Topic 18:
Virtual Memory

COS / ELE 375

Computer Architecture and Organization

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Princeton University
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Virtual Memory

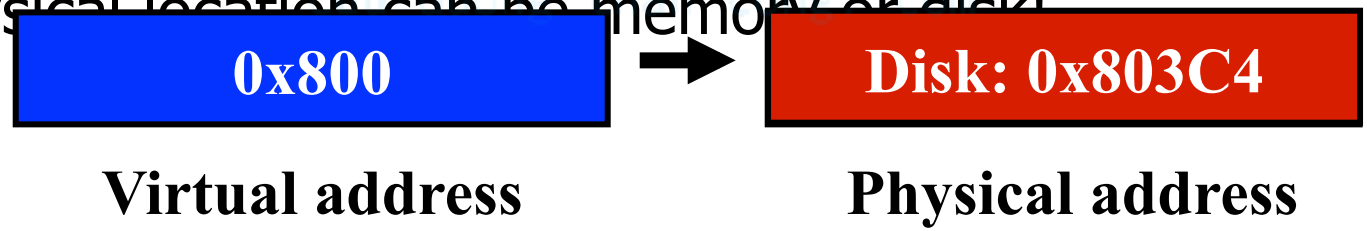
Any time you see virtual, think "using a level of indirection"

Virtual memory: level of indirection to physical memory

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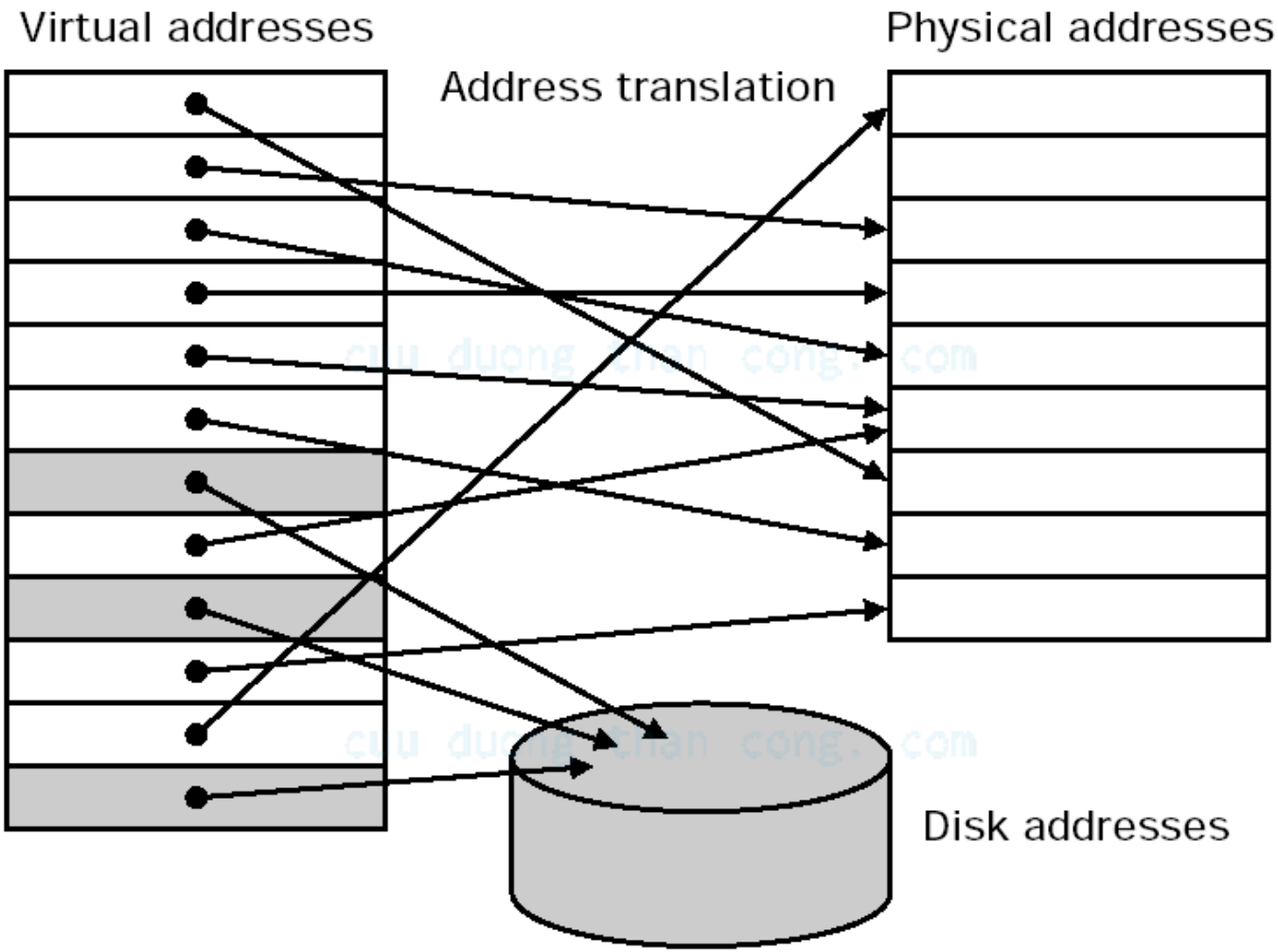
- Program uses virtual memory addresses
- Virtual address is converted to a physical address
- Physical address indicates physical location of data

- Physical location can be memory or disk!



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Virtual Memory



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Virtual Memory: Take 1

Main memory may not be large enough for a task

- Programmers turn to overlays and disk
- Many programs would have to do this
- Programmers should have to worry about main memory size across machines

