

# Operating Systems

## Lecture 6

# Address Translation

Prof. Mengwei Xu

# Recap: Thread Abstraction

- Thread: a single execution sequence that represents a separately schedulable task

Each thread executes a sequence of instructions (assignments, conditionals, loops, procedures, etc) just as in the sequential programming model

The OS can run, suspend, or resume a thread at any time

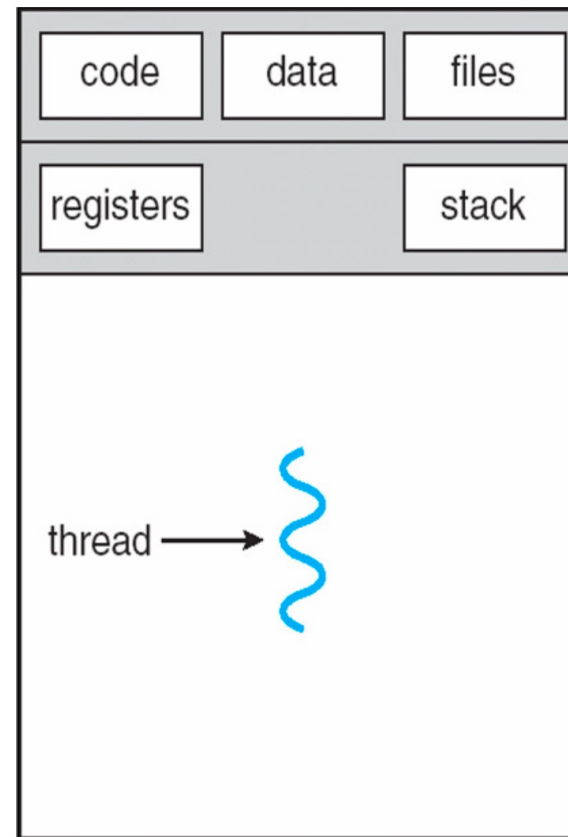
**The minimal scheduling unit in OS!**

# Recap: Thread Abstraction

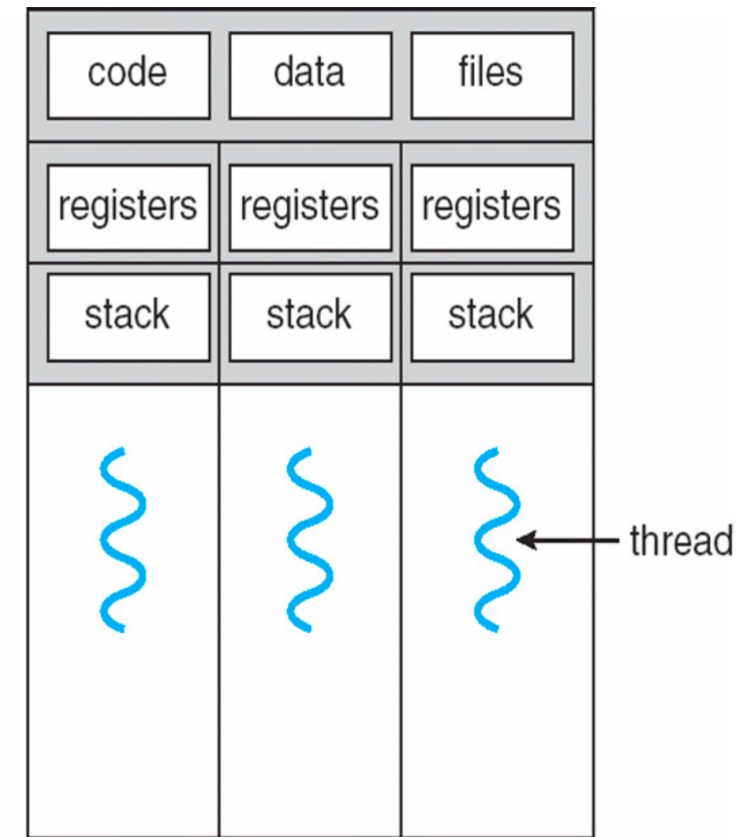
- Thread: a single execution sequence that represents a separately schedulable task

