CS110 Computer Architecture

OS cont.

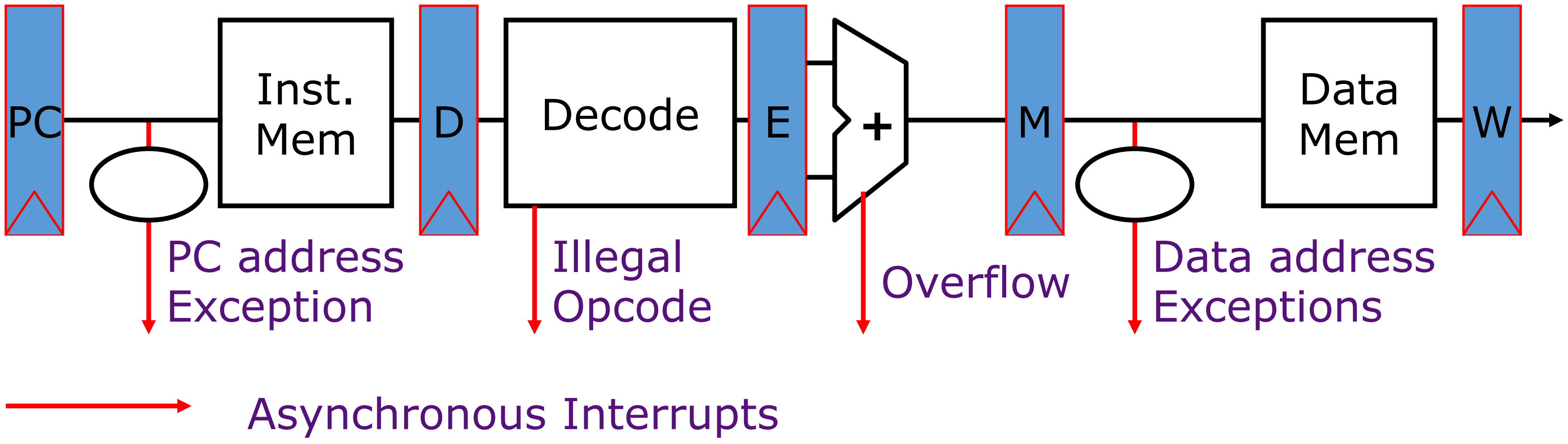
Chundong Wang & Siting Liu

SIST, ShanghaiTech

Review

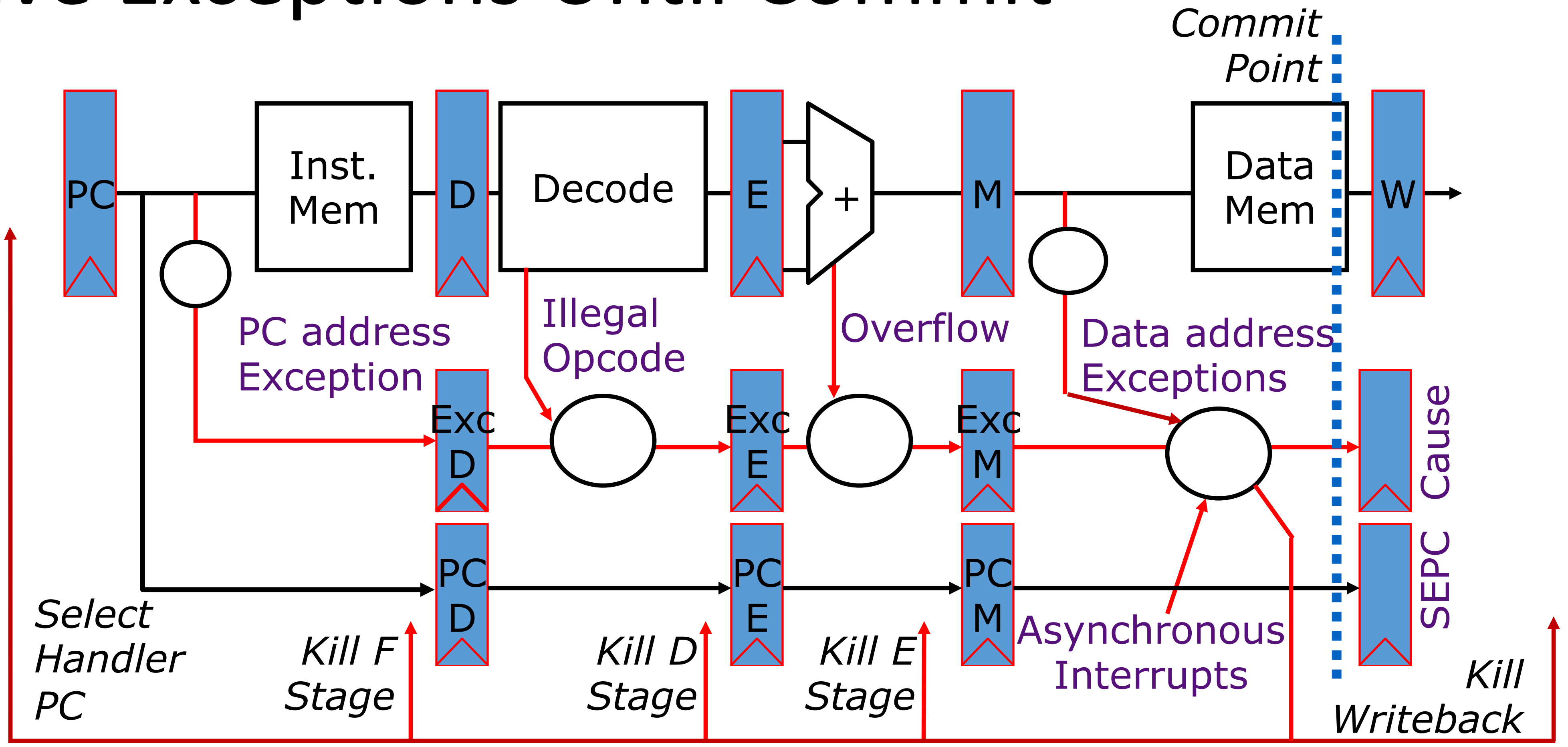
- Booting a Computer
  - BIOS, Bootloader, OS Boot, Init
- Memory-mapped I/O
- Polling vs. Interrupts
- Interrupt vs. exception, and pipeline
- *Supervisor Mode, Syscalls*

Trap Handling in 5-Stage Pipeline



- How to handle multiple simultaneous exceptions in different pipeline stages?
- How and where to handle external asynchronous interrupts?

Save Exceptions Until Commit



Handling Traps in In-Order Pipeline

- Hold exception flags in pipeline until commit point (M stage)
- Exceptions in earlier instructions override exceptions in later instructions
- Exceptions in earlier pipe stages override later exceptions *for a given instruction*
- Inject external interrupts at commit point
- If exception/interrupt at commit: update Cause and SEPC registers, kill all stages, inject handler PC into fetch stage

Trap Pipeline Diagram

	time t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1	-		*overflow!*		
(I_2) 100: XOR		IF_2	ID_2	EX_2	-	-			
(I_3) 104: SUB			IF_3	ID_3	-	-	-		
(I_4) 108: ADD				IF_4	-	-	-	-	
(I_5) Trap Handler code					IF_5	ID_5	EX_5	MA_5	WB_5

Agenda

- OS Boot Sequence and Operation
- Devices and I/O, interrupt and trap
- Application, Multiprogramming/time-sharing

Launching Applications

- Applications are called “processes” in most OSs.
  - Process: separate memory;
  - Thread: shared memory
- Created by another process calling into an OS routine (using a “syscall”, more details later).
  - Depends on OS, but Linux uses fork to create a new process, and execve to load application.
- Loads executable file from disk (using the file system service) and puts instructions & data into memory (.text, .data sections), prepare stack and heap.
- Set argc and argv, jump into the main function.

Supervisor Mode

- If something goes wrong in an application, it could crash the entire machine.
  - And what about malware, etc.?
- The OS may need to enforce resource constraints to applications (e.g., access to devices).
- To help protect the OS from the application, CPUs have a supervisor mode bit.
  - When not in supervisor mode (user mode), a process can only access a subset of instructions and (physical) memory.
  - Process can enter the supervisor mode by using an interrupt, and change out of supervisor mode using a special instruction.





Syscalls

- What if we want to call into an OS routine? (e.g., to read a file, launch a new process, send data, etc.)
  - Need to perform a syscall: set up function arguments in registers, and then raise software interrupt
  - OS will perform the operation and return to user mode
- This way, the OS can mediate access to all resources, including devices and the CPU itself.

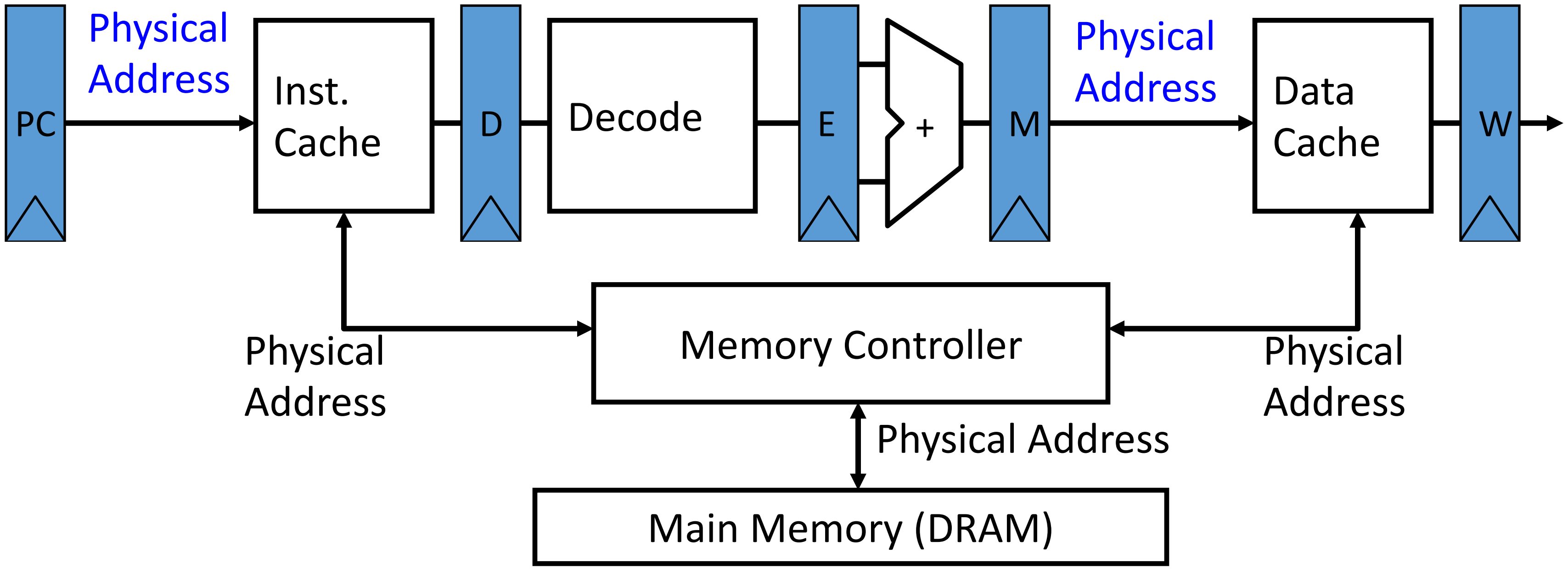
Multiprogramming

- The OS runs multiple applications at the same time.
- But not really (unless you have a core per process)
    - Time-sharing processor
- When jumping into process, set timer interrupt.
    - When it expires, store PC, registers, etc. (process state).
    - Pick a different process to run and load its state.
    - Set timer, change to user mode, jump to the new PC.
- Switches between processes very quickly. This is called a “context switch”.
- Deciding what process to run is called scheduling.

