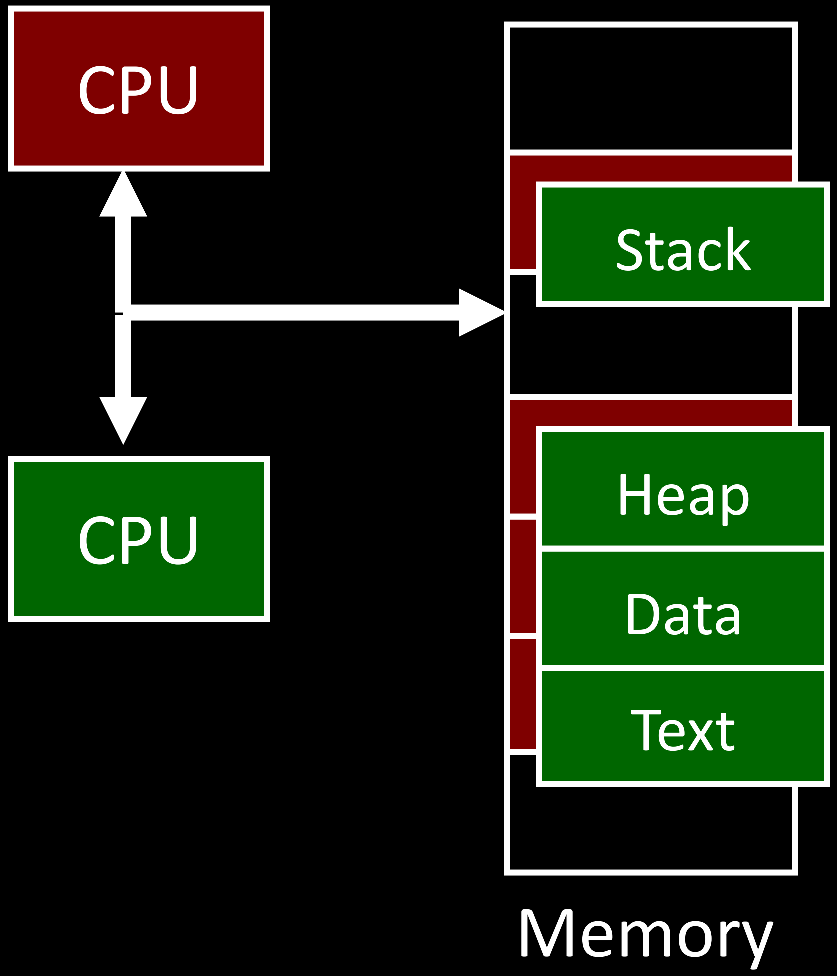
- Web browser, skype, office, … all must co-exist

Many cores per processor (multi-core)
or many processors (multi-processor)

- Multiple programs run *simultaneously*

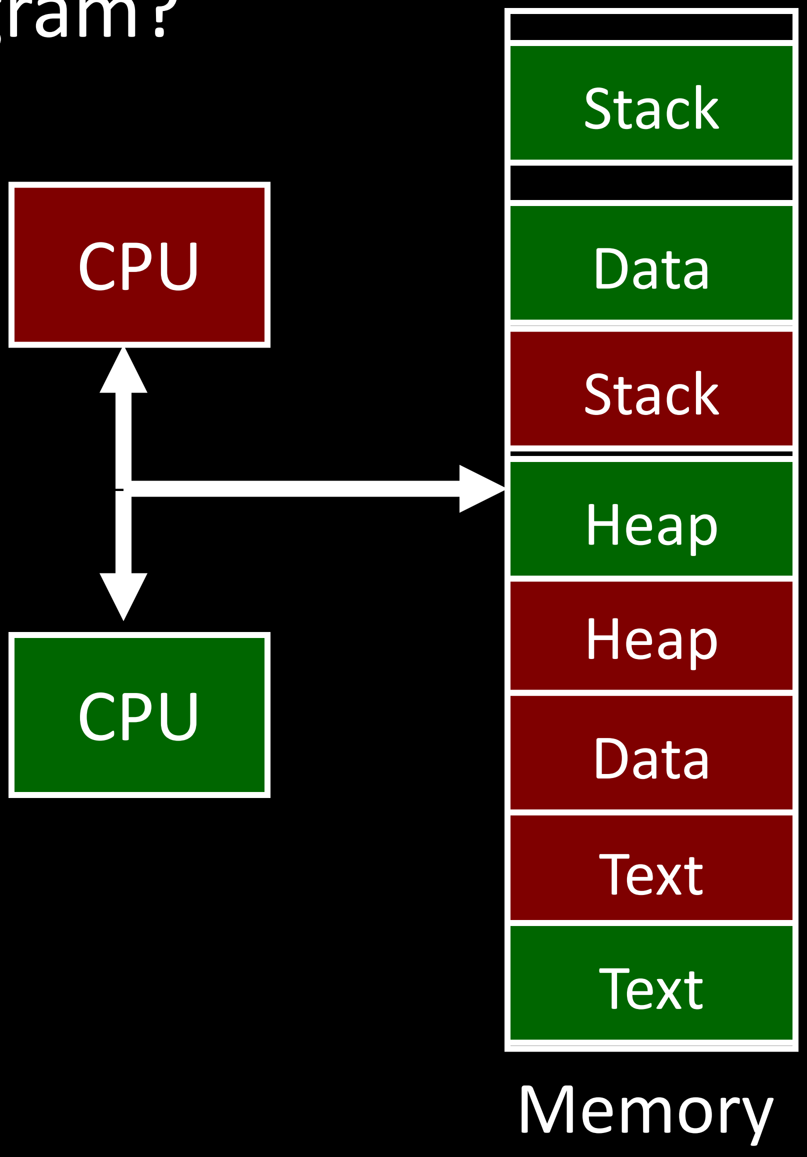
Q: What happens when another program is executed concurrently on another processor?

- Take turns using memory?



Can we relocate second program?

- What if they don't fit?
- What if not contiguous?
- Need to recompile/relink?
- …



All problems in computer science can be solved by another level of indirection.

