Virtual Memory 1

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P & H Chapter 5.4 (up to TLBs)

CPU address/data bus...

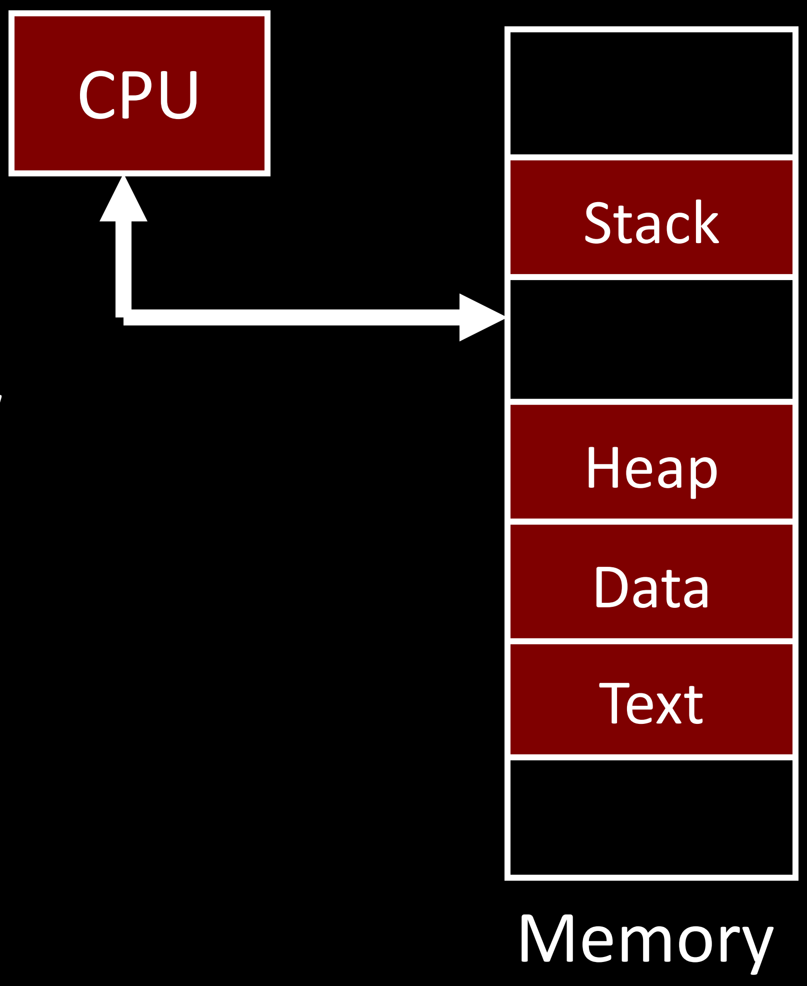
... routed through caches

... 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)

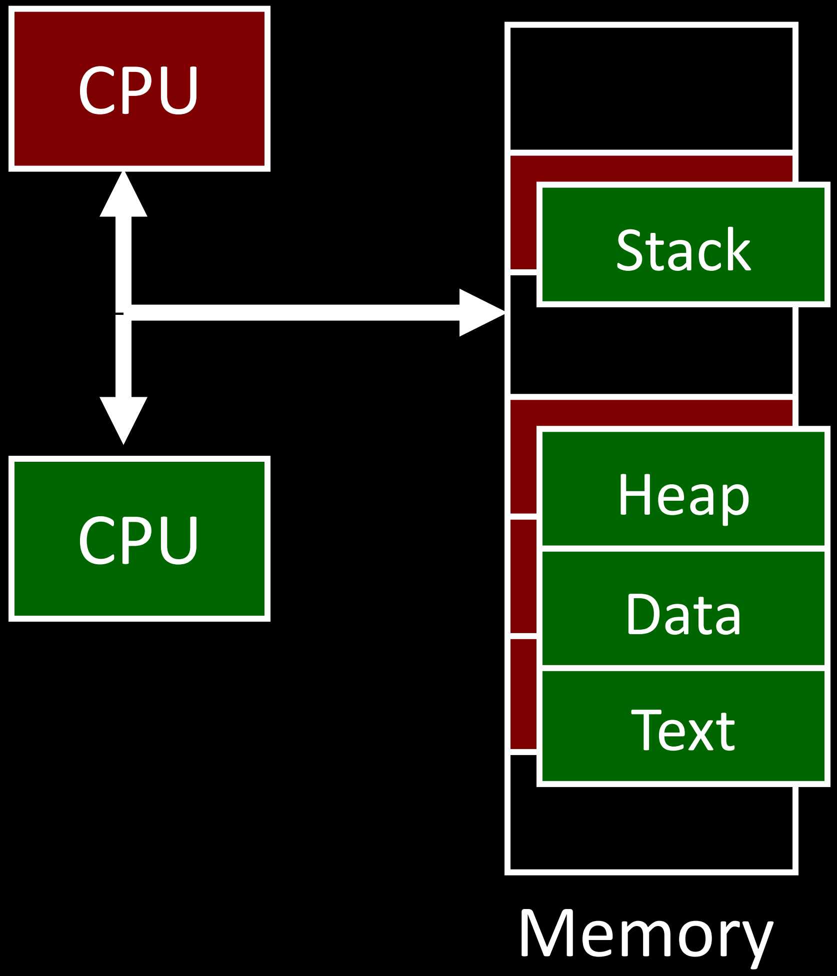
- Web browser, skype, office, … all must co-exist

