Main Memory: Address Translation

(Chapter 8)

CS 4410
Operating Systems

Cornell University
Cornell CIS
Computing and Information Science

Can’t We All Just Get Along?

Physical Reality: different processes/threads share the same hardware → need to multiplex

- CPU (temporal)
- Memory (spatial)
- Disk and devices (later)

Why worry about memory sharing?

- Complete working state of process and/or kernel is defined by its data in memory (+ registers)
- Don’t want different threads to have access to each other’s memory (protection)

Aspects of Memory Multiplexing

Isolation

Don’t want distinct process states collided in physical memory (unintended overlap → chaos)

Sharing

Want option to overlap when desired (for communication)

Virtualization

Want to create the illusion of more resources than exist in underlying physical system

Utilization

Want to best use of this limited resource

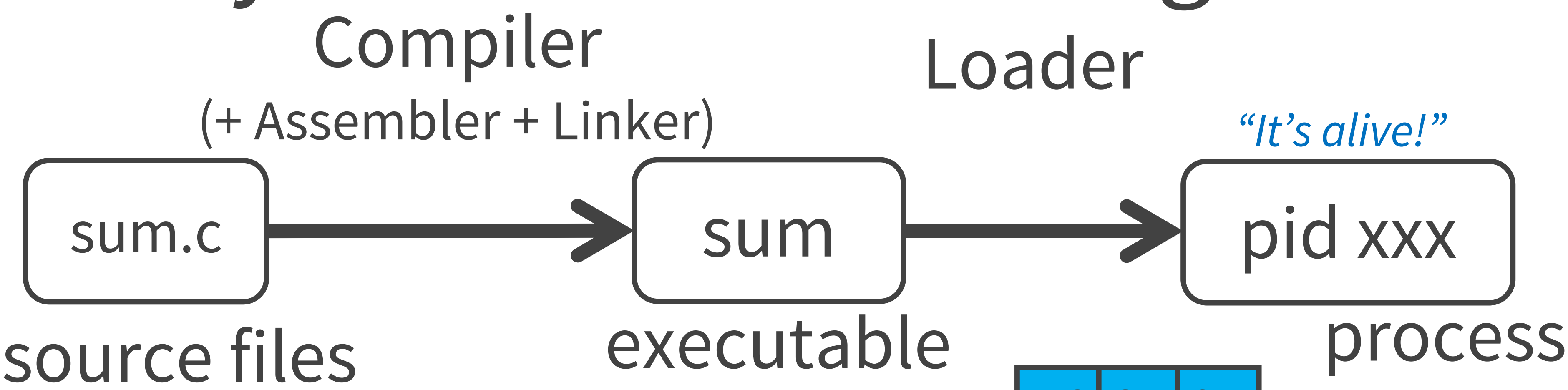
Address Translation

- Paged Translation
- Efficient Address Translation

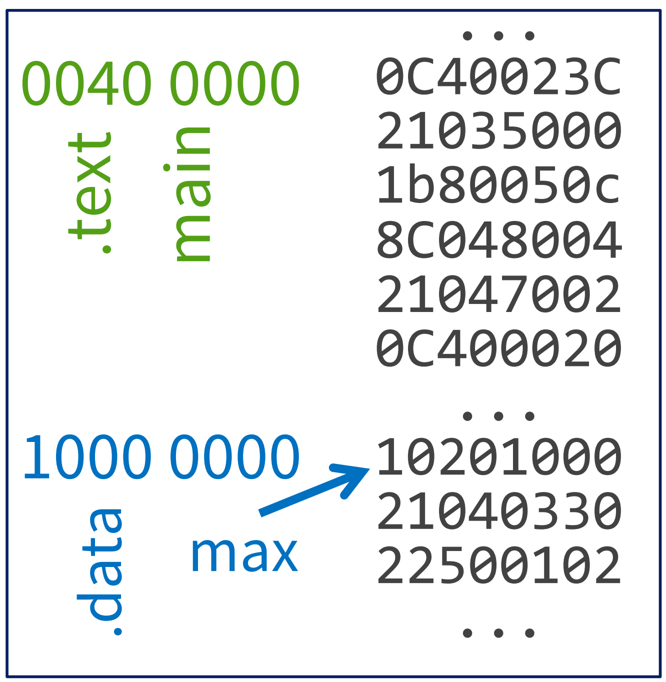
All in the context of the OS

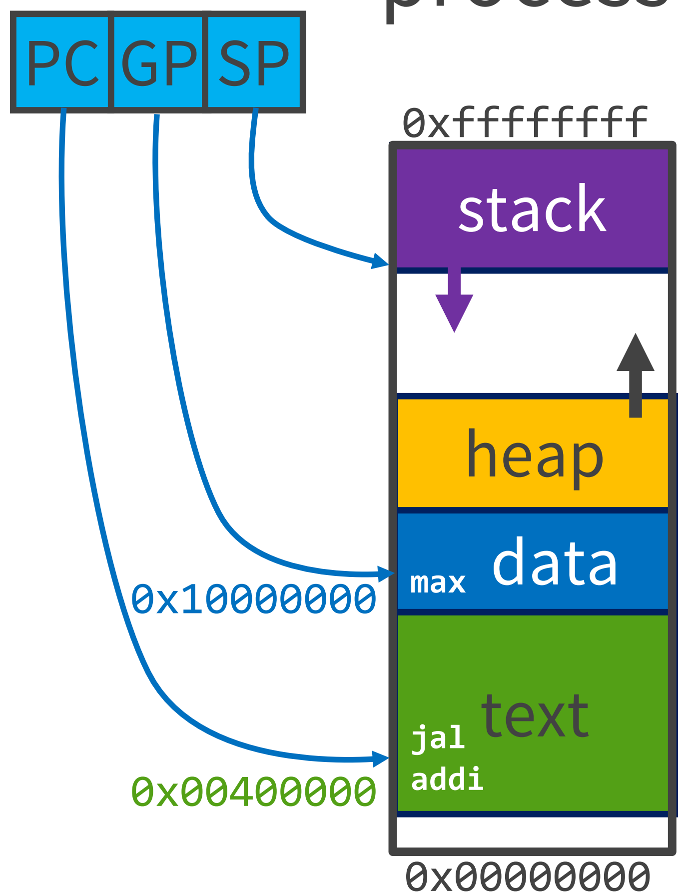
Social Network

A Day in the Life of a Program

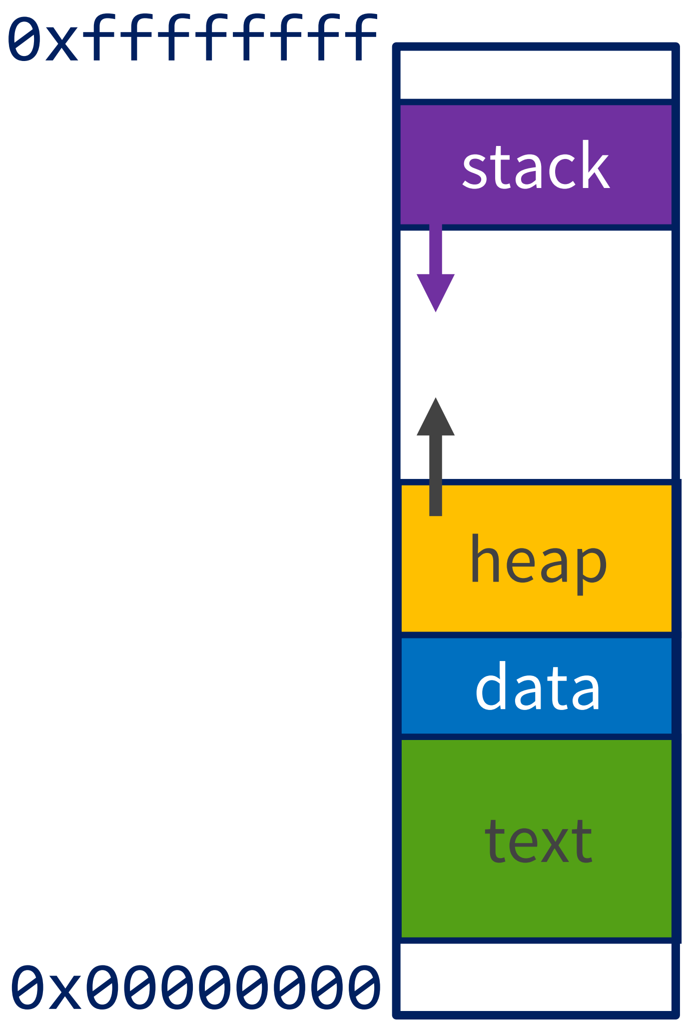



```c
#include <stdio.h>

int max = 10;

int main () {
    int i;
    int sum = 0;
    add(m, &sum);
    printf("%d",i);
    ...

}
```