– David Wheeler

– or, Butler Lampson

– or, Leslie Lamport

– or, Steve Bellovin

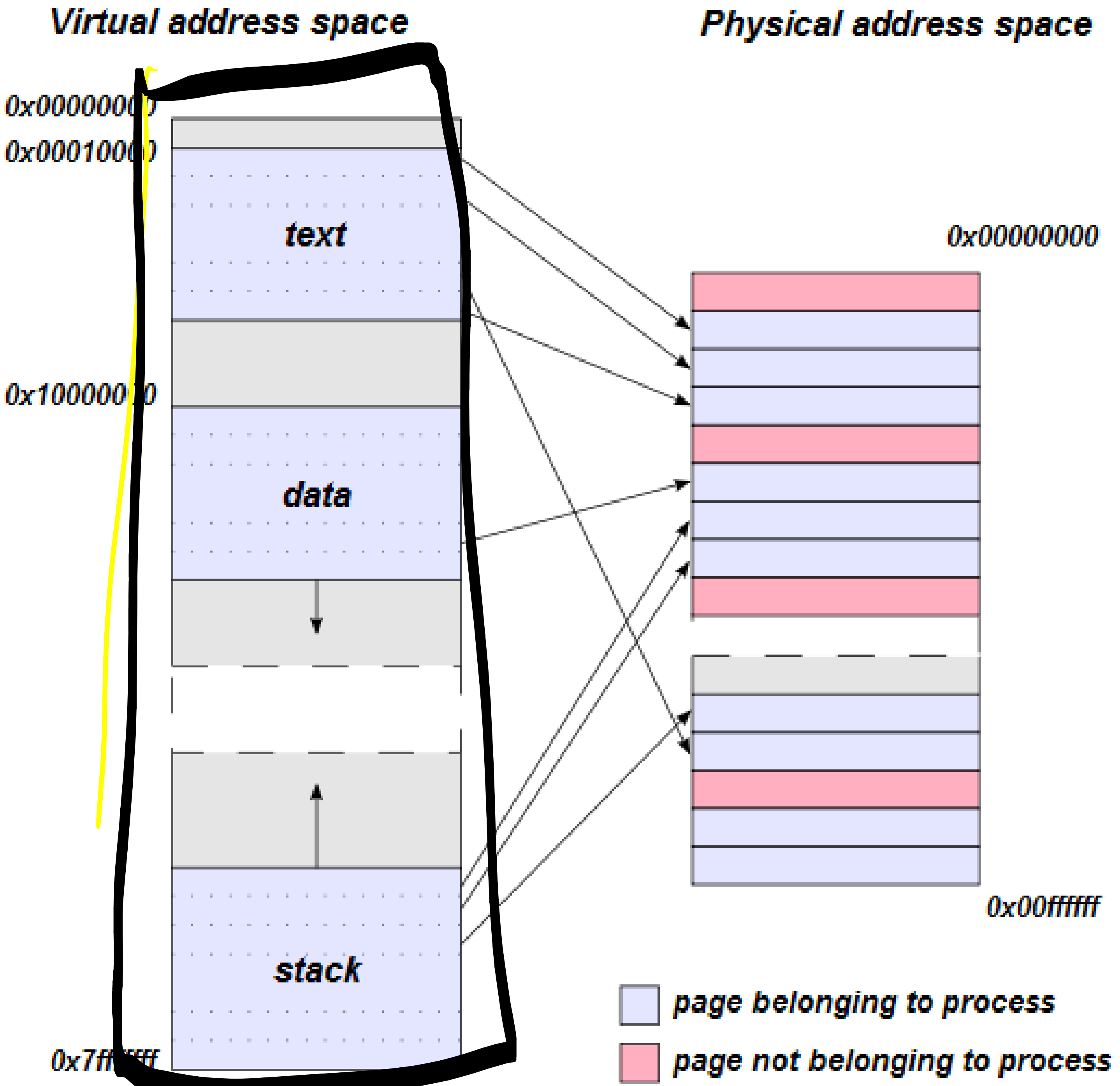
Virtual Memory: A Solution for All Problems

Each process has its own virtual address space

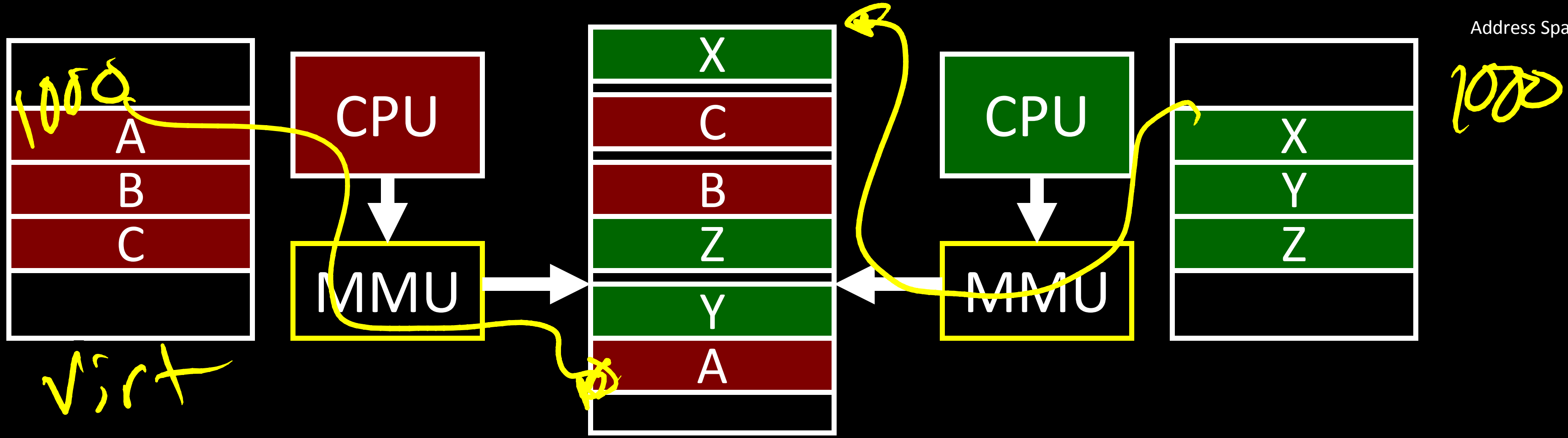
- Programmer can code as if they own all of memory

On-the-fly at runtime, for each memory access

- all access is *indirect* through a virtual address
- translate fake virtual address to a real physical address
- redirect load/store to the physical address


Virtual address space
Physical address space
0x00010000
0x10000000
text
data
stack
0x00000000
0x00ffffff
page belonging to process
page not belonging to process

wikipedia



Programs load/store to virtual addresses

Actual memory uses physical addresses

Memory Management Unit (MMU)

- Responsible for translating on the fly
- Essentially, just a big array of integers:
  paddr = PageTable[vaddr];

Advantages

Easy relocation

- Loader puts code anywhere in physical memory
- Creates virtual mappings to give illusion of correct layout

Higher memory utilization

- Provide illusion of contiguous memory
- Use all physical memory, even physical address 0x0