Threads in the same process share memory space, but not execution context

- There will be thread context switch



single-threaded process



multithreaded process

# Recap: Thread vs. Process

	Thread	Process
Currency	Both of them can be scheduled by OS.	
Context	Different threads/processes have their dedicated execution contexts (registers values and stacks). Scheduling them incurs context switching.	
Definition	A single execution sequence that represents a separately schedulable task	An execution of any program
	The minimal scheduling unit “a lightweight process”	The minimal dedicated memory space
Resources	Consume less resources	Consume more resources
Memory	Threads in the same process share memory space	Processors do not share memory space
Communications	Easier and faster for threads in the same process to communicate with each other	More complex and slow for different processes to communicate with each other

# Recap: POSIX Thread Example

```
1  #include <stdio.h>
2  #include <stdlib.h>
3  #include <pthread.h>
4
5  void *print_message_function( void *ptr );
6
7  main()
8  {
9      pthread_t thread1, thread2;
10     char *message1 = "Thread 1";
11     char *message2 = "Thread 2";
12     int  iret1, iret2;
13
14     iret1 = pthread_create( &thread1, NULL, print_message_function, (void*) message1);
15     iret2 = pthread_create( &thread2, NULL, print_message_function, (void*) message2);
16
17     pthread_join( thread1, NULL);
18     pthread_join( thread2, NULL);
19
20     printf("Thread 1 returns: %d\n",iret1);
21     printf("Thread 2 returns: %d\n",iret2);
22     exit(0);
23 }
24
25 void *print_message_function( void *ptr )
26 {
27     char *message;
28     message = (char *) ptr;
29     printf("%s \n", message);
30 }
```

What's the possible output?

# Recap: Thread Data Structures

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- Thread Control Block (TCB)
  - Stack pointer: each thread needs their own stack
  - Copy of processor registers
    - ☐ General-purpose registers for storing intermediate values
    - ☐ Special-purpose registers for storing instruction pointer and stack pointer
  - Metadata
    - ☐ Thread ID
    - ☐ Scheduling priority
    - ☐ Status
  - What's different from PCB??

# Recap: Thread Data Structures

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- Thread Control Block (TCB)
- Shared state
- OS does not enforce physical division on threads' own separated states
  - If thread A has a pointer to the stack location of thread B, can A access/modify the variables on the stack of thread B?

# Recap: Thread Implementation

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- Kernel threads
  - What are the use cases?
- User-level threads
  - Can be implemented with or without kernel help



# Recap: Thread Implementation

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- Create a thread
  - Allocate per-thread state: the TCB and stack
  - Initialize per-thread state: registers (args)
  - Put TCB on ready list
- Delete a thread
  - Remove the thread from the ready list so it will never run again
  - Free the per-thread state allocated for the thread
  - Can a thread delete itself?
- Context Switch
  - Voluntary: thread\_yield
  - Involuntary: interrupts and exceptions

# Implementing Multi-threaded Processes

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- Implementing user-level multi-threaded processes through
  1. Kernel threads (each thread op traps into kernel)
  2. User-level libraries (no kernel support)
  3. Hybrid mode

# Implementing Multi-threaded Processes

- Implementing multi-threaded processes through kernel threads
  - Each thread operation invokes the corresponding kernel thread syscall

## Create a kernel thread

- Allocate per-thread state in kernel: the TCB and stack
- Initialize per-thread state: registers (args)
- Put TCB on ready list

## Create a user-level thread

- User lib allocates a user-level stack
- Invokes `thread_create()` syscall
- Stores a pointer to the TCB in the PCB (why?)



How about `join`, `yield`, `exit`?