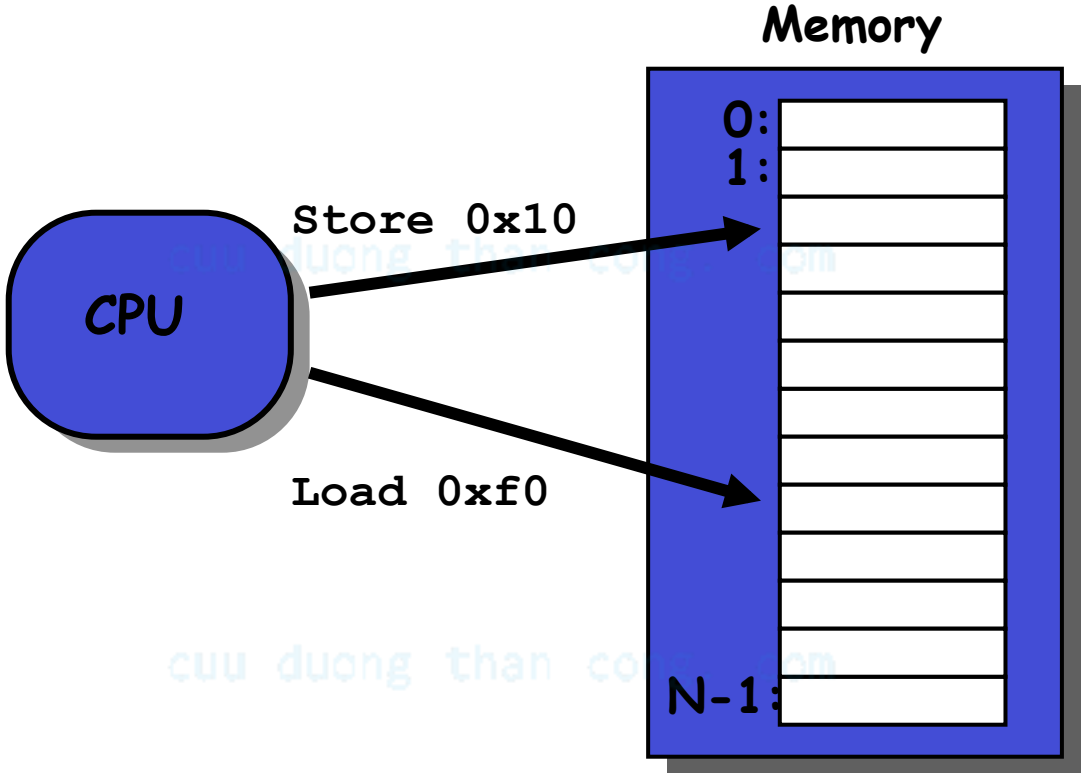
Use virtual memory to make memory look bigger for all programs

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A System with Only Physical Memory

Examples: Most Cray machines, early PCs, nearly all current embedded systems, etc.

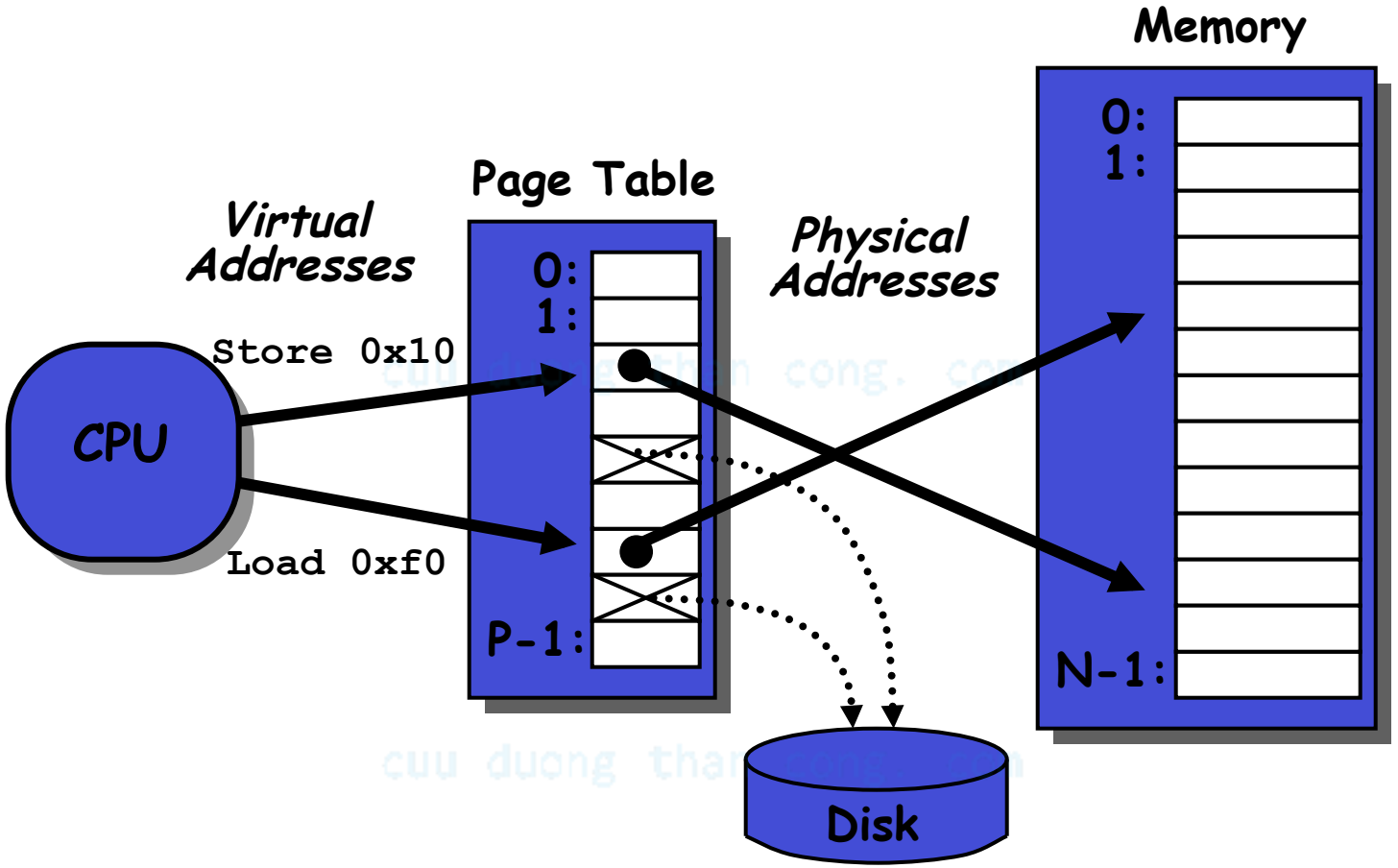


CPU's load or store addresses used directly to access memory.

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A System with Virtual Memory

Examples: modern workstations, servers, PCs, etc.