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

- Multiple programs run *simultaneously*

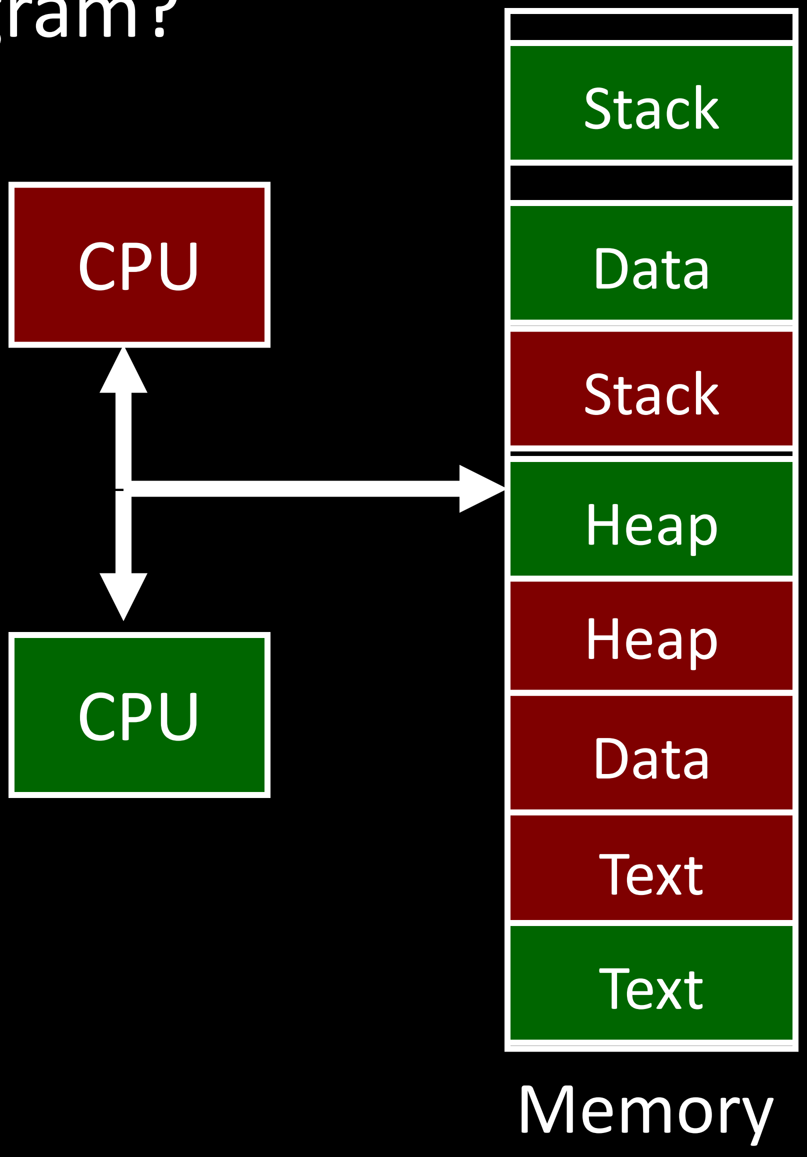
Q: What happens when another program is executed concurrently on another processor?

- 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

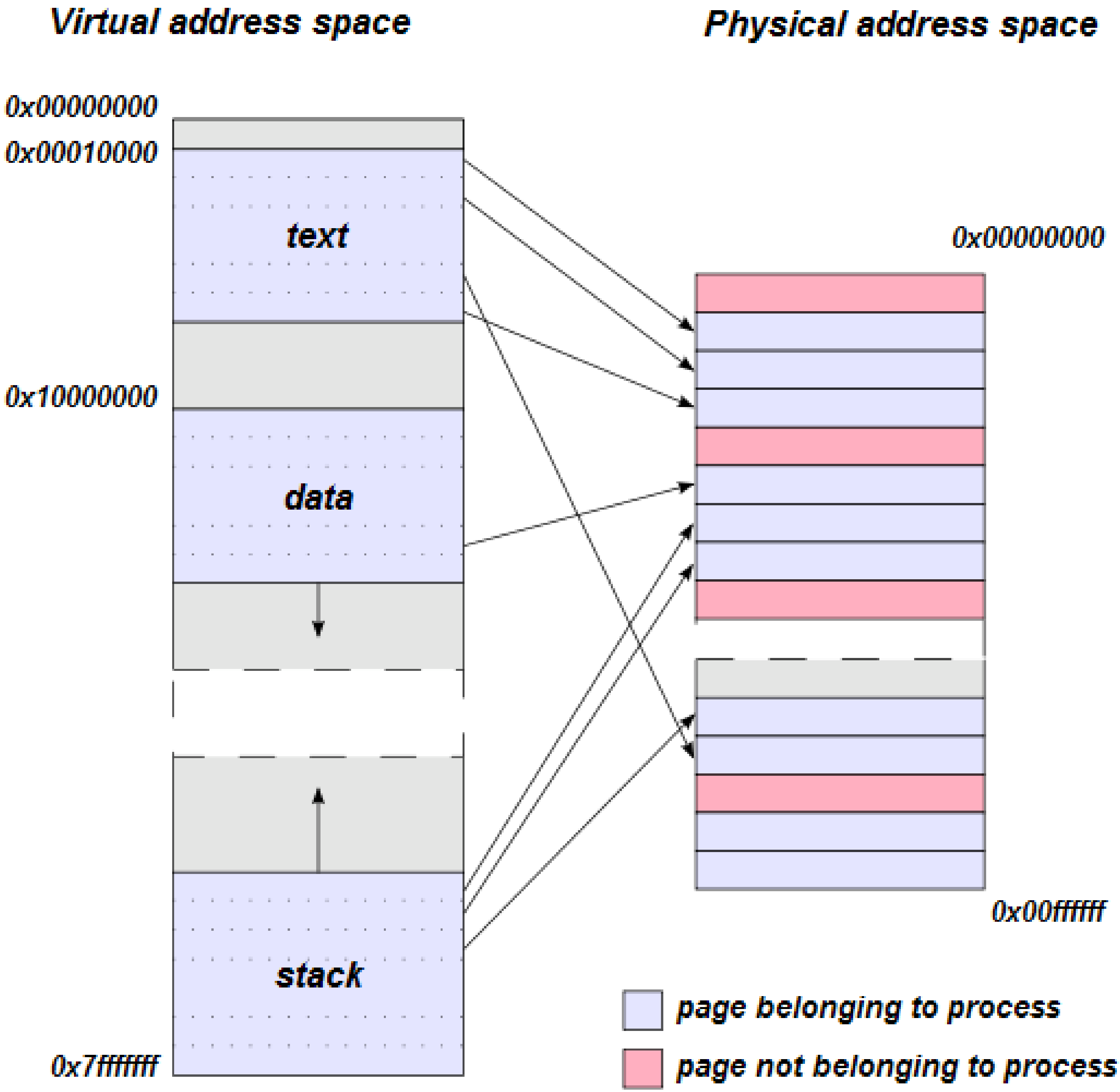
Virtual Memory: A Solution for All Problems