# Implementing Multi-threaded Processes

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- Implementing multi-threaded processes in user libraries
  - The library maintains everything in user space
    - TCBs, stacks, ready list, finished list
  - The library determines which thread to run
  - A thread op is just a procedure call

# Implementing Multi-threaded Processes

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- How can we make user-level threads run currently, as kernel is not aware of their existence?
- How can program change the PC and stack pointer?

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  - The library determines which thread to run
  - A thread op is just a procedure call
- How can we make user-level threads run currently, as kernel is not aware of their existence?
  - The preemptive way: timer interrupts (upcall) from kernel
  - The cooperative way: threads yield voluntarily
- How can program change the PC and stack pointer?
  - `jmp` and `esp`

# Threads in Kernel vs. User

	User-level Threads	Kernel Threads
Currency	Both of them run currently	
Context	Share heap/code, but have separated stack/registers	
Role of kernel	No kernel assistance at all	Each thread operation invokes kernel syscall
Speed (context switch, creating, etc)	Fast	Slow
Memory cost	Small	Large
I/O waiting time	Cannot avoid the I/O waiting time (though there are certain optimizations to do so)	Kernel can schedule another thread when I/O blocks
Multi-core processor	No parallel on multi-core processors	Can schedule many threads in the same process at the same time on multi-core processors

# Implementing Multi-threaded Processes

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- Implementing multi-threaded processes in hybrid way: optimizations based on kernel threads
  - Hybrid thread join: for example, no need for syscall if the thread to be joined is already finished (with exit value saved in memory)
  - Per-processor kernel thread with user-level thread implementation
  - Scheduler activations: in recent Windows, the user-level scheduler can be notified when a thread blocks in a syscall, so it can schedule another thread to fully utilize the processor.



# Goals for Today

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- Address Translation Concept
- Segmentation (分段)
- Paging (分页)