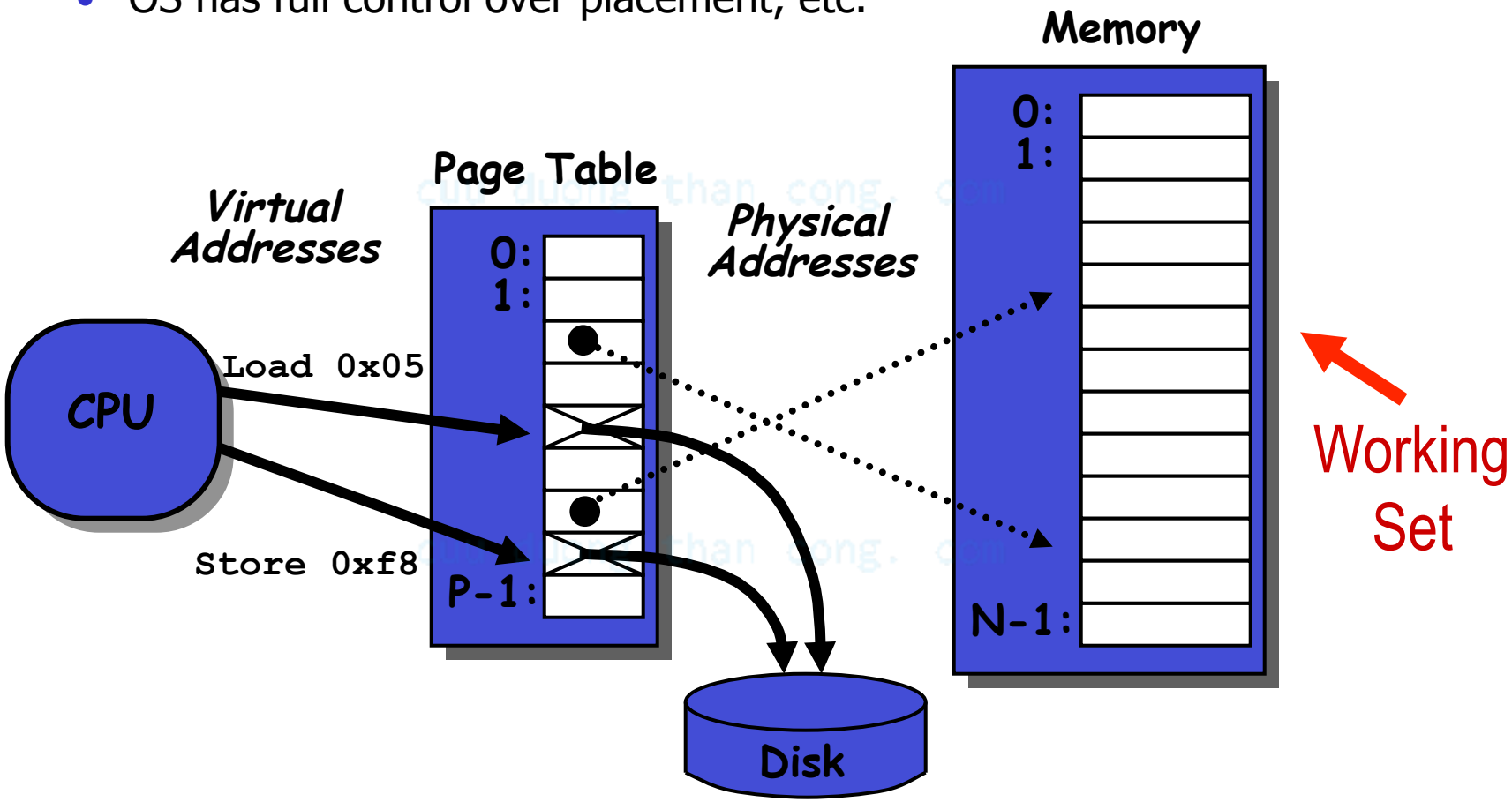
Address Translation: the hardware converts *virtual addresses* into *physical addresses* via an OS-managed lookup table (*page table*)

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Page Faults (Similar to "Cache Misses")

What if an object is on disk rather than in memory?

1. Page table indicates that the virtual address is not in memory
2. OS trap handler is invoked, moving data from disk into memory
   - Current process suspends, others can resume
   - OS has full control over placement, etc.



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Virtual Memory: Take 2

Concurrently executing programs will interfere in memory

- At some point, programs assume addresses
- These addresses may conflict if we don't manage them.
- Which programs will execute concurrently?
  - Don't know
  - Manage dynamically

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- Programs can maliciously interfere with each other!
- They need protection from one another

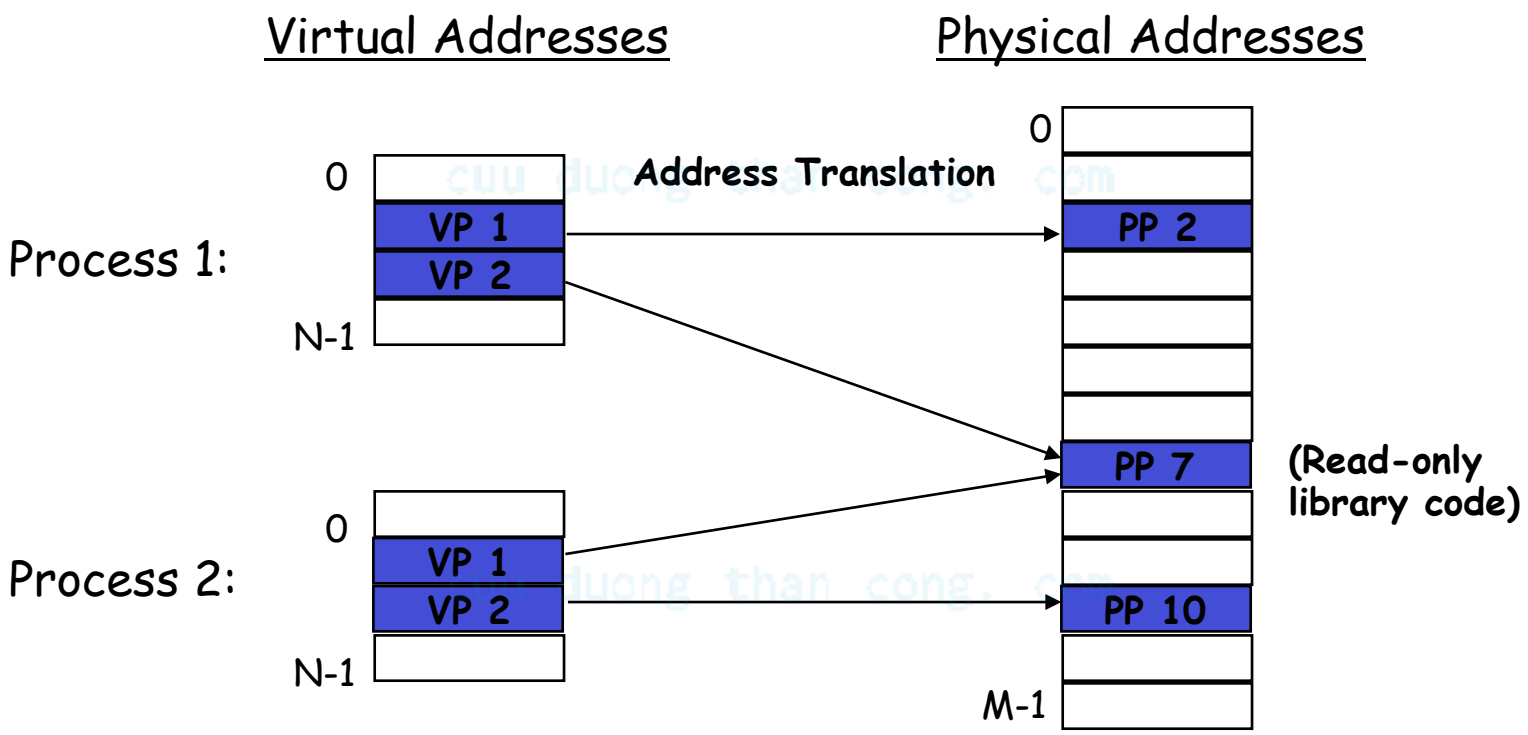
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Use virtual memory to avoid/manage conflict between programs