Each process has its own virtual address space

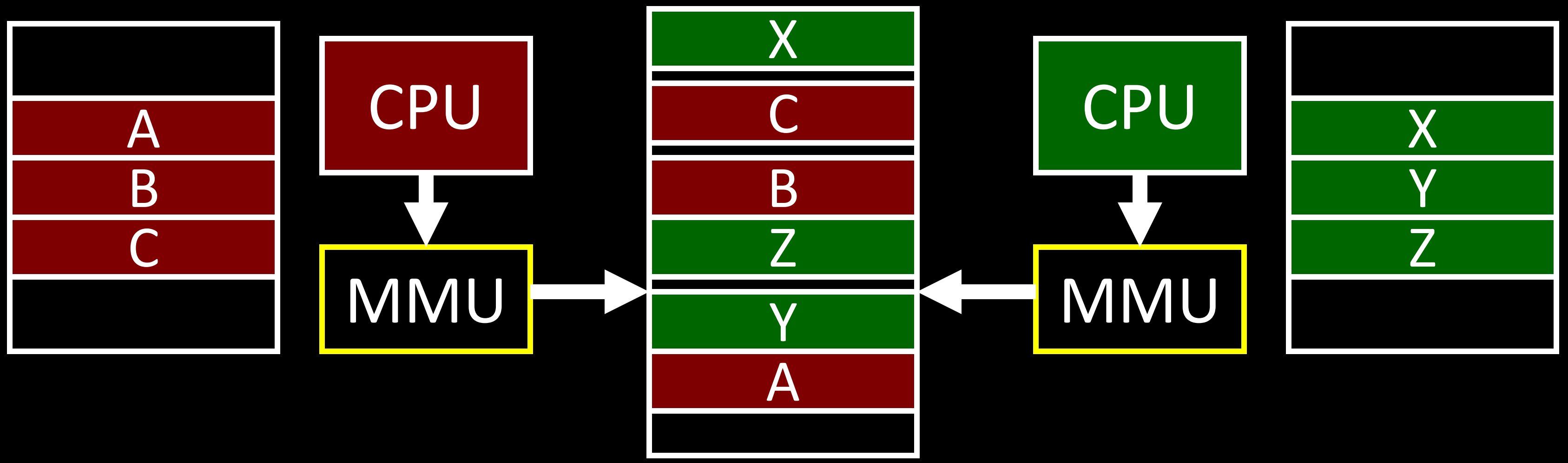
- Programmer can code as if they own all of memory

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
0x00000000
0x00010000
0x10000000
0x7fffffff
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?

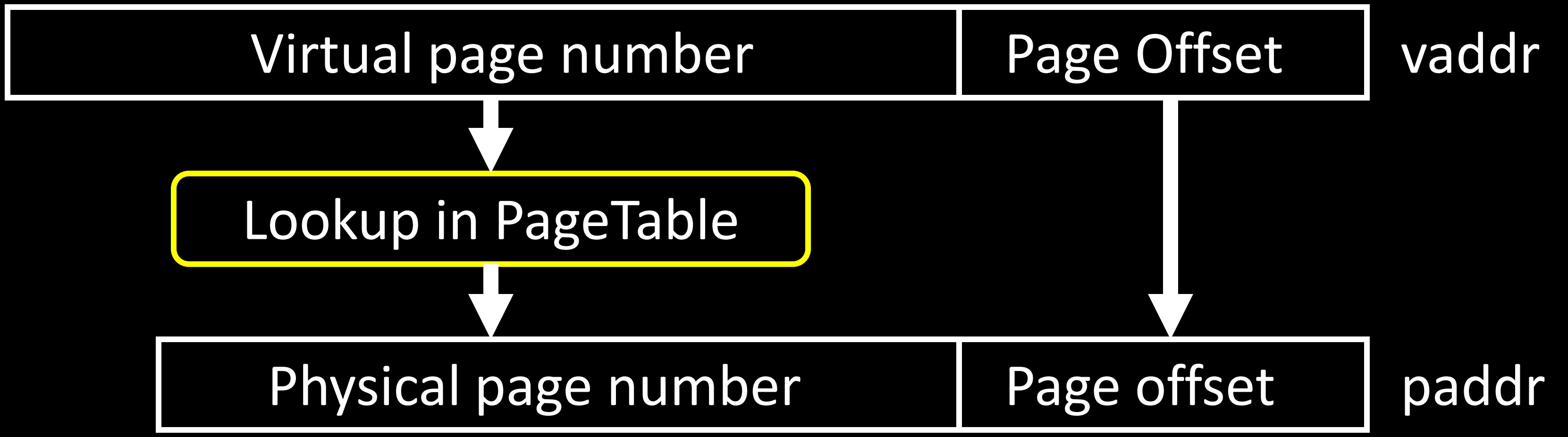
```
paddr = PageTable[vaddr];
```

Granularity?