Logical view of process memory



What’s wrong with this

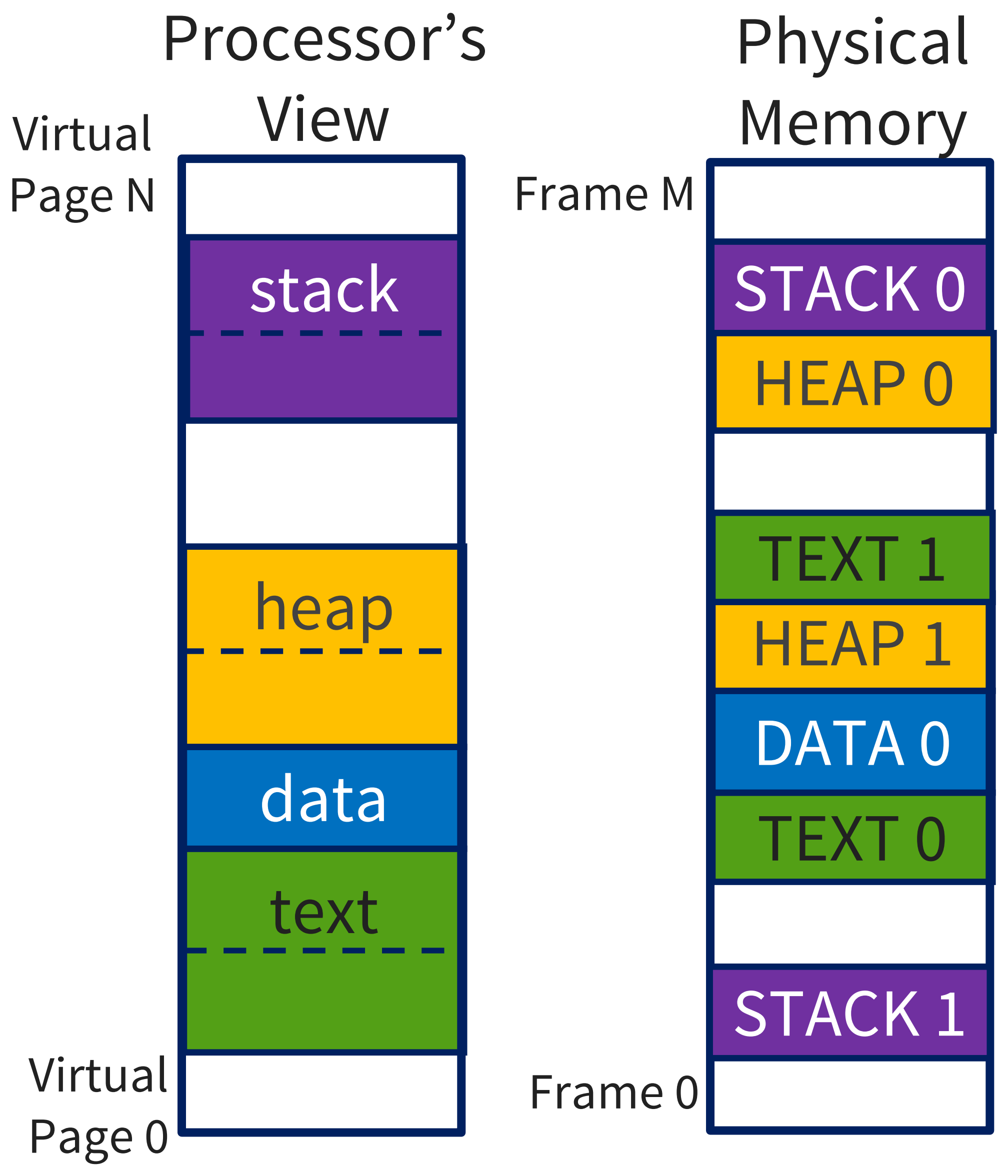
…in the context of:

multiple processes?

multiple threads?

Paged Translation

TERMINOLOGY ALERT:
Page: the data itself
Frame: physical location



No more external fragmentation!

Paging Overview

Divide:

- Physical memory into fixed-sized blocks called **frames**
- Logical memory into blocks of same size called **pages**

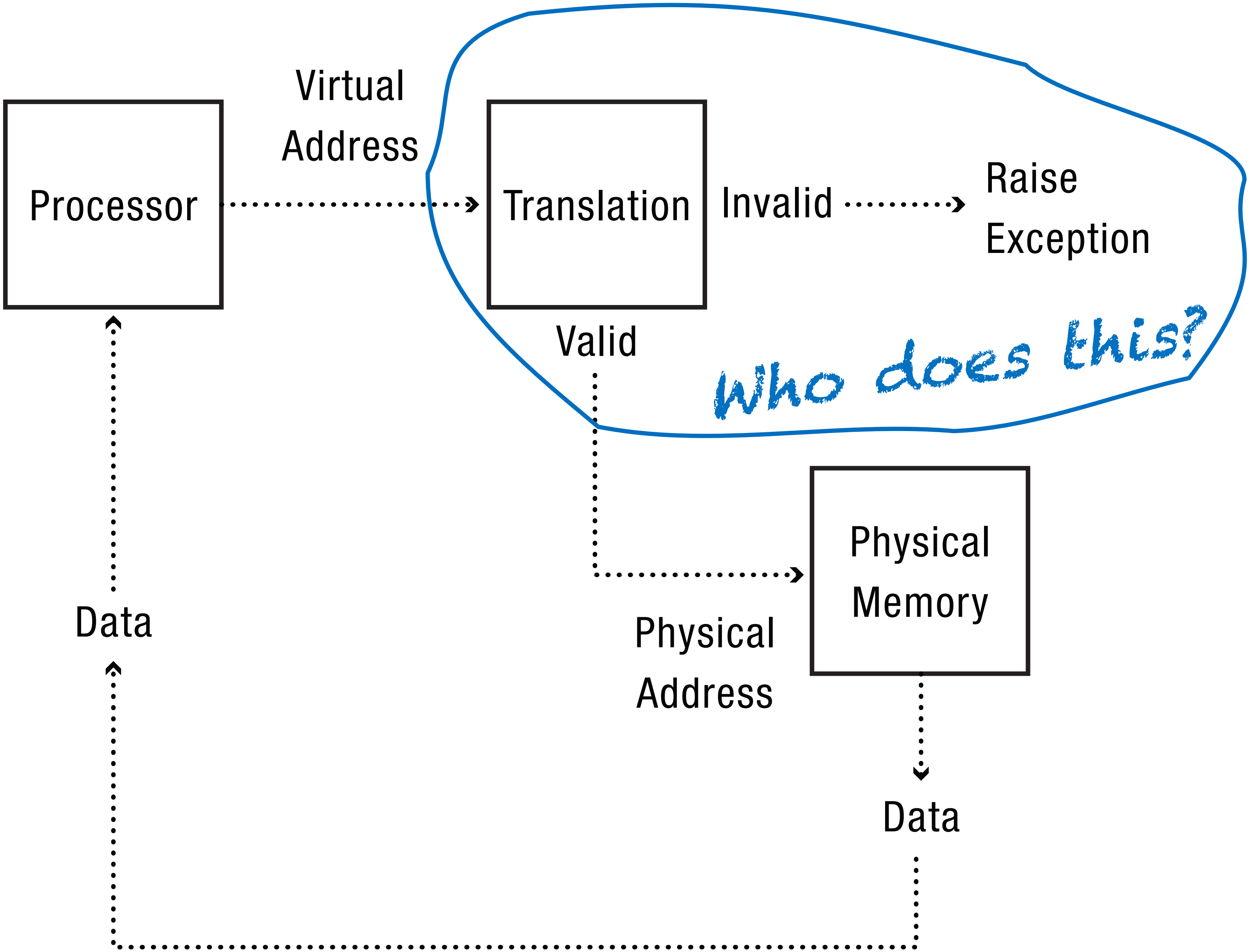
Management:

- Keep track of all free frames.
- To run a program with ***n*** pages, need to find ***n*** free frames and load program

Notice:

- Logical address space can be noncontiguous!
- Process given frames when/where available

Address Translation, Conceptually



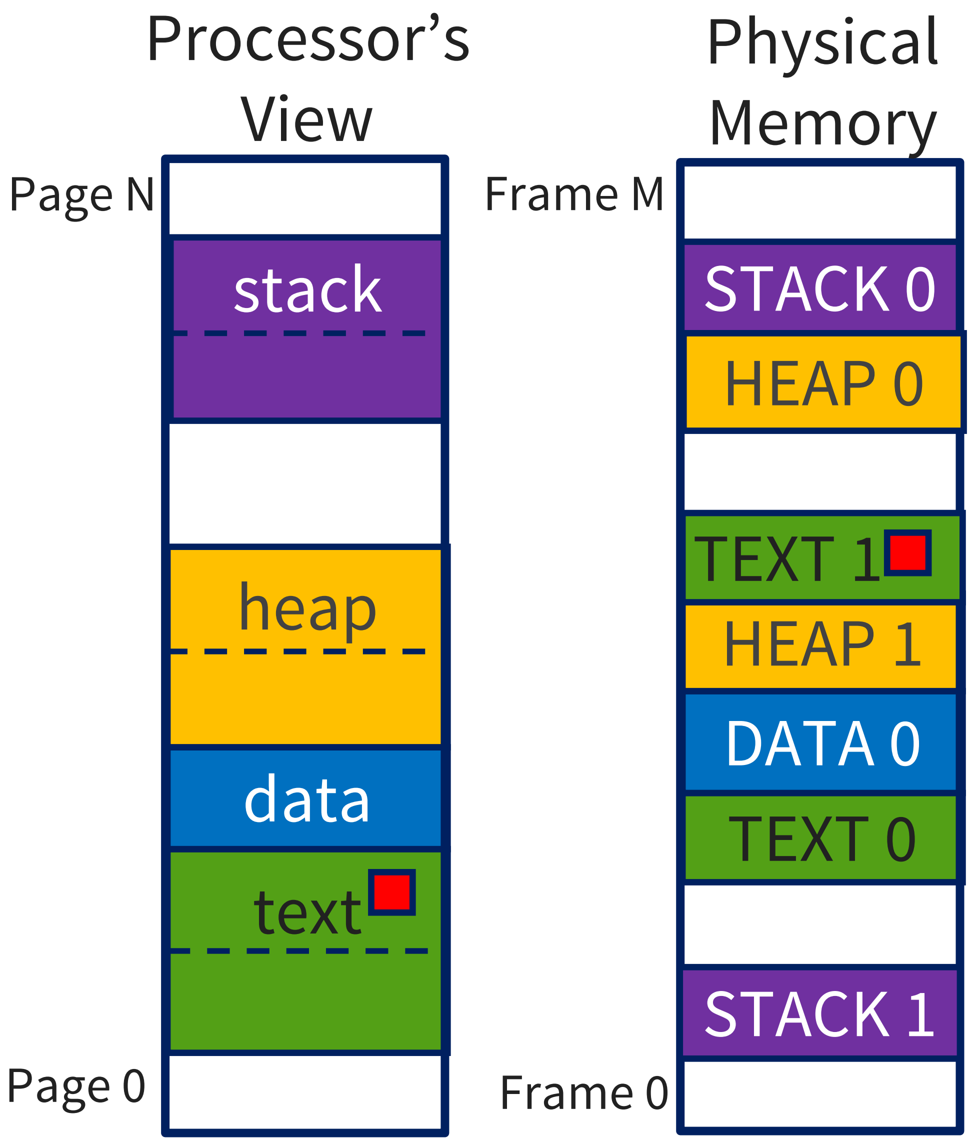
Memory Management Unit (MMU)

