Operating Systems

09. Memory Management – Part 1

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CPU Access to Memory

The CPU reads instructions and reads/write data from/to memory

Functional interface:

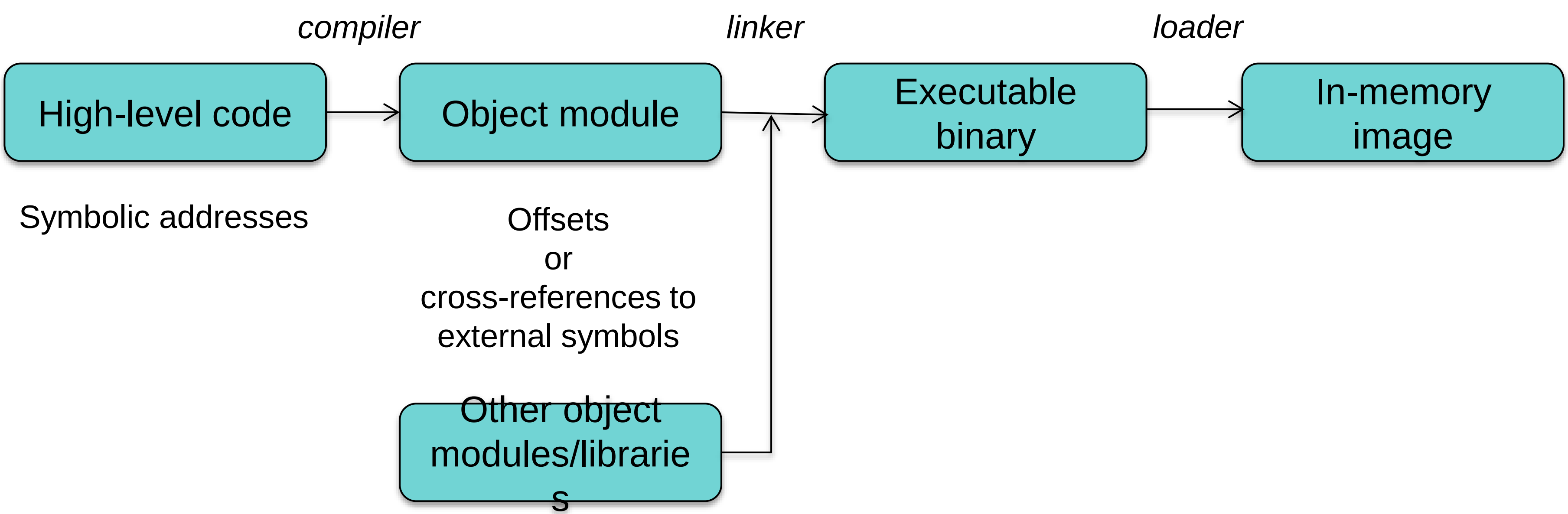
value = read(address)

write(*address*, *value*)

Programs have references to memory

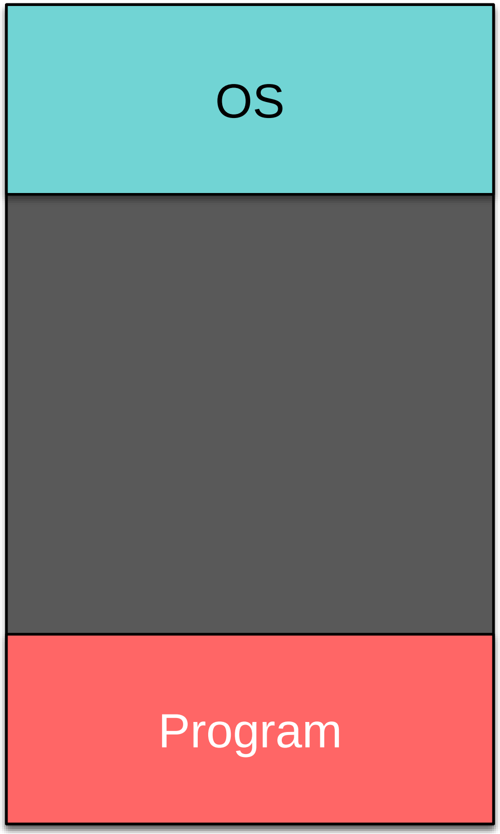
- Programs make use of memory addresses
  - Instruction execution: addresses for branching
  - Data access: addresses for reading/writing data