- Per word…
- Per block…
- Variable…

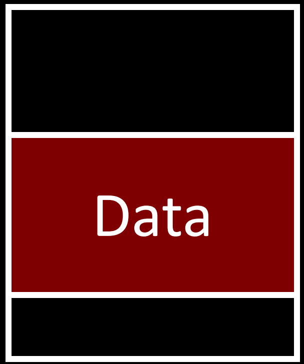
Typical:

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

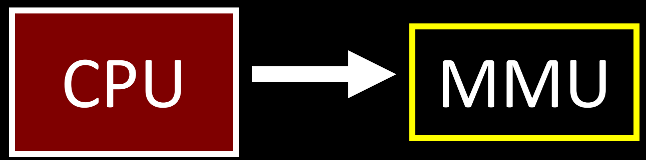


Attempt #1: For any access to virtual address:

- 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?

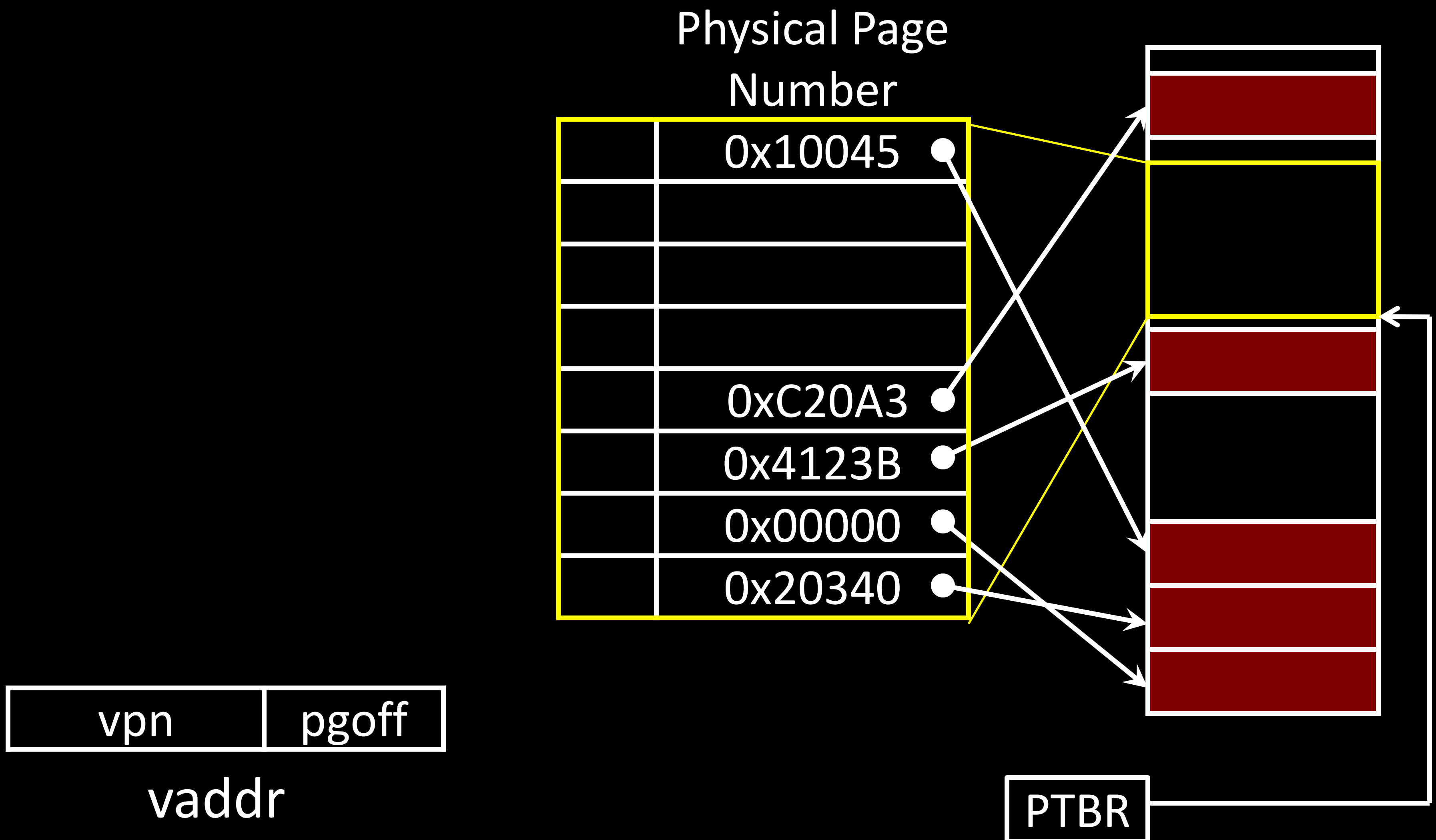
A: In memory, of course…

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):

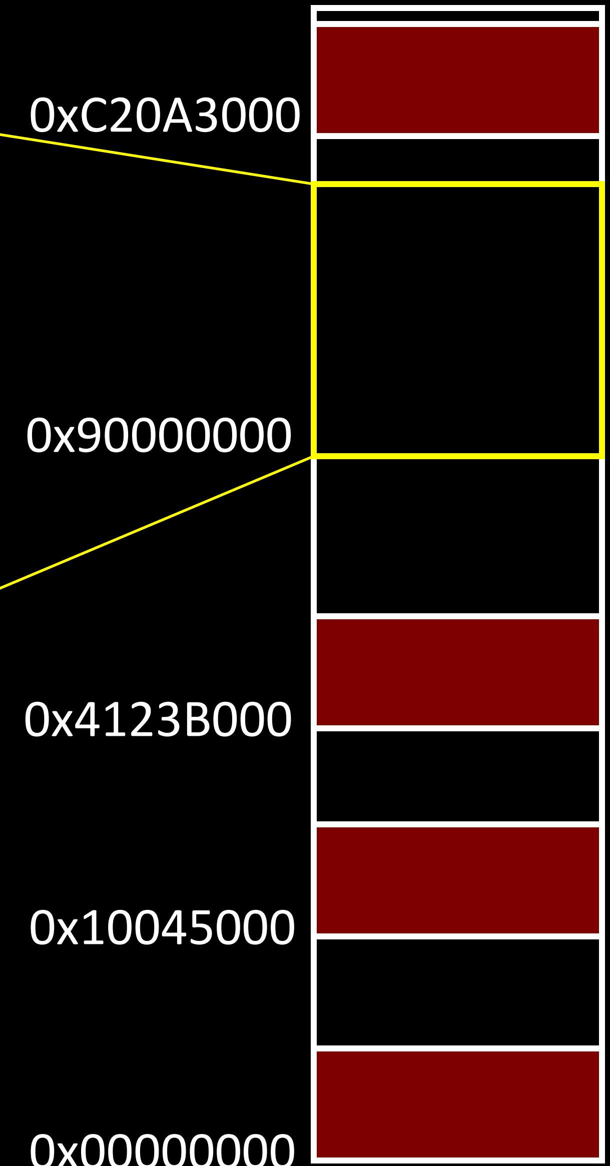
- total memory: 2^{32} bytes = 4GB
- page size: 2^{12} bytes = 4KB
- entries in PageTable?
- size of PageTable?