- Hardware device
- Maps virtual to physical address (used to access data)

User Process:

- deals with *virtual* addresses
- *Never* sees the physical address

High-Level Address Translation



red cube is 255th byte in page 2.

Where is the red cube in physical memory?

Logical Address Components

Page number – Upper bits

- Must be translated into a physical frame number

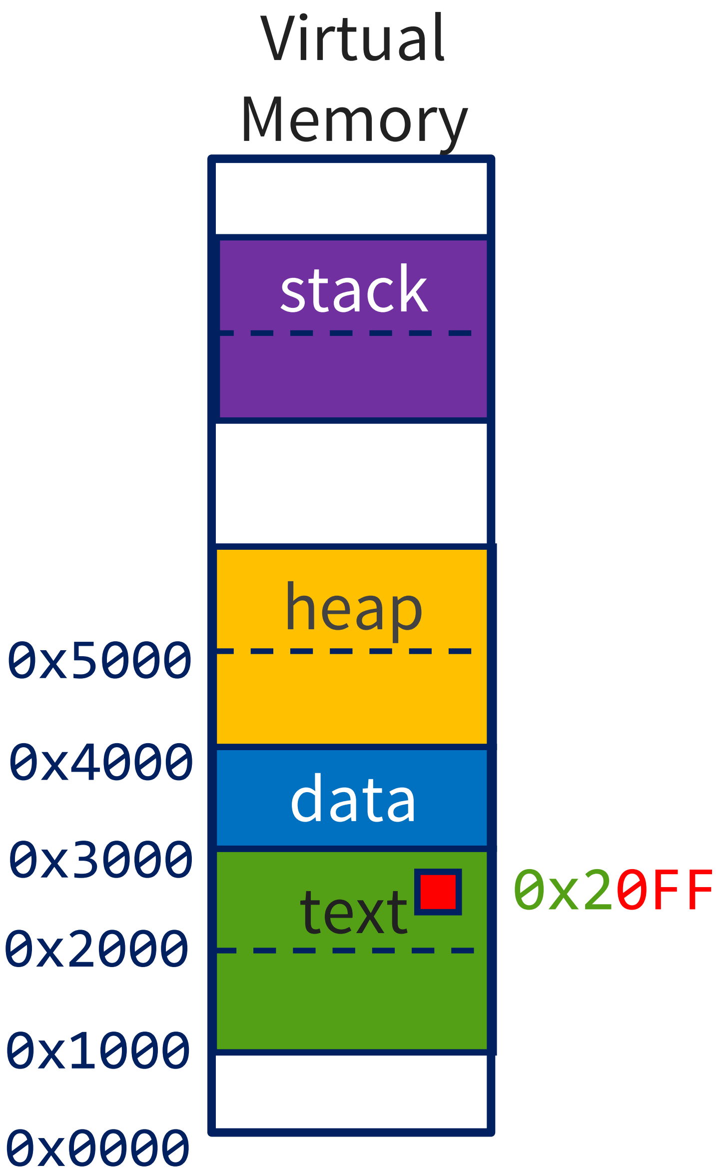
Page offset – Lower bits

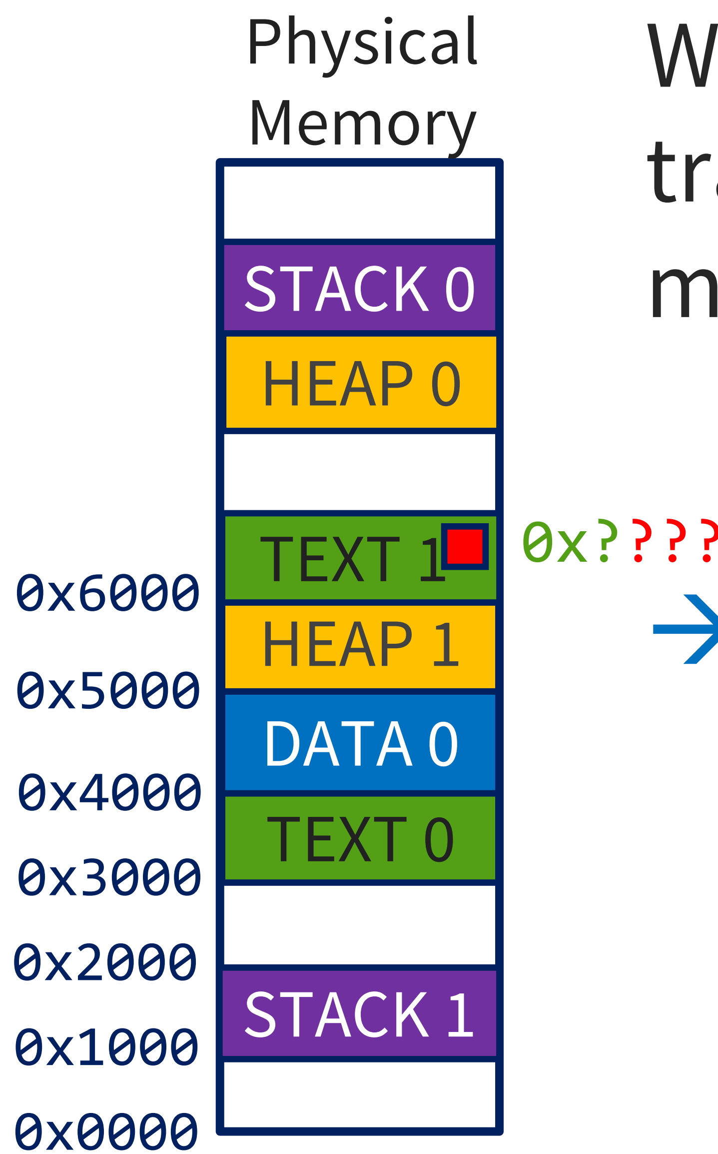
- Does not change in translation

page number	page offset
$m - n$	n

For given logical address space 2^m and page size 2^n

High-Level Address Translation



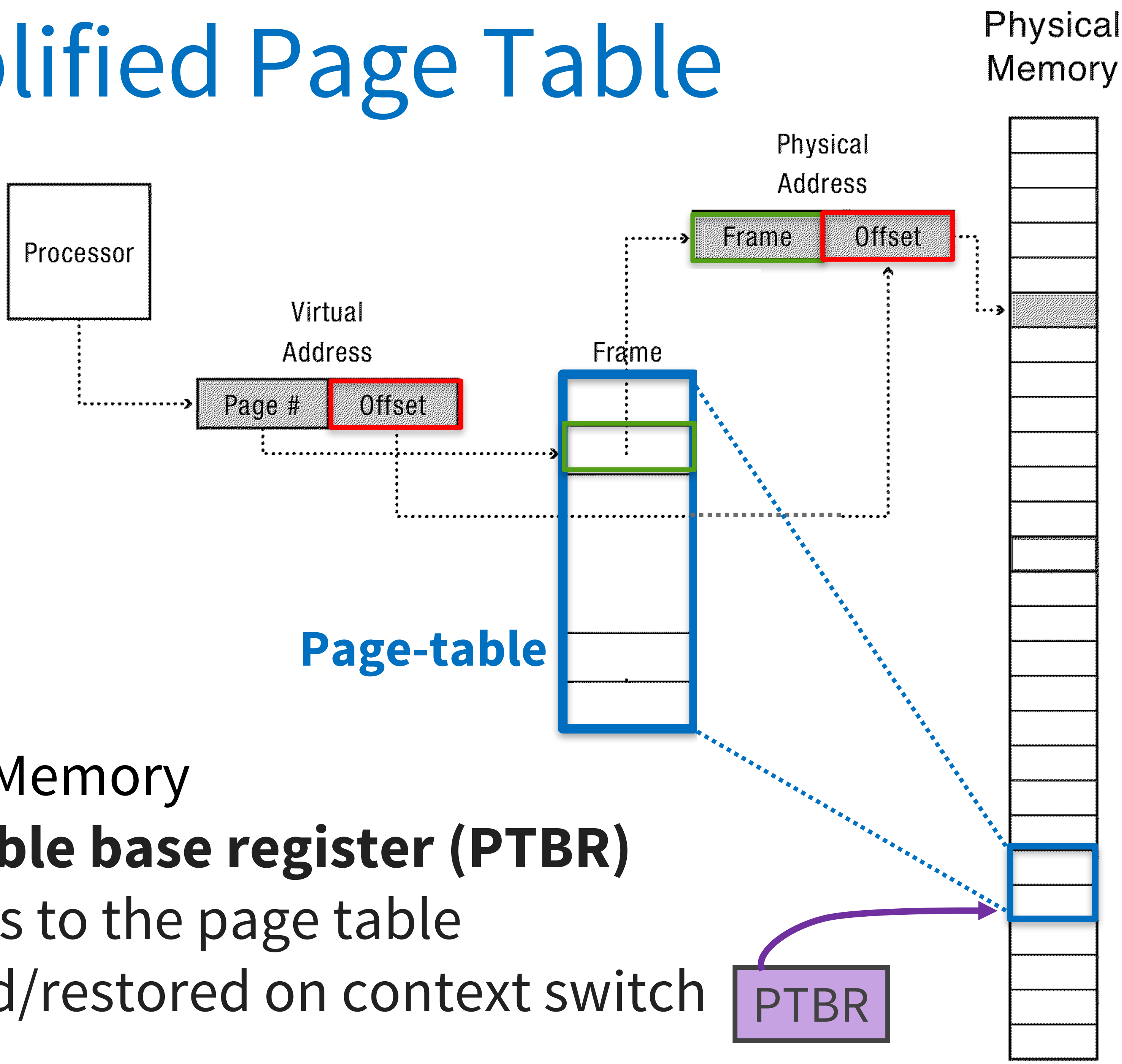


Who keeps track of the mapping?

→ Page Table

0	-
1	3
2	6
3	4
4	8
5…	5

Simplified Page Table



Lives in Memory