Static linking



Monoprogramming

- Run one program at a time
- Share memory between the program and the OS

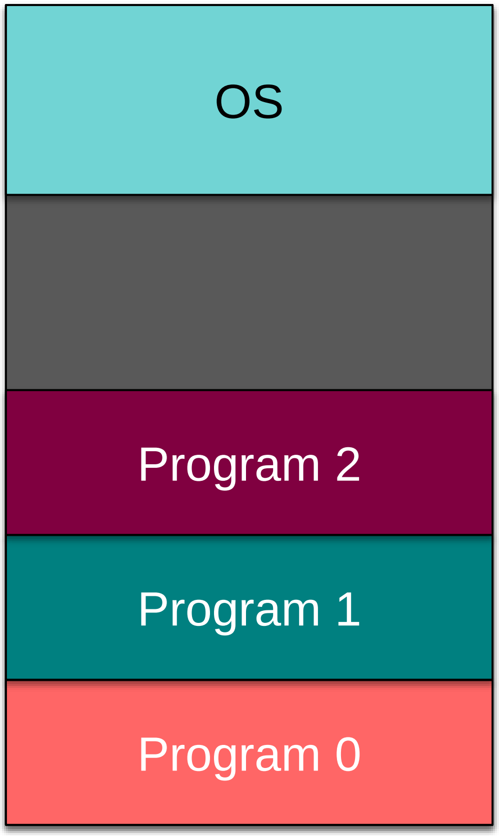


Absolute memory addresses are no problem

This was the model in old MS-DOS (and other) systems

Multiprogramming

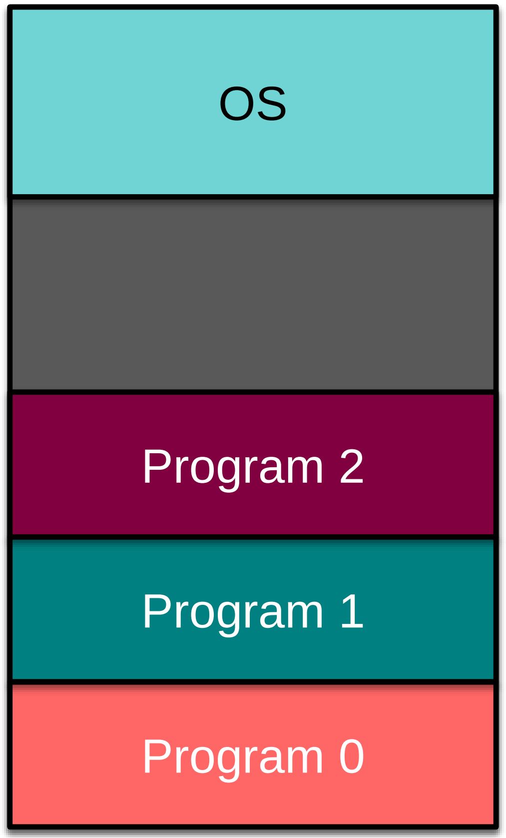
- Keep more than one process in memory
- More processes in memory improves CPU utilization



Absolute memory addresses are a problem!!

Justifying Multiprogramming: CPU Utilization

- Keep more than one process in memory
- More processes in memory improves CPU utilization



- If a process spends 20% of its time computing, then would switching among 5 processes give us 100% CPU utilization?
- Not quite. For *n* processes, if p = *% time a process is blocked* on I/O then:

  probability all are blocked = p^n

- CPU is not idle for $(1-p^n)$ of the time
- 5 processes: 67% utilization

How do programs specify memory access?

- Absolute code

  If you know where the program gets loaded (any relocation is done at link time)

- Position independent code

  All addresses are relative (e.g., gcc –fPIC option)