Easy sharing

- Different mappings for different programs / cores

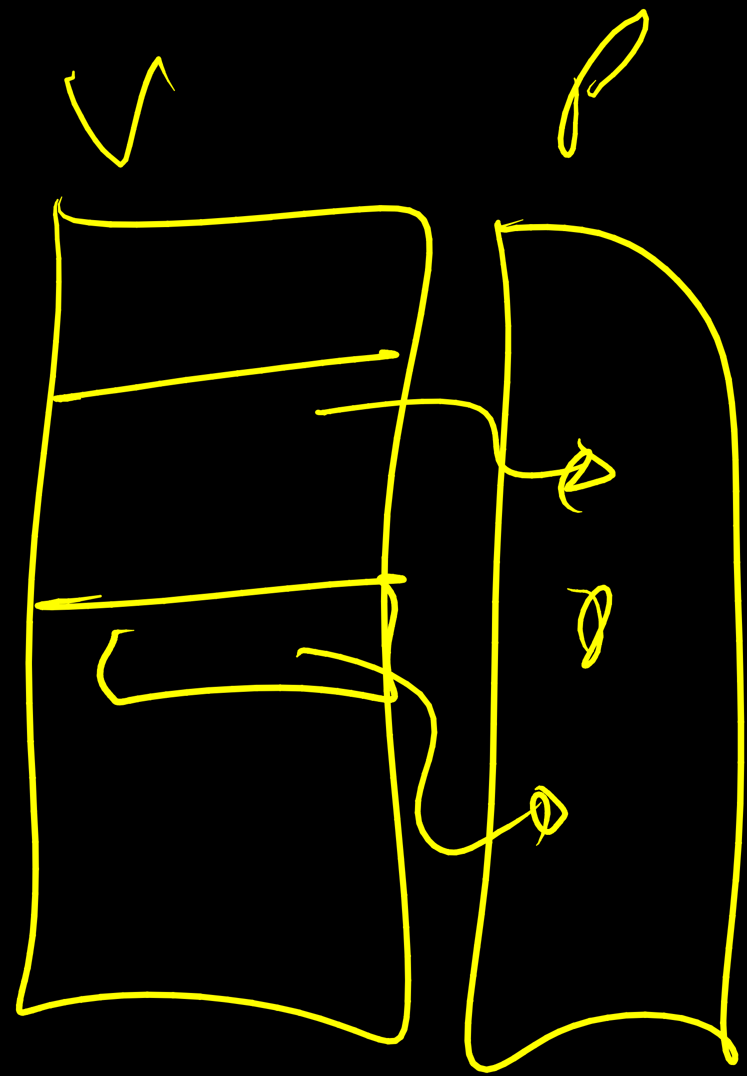
And more to come…

Address Translation

Pages, Page Tables, and the Memory Management Unit (MMU)

Attempt #1: How does MMU translate addresses?

paddr = PageTable[vaddr];

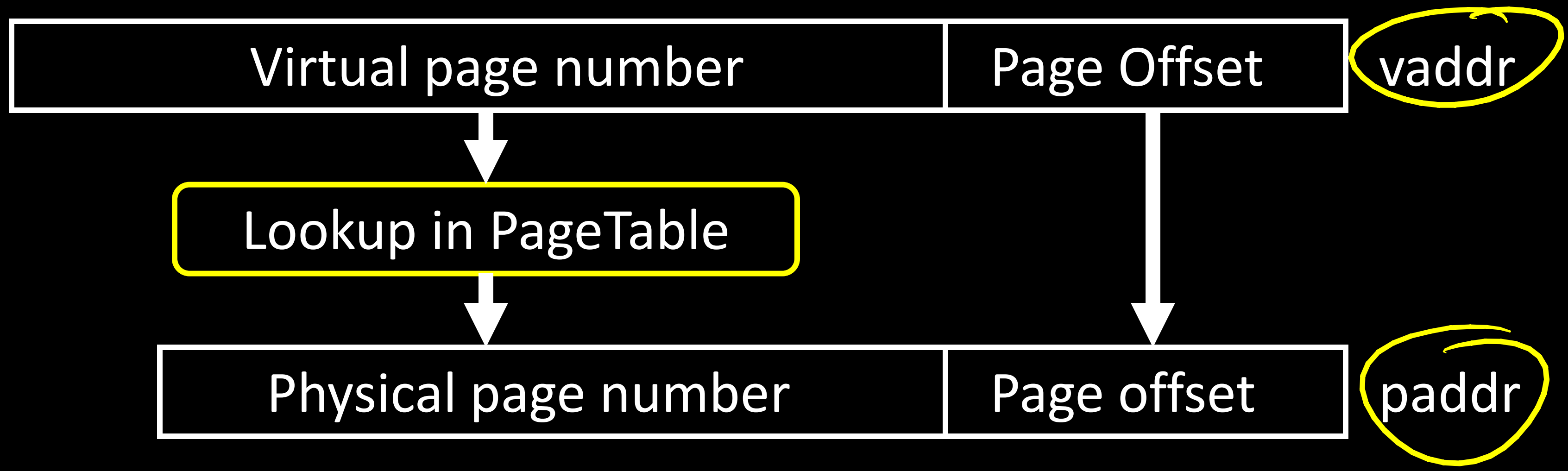


Granularity?

- Per word…
- Per block…
- Variable…

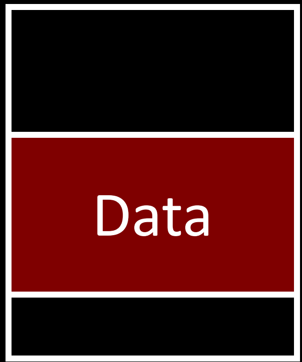
Typical:

- 4KB – 16KB pages
- 4MB – 256MB jumbo pages

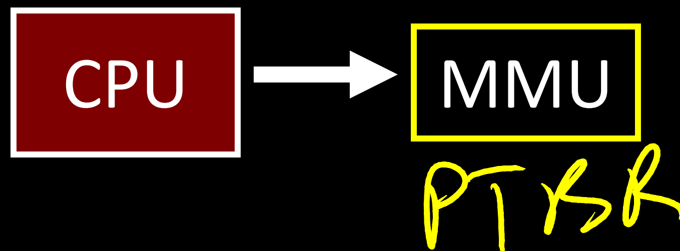


Attempt #1: For any access to virtual address:

- Calculate virtual page number and page offset
- Lookup physical page number at PageTable[vpn]
- Calculate physical address as ppn:offset



Read Mem[0x00201538]



Q: Where to store page tables?