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		



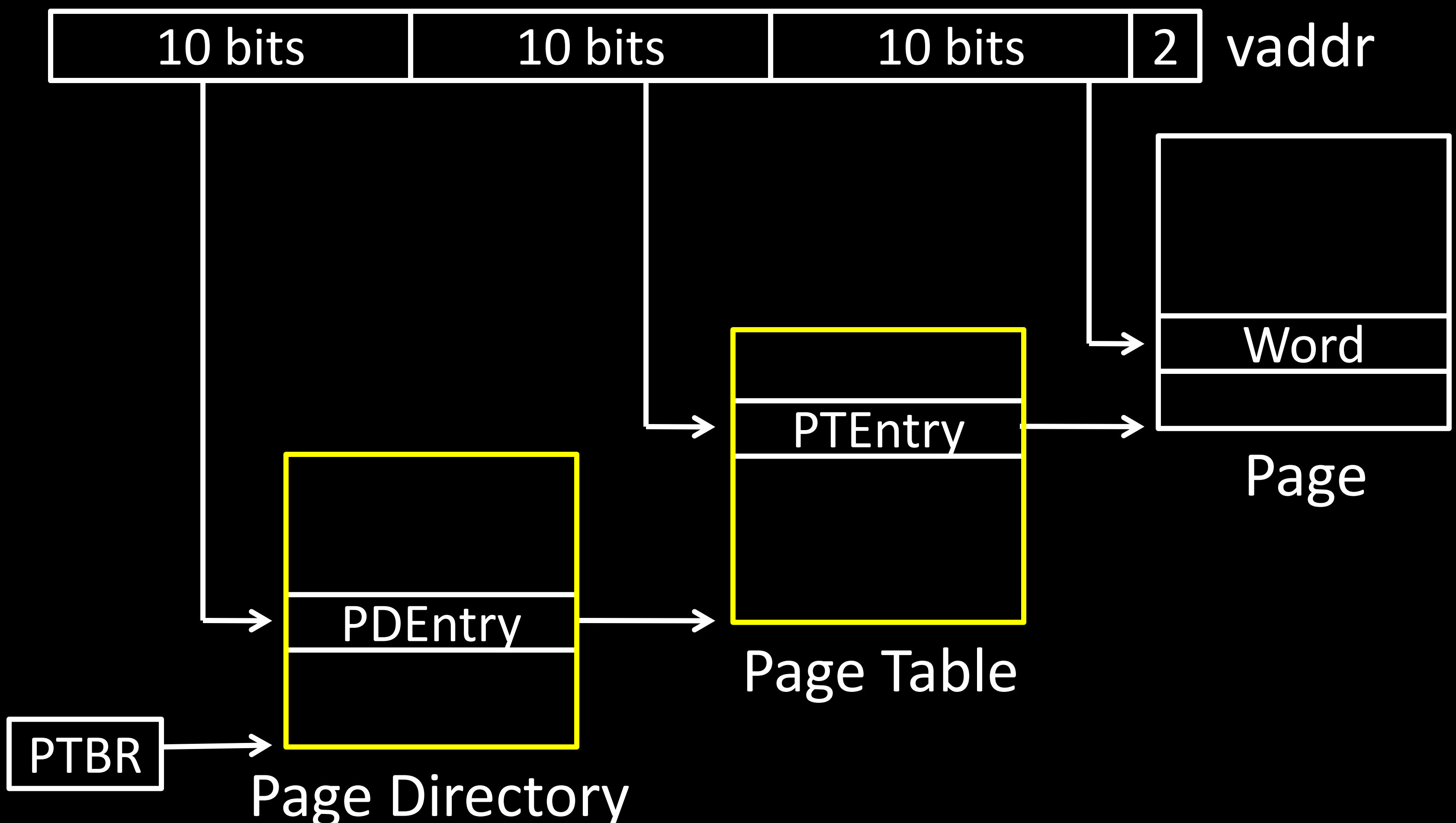
Cool Trick #1: Don’t map all pages

Need valid bit for each page table entry

Q: Why?