- Dynamically relocatable code

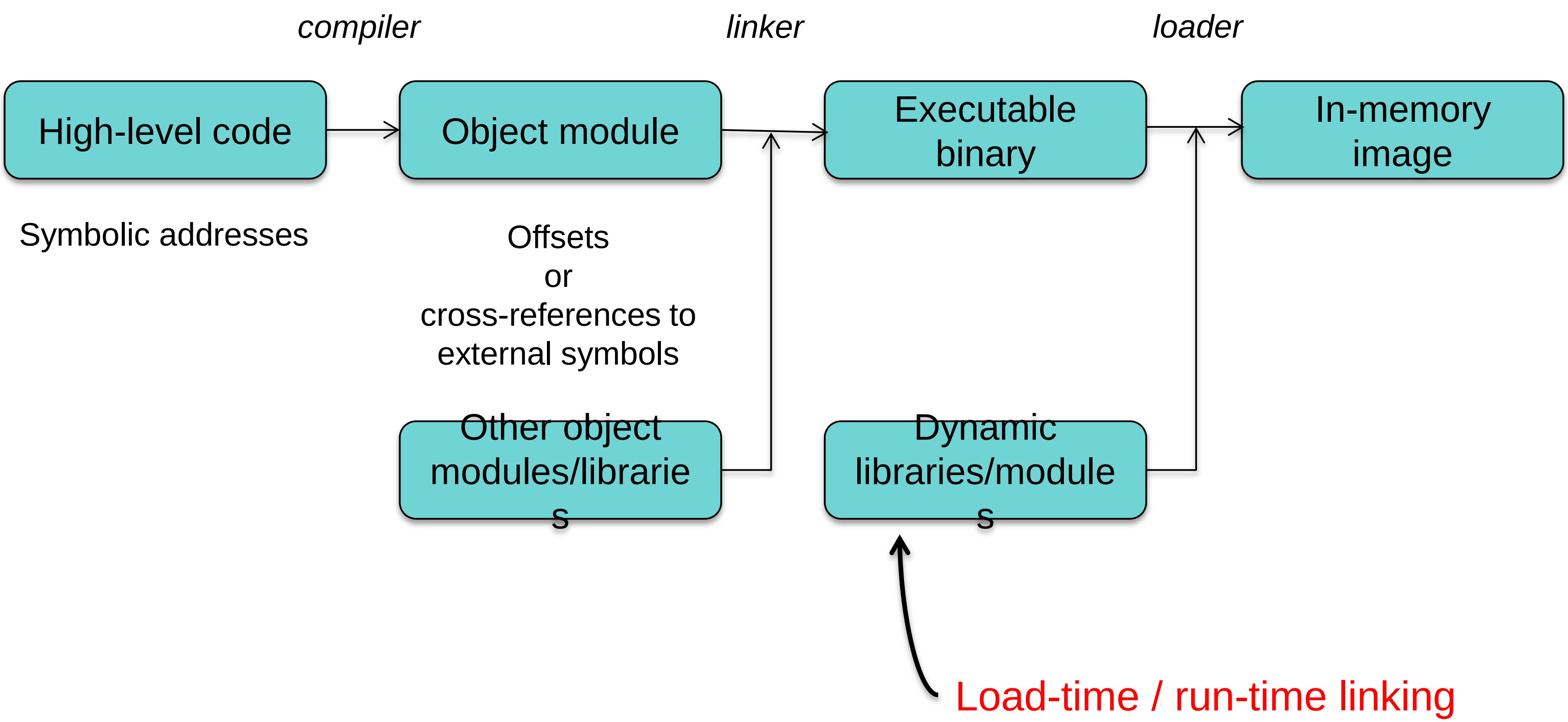
  Relocated at load time

- Or … use **logical addresses**

  Absolute code with with addresses translated at run time

  Need special memory translation hardware

Dynamic Linking



Dynamic Linking

- A process loads libraries at load time
  - Symbol references are resolved at load time
- OS loader finds the dynamic libraries and brings them into the process' memory address space

Dynamic Loading

- A process can load a module at runtime on request
  - Similar to dynamic linking
  - Program is written to load a specific library
  - Resolve symbols to get pointers to data & functions

- The library can be unloaded when not needed

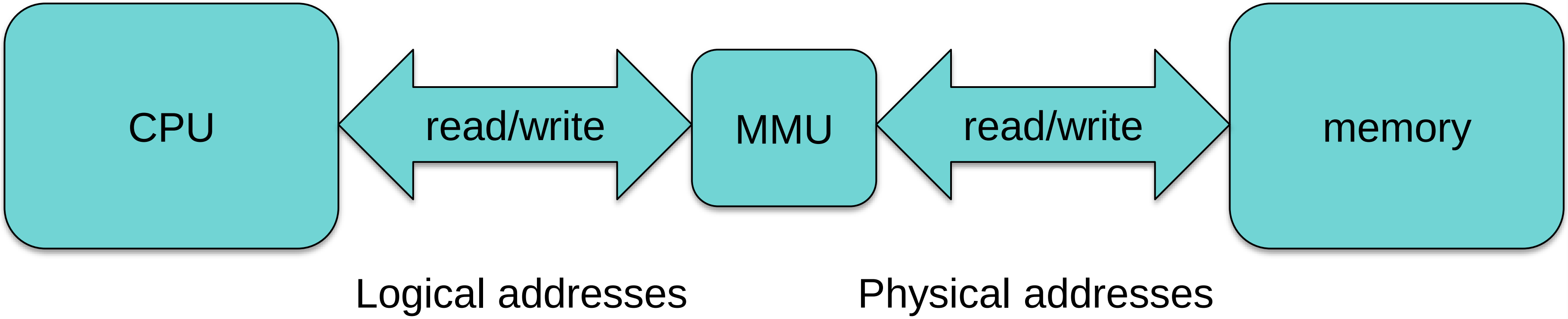
Shared libraries

- Dynamic linking + sharing
- Libraries that are loaded by programs when they start
  - All programs that start later use the shared library
  - Program loader searches for needed shared libraries
- Object code is linked with a stub
  - Stub checks whether the needed library is in memory
  - If not, the stub loads it
  - Stub is then replaced with the address of the library
- Operating system:
  - Checks if the shared library is already in another process' memory
  - Shares memory region among processes
- Need position independent code or pre-mapped code (reserved regions of memory that processes share)

Logical addressing

Memory management unit (MMU):