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Separate Virtual Address Spaces

- Each process has its own virtual address space
- OS controls how virtual is assigned to physical memory

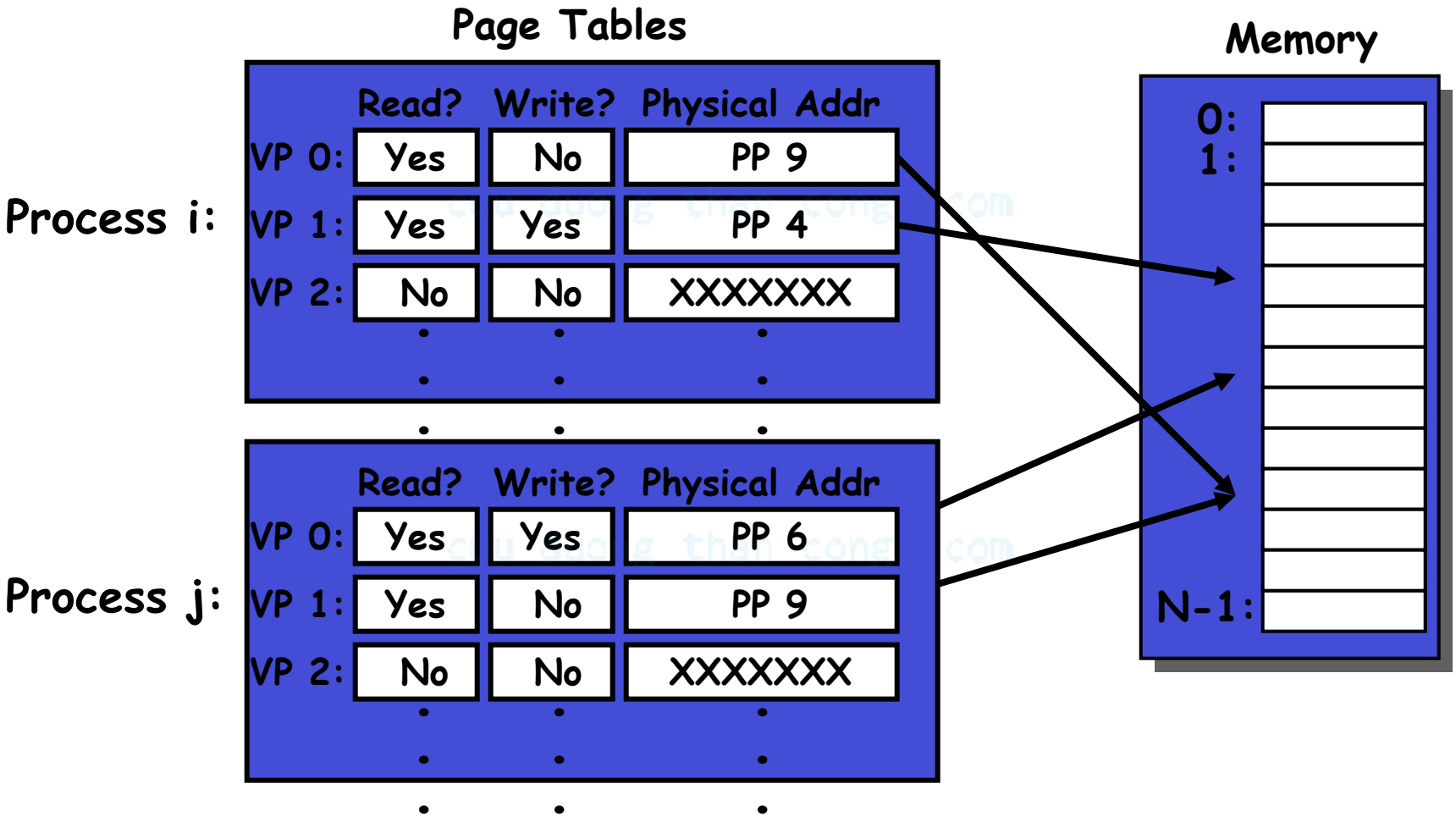


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Motivation: Process Protection

Page table entry contains access rights information

- Hardware enforces this protection (trap into OS if violation occurs)



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Virtual Memory: Take 3

Programs and data exist on disk

- Registers, caches, and memory just make using the data on disk faster
- Locality at different granularities

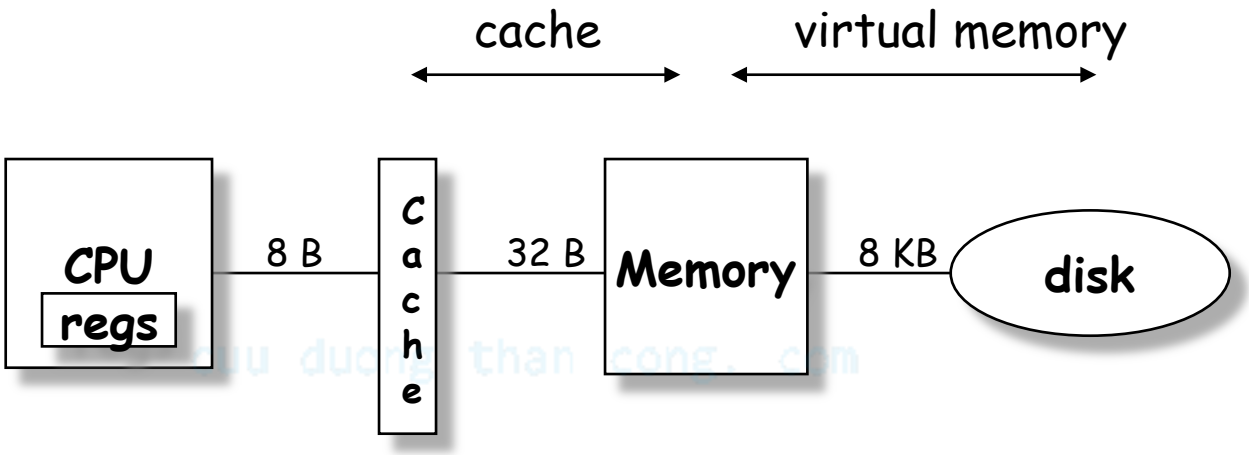
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Use virtual memory to improve performance, hide physical location from program