Protection, Translation, Paging

- Supervisor mode does not fully isolate applications from each other or from the OS.
  - Application could overwrite another application’s memory.
  - Also, may want to address more memory than we actually have (e.g., for sparse data structures).
- Solution: Virtual Memory. Gives each process the illusion of a full memory address space that it has completely for itself.

"Bare" 5-Stage Pipeline

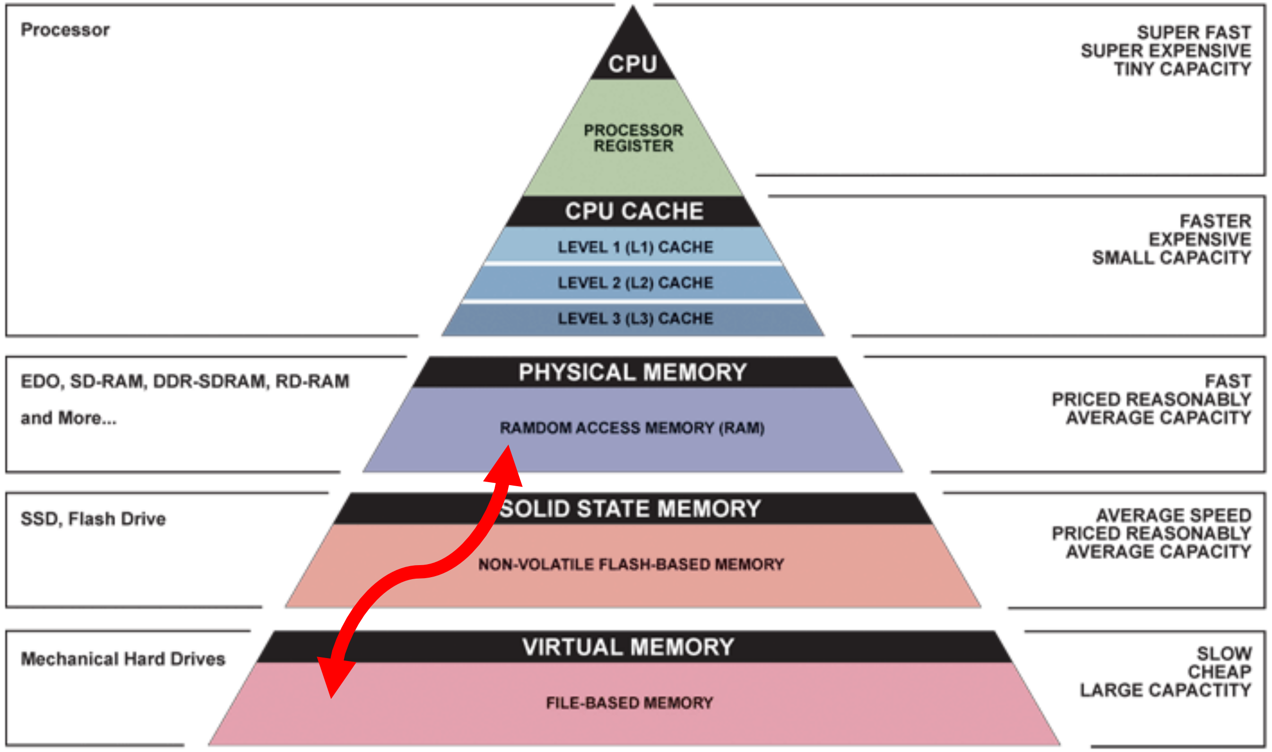


- In a bare machine, the only kind of address is a physical address

上海科技大学
ShanghaiTech University

What do we need Virtual Memory for? Reason 1: Adding Disks to Hierarchy

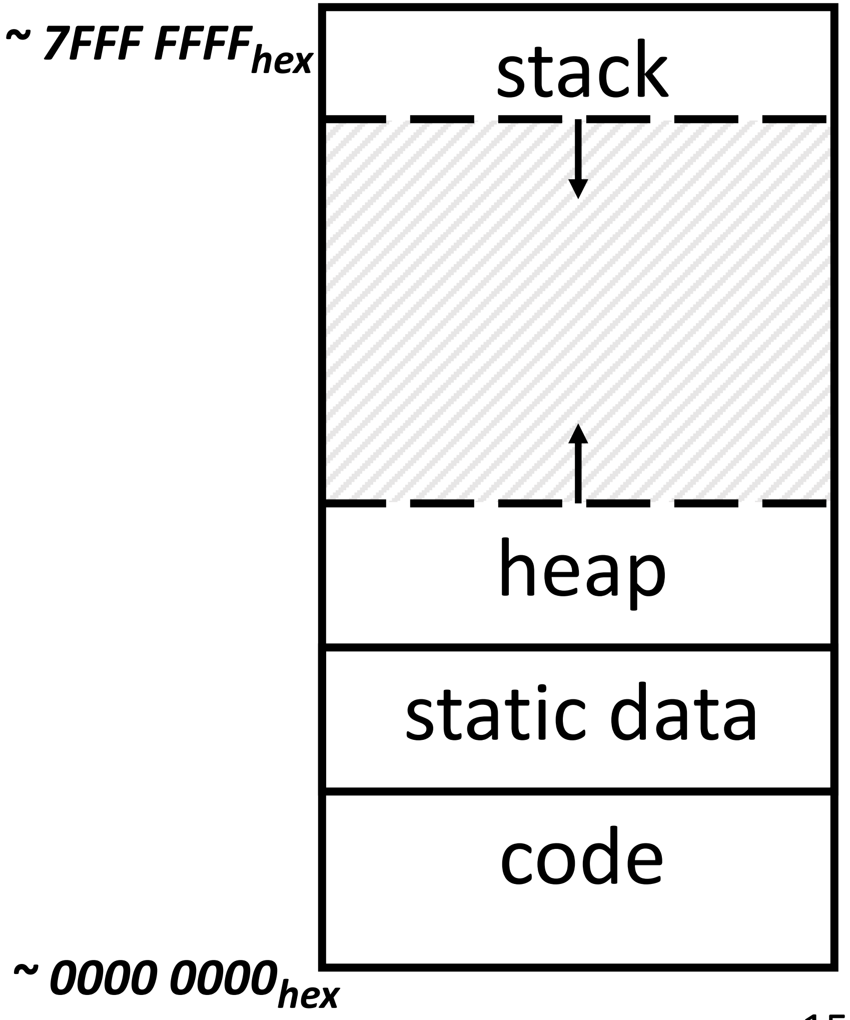
- Need to devise a mechanism to “connect” memory and disk in the memory hierarchy



▲ Simplified Computer Memory Hierarchy
Illustration: Ryan J. Leng

What do we need Virtual Memory for?
Reason 2: Simplifying Memory for Apps

- Applications should see the straightforward memory layout we saw earlier ->
- User-space applications should think they own all of memory
- So we give them a **virtual** view of memory



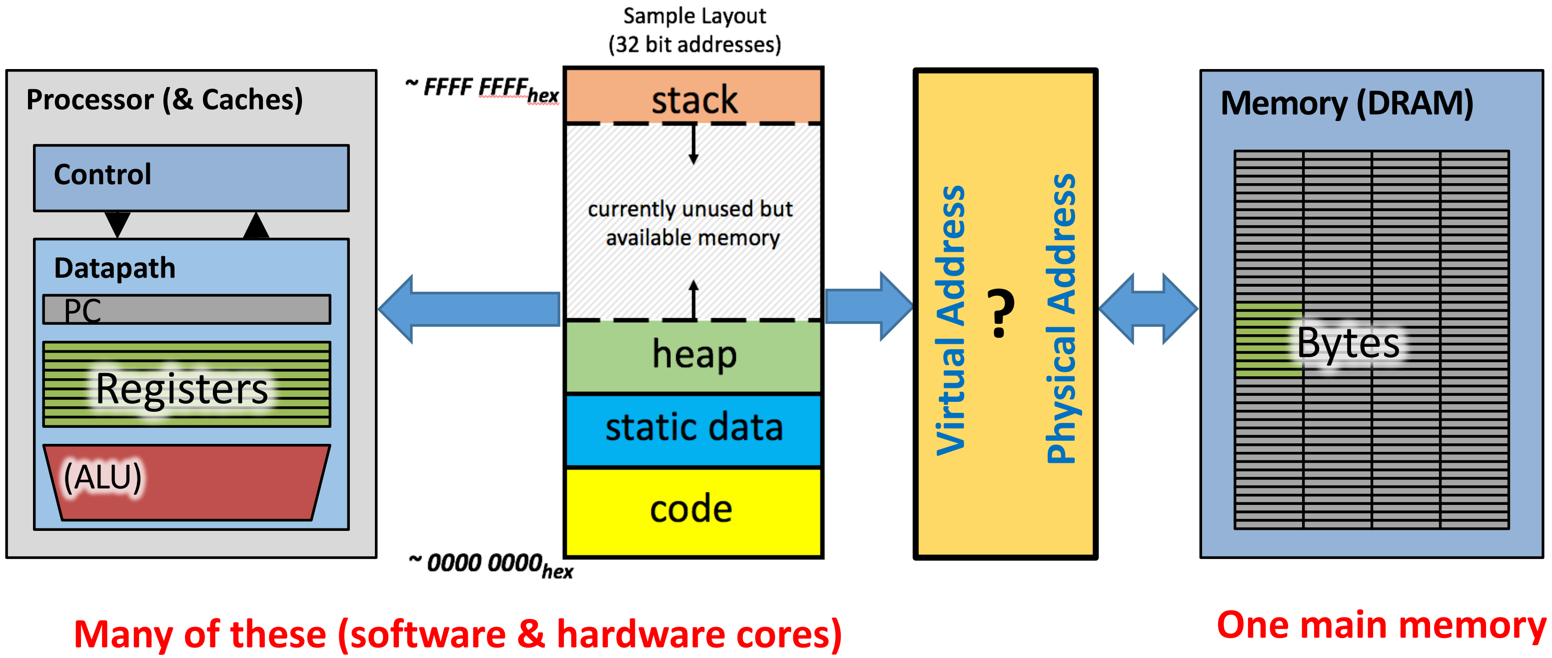
What do we need Virtual Memory for?
Reason 3: Protection Between Processes

- With a bare system, addresses issued with loads/stores are real **physical** addresses
- This means any program can issue any address, therefore can access any part of memory, even areas which it doesn't own
  - Ex: The OS data structures
- We should send all addresses through a mechanism that the OS controls, before they make it out to DRAM - **a translation mechanism**

Address Spaces

- The set of addresses labeling all of memory that we can access
- Now, 2 kinds:
  - **Virtual Address Space** - the set of addresses that the user program knows about
  - **Physical Address Space** - the set of addresses that map to actual physical cells in memory
    - Hidden from user applications
- So, we need a way to map between these two address spaces

Virtual vs. Physical Addresses



- Processes use virtual addresses, e.g., 0 … 0xffff,ffff
  - Many processes, all using same (conflicting) addresses
- Memory uses physical addresses (also, e.g., 0 ... 0xffff,ffff)
  - ***Memory manager maps virtual to physical addresses***

Dynamic Address Translation

Motivation

Multiprogramming, multitasking: Desire to execute more than one process at a time (more than one process can reside in main memory at the same time).