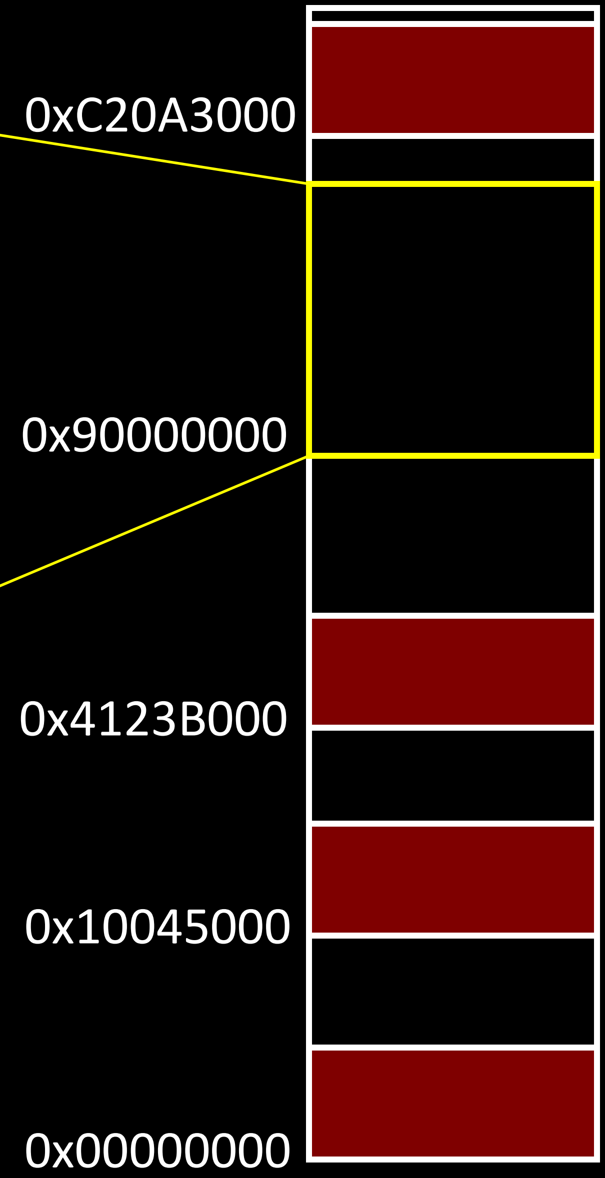
Assume most of PageTable is empty

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					

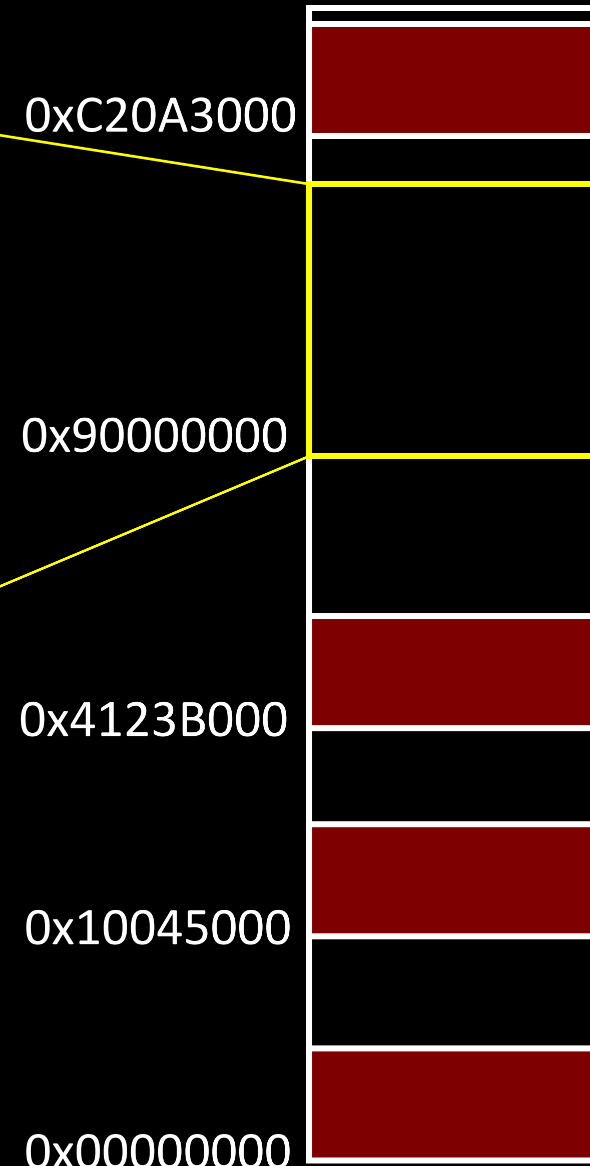


Cool Trick #2: Page permissions!

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"

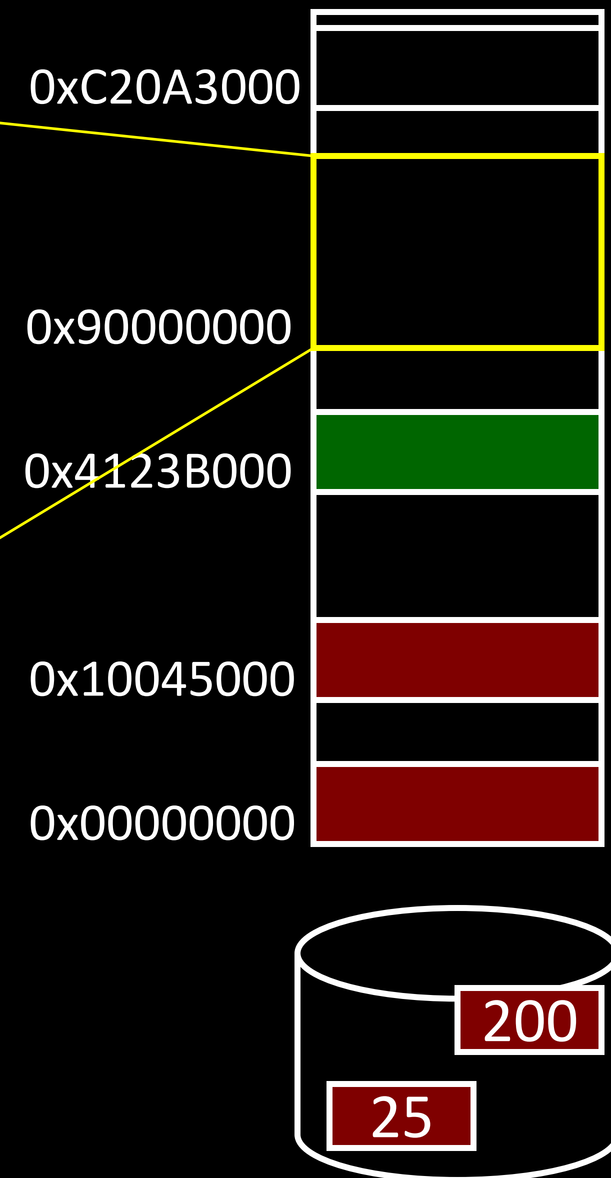
View memory as a "cache" for secondary storage