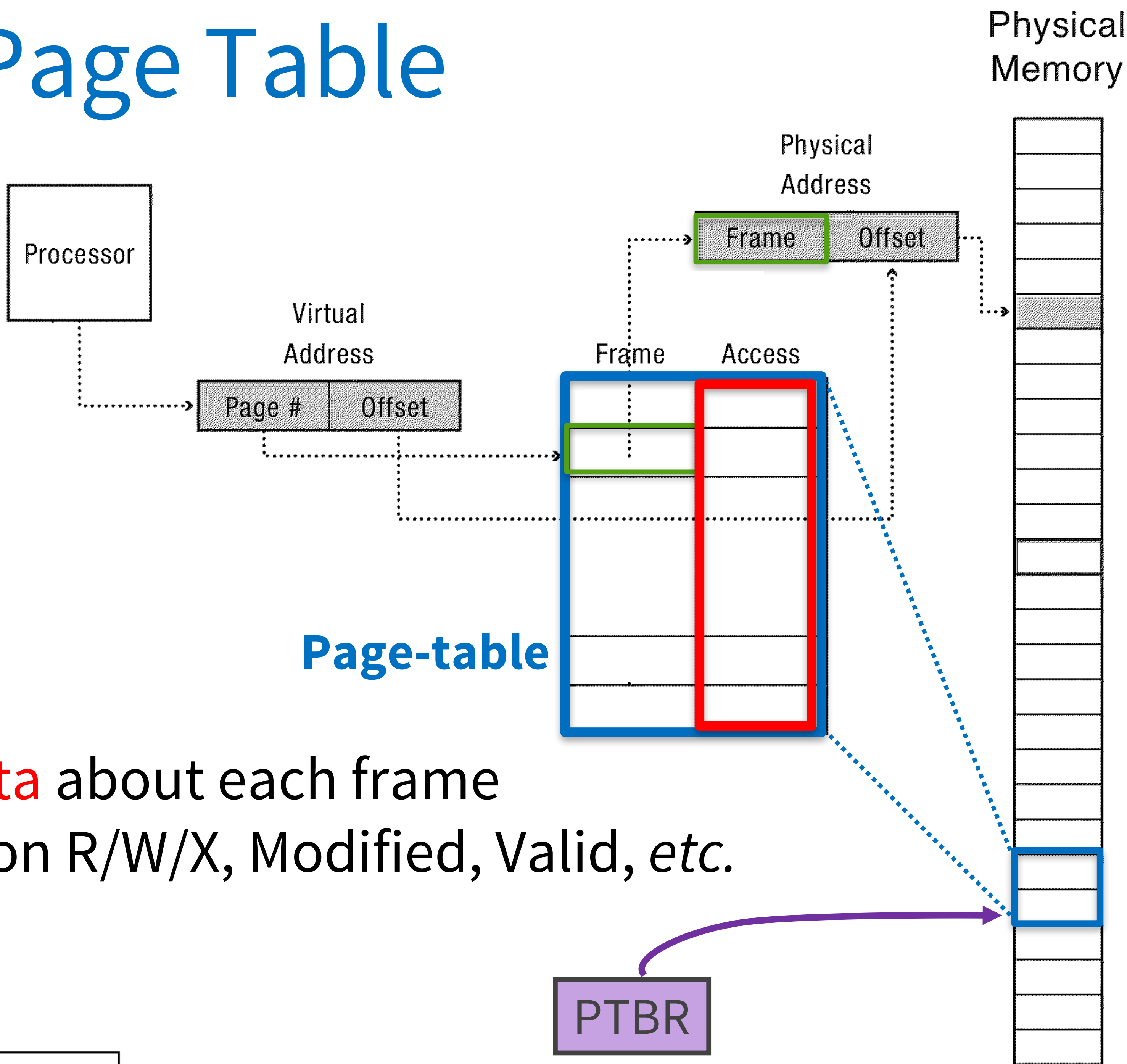
Page-table base register (PTBR)

- Points to the page table
- Saved/restored on context switch

Leveraging Paging

- Protection
- Dynamic Loading
- Dynamic Linking
- Copy-On-Write

Full Page Table



Meta Data about each frame

Protection R/W/X, Modified, Valid, *etc.*

Social Network

Leveraging Paging

- Protection
- Dynamic Loading
- Dynamic Linking
- Copy-On-Write

Dynamic Loading & Linking

Dynamic Loading

- Routine is not loaded until it is called
- Better memory-space utilization; unused routine is never loaded
- No special support from the OS needed

Dynamic Linking

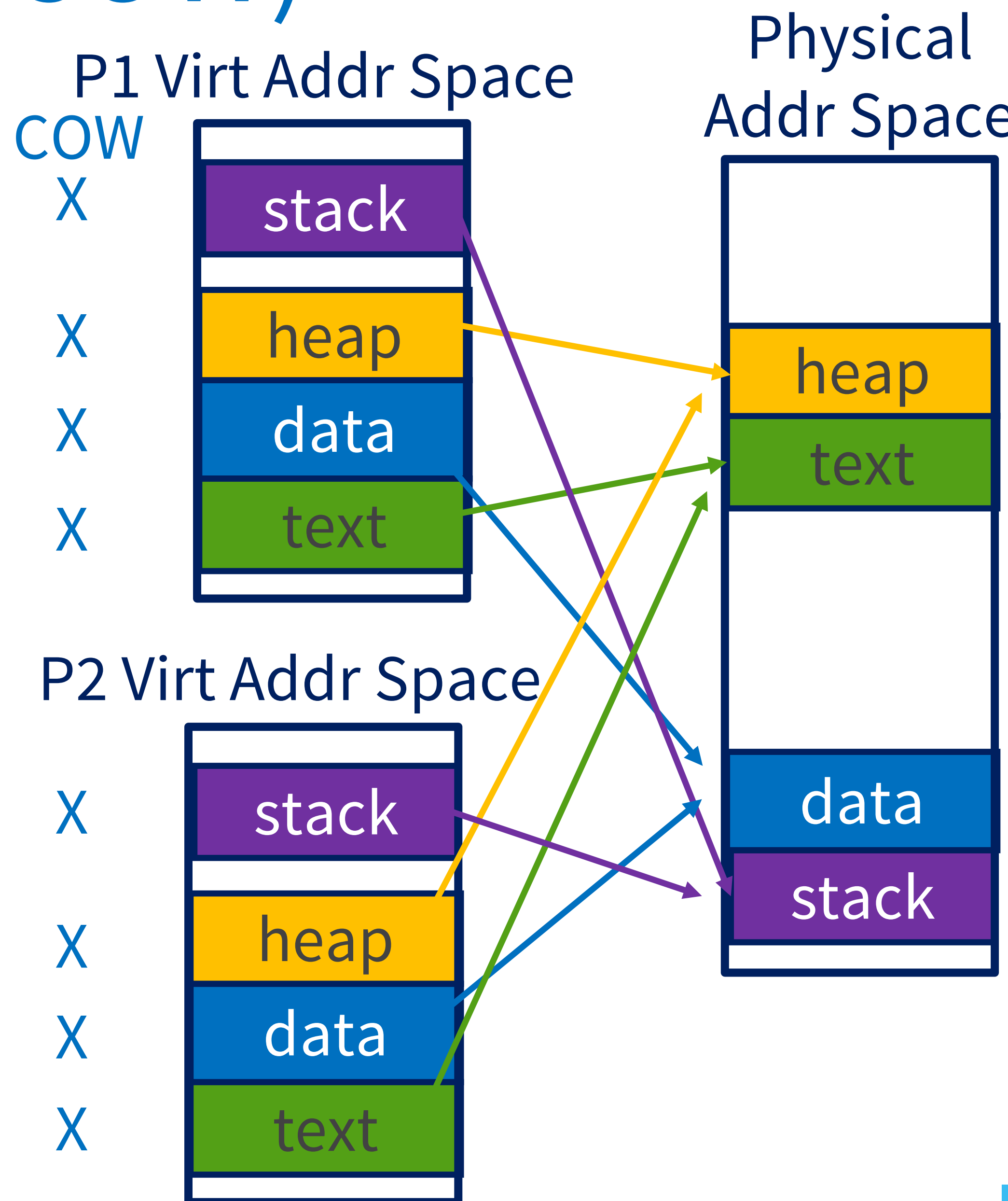
- Routine is not linked until execution time
- Locate (or load) library routine when called
- AKA **shared libraries** (*e.g.*, DLLs)