Location-independent programs

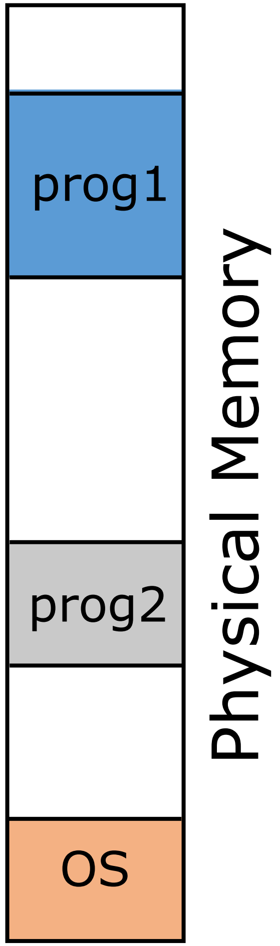
Programming and storage management ease

=> ***base register*** ← *add offset to each address*

Protection

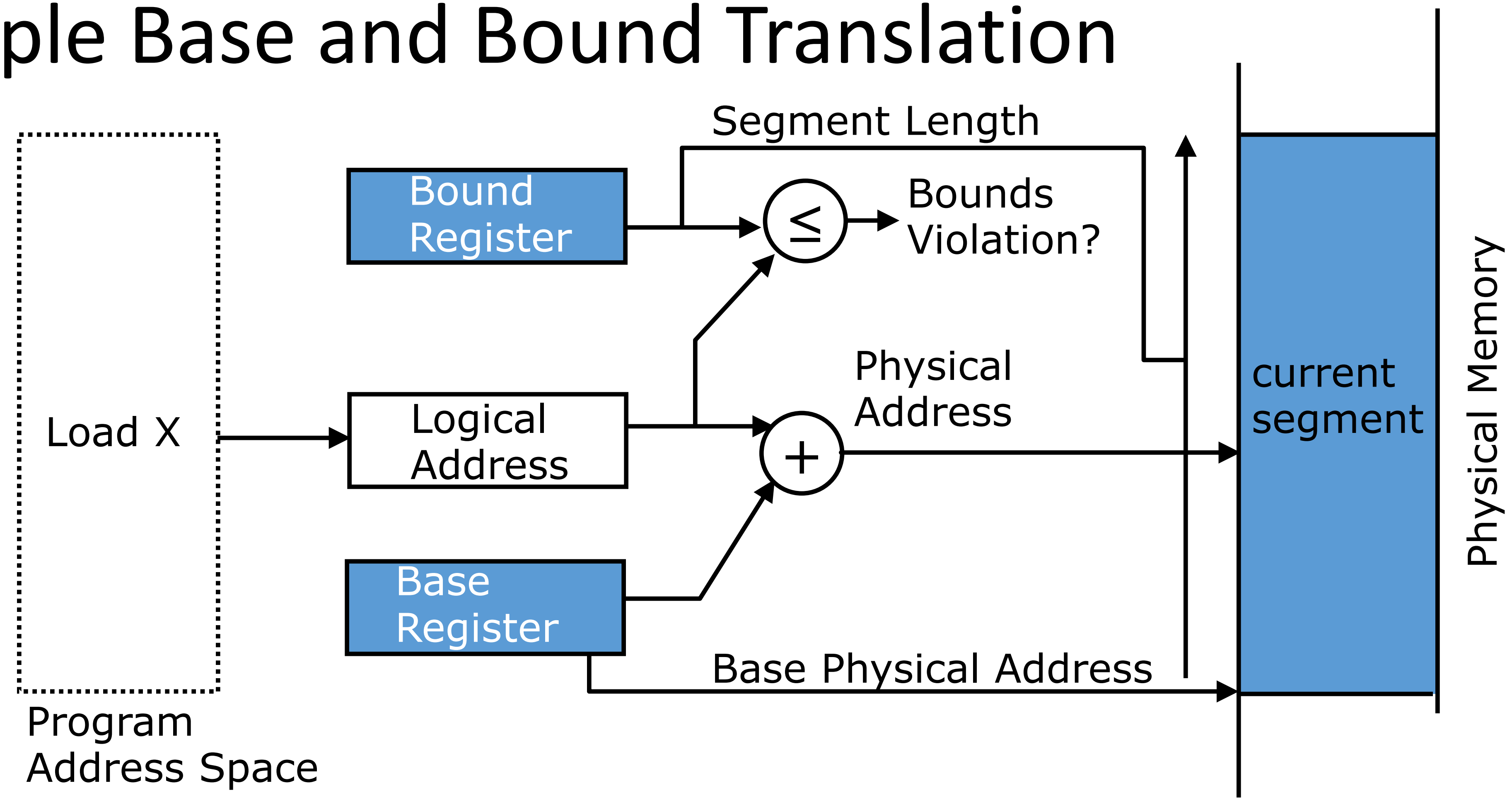
Independent programs should not affect each other inadvertently

=> ***bound register*** ← *check range of access*



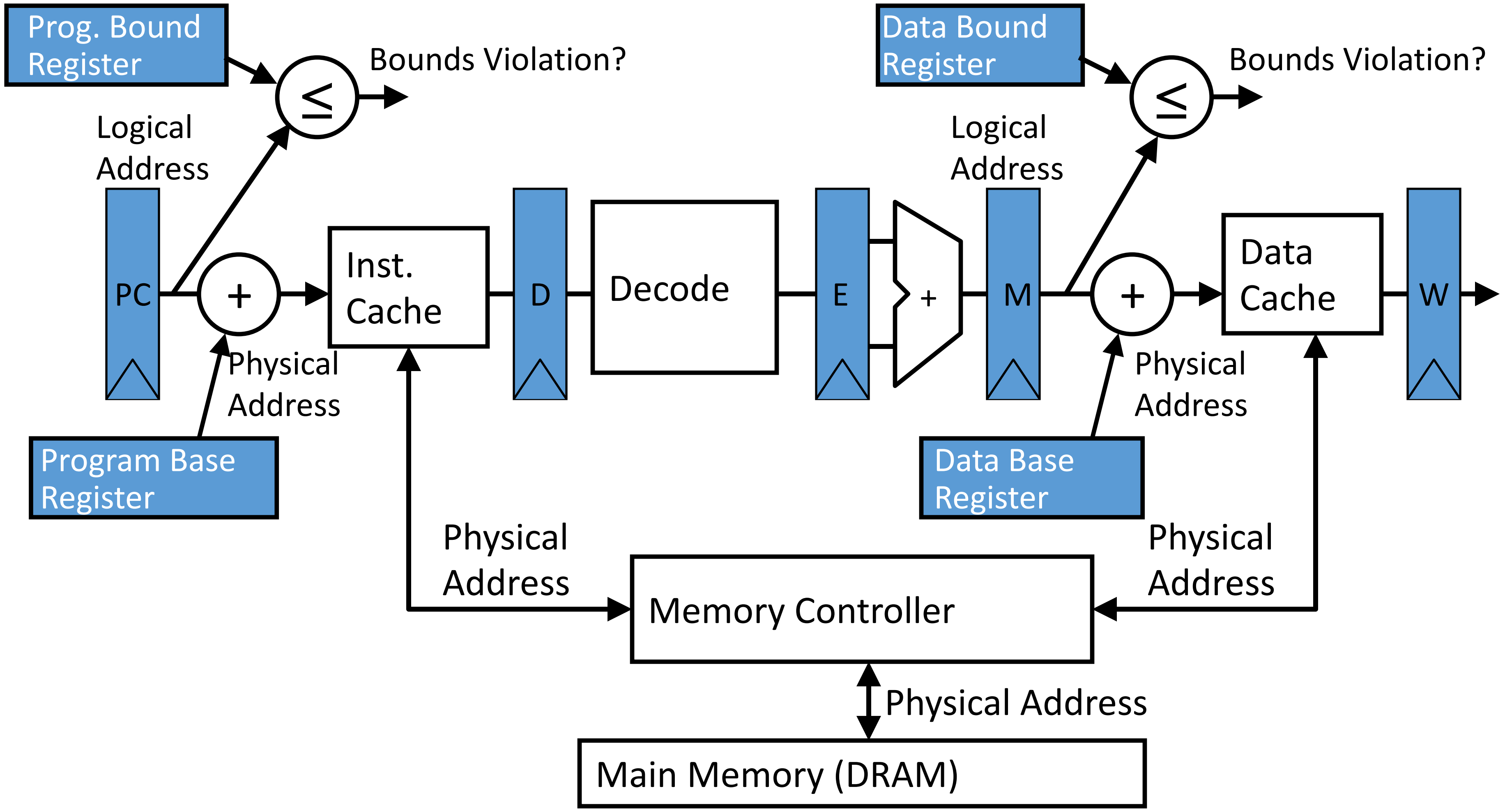
(Note: Multiprogramming drives requirement for resident *supervisor (OS)* software to manage context switches between multiple programs)