- 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

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"

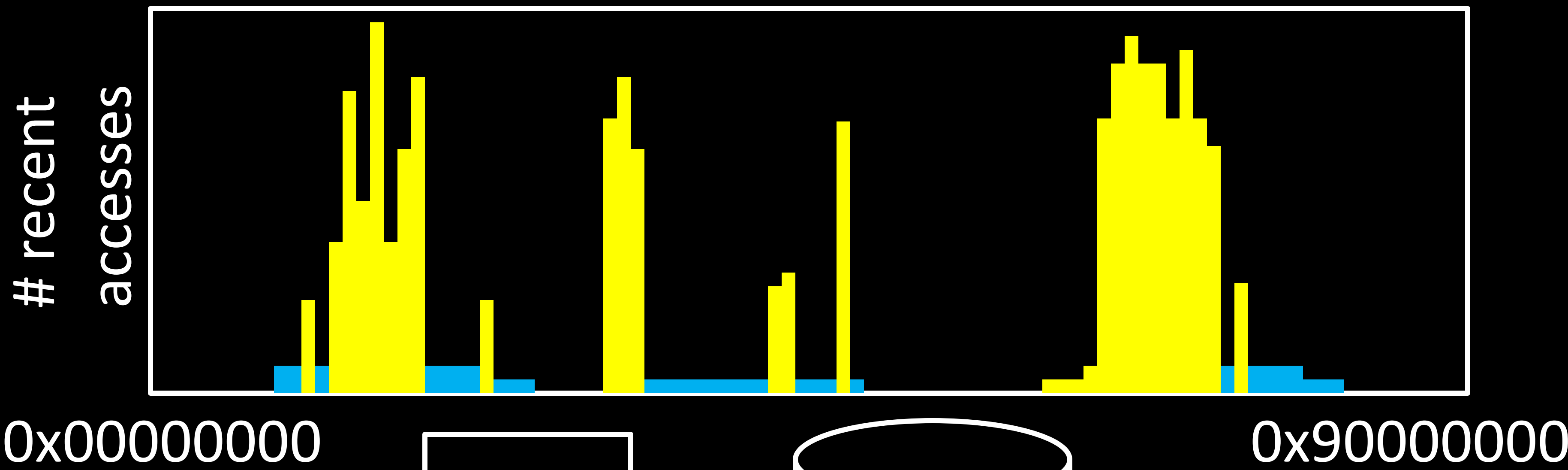
- Firefox will fault if it tries to access the page

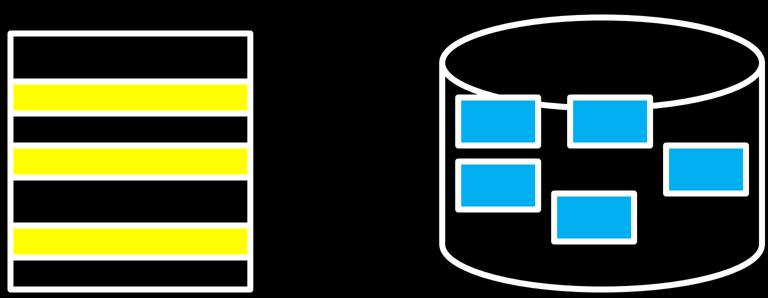
(5) Give the newly freed physical page to Skype

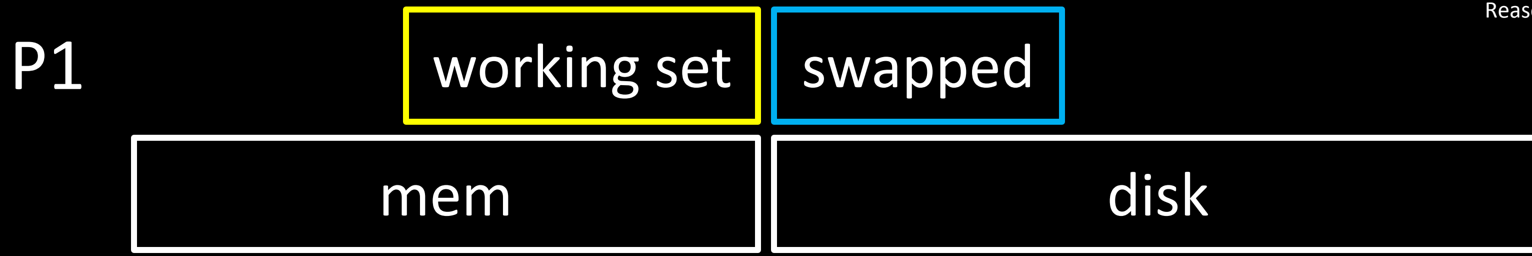
- clear the page (fill with zeros)
- add a new entry to Skyps's PageTable

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



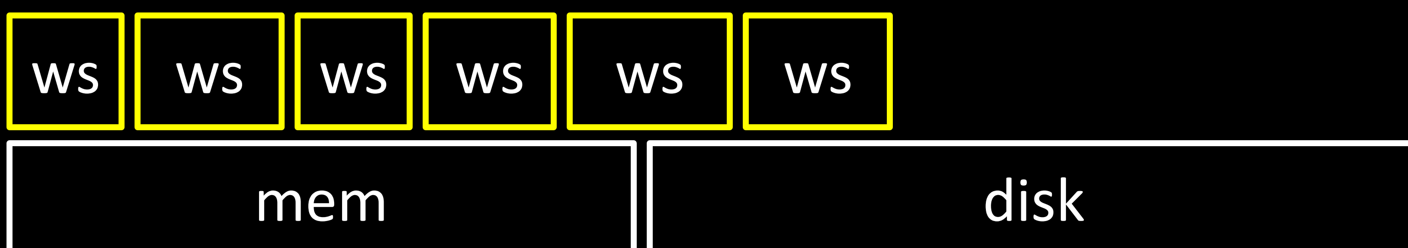




Q: What if working set is too large?