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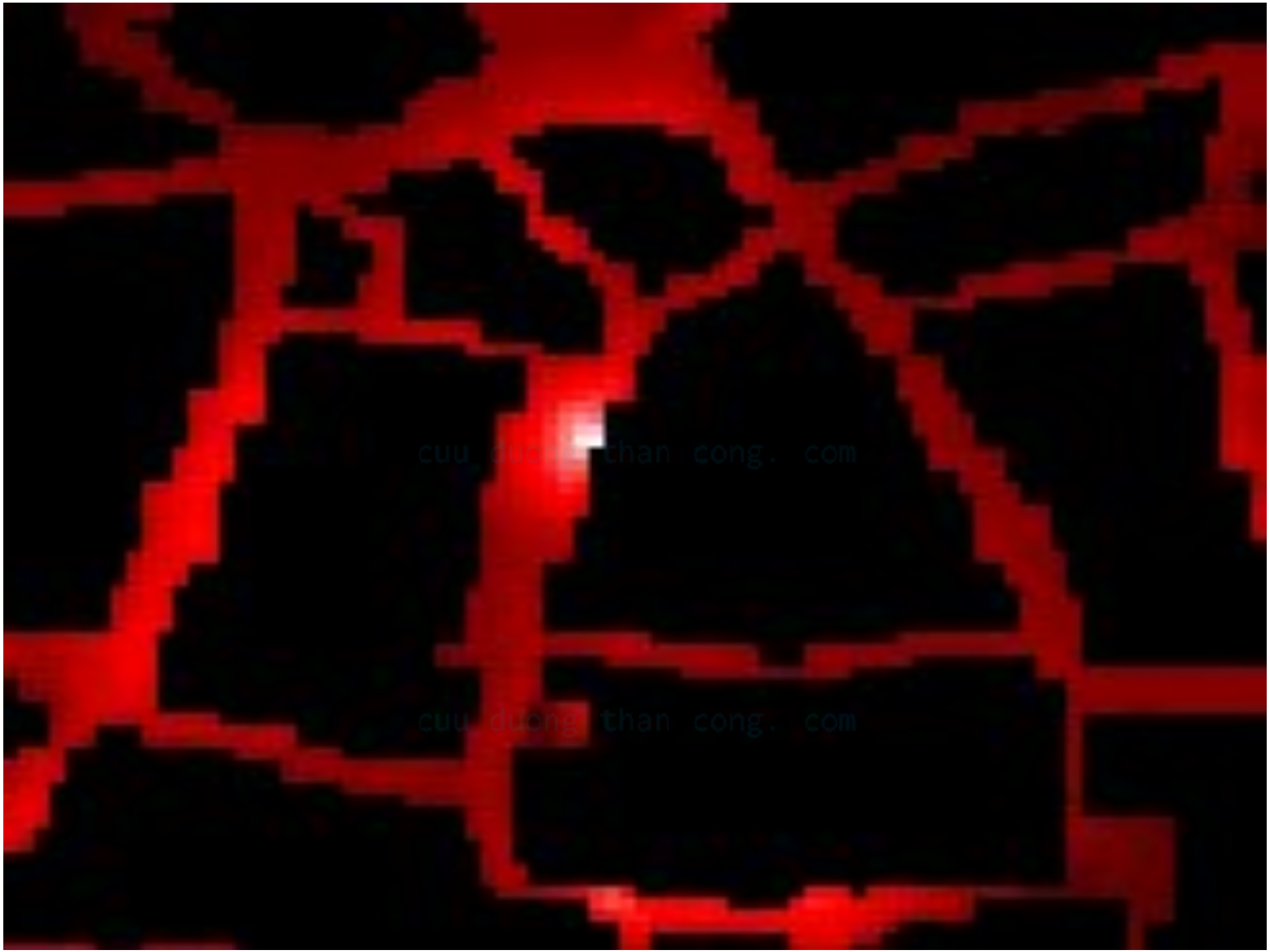
Levels in Memory Hierarchy



	Register	Cache	Memory	Disk Memory
size:	200 B	32 KB / 4MB	128 MB	20 GB
speed:	3 ns	6 ns	60 ns	8 ms
$/Mbyte:		$100/MB	$1.50/MB	$0.05/MB
block size:	8 B	32 B	8 KB	

larger, slower, cheaper

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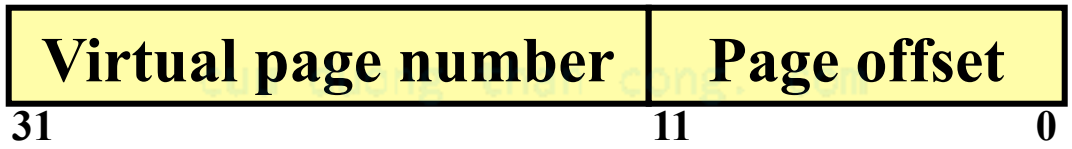
Virtual Memory

Just like caches, but origins are different

- Cache - performance goals
- Virtual Memory - programmability/multiprogram goals