Simple Base and Bound Translation



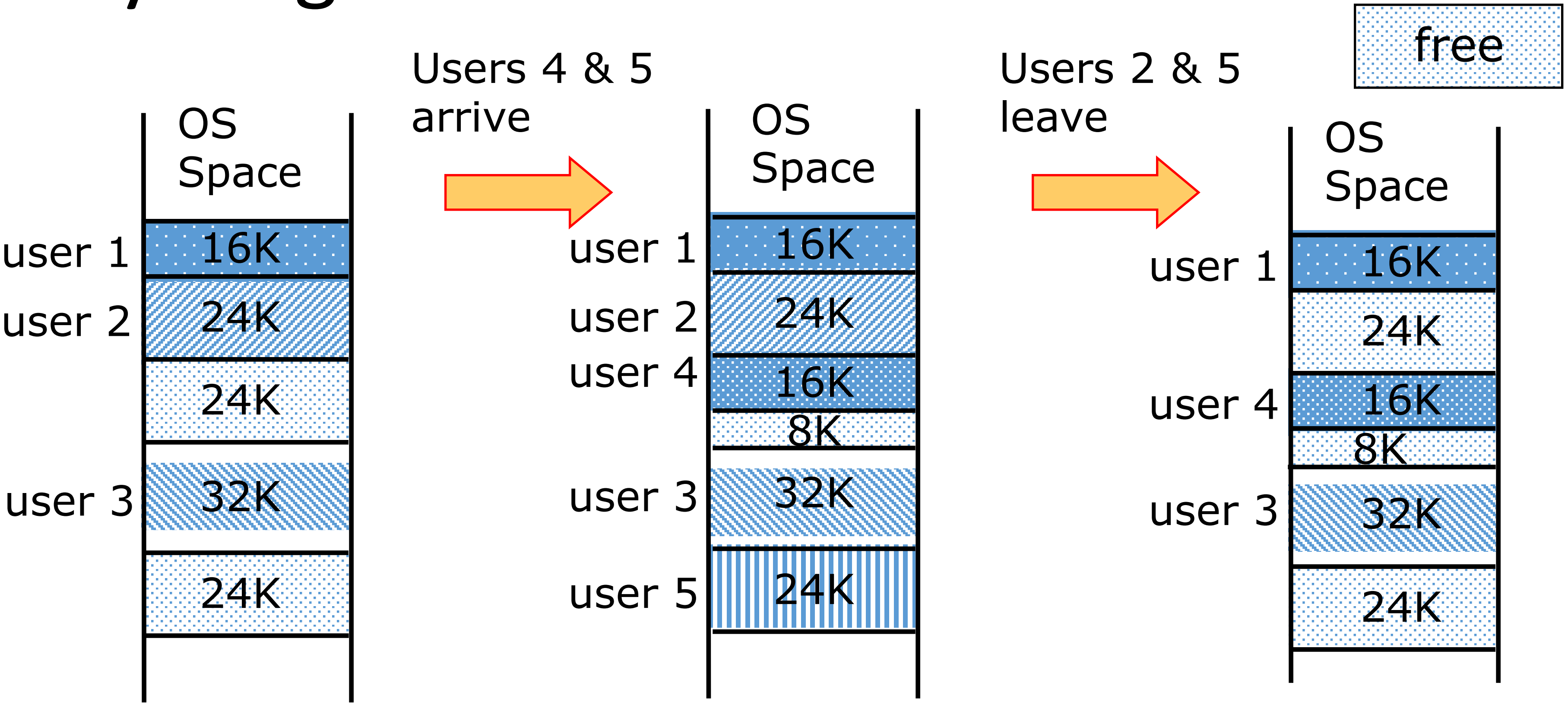
Base and bounds registers are visible/accessible only when processor is running in *supervisor mode*

Base and Bound Machine



[Can fold addition of base register into (register+immediate) address calculation using a carry-save adder (sums three numbers with only a few gate delays more than adding two numbers)]

Memory Fragmentation



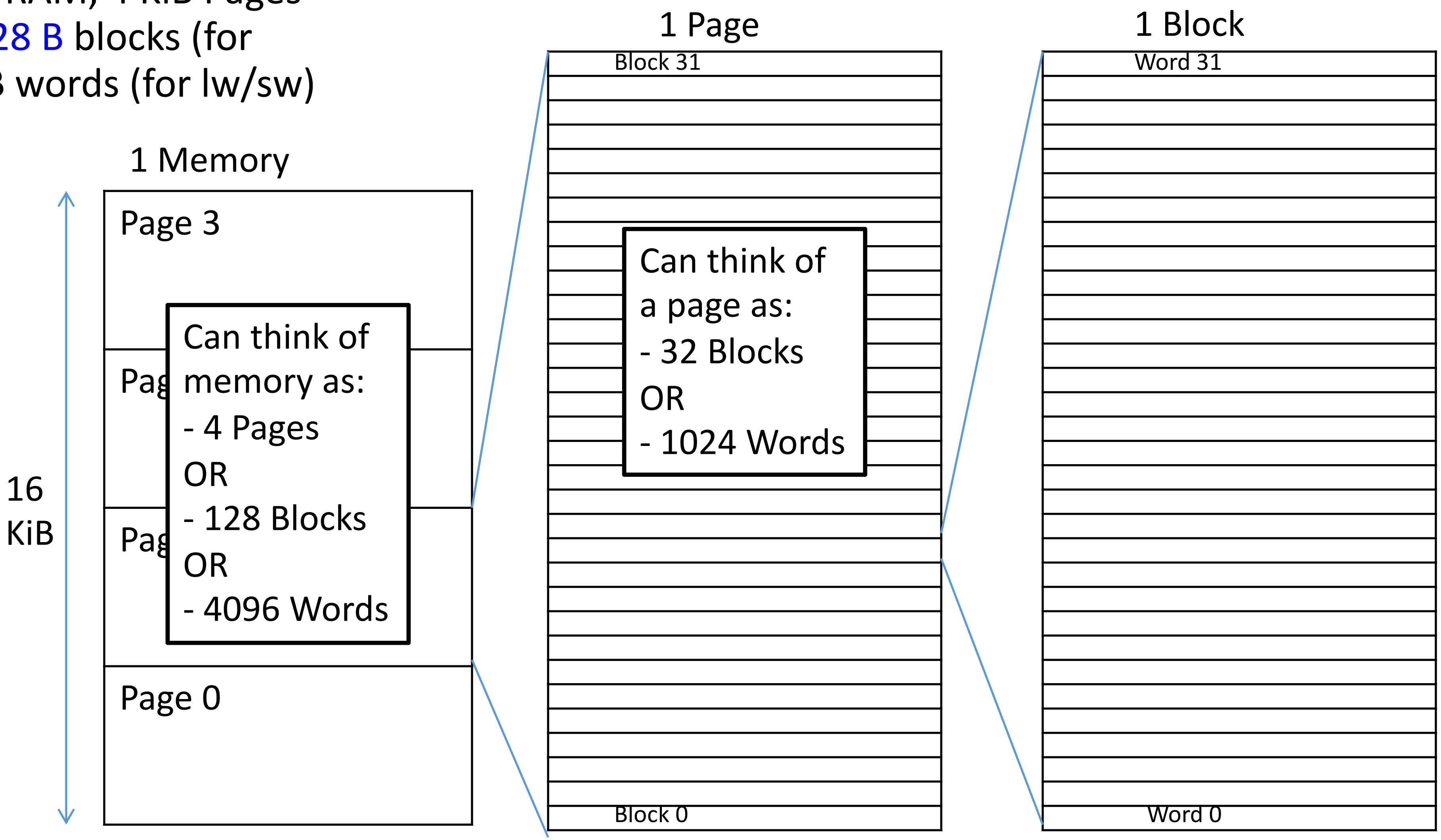
As users come and go, the storage is “fragmented”. Therefore, at some stage programs have to be moved around to compact the storage.

Blocks vs. Pages

- In caches, we dealt with individual *blocks*
  - Usually ~64B on modern systems
  - We could “divide” memory into a set of blocks
- In VM, we deal with individual *pages*
  - Usually ~4 KB on modern systems
    - Larger sizes also available: 2MB, very modern 1GB!
  - Now, we’ll “divide” memory into a set of pages
- Common point of confusion: Bytes, Words, Blocks, Pages are all just different ways of looking at memory!

Bytes, Words, Blocks, Pages

Ex: 16 KiB DRAM, 4 KiB Pages (for VM), 128 B blocks (for caches), 4 B words (for lw/sw)

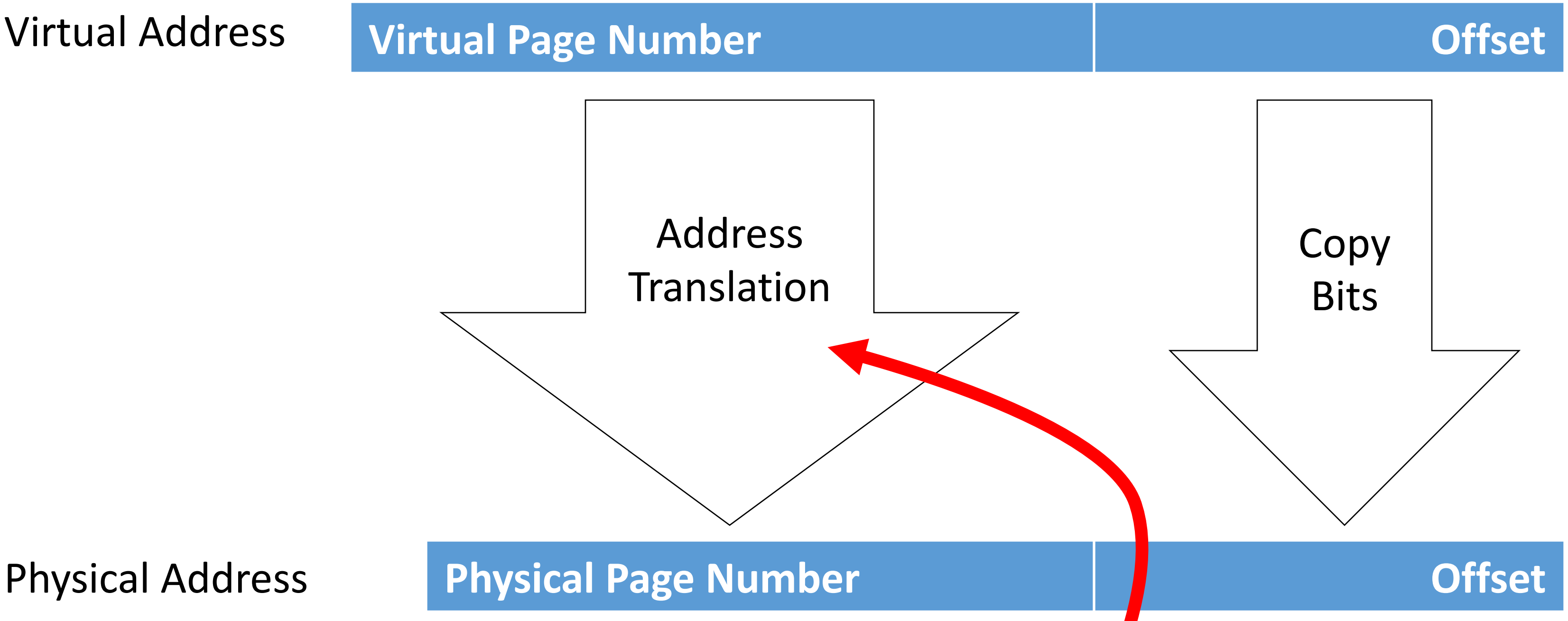


Address Translation

- So, what do we want to achieve at the hardware level?
  - Take a Virtual Address, that points to a spot in the Virtual Address Space of a particular program, and map it to a Physical Address, which points to a physical spot in DRAM of the whole machine