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

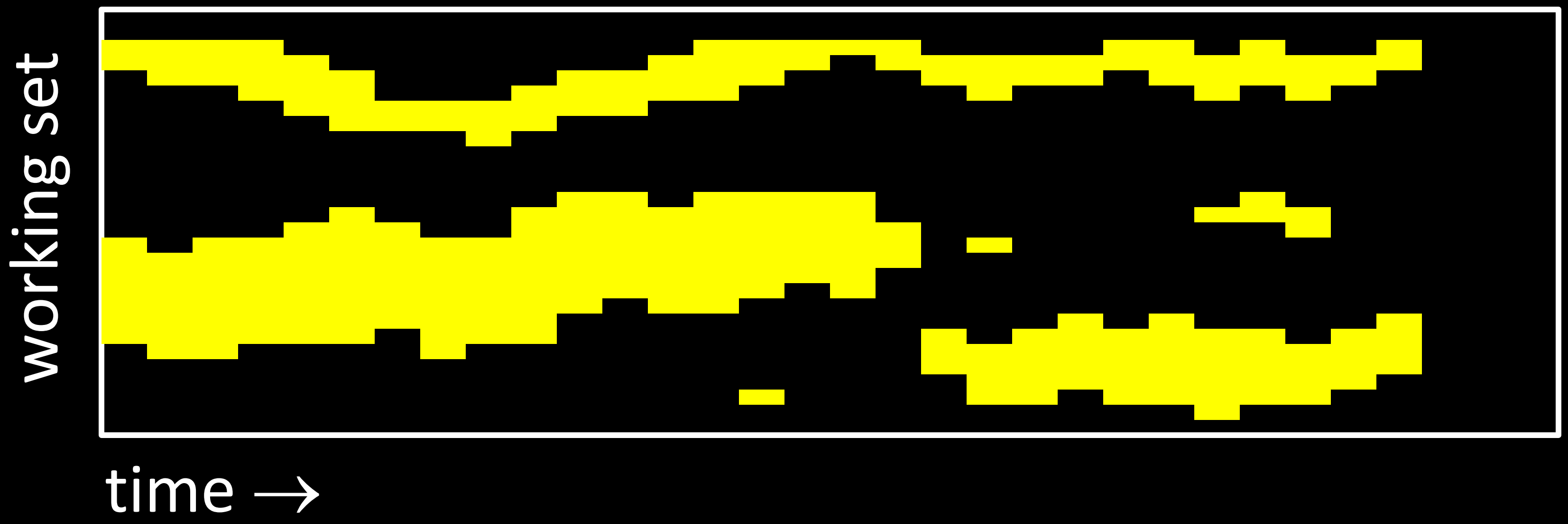
- I/O (disk activity) at 100% utilization
  - But no useful work is getting done

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

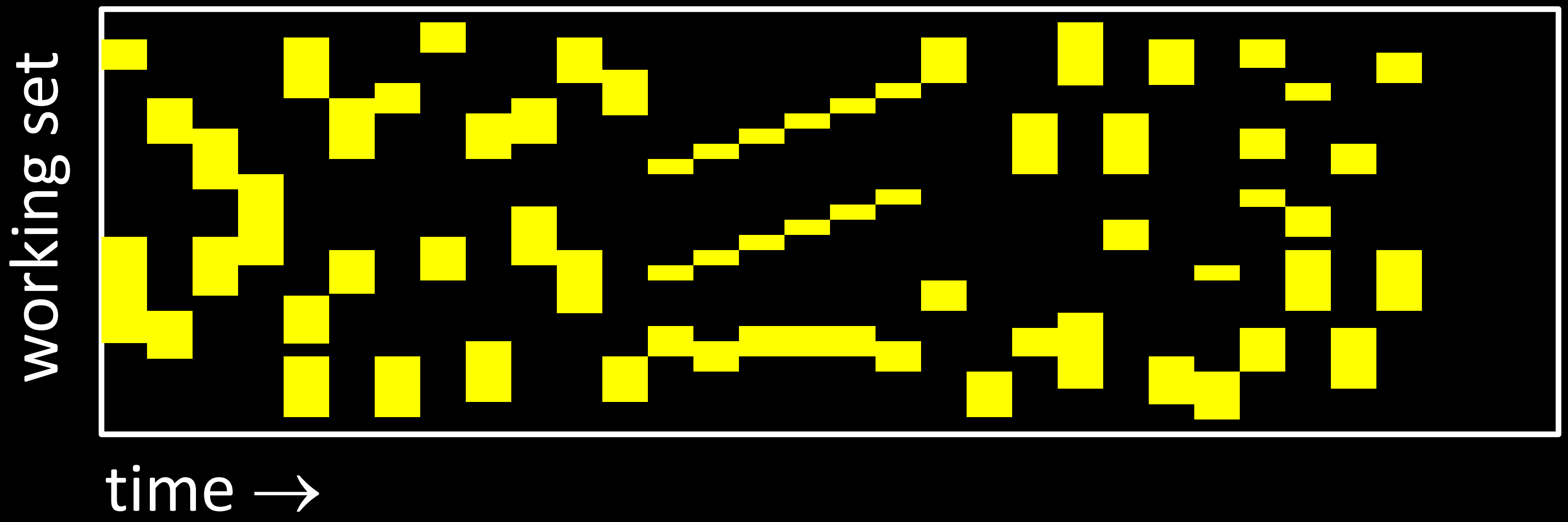
Non-ideal: Speed of disk

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.