Leveraging Paging

- Protection
- Dynamic Loading
- Dynamic Linking
- Copy-On-Write

Copy on Write (COW)

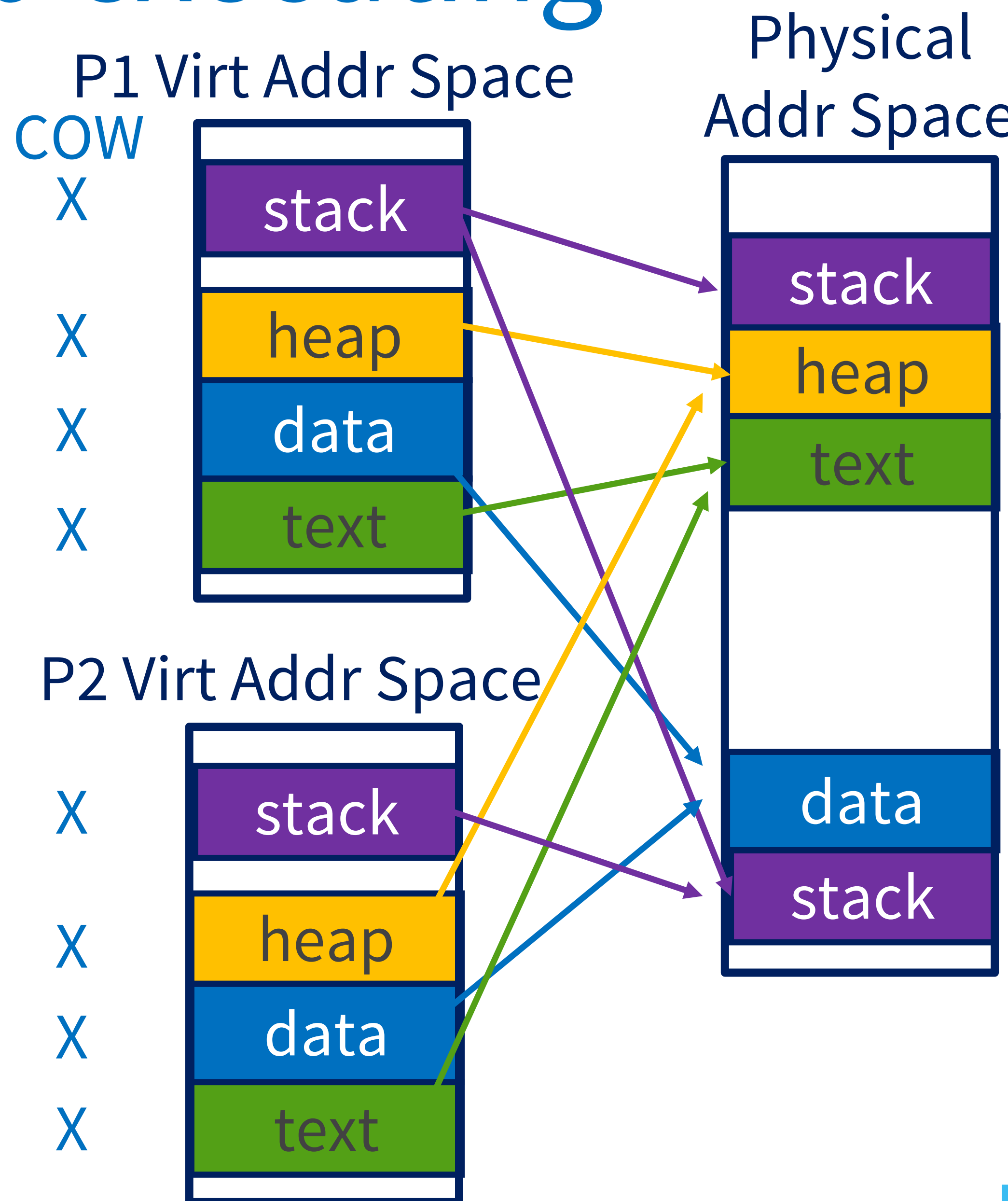
- P1 forks()
- P2 created with
  - own page table
  - same translations
- All pages marked COW (in Page Table)



COW, then keep executing

Option #1: Child keeps executing

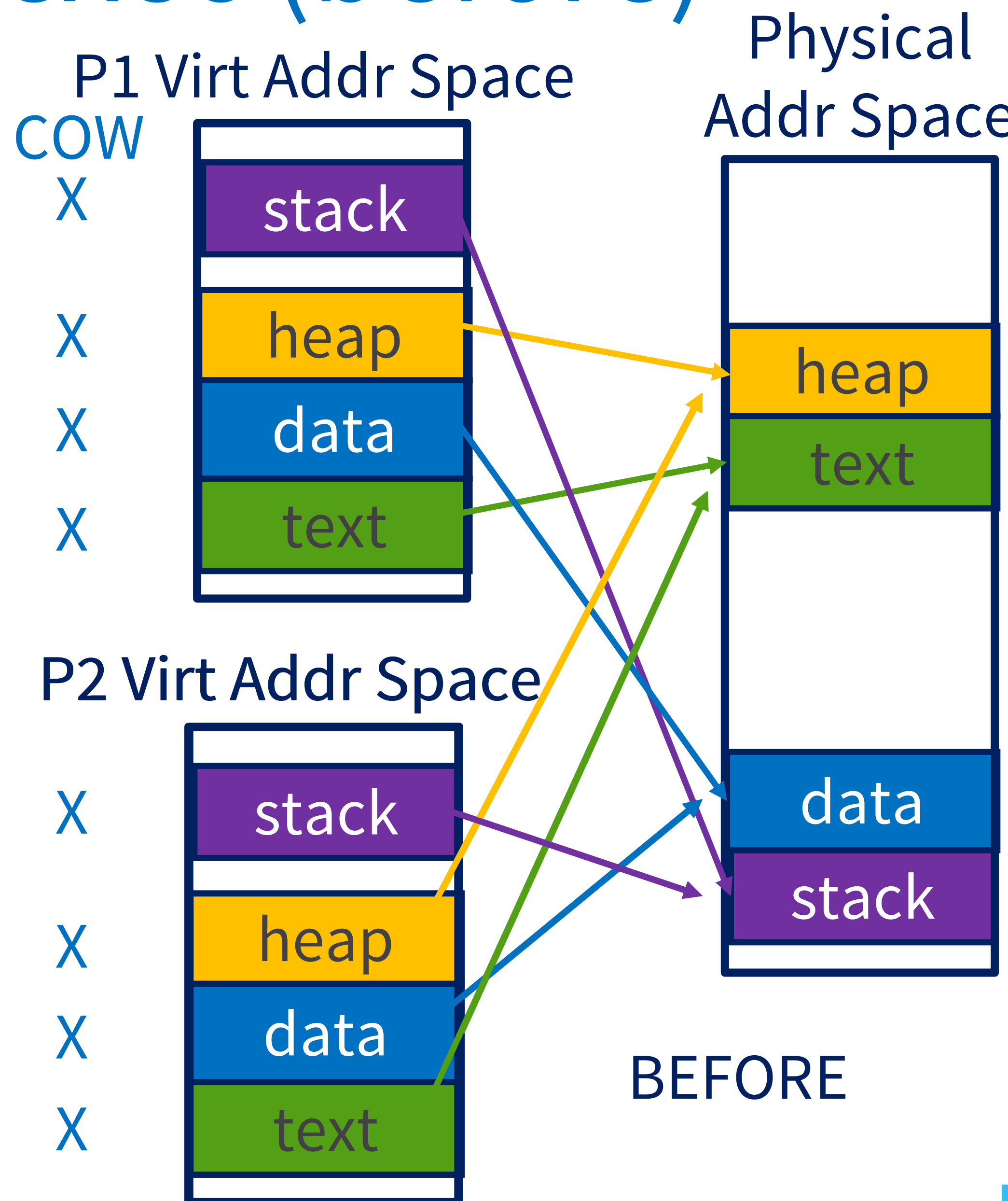
Upon page fault:
- Allocate new frame
- Copy frame
- Both pages no longer COW



COW, then call exec (before)

Option #2: Child calls exec()