Virtual Address	**Virtual Page Number**	**Offset**
Physical Address	**Physical Page Number**	**Offset**

Address Translation



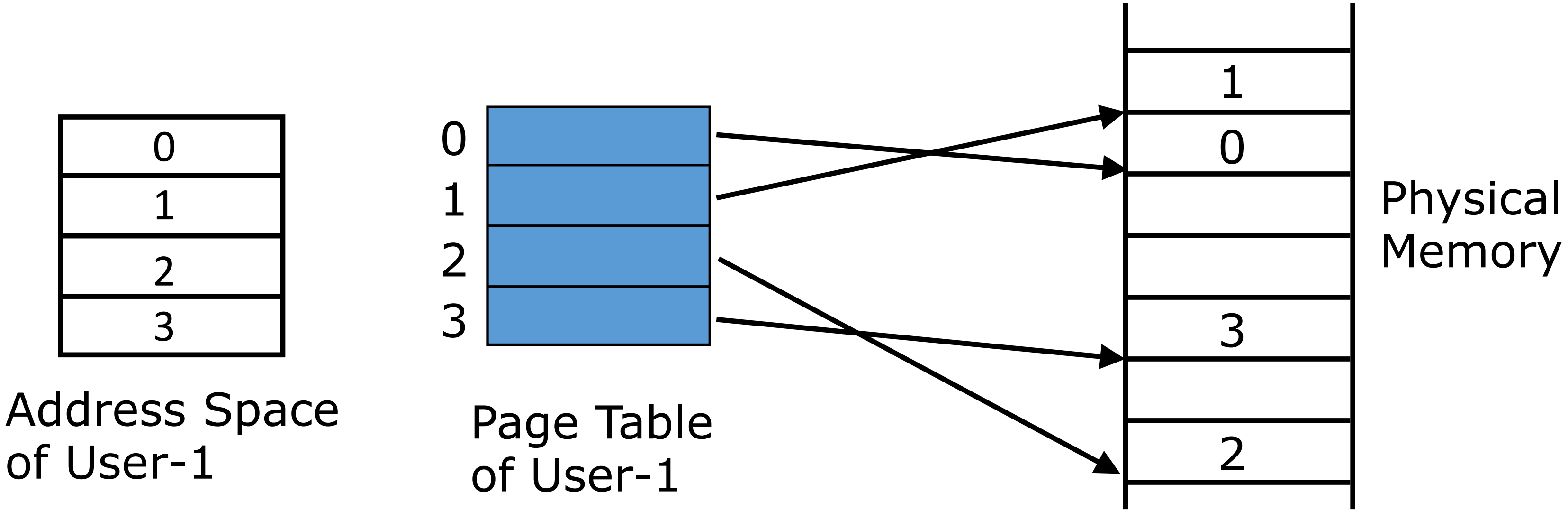
The rest of the lecture is all about implementing

Paged Memory Systems

- Processor-generated address can be split into:

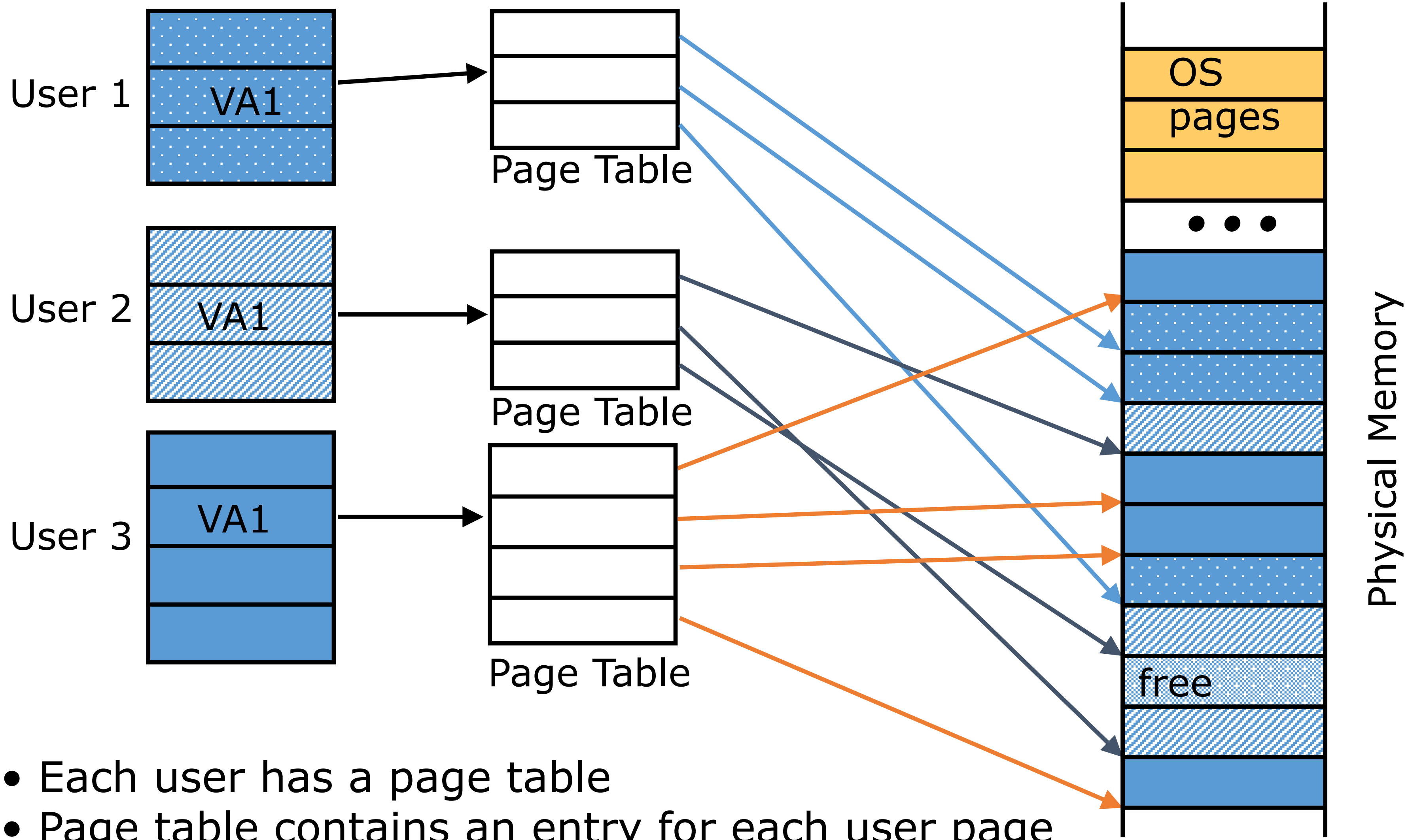
page number	offset

- A page table contains the physical address of the base of each page



Page tables make it possible to store the pages of a program non-contiguously.

Private Address Space per User



- Each user has a page table
- Page table contains an entry for each user page

Where Should Page Tables Reside?

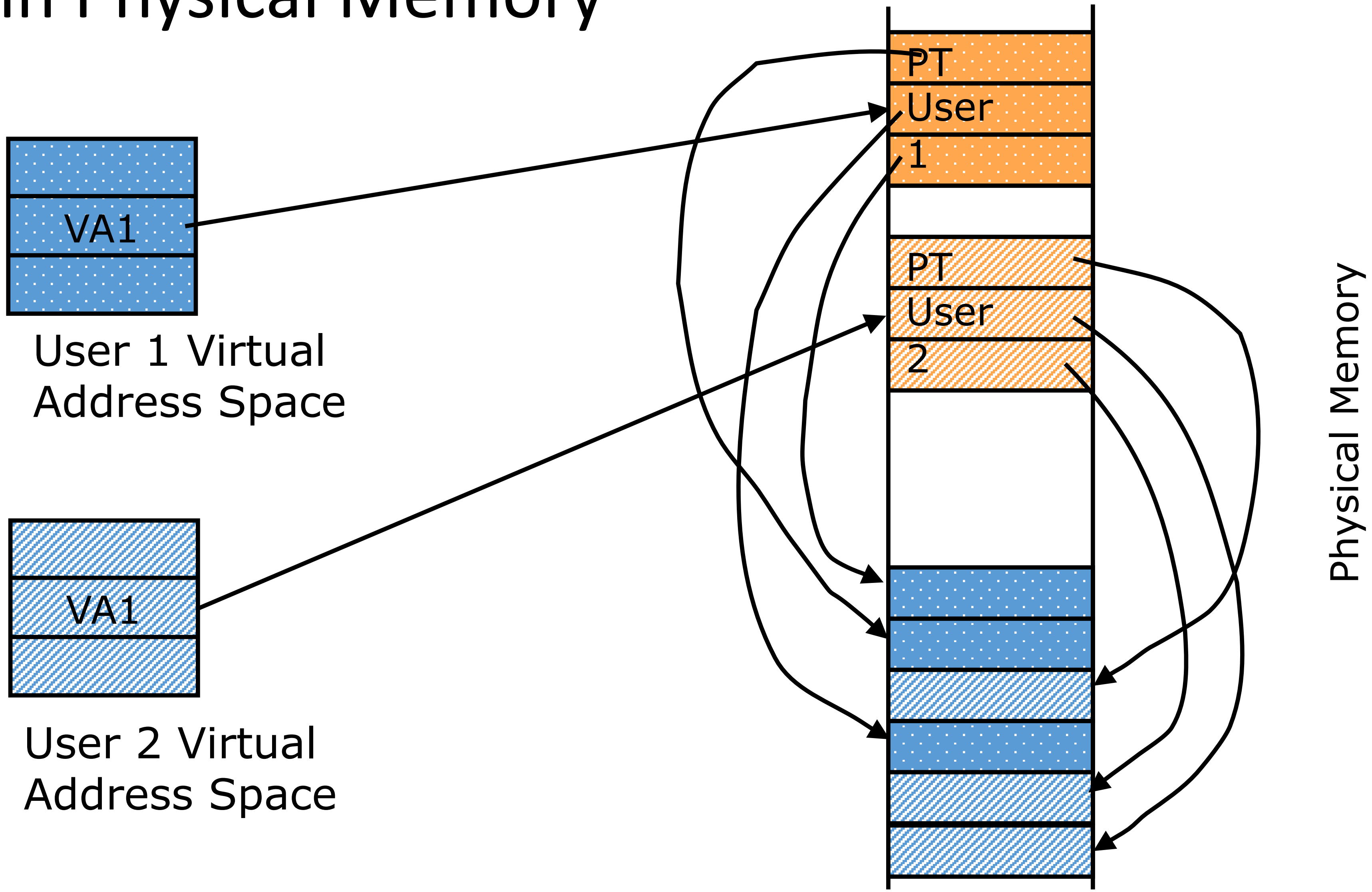
- Space required by the page tables (PT) is proportional to the address space, number of users, ...