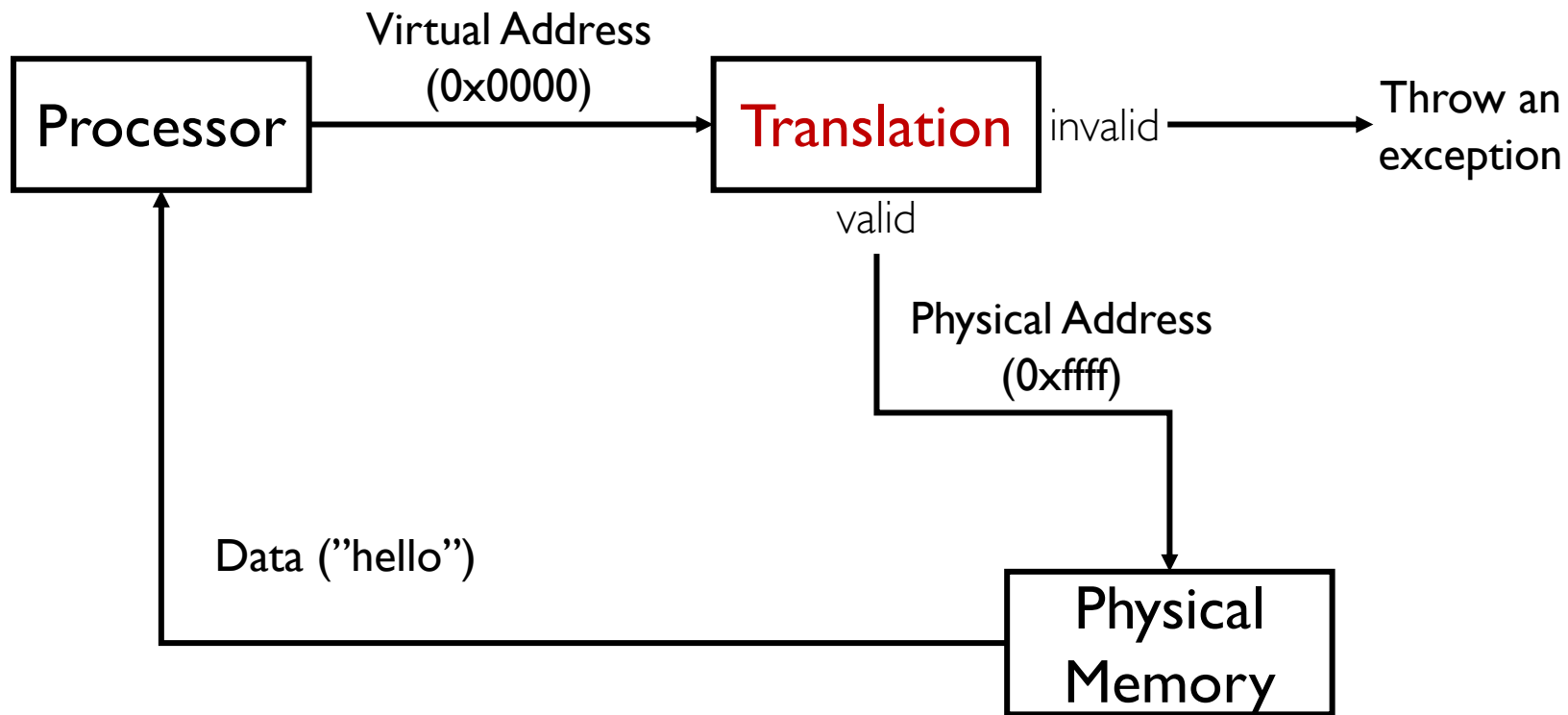
# Goals for Today

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# Address Translation

- From virtual memory address (虚拟内存地址) to physical memory address (物理内存地址)



# Address Translation

---

- From virtual memory address (虚拟内存地址) to physical memory address (物理内存地址)
- The goals and motivations of address translation
  - Memory protection
  - Memory sharing
  - Flexible memory placement
  - Sparse addresses
  - Runtime lookup efficiency
  - Compact translation tables
  - Portability

# Address Translation

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- From virtual memory address (虚拟内存地址) to physical memory address (物理内存地址)
- The goals and motivations of address translation
- When translation exists, processor uses virtual addresses, physical memory uses physical addresses
  - Not every processor/OS has address translation, e.g., certain embedded chips.

# Address Translation

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- Address translation involves intensive hardware-OS cooperation

# Address Translation

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- From virtual memory address (虚拟内存地址) to physical memory address (物理内存地址)
- The goals and motivations of address translation
- When translation exists, processor uses virtual addresses, physical memory uses physical addresses
- Address translation involves intensive hardware-OS cooperation
- Address space: all the addresses and state a process can touch
  - Each process and kernel has different address space