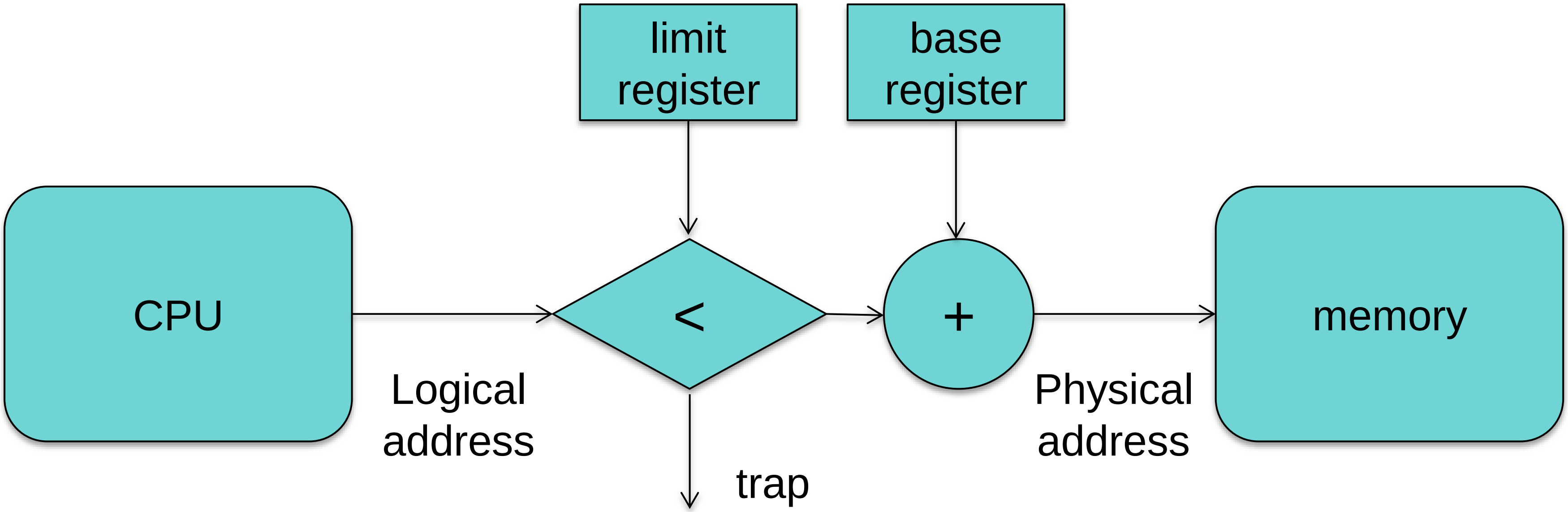
Real-time, on-demand translation between *logical* (virtual) and *physical* addresses



Relocatable addressing

Base & limit

- *Physical address = logical address + base register*
- But first check that: *logical address < limit*



Allocating memory

Multiple Fixed Partitions

- Divide memory into predefined partitions (segments)
  - Partitions don't have to be the same size
  - For example: a few big partitions and many small ones
- New process gets queued for a partition that can hold it
- Unused memory in a partition is wasted
  - *Internal fragmentation*
  - Unused partitions: *external fragmentation*
- Contiguous allocation:
  Process takes up a contiguous region of memory

Variable partition multiprogramming

- Create partitions as needed
- New process gets queued
- OS tries to find a hole for it

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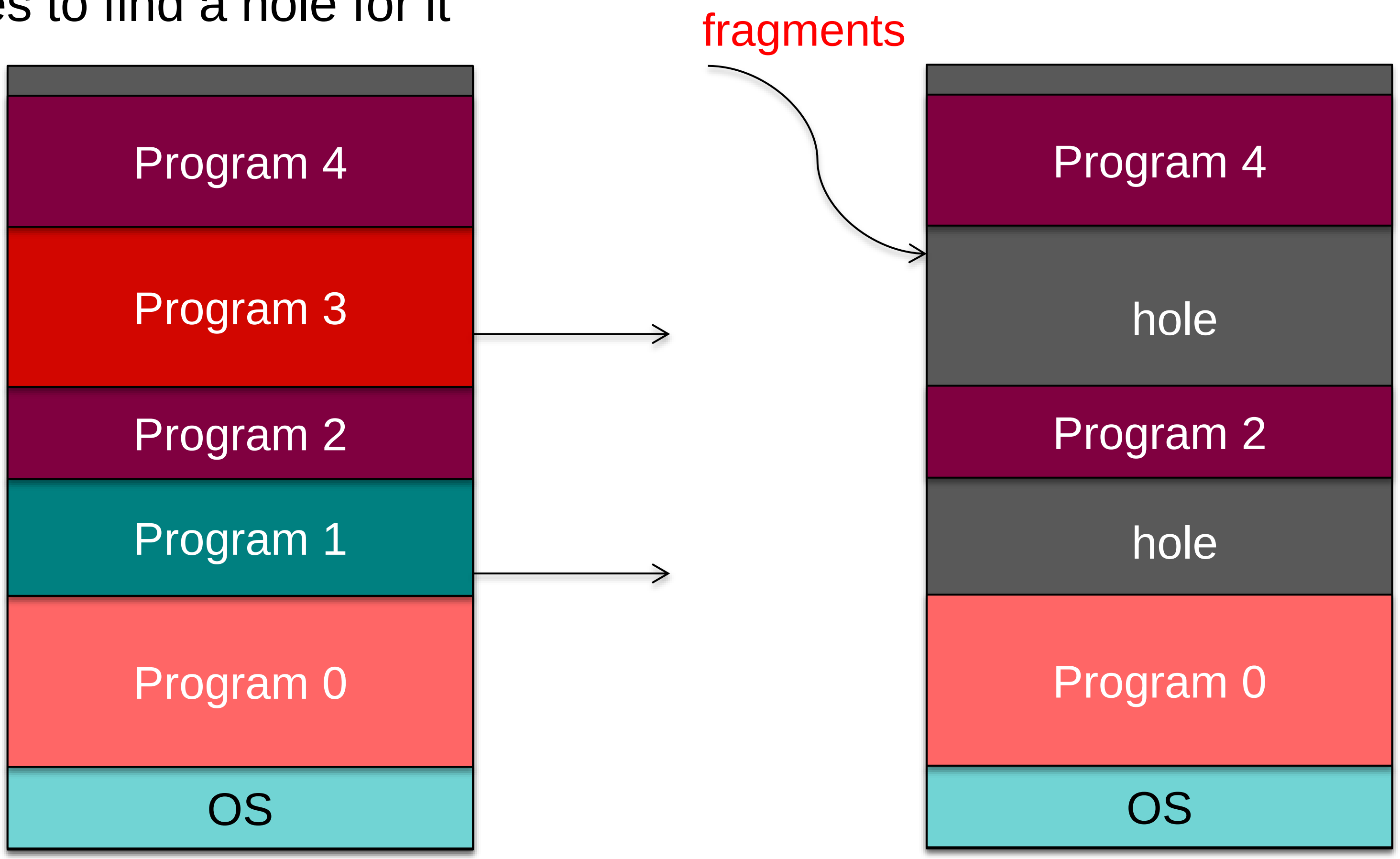