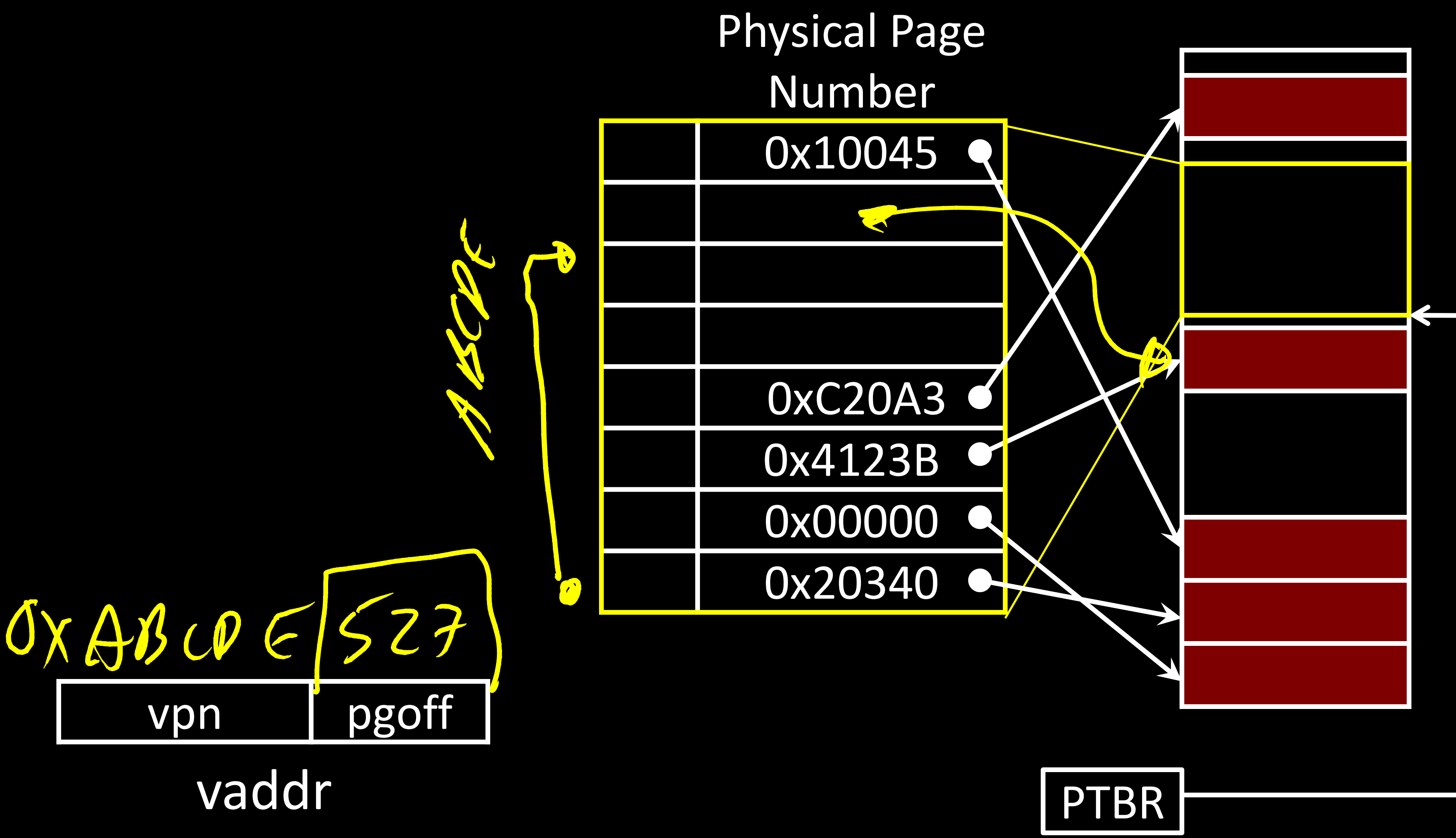
A: In memory, of course…

Special *page table base register*

(CR3:PTBR on x86)

(Cop0:ContextRegister on MIPS)

* lies to children



* lies to children

Overhead for VM Attempt #1 (example)

Virtual address space (for each process):

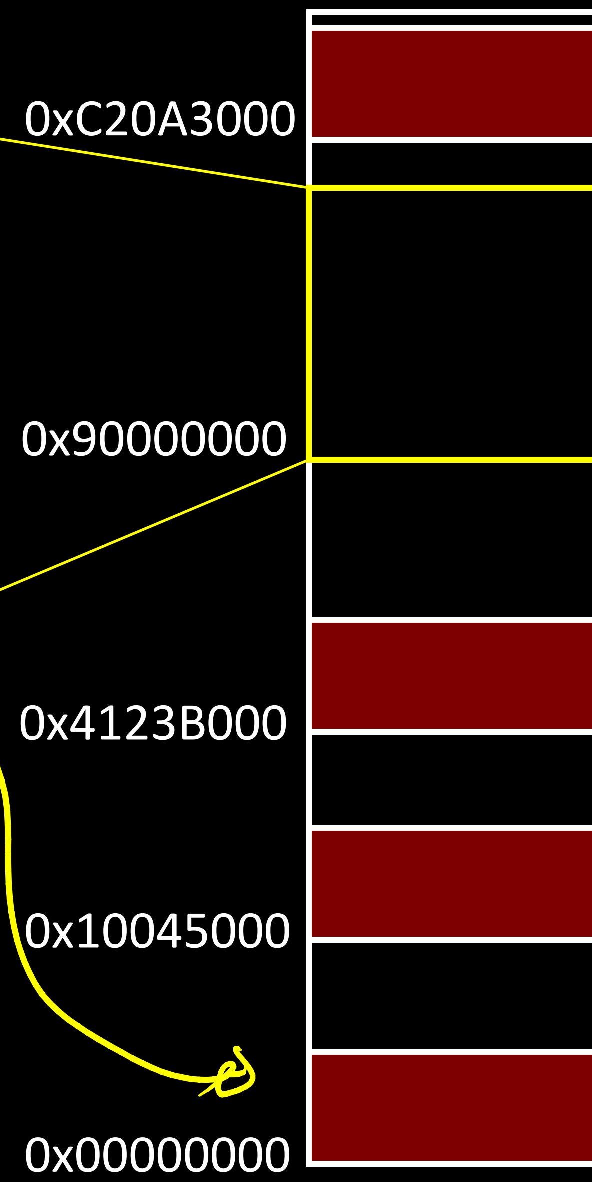
- total memory: 2^{32} bytes = 4GB
- page size: 2^{12} bytes = 4KB
- entries in PageTable?
- size of PageTable?

Physical address space:

- total memory: 2^{29} bytes = 512MB
- overhead for 10 processes?

* lies to children

V		Physical Page Number
0		
1		0x10045
0		
0		
1		0xC20A3
1		0x4123B
1		0x00000
0		