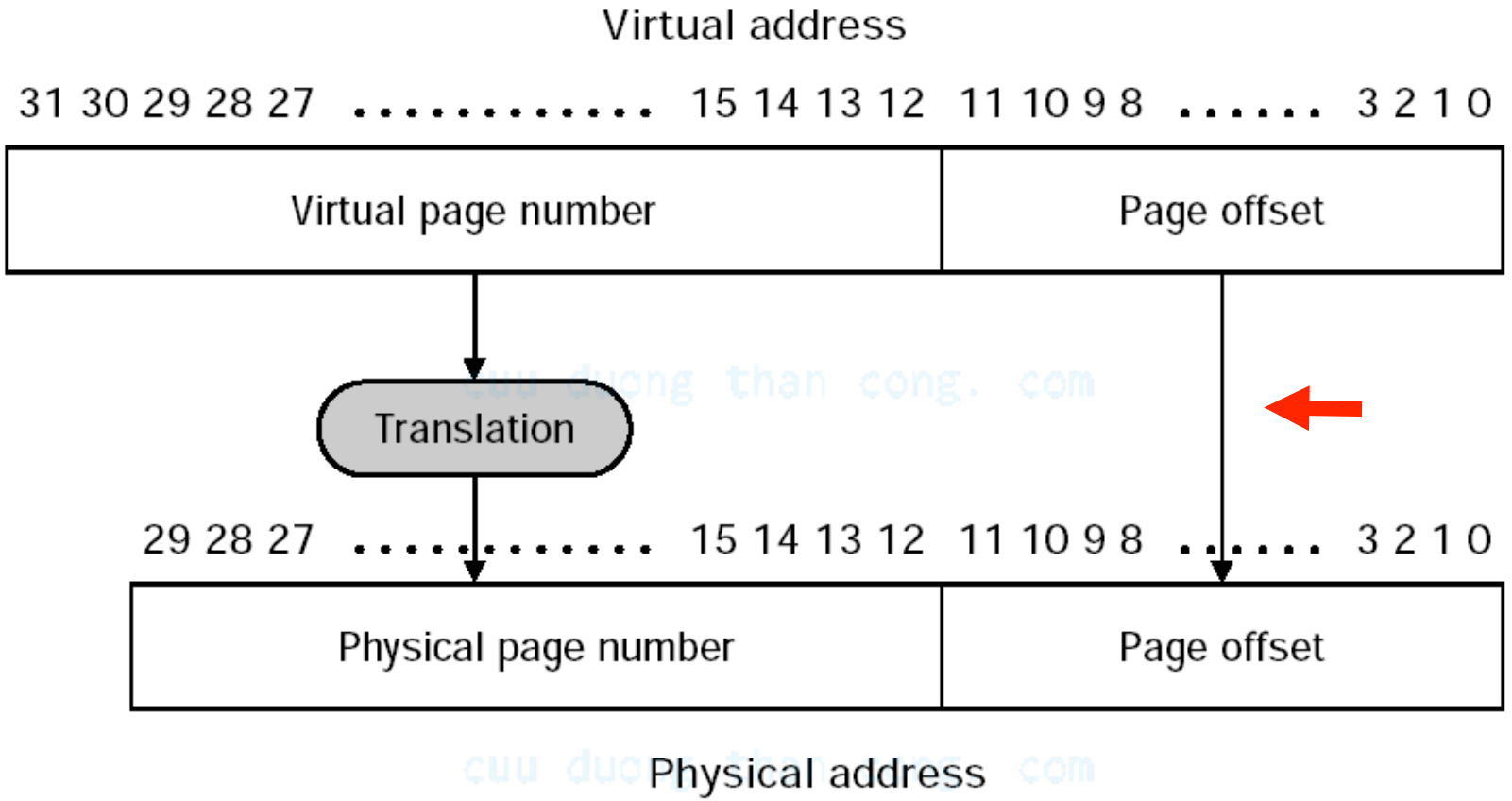
Blocks are called Pages

- A virtual address consists of
  - A virtual page number
  - A page offset field (low order bits of the address)



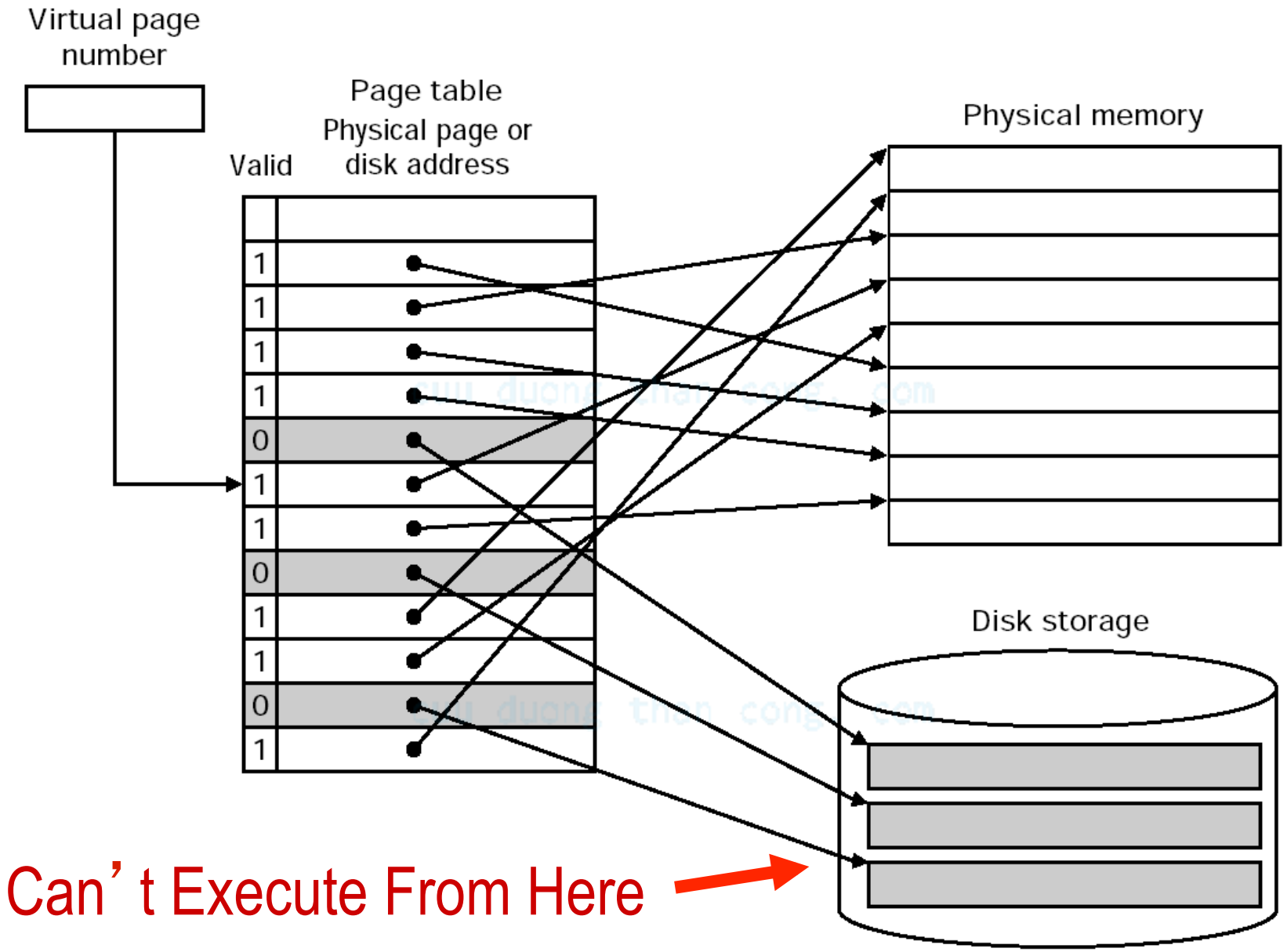
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Page Tables



Each process gets its own page table, why?