Allocation algorithms

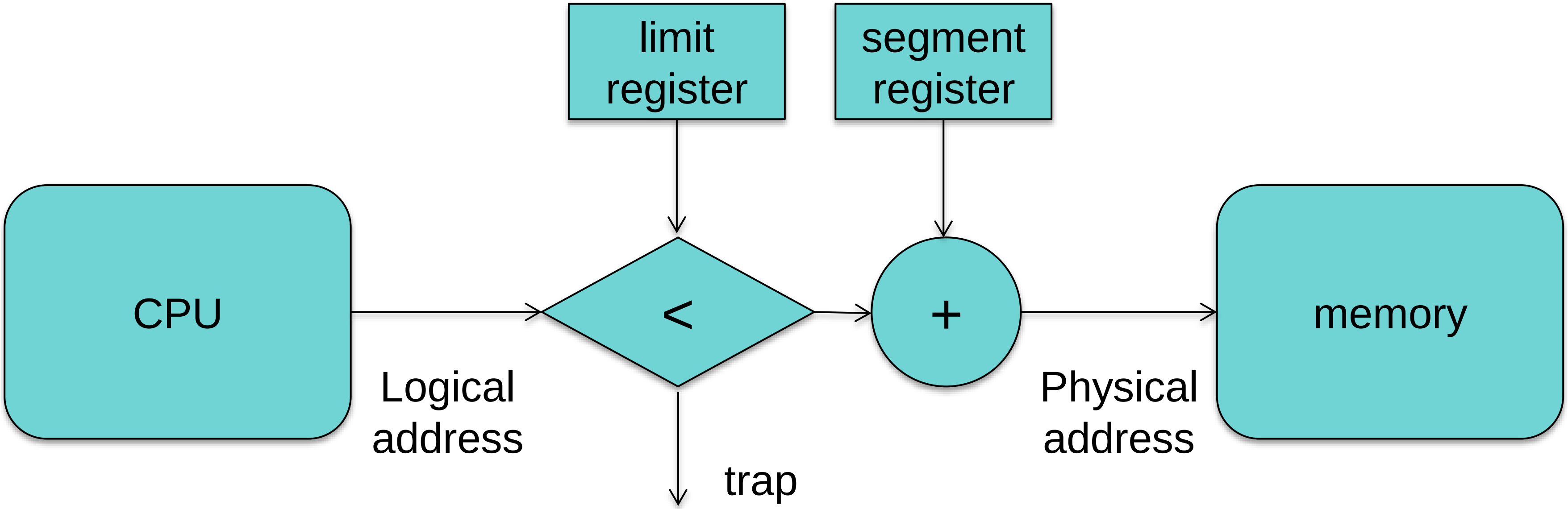
- First fit: find the first hole that fits
- Best fit: find the hole that best fits the process
- Worst fit: find the largest available hole
  - *Why?* Maybe the remaining space will be big enough for another process. In practice, this algorithm does not work well.

Variable partition multiprogramming

- What if a process needs more memory?
  - Always allocate some extra memory just in case
  - Find a hole big enough to relocate the process
- Combining holes (fragments)
  - Memory compaction
  - Usually not done because of CPU time to move a lot of memory

Segmentation hardware

- Divide a process into segments and place each segment into a partition of memory
  - Code segment, data segment, stack segment, etc.
- Discontiguous memory allocation