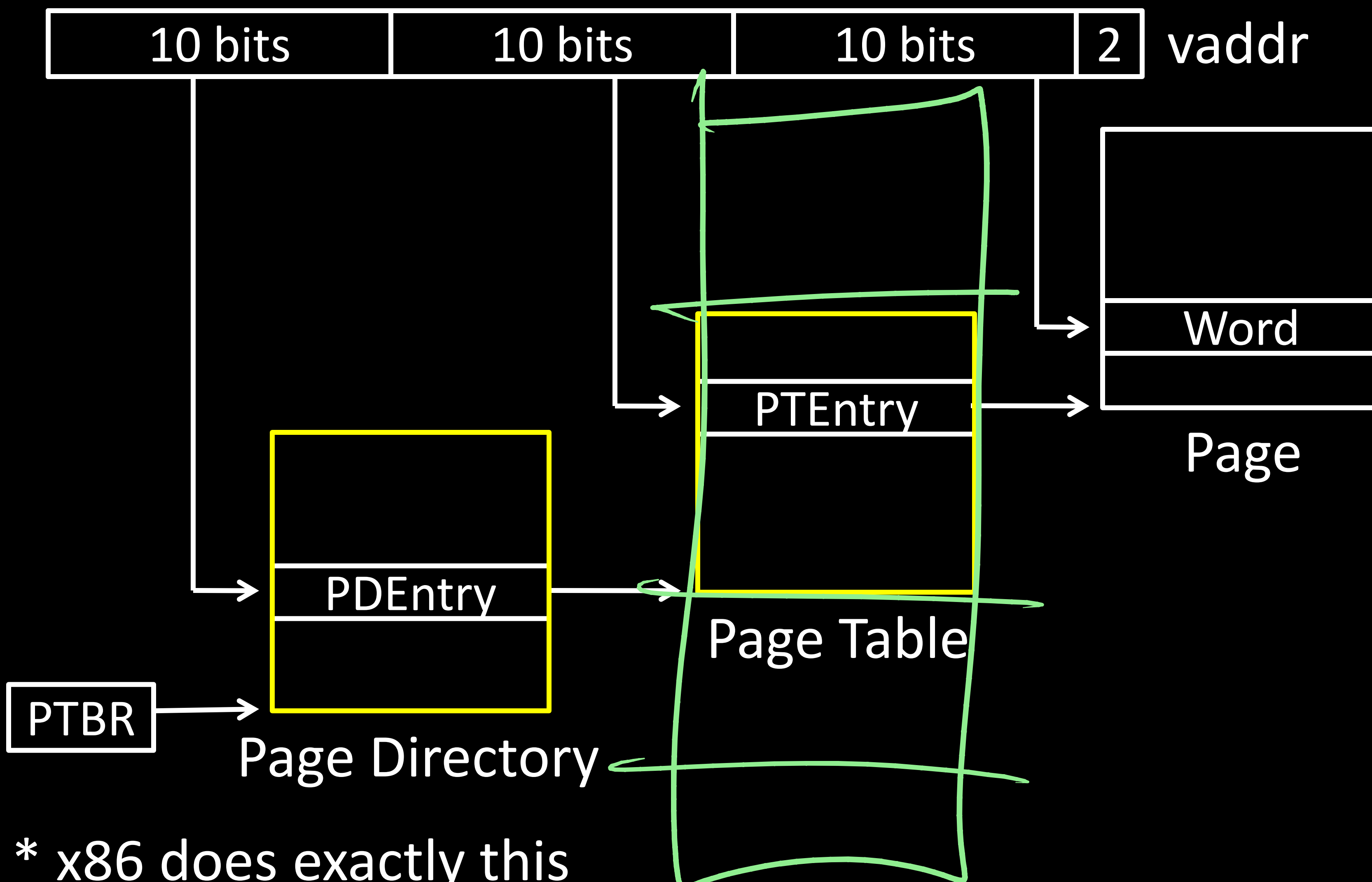
Cool Trick #1: Don’t map all pages

Need valid bit for each page table entry

Q: Why?

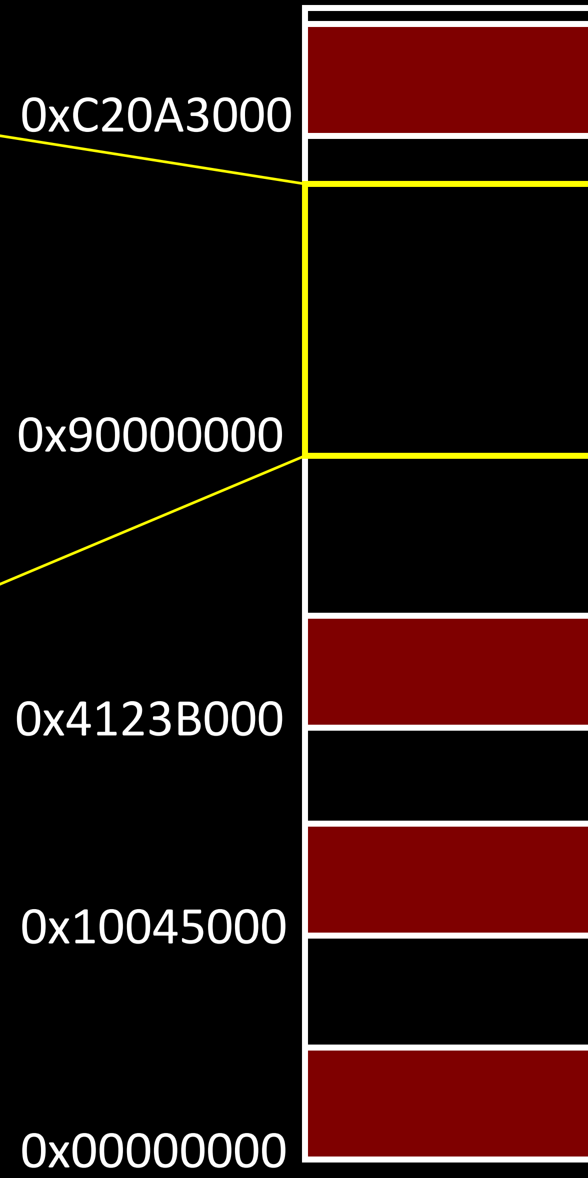
Assume most of PageTable is empty

How to translate addresses? Multi-level PageTable



* x86 does exactly this

V	R	W	X		Physical Page Number
0					
1					0x10045
0					
0					
1					0xC20A3
1					0x4123B
1					0x00000
0					

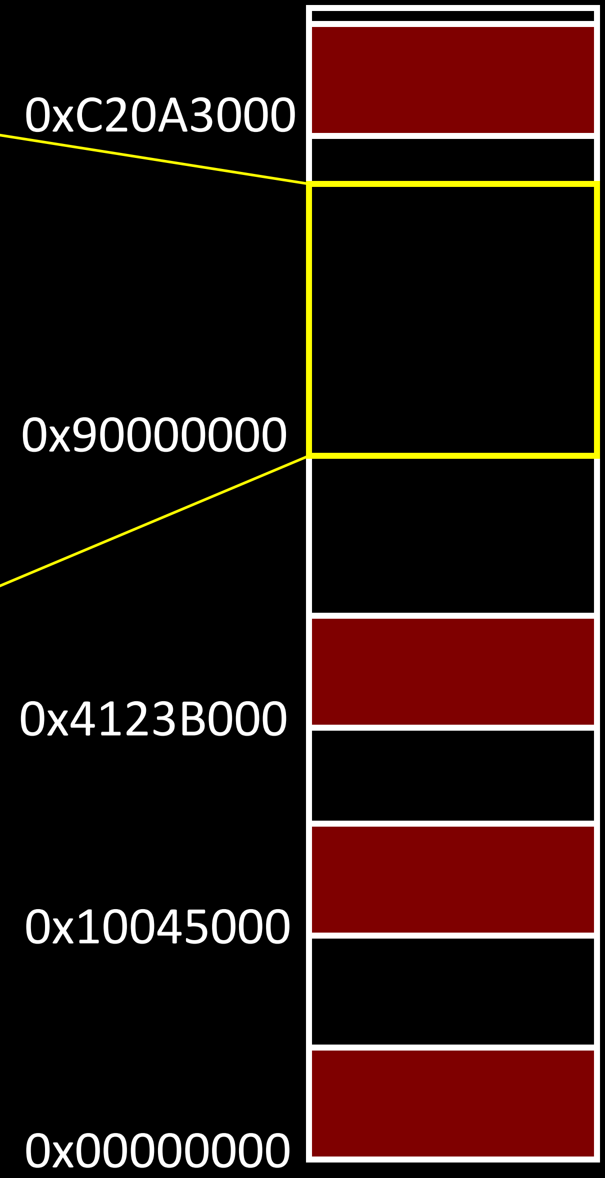


Cool Trick #2: Page permissions!