Page Tables



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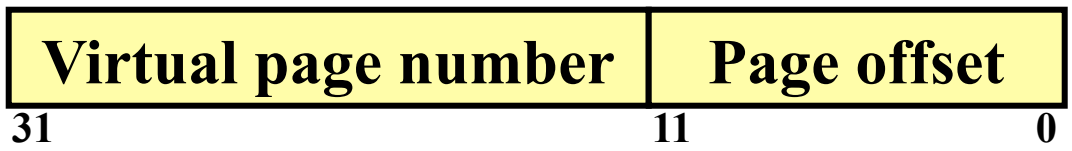
Page Faults

Blocks are called Pages

Page Tables translate virtual to physical page numbers

Misses are call Page faults (handled as an exception)

- Retrieve data from disk
- Huge miss penalty, pages are fairly large (how big?)
- Reducing page faults is important
- Can handle the faults in software instead of hardware
- Using write-through is too expensive, use writeback



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Servicing a Page Fault

1. Make space in memory by writing physical page to disk
   - Page Frames
   - Replacement policy?

2. Load page
   - Loading pages could waste processor time, use DMA
   - DMA allows processor to do something else

3. OS updates the process's page table
   - Desired data is in memory for process to resume

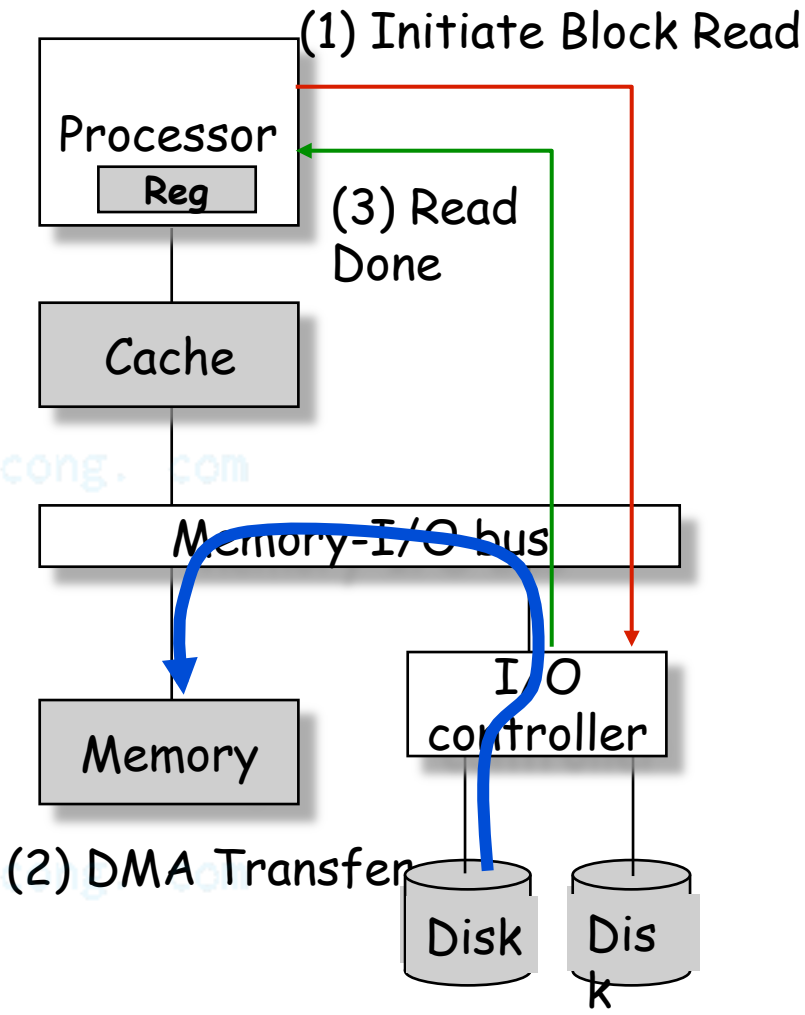
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Servicing a Page Fault