# Goals for Today

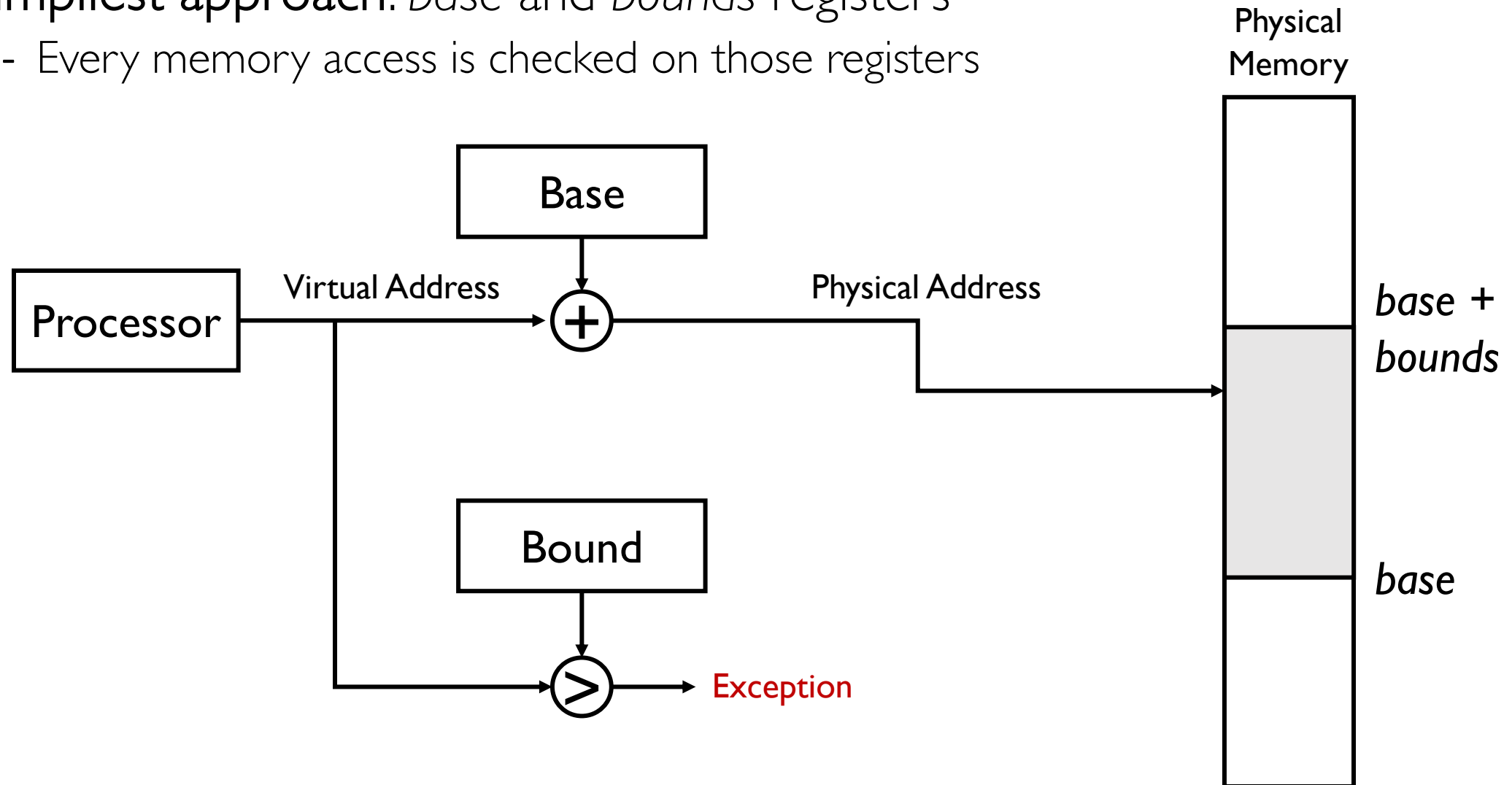
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- Address Translation Concept
- Segmentation (分段)
- Paging (分页)