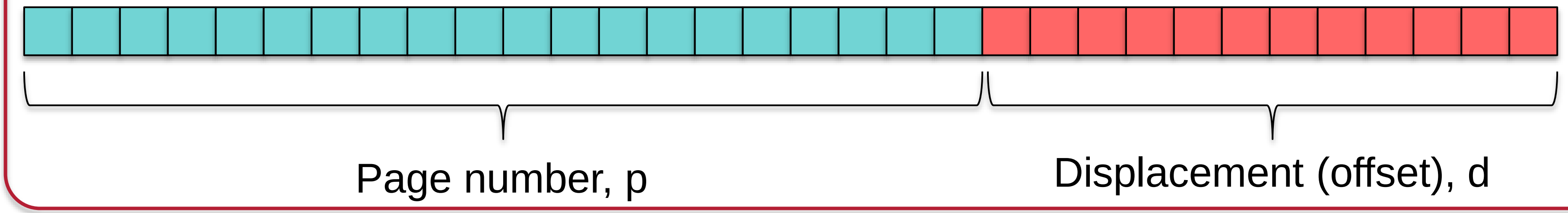


Paging

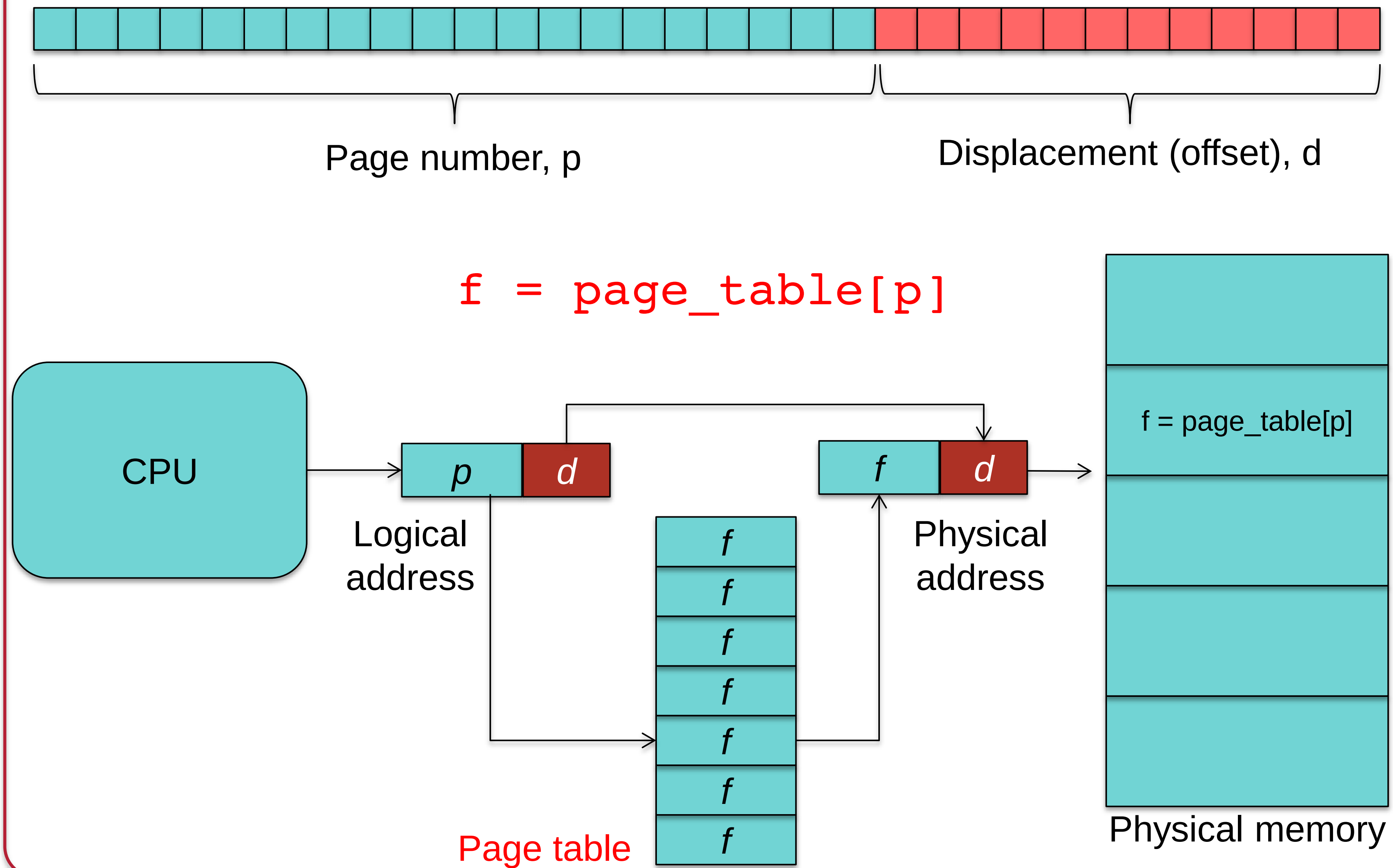
- Memory management scheme
  - Physical space can be non-contiguous
  - No fragmentation problems
  - No need for compaction
- Paging is implemented by the Memory Management Unit (MMU) in the processor