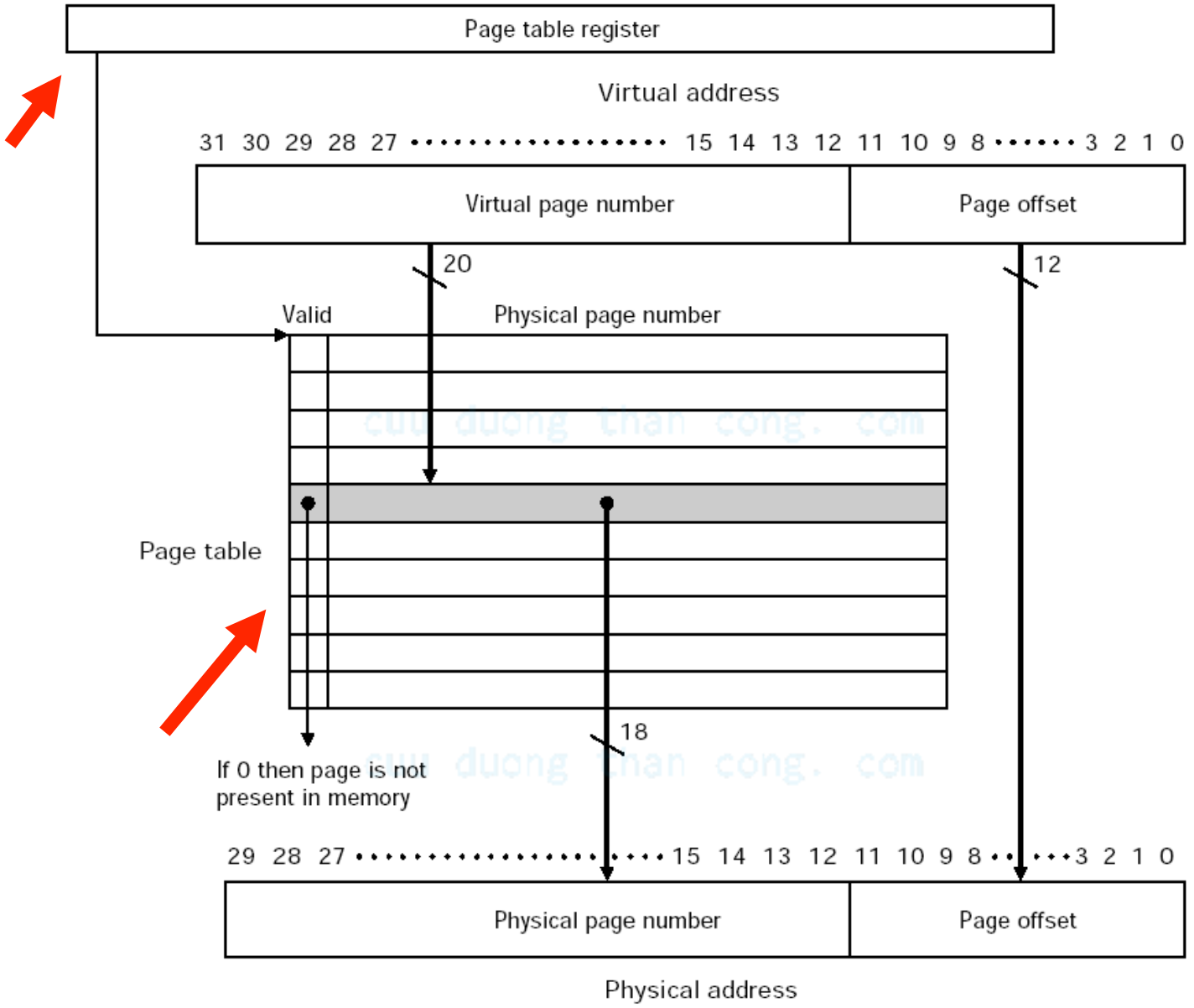
1. Processor Signals Controller

   "Read block of length P starting at disk address X and store starting at memory address Y"
2. DMA Read Occurs
3. I / O Controller Signals Completion
   - Interrupts processor
   - Can resume suspended process



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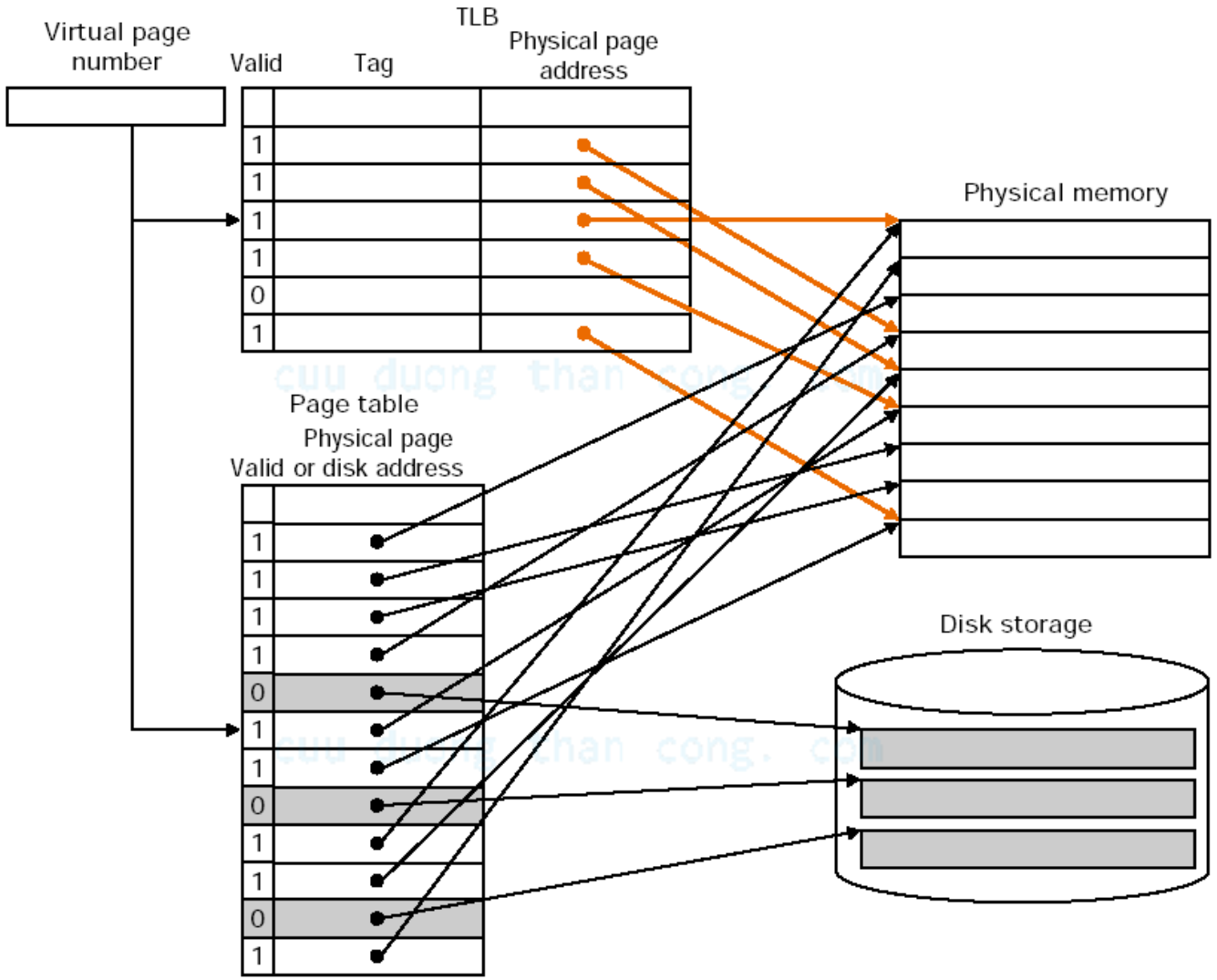
Where Is the Page Table?



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Making Translation Faster: The TLB

Translation Look-Aside Buffer



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TLB Design Issues

Accessed frequently: speed is important

TLB Miss Involves (not to be confused with page fault):

1. Stall pipeline
2. Invoke Operating System (what about OS pages?)
3. Read Page Table
4. Write entry in TLB (evicting old entry?)
5. Return to user code
6. Restart at reference



MIPS.
Another HW Option?

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TLB Design Issues

Clearly, we want to minimize TLB misses:

- Can be fully-associative, set-associative, or direct mapped
- Often fully associative, can be set associative

- Sized to maximize hits, but make timing
- Usually not more than 128, 256 entries (associtivity)

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Loading Your Program: A Neat Trick

1. Ask operating system to create a new process
2. Construct a page table for this process
3. Mark all page table entries as invalid with a pointer to the disk image of the program
4. Run the program and get an immediate page fault on the first instruction.

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Process Interactions

Virtual Addresses are per Process

Context Switch: Save “state”: regs, PC, page table (PTBR)

TLB?

- Could Flush TLB
  - Every time perform context switch
  - Refill for new process by series of TLB misses
  - ~100 clock cycles each

- Could Include Process ID Tag with TLB Entry
  - Identifies which address space being accessed
  - OK even when sharing physical pages

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Virtual Memory Summary

Virtual memory provides

- Protection and sharing
- Illusion of large main memory
- Speed/Caching (when viewed from disk perspective)

- Virtual Memory requires twice as many memory accesses, so cache page table entries in the TLB.

- Three things can go wrong on a memory access
  - TLB miss
  - Page fault
  - Cache miss



Caches and virtual memory?

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