Keep R, W, X permission bits for each page table entry

Q: Why?

V	R	W	X		Physical Page Number
0					
1					0xC20A3
0					
0					
1					0xC20A3
1					0x4123B
1					0x00000
0					



Cool Trick #3: Aliasing

Map the same physical page at several virtual addresses

Q: Why?

Paging

Can we run process larger than physical memory?

- The "virtual" in "virtual memory"

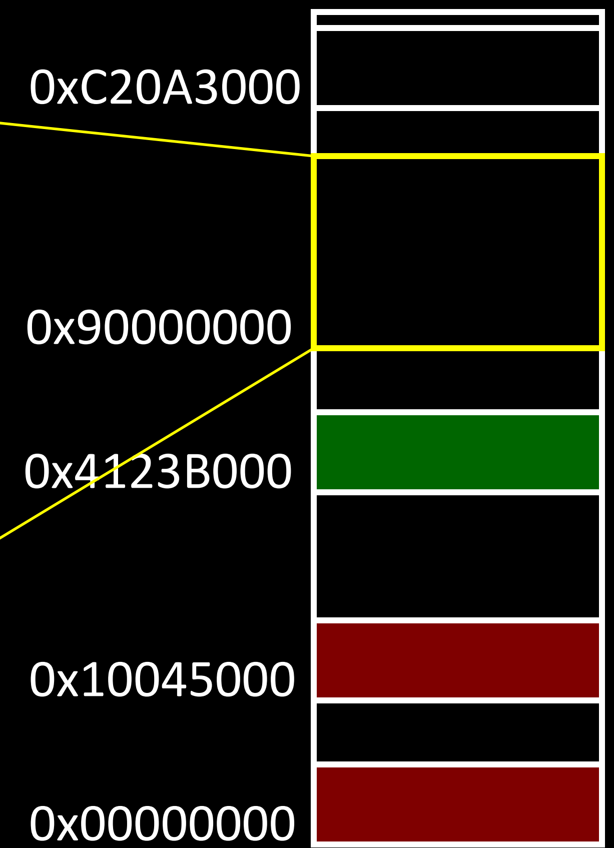
View memory as a "cache" for secondary storage

- Swap memory pages out to disk when not in use
- Page them back in when needed

Assumes Temporal/Spatial Locality

- Pages used recently most likely to be used again soon

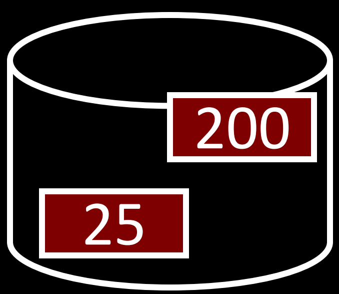
V	R	W	X	D	Physical Page Number
0					invalid
1				0	0x10045
0					invalid
0					invalid
0				0	disk sector 200
0				0	disk sector 25
1				1	0x00000
0					invalid



Cool Trick #4: Paging/Swapping

Need more bits:

Dirty, RecentlyUsed, …



Role of the Operating System

Context switches, working set,

shared memory

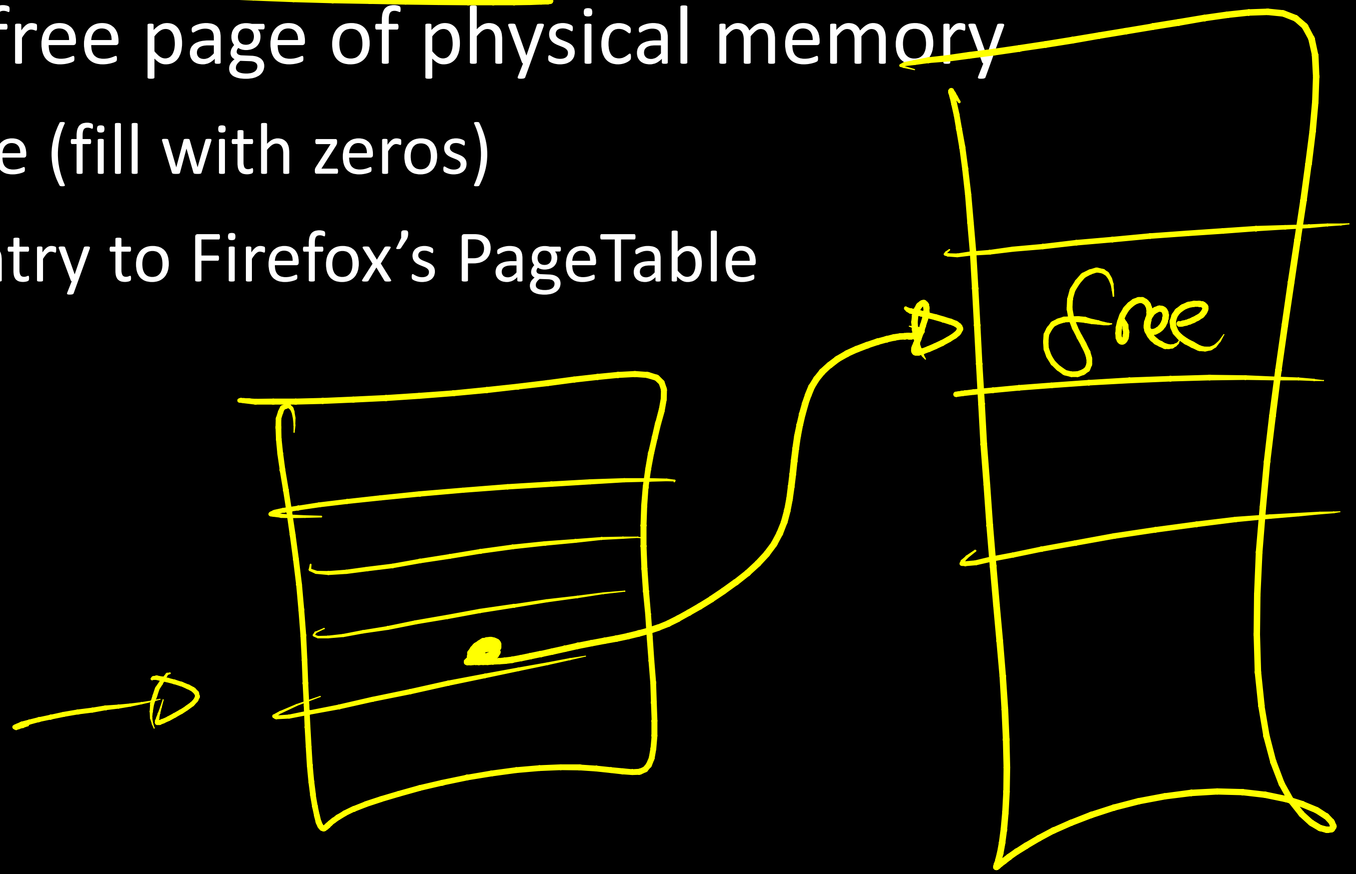
Suppose Firefox needs a new page of memory