Paging

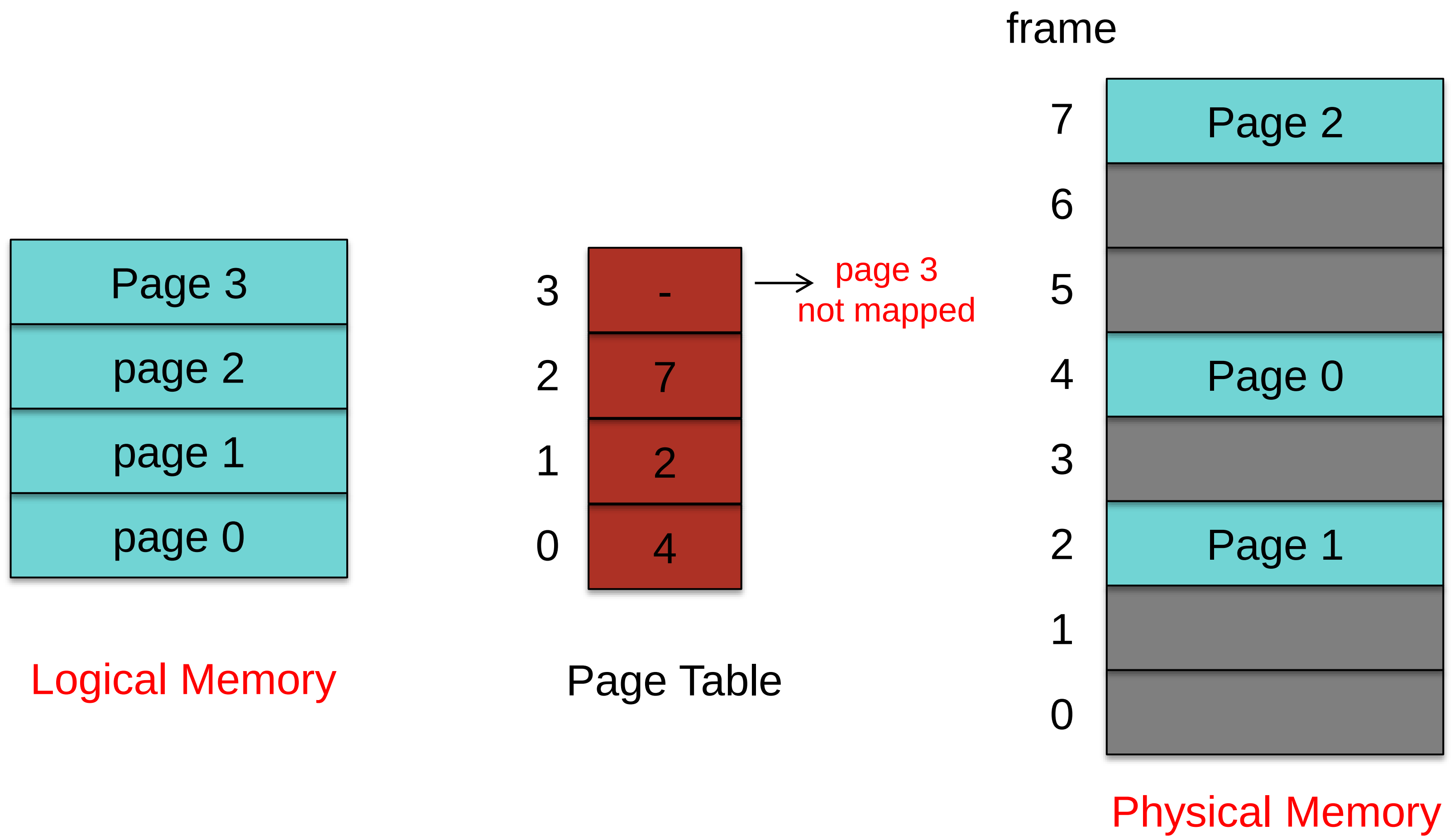
- Translation:
  - Divide physical memory into fixed-size blocks: page frames
  - A logical address is divided into blocks of the same size: pages
  - All memory accesses are translated: page → page frame
  - A page table maps pages to frames
- Example:
  - 32-bit address, 4 KB page size:
    - Top 20 bits identify the page number
    - Bottom 12 bits identify offset within the page/frame



Page translation



Logical vs. physical views of memory



Hardware Implementation

- Where do you keep the page table?
  In memory

- Each process gets its own virtual address space
  - Each process has its own page table
  - Change the page table by changing a *page table base register*
    - CR3 register on Intel IA-32 and x86-64 architectures

- Memory translation is now slow!
  - To read a byte of memory, we need to read the page table first
  - Each memory access is now 2x slower!