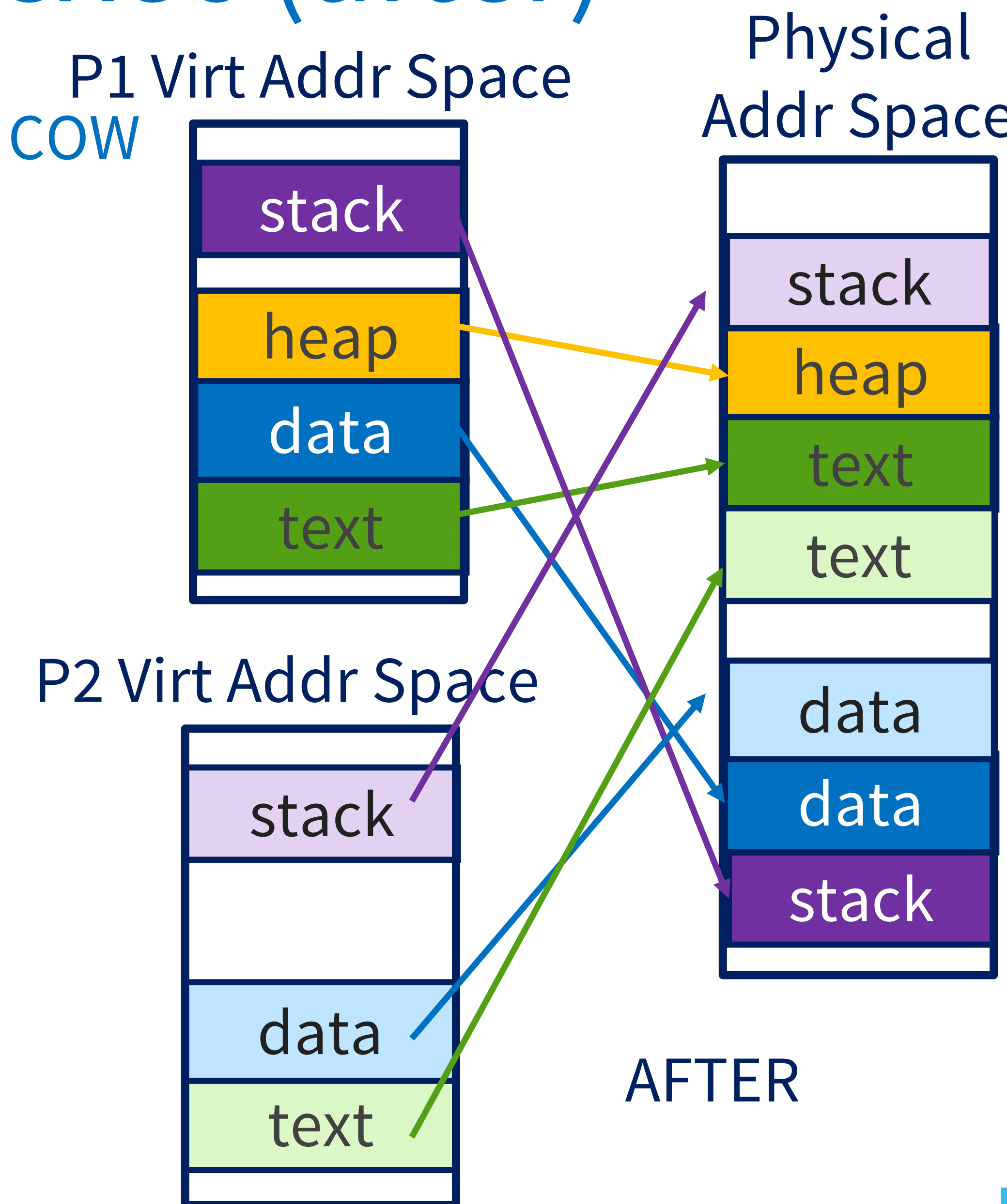
- Load new frames
- Copy frame
- Both pages now COW



COW, then call exec (after)

Option #2: Child calls exec()

- Load new frames
- Copy frame
- Both pages no longer COW



Downsides to Paging

Memory Consumption:

- Internal Fragmentation
  - Make pages smaller? But then…
- Page Table Space: consider 32-bit address space, 4KB page size, each PTE 8 bytes
  - How big is this page table?
  - How many pages in memory does it need?

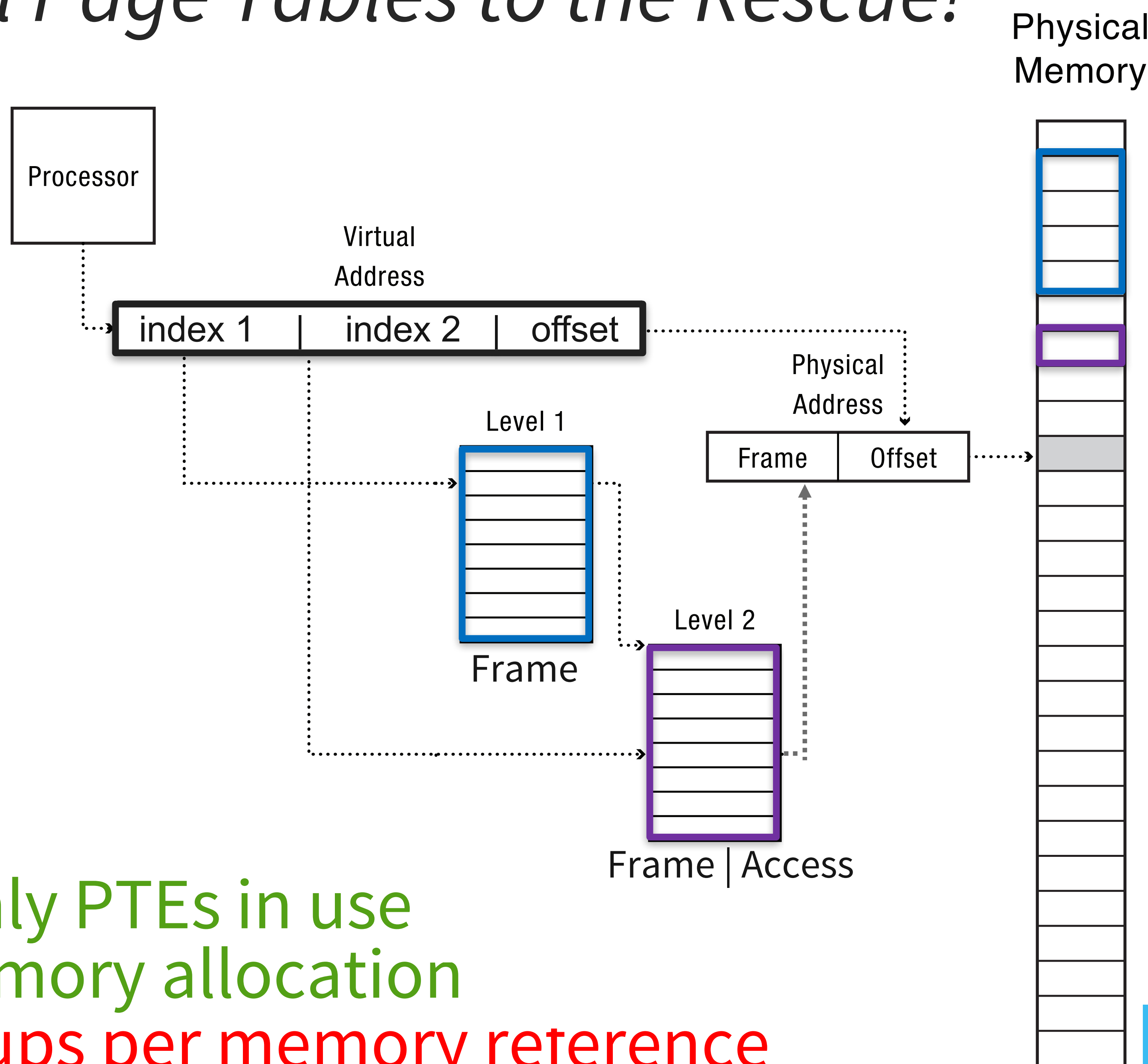
Performance: every data/instruction access requires *two* memory accesses:

- One for the page table
- One for the data/instruction

Address Translation

- Paged Translation
- Efficient Address Translation
  - Multi-Level Page Tables
  - Inverted Page Tables
  - TLBs

Multi-Level Page Tables to the Rescue!



+ Allocate only PTEs in use
+ Simple memory allocation
− ***more*** lookups per memory reference