  $\Rightarrow$ *Too large to keep in CPU registers*

- Idea: Keep PTs in the main memory
  - Needs one reference to retrieve the page base address and another to access the data word

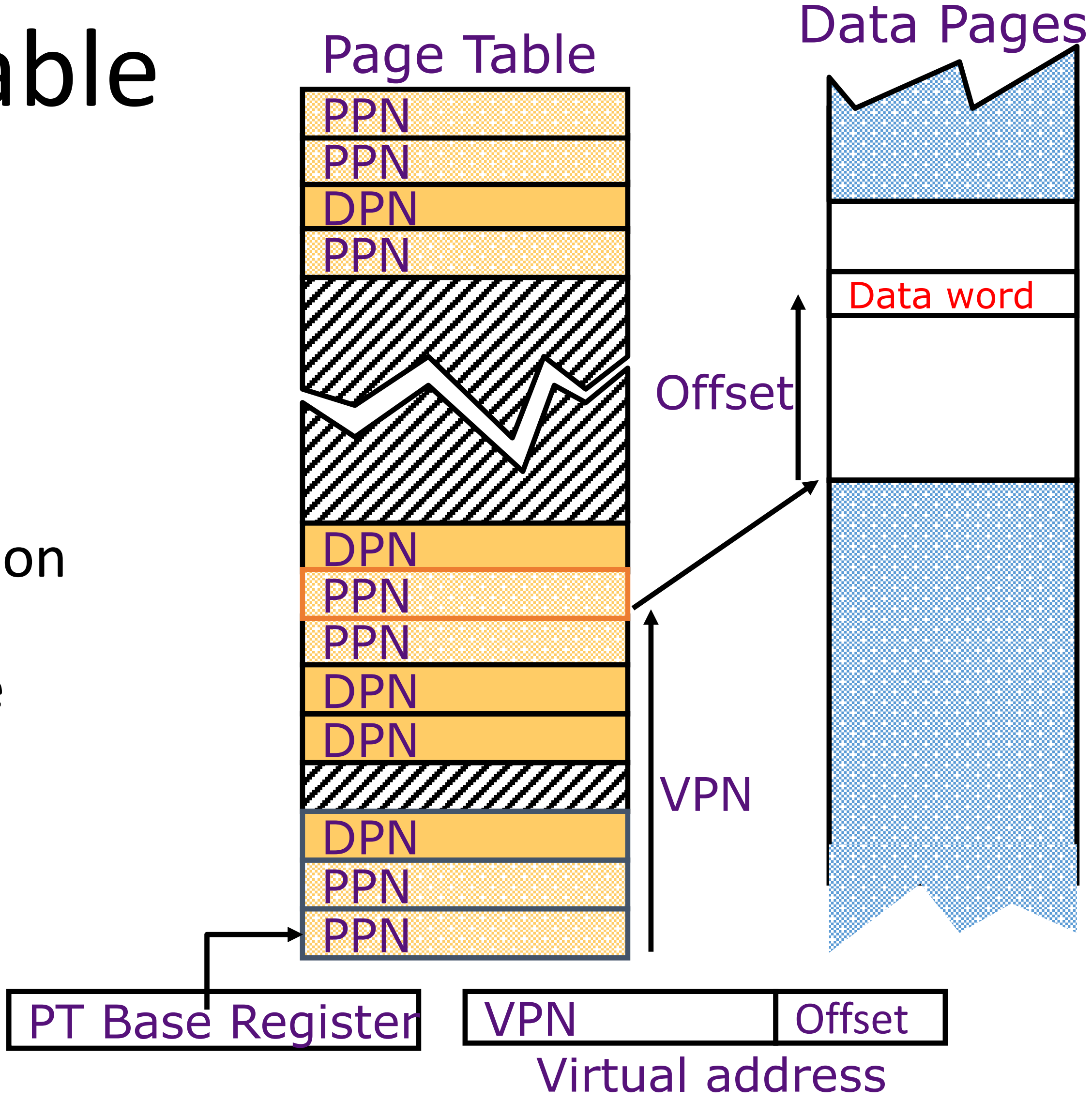
    => *doubles the number of memory references!*

Page Tables in Physical Memory



Linear (simple) Page Table

- Page Table Entry (PTE) contains:
  - 1 bit to indicate if page exists
  - And either PPN or DPN:
  - PPN (physical page number) for a memory-resident page
  - DPN (disk page number) for a page on the disk
  - Status bits for protection and usage (read, write, exec)
- OS sets the Page Table Base Register whenever active user process changes



Suppose an instruction references a memory page that isn’t in DRAM?

- We get an exception of type “page fault”
- Page fault handler does the following:
  - If virtual page doesn’t yet exist, assign an unused page in DRAM, or if page exists …
  - Initiate transfer of the page we’re requesting from disk to DRAM, assigning to an unused page
  - If no unused page is left, a *page currently in DRAM is selected to be replaced* (based on usage)
  - The replaced page is written (back) to disk, page table entry that maps that VPN->PPN is marked as invalid/DPN
  - Page table entry of the page we’re requesting is updated with a (now) valid PPN





Size of Linear Page Table

With 32-bit memory addresses, 4-KB pages:

=> $2^{32} / 2^{12} = 2^{20}$ virtual pages per user, assuming 4-Byte PTEs,

=> 2^{20} PTEs, i.e, 4 MB page table per process!

Larger pages?

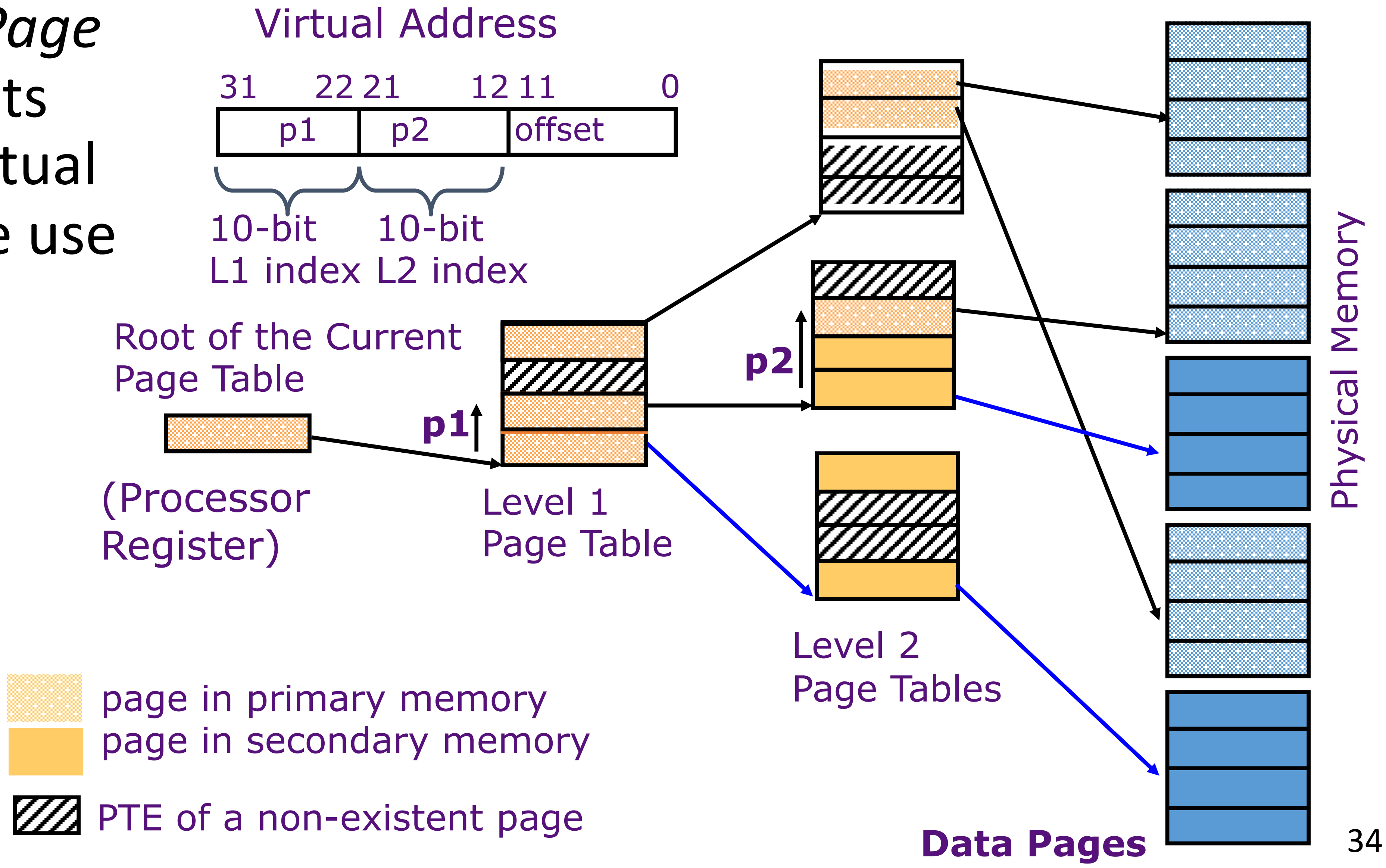
- Internal fragmentation (Not all memory in page gets used)
- Larger page fault penalty (more time to read from disk)

What about 64-bit virtual address space???