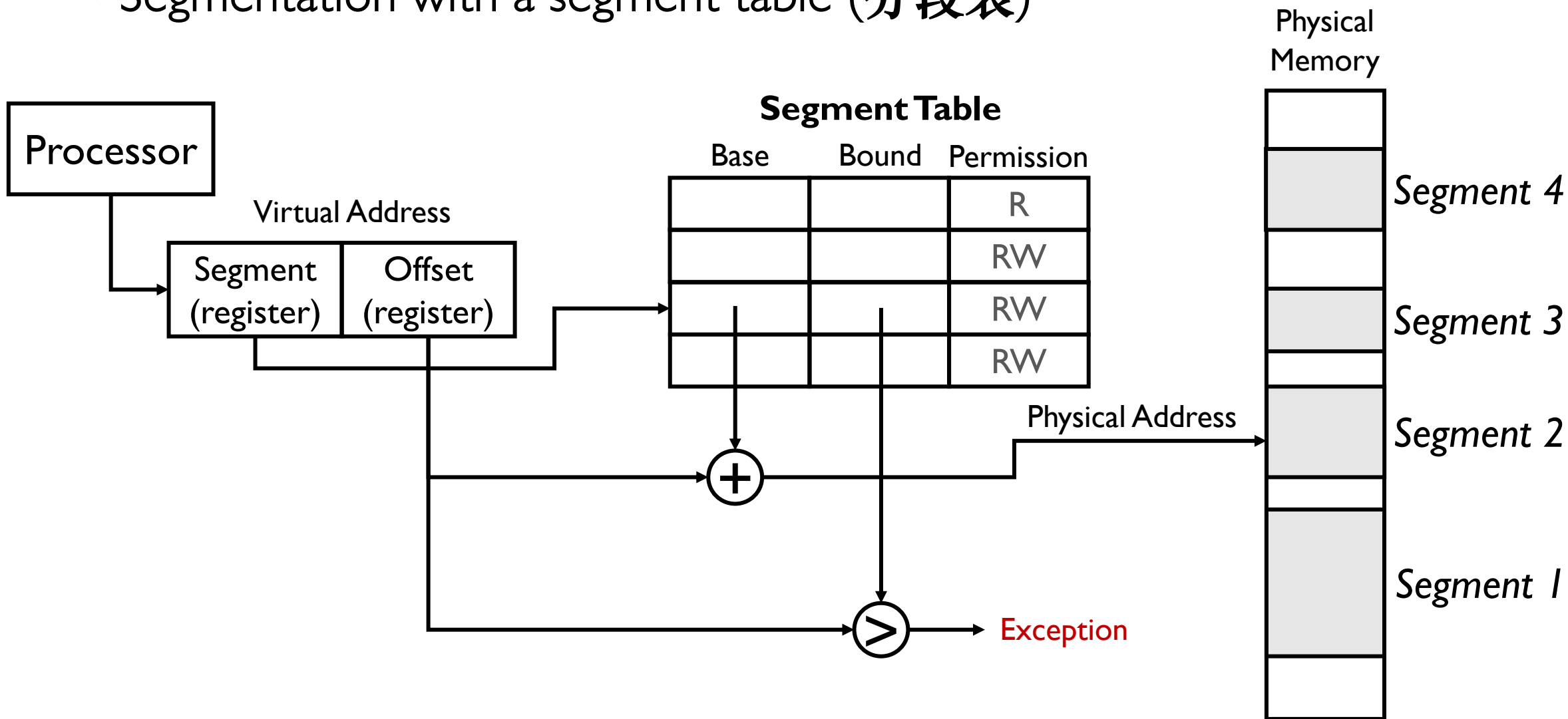
# Segmented Memory

- Simplest approach: *base* and *bounds* registers
  - Every memory access is checked on those registers



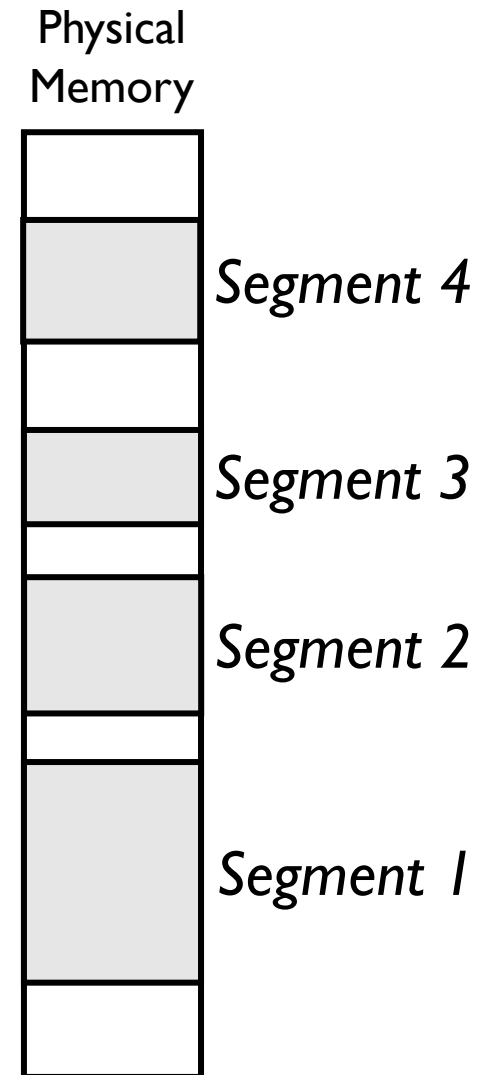
# Segmented Memory

- Segmentation with a segment table (分段表)