(1) Invoke the Operating System

```
void *sbrk(int nbytes);
```

(2) OS finds a free page of physical memory

- clear the page (fill with zeros)
- add a new entry to Firefox's PageTable



Suppose Firefox is idle, but Skype wants to run

(1) Firefox invokes the Operating System

```
int sleep(int nseconds);
```

(2) OS saves Firefox’s registers, load skype’s

- (more on this later)

(3) OS changes the CPU’s Page Table Base Register

- Cop0:ContextRegister / CR3:PDBR

(4) OS returns to Skype

Suppose Firefox and Skype want to share data

(1) OS finds a free page of physical memory

- clear the page (fill with zeros)
- add a new entry to Firefox's PageTable
- add a new entry to Skype's PageTable
  - can be same or different vaddr
  - can be same or different page permissions

Shared Mem

Suppose Skype needs a new page of memory, but Firefox is hogging it all

(1) Invoke the Operating System

```
void *sbrk(int nbytes);
```

(2) OS can't find a free page of physical memory

- Pick a page from Firefox instead (or other process)

(3) If page table entry has dirty bit set…

- Copy the page contents to disk

(4) Mark Firefox's page table entry as "on disk"

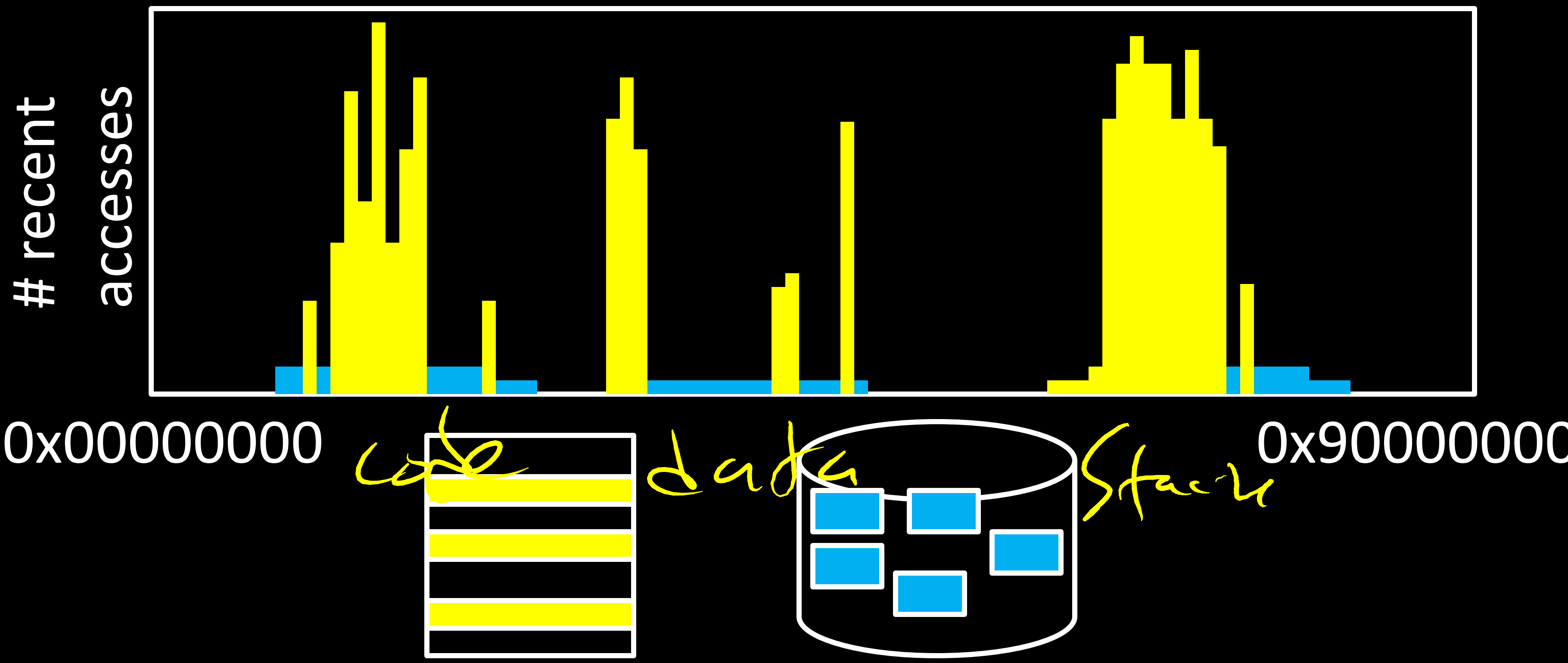
- Firefox will fault if it tries to access the page

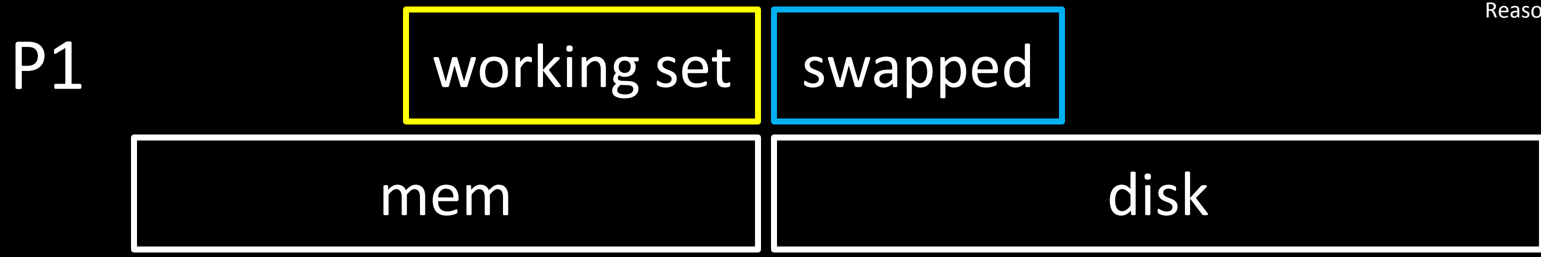
(5) Give the newly freed physical page to Skype

- clear the page (fill with zeros)
- add a new entry to Skyps's PageTable

OS multiplexes physical memory among processes

- assumption # 1:
  processes use only a few pages at a time
- working set = set of process's recently actively pages

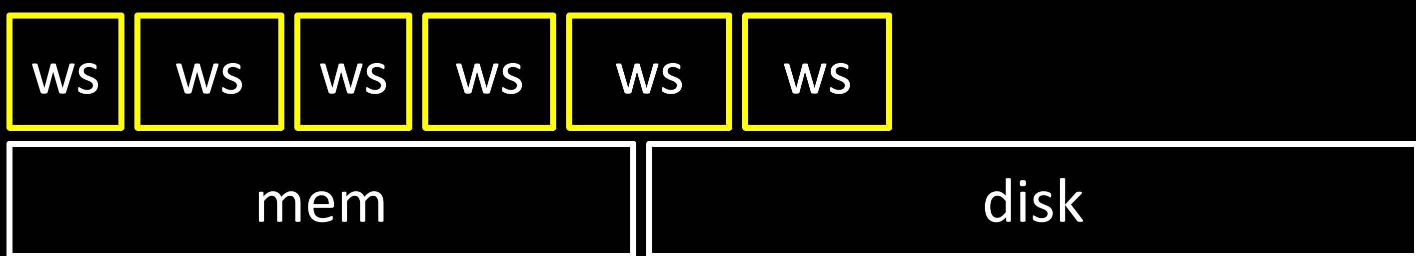




Q: What if working set is too large?