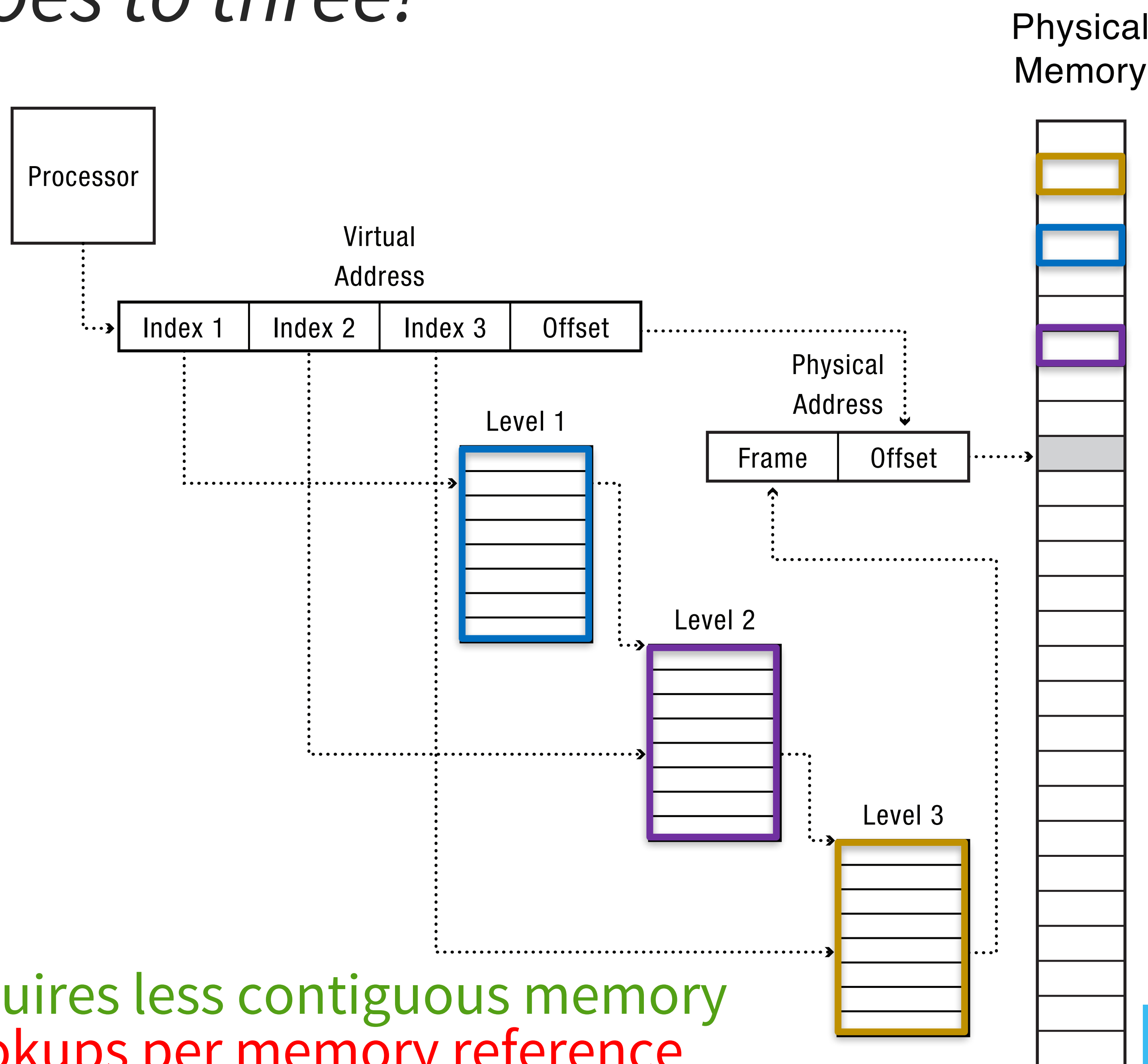
Two-Level Paging Example

32-bit machine, 1KB page size

- Logical address is divided into:
  - a page offset of 10 bits (1024 = 2^10)
  - a page number of 22 bits (32-10)
- Since the page table is paged, the page number is further divided into:
  - a 12-bit first index
  - a 10-bit second index
- Thus, a logical address is as follows:

page number		page offset
index 1	index 2	offset
12	10	10

This one goes to three!



+ First Level requires less contiguous memory

− ***even more*** lookups per memory reference

Complete Page Table Entry (PTE)

Valid	Protection R/W/X	Ref	Dirty	Index

Index is an index into:

- table of memory frames (if bottom level)
- table of page table frames (if multilevel page table)
- backing store (if page was swapped out)

Synonyms:

- Valid bit == Present bit
- Dirty bit == Modified bit
- Referenced bit == Accessed bit

Address Translation

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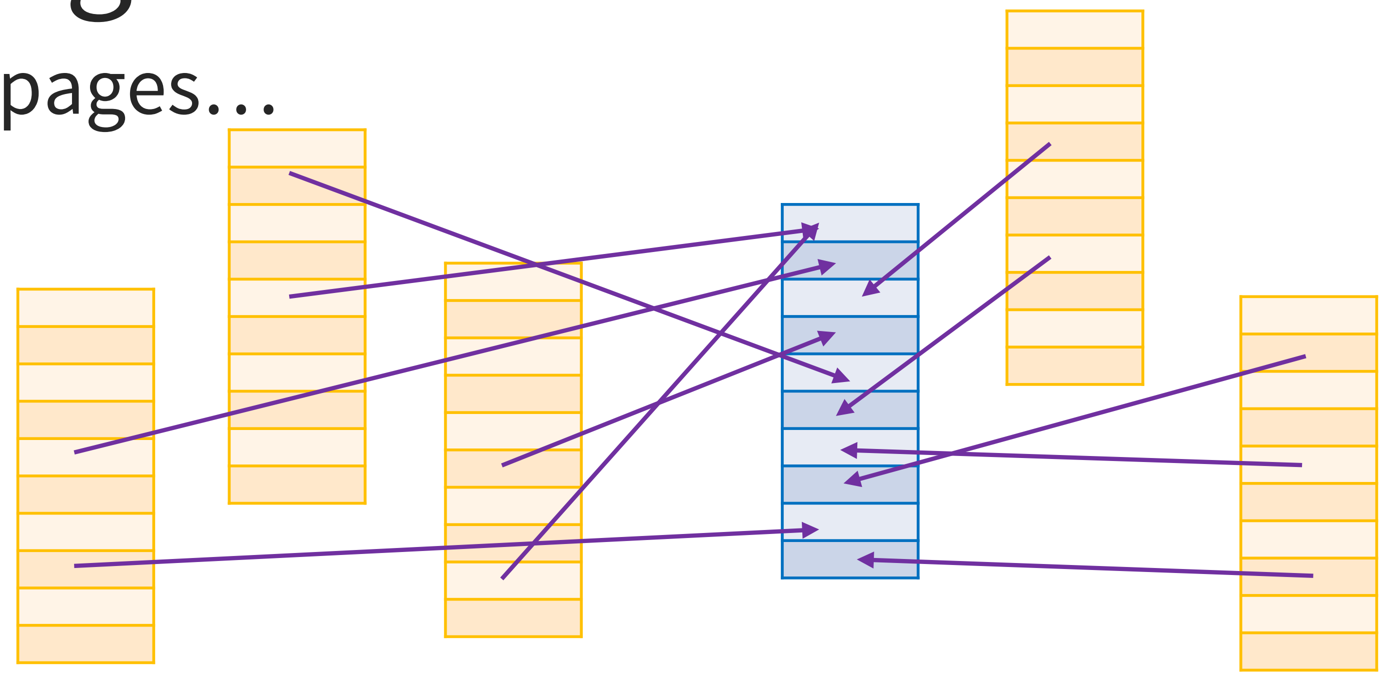
Inverted Page Table: Motivation

So many virtual pages…



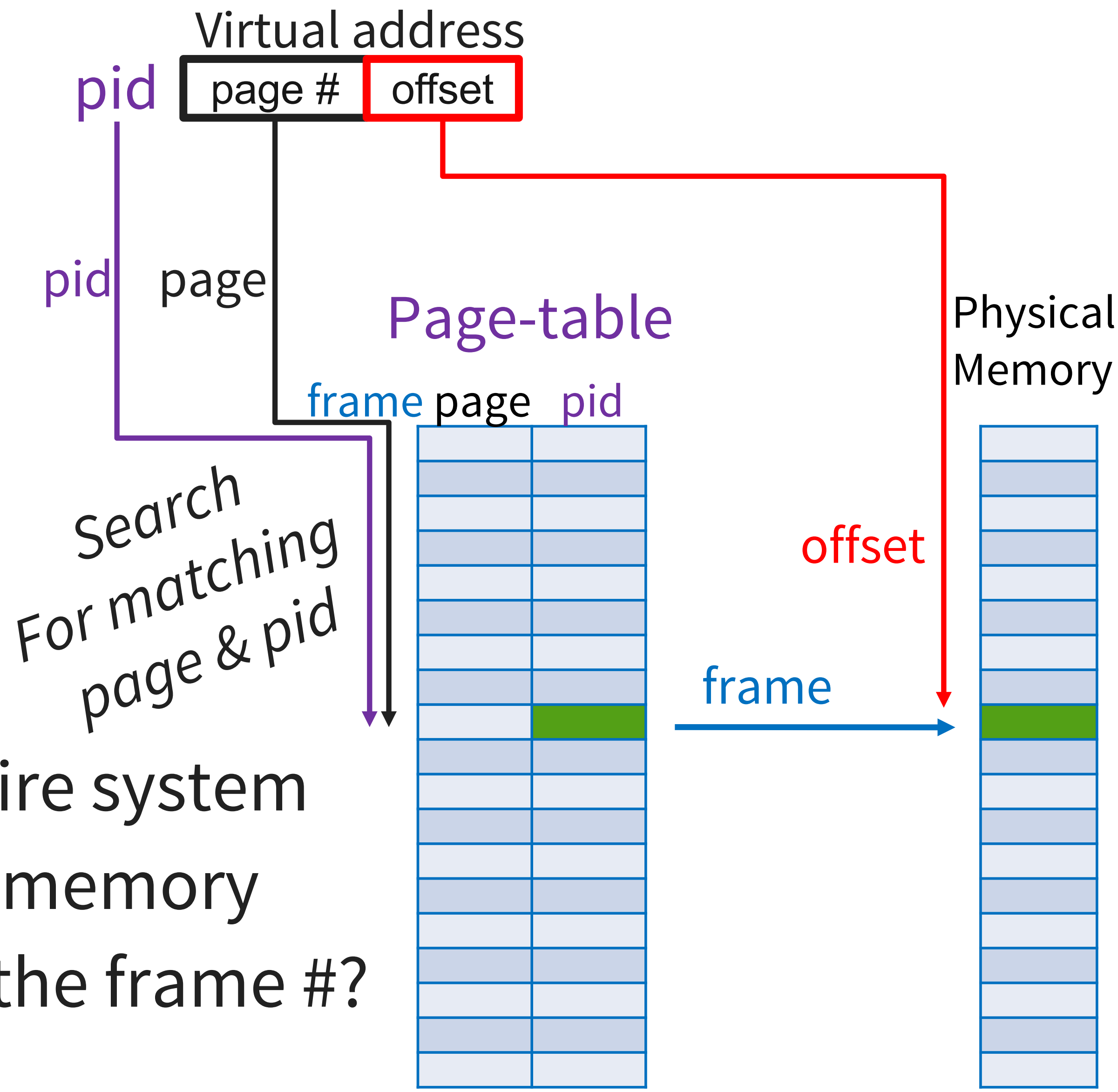
… comparatively few physical frames

Traditional Page Tables:

- map pages to frames
- are *numerous and sparse*

Why not map frames to pages? (How?)