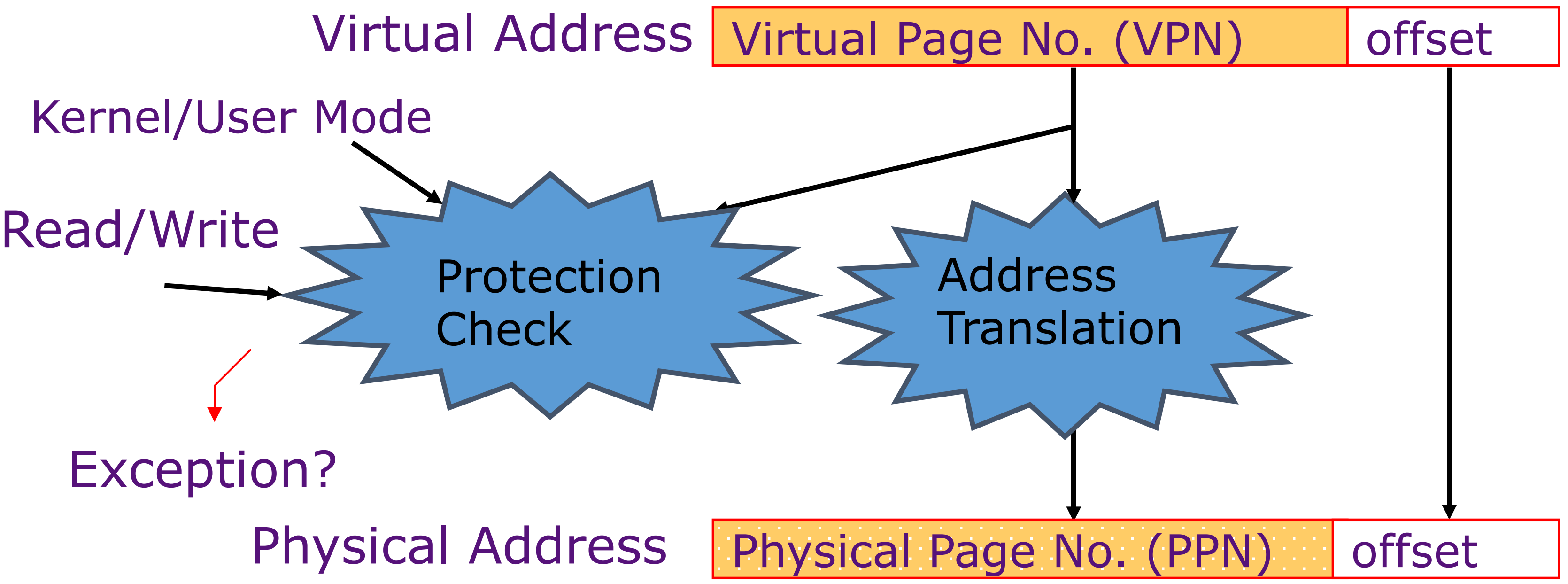
- Even 1MB pages would require 2^{44} 8-Byte PTEs (35 TB!)

What is the "saving grace" ? Most processes only use a set of high address (stack), and a set of low address (instructions, heap)

Hierarchical Page Table – exploits sparsity of virtual address space use



Address Translation & Protection



- Every instruction and data access needs address translation and protection checks

Why?

- *A good VM design needs to be fast (~ one cycle) and space efficient*

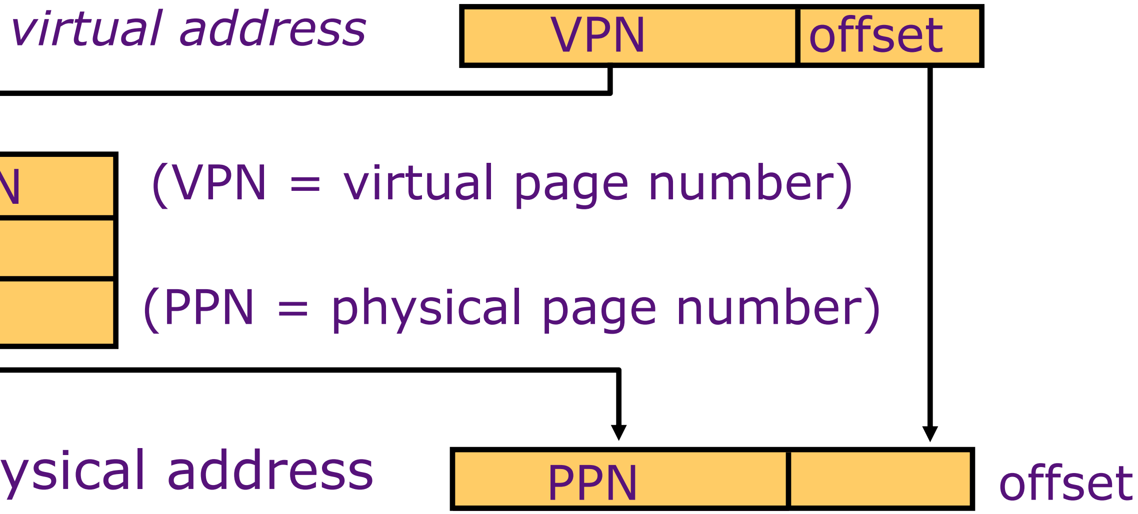
Translation Lookaside Buffers (TLB)

Address translation is very expensive!

- In a two-level page table, each reference becomes several memory accesses

Solution: *Cache some translations in TLB*

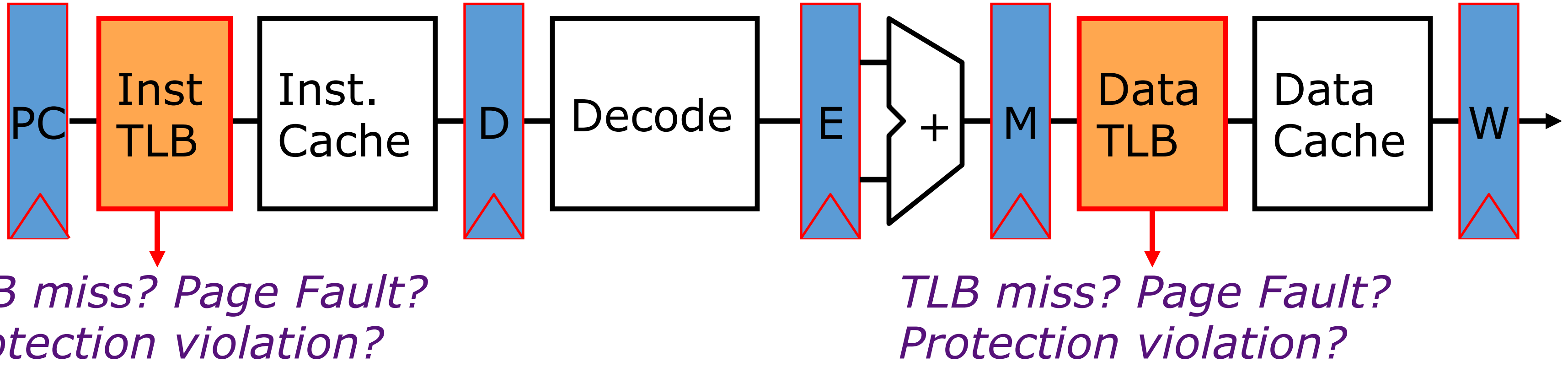
TLB hit	=>	*Single-Cycle Translation*
TLB miss	=>	*Page-Table Walk to refill*



TLB Designs

- Typically 32-128 entries, usually fully associative
  - Each entry maps a large page, hence less spatial locality across pages => more likely that two entries conflict
  - Sometimes larger TLBs (256-512 entries) are 4-8 way set-associative
  - Larger systems sometimes have multi-level (L1 and L2) TLBs
- Random or FIFO replacement policy
- Upon context switch? New VM space! Flush TLB …
- "TLB Reach": Size of largest virtual address space that can be simultaneously mapped by TLB

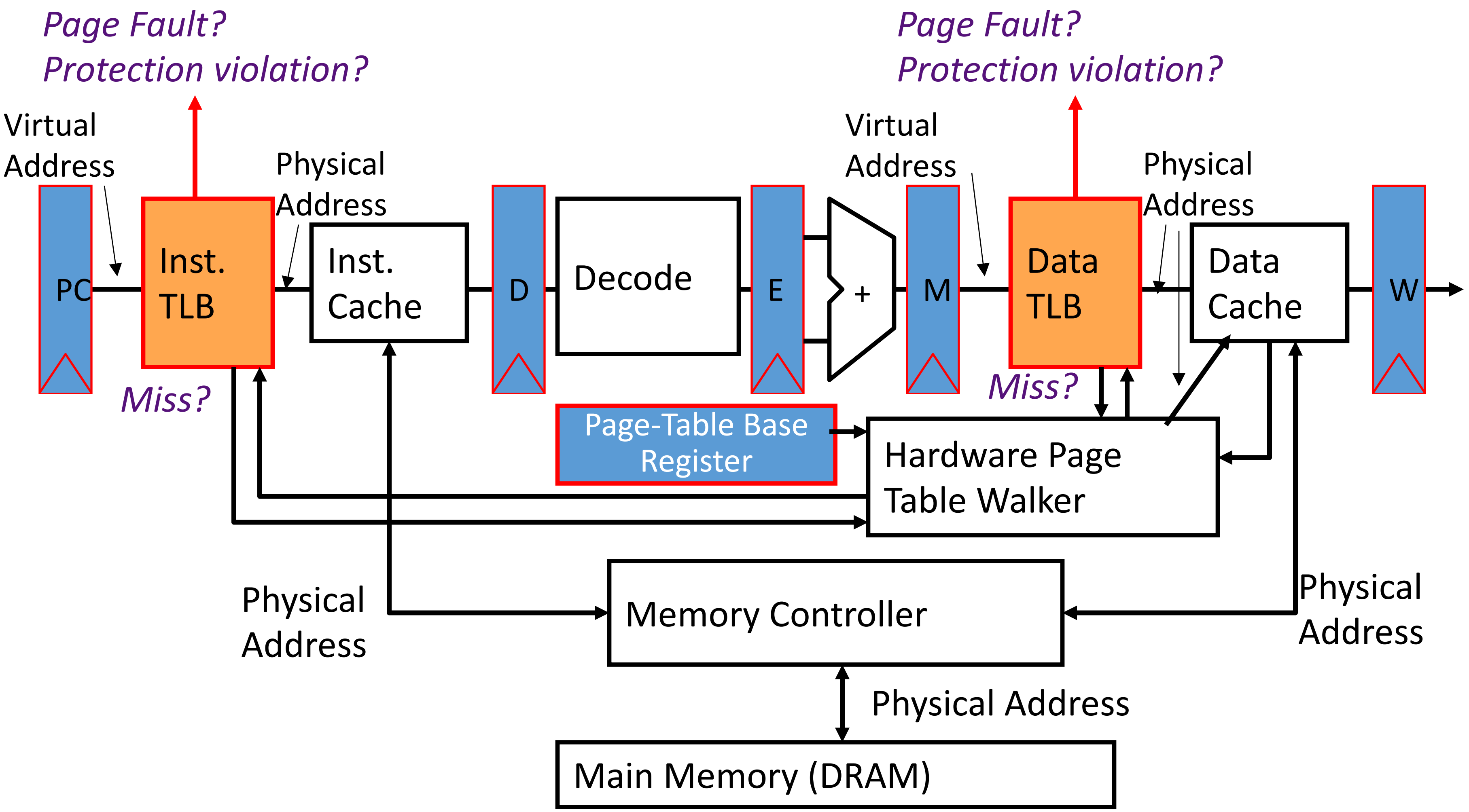
VM-related events in pipeline



- Handling a TLB miss needs a hardware or software mechanism to refill TLB
  - usually done in hardware now
- Handling a page fault (e.g., page is on disk) needs a *precise* trap so software handler can easily resume after retrieving page
- Handling protection violation may abort process