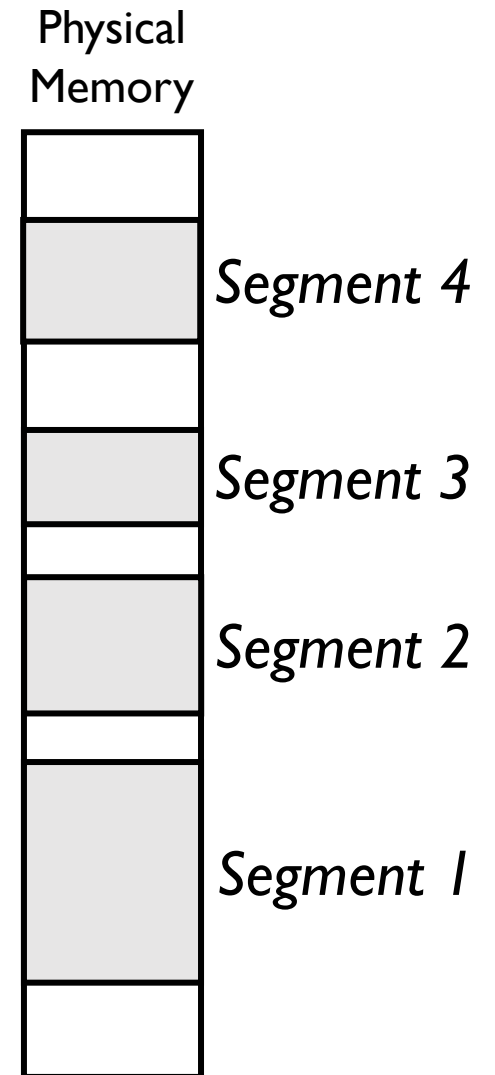
# Segmented Memory

- Segmentation with a segment table (分段表)
  - *Why there are “holes” in the physical memory*
  - *What if a program branches into those “holes”?*



# Segmented Memory

- Segmentation with a segment table (分段表)
  - Why there are “holes” in the physical memory
    - Processes come and go..
  - What if a program branches into those “holes”?
    - Segmentation error..



# Segmented Memory

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- The real segmentation implementation could vary a lot
  - Some OSes like Multics allocates a segment for each data structure to allow fine-grained protection and sharing between processes
  - Most modern systems use segments only for coarse-grained memory regions

# Segmented Memory

- An x86 view of memory segmentation (each 16-bits long)

- Code segment: CS
- Data segment: DS
- Stack segment: SS
- Extra segment: ES, FS GS

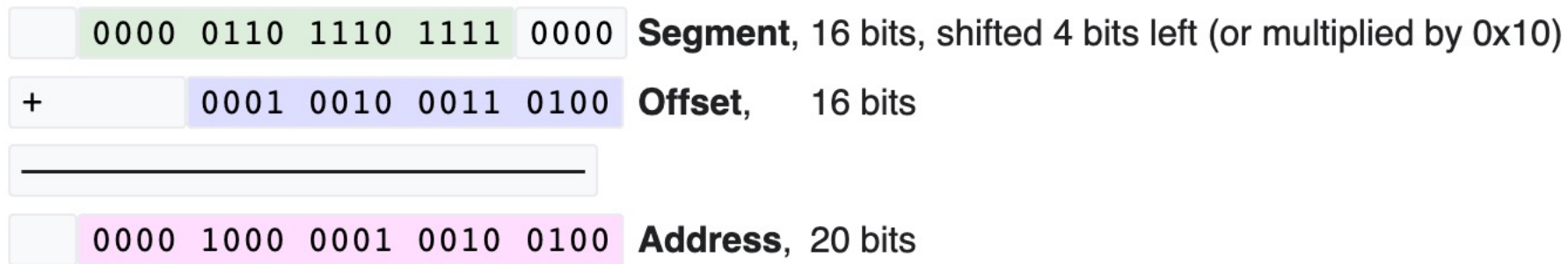
```
movl $foo, 0x10(%esp)
=
movl $foo, %ss:0x10(%esp)
```