Case 1: Single process using too many pages

Case 2: Too many processes



Thrashing b/c working set of process (or processes) greater than physical memory available

- Firefox steals page from Skype
- Skype steals page from Firefox

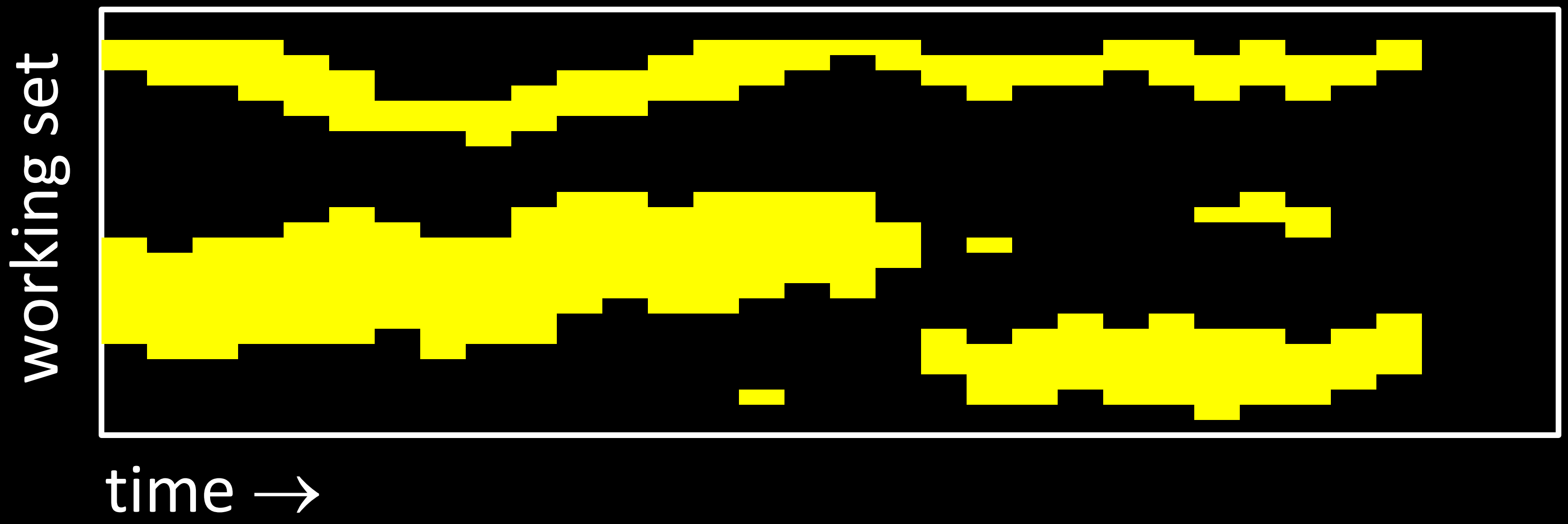
- I/O (disk activity) at 100% utilization
  - But no useful work is getting done

Ideal: Size of disk, speed of memory (or cache)

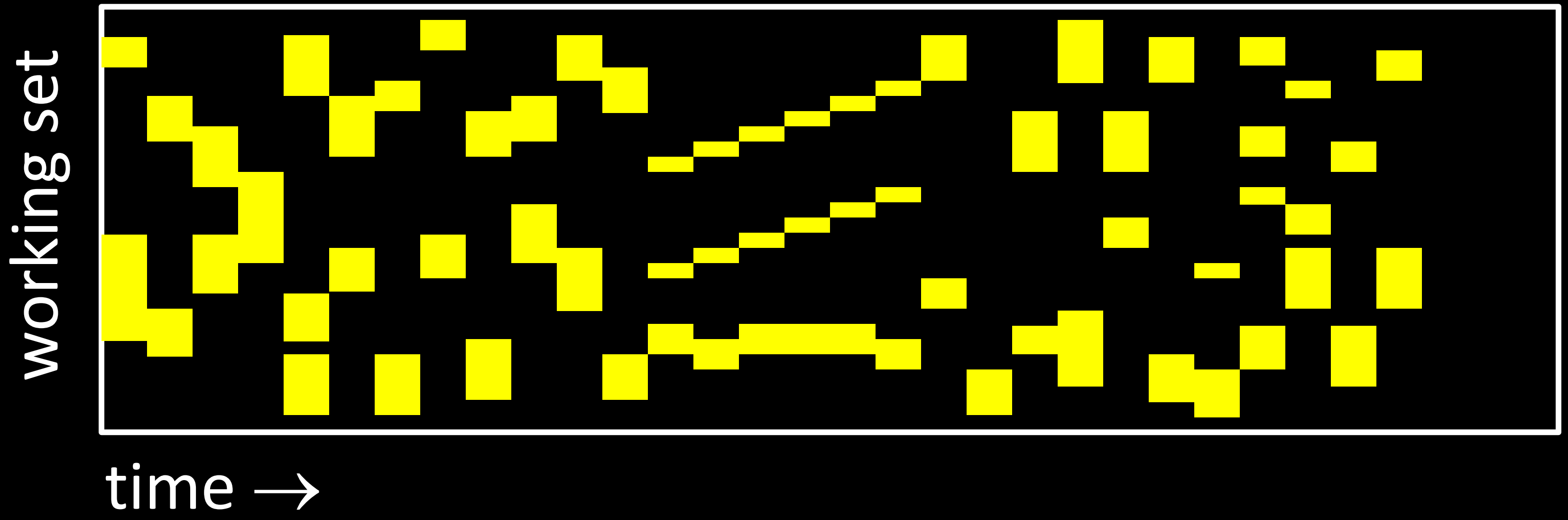
Non-ideal: Speed of disk

OS multiplexes physical memory among processes

- assumption # 2:
  recent accesses predict future accesses
- working set usually changes slowly over time



Q: What if working set changes rapidly or unpredictably?



A: Thrashing b/c recent accesses don't predict future accesses

How to prevent thrashing?

- User: Don’t run too many apps
- Process: efficient and predictable mem usage
- OS: Don’t over-commit memory, memory-aware scheduling policies, etc.