Page-Based Virtual-Memory Machine

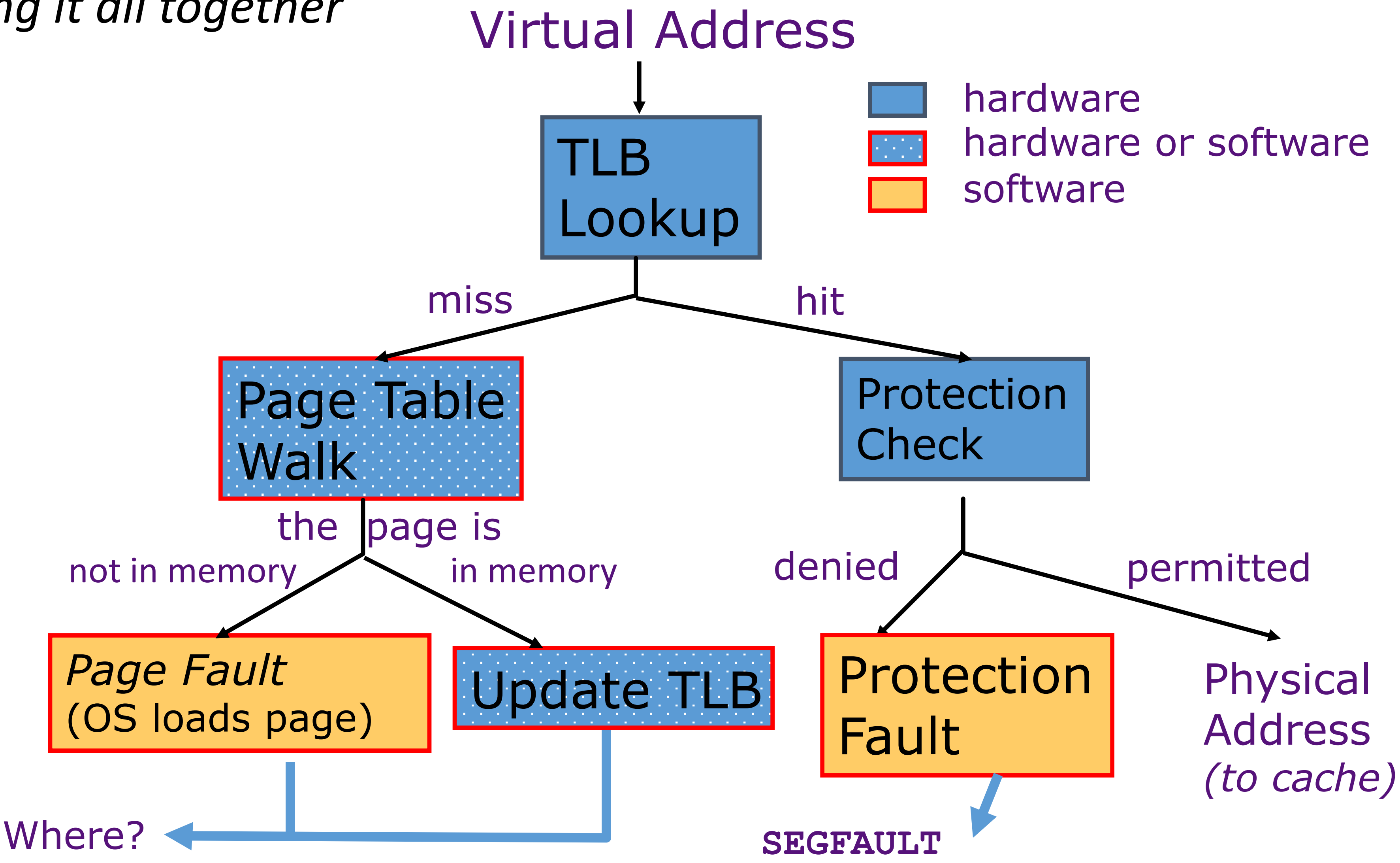
(Hardware Page-Table Walk)



- Assumes page tables held in untranslated physical memory

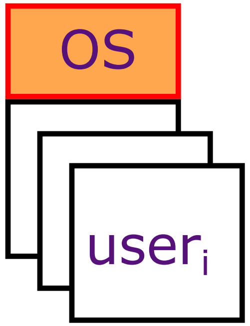
Address Translation:

putting it all together



Modern Virtual Memory Systems

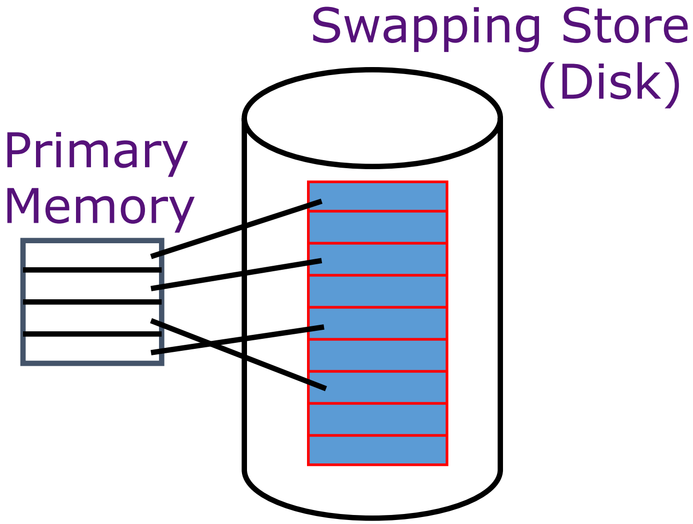
Illusion of a large, private, uniform store



Protection & Privacy

several users, each with their private address space and one or more shared address spaces

page table = name space

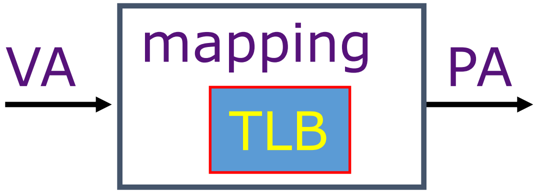


Demand Paging

Provides the ability to run programs larger than the primary memory

Hides differences in machine configurations

The price is address translation on each memory reference



Unlimited?

```
wangc@64G:~$ ulimit -s
8192
wangc@64G:~$ ulimit -a
core file size          (blocks, -c) 0
data seg size           (kbytes, -d) unlimited
scheduling priority             (-e) 0
file size               (blocks, -f) unlimited
pending signals                 (-i) 256820
max locked memory       (kbytes, -l) 16384
max memory size         (kbytes, -m) unlimited
open files                      (-n) 1024
pipe size            (512 bytes, -p) 8
POSIX message queues     (bytes, -q) 819200
real-time priority              (-r) 0
stack size              (kbytes, -s) 8192
cpu time               (seconds, -t) unlimited
max user processes              (-u) 256820
virtual memory          (kbytes, -v) unlimited
file locks                      (-x) unlimited
wangc@64G:~$
```





Remember: Out of Memory

- Insufficient free memory: **`malloc()`** returns **`NULL`**

```c
/*
        This is a test for CS 110. All copyrights ...
 */

#include <stdio.h>
#include <stdlib.h>

int main(int argc, char **argv) {
        const int G = 1024 * 1024 * 1024;
        for (int n = 0; ; n++) {
                char *p = malloc(G * sizeof(char)); // 1GB every time
                if (p == NULL) {
                        fprintf(stderr,
                                "failed to allocate > %g TeraBytes\n",
                                        n / 1024.0);
                        return 1;
                }
                // no free, keep allocating until out of memory
        }
        return 0;
}
```

```
wangc@64G:~/TT$ gcc test.c -o t -Wall -O3
wangc@64G:~/TT$ ./t
failed to allocate > 127.99 TeraBytes
wangc@64G:~/TT$
```

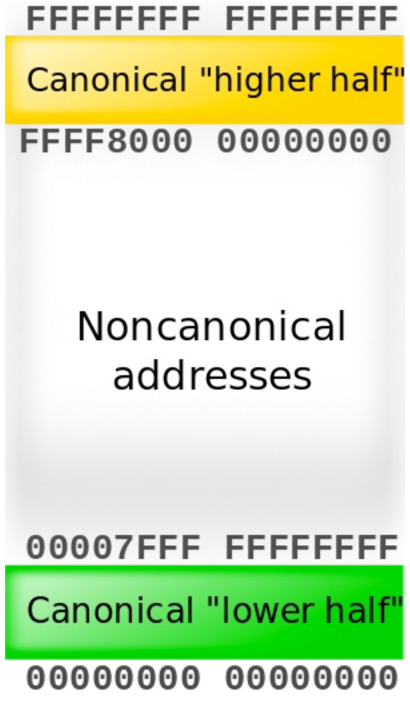
Limited VM Space with x86-64

- 64-bit Linux allows up to **128TB** of virtual address space for individual processes, and can address approximately 64 TB of physical memory, subject to processor and system limitations.
- For Windows 64-bit versions, both 32- and 64-bit applications, if not linked with "*large address aware*", are limited to **2GB** of virtual address space; otherwise, **128TB** for Windows 8.1 and Windows Server 2012 R2 or later.

Source: https://en.wikipedia.org/wiki/X86-64

48bit for address translation only

- Still provides plenty of space!
- Higher bits “sign extended”: “canonical form”
- Convention: “Higher half” for the Operating System
- Intel has plans (“whitepaper”) for 56 bit translation – no hardware yet



- https://en.wikipedia.org/wiki/X86-64#Virtual_address_space_details

Using 128TB of Memory!?

- A lazy allocation of virtual memory
  - Not used ➔ not allocated
  - Try reading and writing from those pointers: works!
  - Even writing Gigabaytes of memory: works!
- Memory Compression!
  - Take not-recently used pages, compress them => free the physical page
- https://www.lifewire.com/understanding-compressed-memory-os-x-2260327

Process Name	Memory	Threads	Ports	PID	User	Compressed M...	Real Mem
a.out	60.51 GB	1	10	22329	schwerti	54.30 GB	6.22 GB

Conclusion: VM features track historical uses

- **Bare machine, only physical addresses**
  - One program owned entire machine
- **Batch-style multiprogramming**
  - Several programs sharing CPU while waiting for I/O
  - Base & bound: translation and protection between programs (not virtual memory)
  - Problem with external fragmentation (holes in memory), needed occasional memory defragmentation as new jobs arrived
- **Time sharing**
  - More interactive programs, waiting for user. Also, more jobs/second.
  - Motivated move to fixed-size page translation and protection, no external fragmentation (but now internal fragmentation, wasted bytes in page)
  - Motivated adoption of virtual memory to allow more jobs to share limited physical memory resources while holding working set in memory