Inverted Page Table: Implementation



Implementation:

- 1 Page Table for entire system
- 1 entry per frame in memory
- Why don't we store the frame #?

Not to scale! Page table << Memory

Inverted Page Table: Discussion

Tradeoffs:

↓ memory to store page tables

↑ time to search page tables

Solution: hashing

- hash(page,pid) → PT entry (or chain of entries)
- What about:
  - collisions…
  - sharing…

Address Translation

- Paged Translation
- Efficient Address Translation
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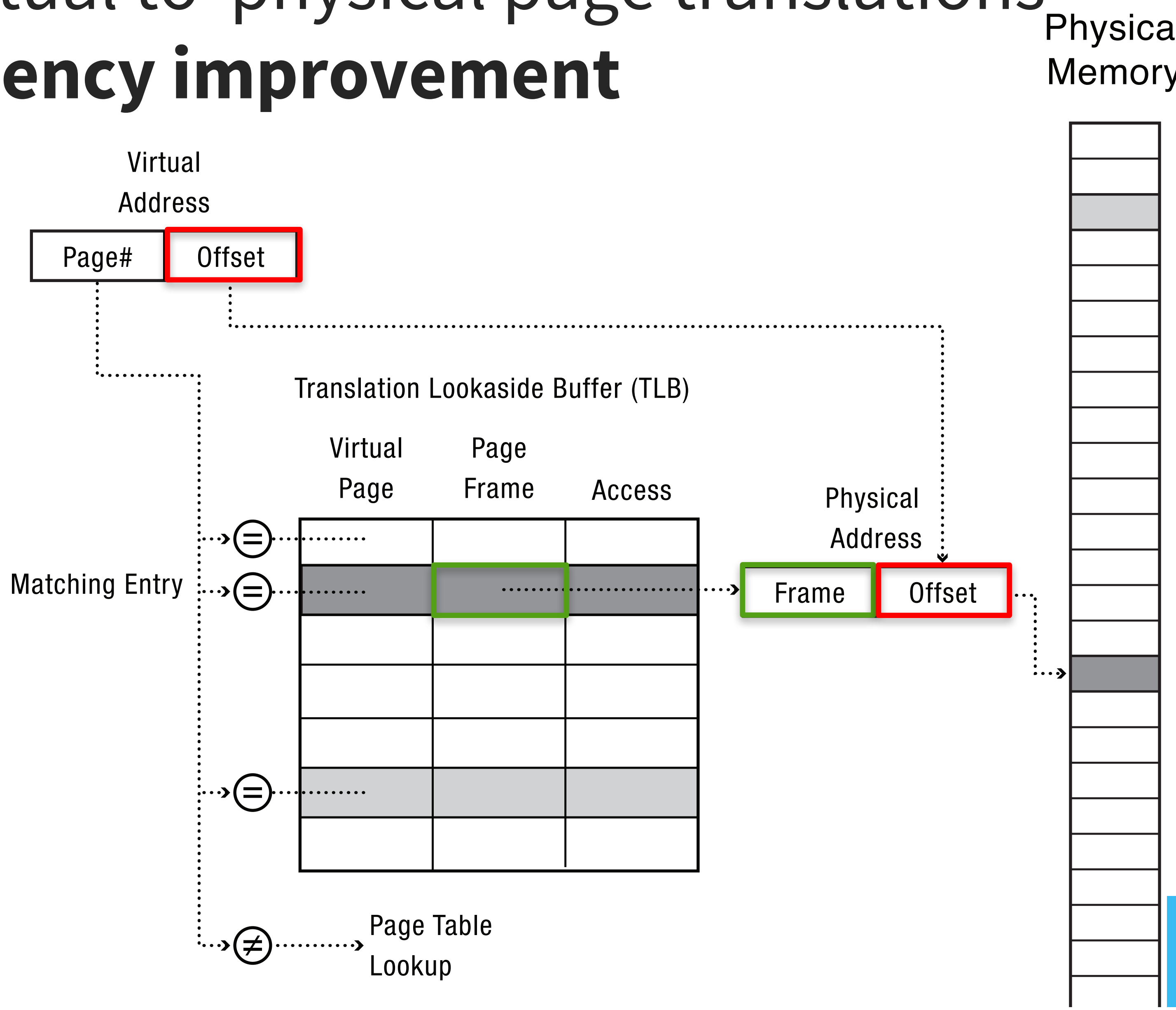
Translation Lookaside Buffer (TLB)

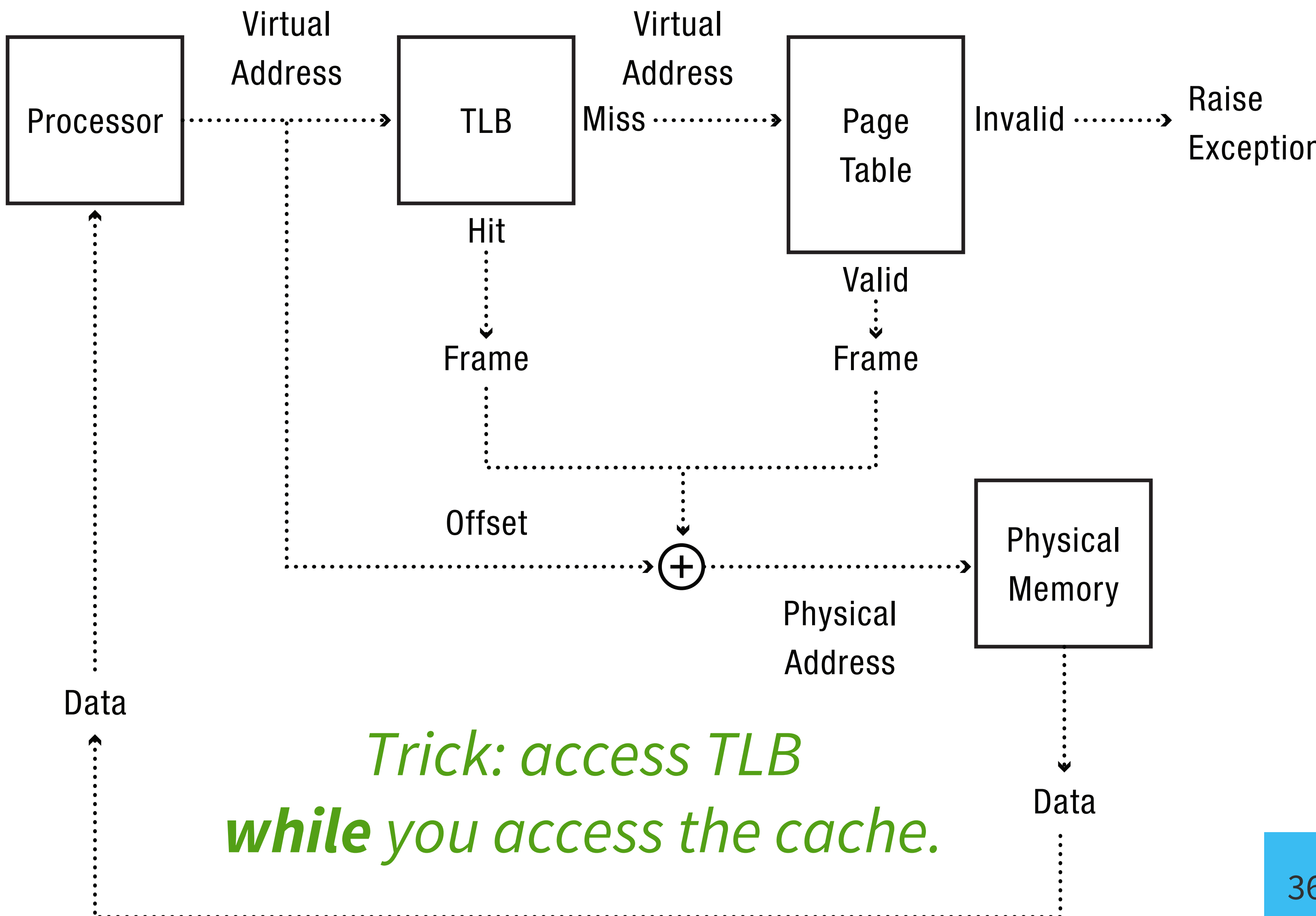
Cache of virtual to physical page translations

Major efficiency improvement



Address Translation with TLB

Access TLB before you access memory.



*Trick: access TLB **while** you access the cache.*

Address Translation Uses!

Process isolation

- Keep a process from touching anyone else's memory, or the kernel's

Efficient interprocess communication

- Shared regions of memory between processes

Shared code segments

- common libraries used by many different programs

Program initialization

- Start running a program before it is entirely in memory

Dynamic memory allocation

- Allocate and initialize stack/heap pages on demand

MORE Address Translation Uses!

Program debugging

- Data breakpoints when address is accessed

Memory mapped files

- Access file data using load/store instructions

Demand-paged virtual memory

- Illusion of near-infinite memory, backed by disk or memory on other machines

Checkpointing/restart

- Transparently save a copy of a process, without stopping the program while the save happens

Distributed shared memory

- Illusion of memory that is shared between machines