Hardware Implementation: TLB

- Cache frequently-accessed pages
  - Translation lookaside buffer (TLB)
  - Associative memory: key (page #) and value (frame #)
- TLB is on-chip & fast … but small (64-1,024 entries)
  - Locality in the program ensures lots of repeated lookups
- TLB miss = page # not cached in the TLB
  - Need to do page table lookup in memory
- Hit ratio = % of lookups that come from the TLB

Address Space Identifiers: Tagged TLB

- There is only one TLB per system
- When we context switch, we switch address spaces
  - New page table
  - BUT … TLB entries belong to the old address space
- Either:
  - Flush (invalidate) the entire TLB
  - Have a Tagged TLB with an Address Space Identifier (ASID)

Protection

- An MMU can enforce memory protection

- Page table stores status & protection bits per frame
  - Valid/invalid: is there a frame mapped to this page?
  - Read-only
  - No execute
  - Kernel only access
  - Dirty: the page has been modified since the flag was cleared
  - Accessed: the page has been accessed since the flag was cleared

Multilevel (Hierarchical) page tables

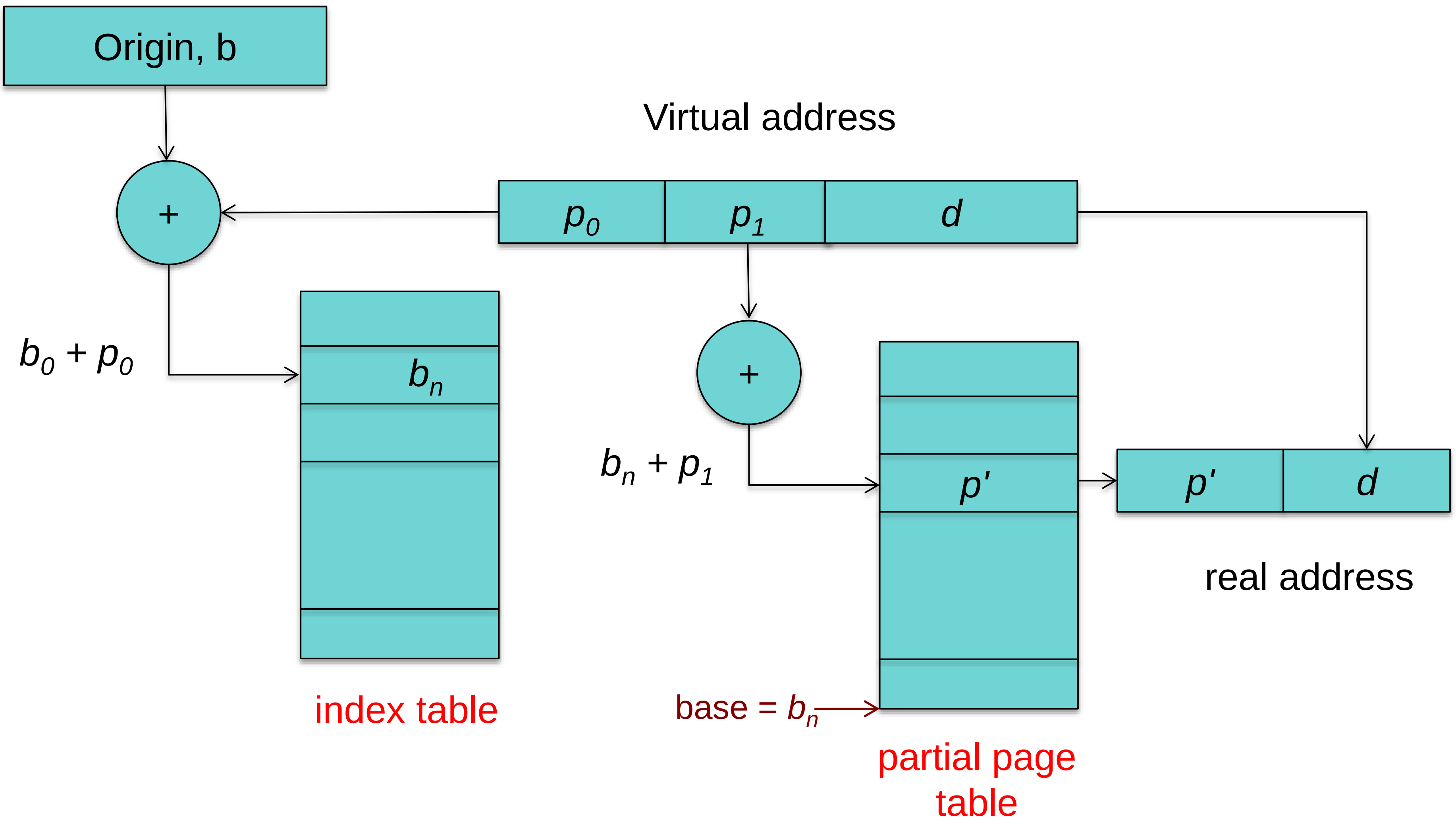
- Most processes use only a small part of their address space

- Keeping an entire page table is wasteful
  - Example

    32-bit system with 4KB pages: 20-bit page table

    $\Rightarrow 2^{20}$ = 1,048,576 entries in the page table

Multilevel page table



Inverted page tables

- # of pages on a system may be huge
- # of page frames will be more manageable (limited by physical memory)
- Inverted page table
  - i^{th} entry: contains info on what is in page frame *i*
- Table access is no longer a simple index but a search
  - Use hashing and take advantage of associative memory

Next Lecture

- Sharing memory across address spaces
- Copy on write
- Demand paging
  - Load needed pages on demand
  - Page faults
  - Page replacement: FIFO, LRU, second chance
  - Thrashing
  - Working set: time window

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The End

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