- Developer practice

- All CPU instructions are implicitly fetched from the code segment (CS register).
- Most memory references come from the data segment specified by the segment selector held in the DS register. These may also come from the extra segment specified by the segment selector held in the ES register, if a segment-override prefix precedes the instruction that makes the memory reference.
- Processor stack references, either implicitly (e.g. push and pop instructions) or explicitly (memory accesses using (E)SP or (E)BP registers) use the stack segment (SS register).
- String instructions (e.g. stos, movs), along with data segment, also use the extra segment specified by the segment selector held in the ES register.

# Segmented Memory

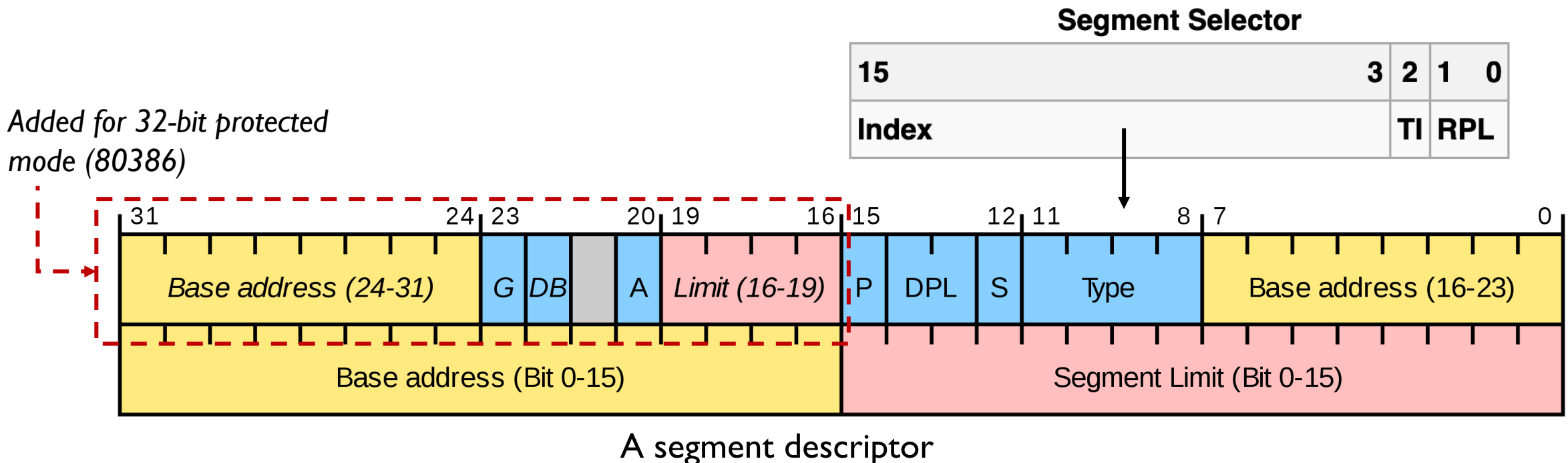
- An x86 view of memory segmentation
  - In real mode, there is no segment table



**In real mode**  
no segment table!

# Segmented Memory

- An x86 view of memory segmentation
  - In protected mode, the segment table is called global descriptor table (GDT, 全局描述符表) or local descriptor table (LDT, 局部描述符表)
  - Linear address = base address + offset





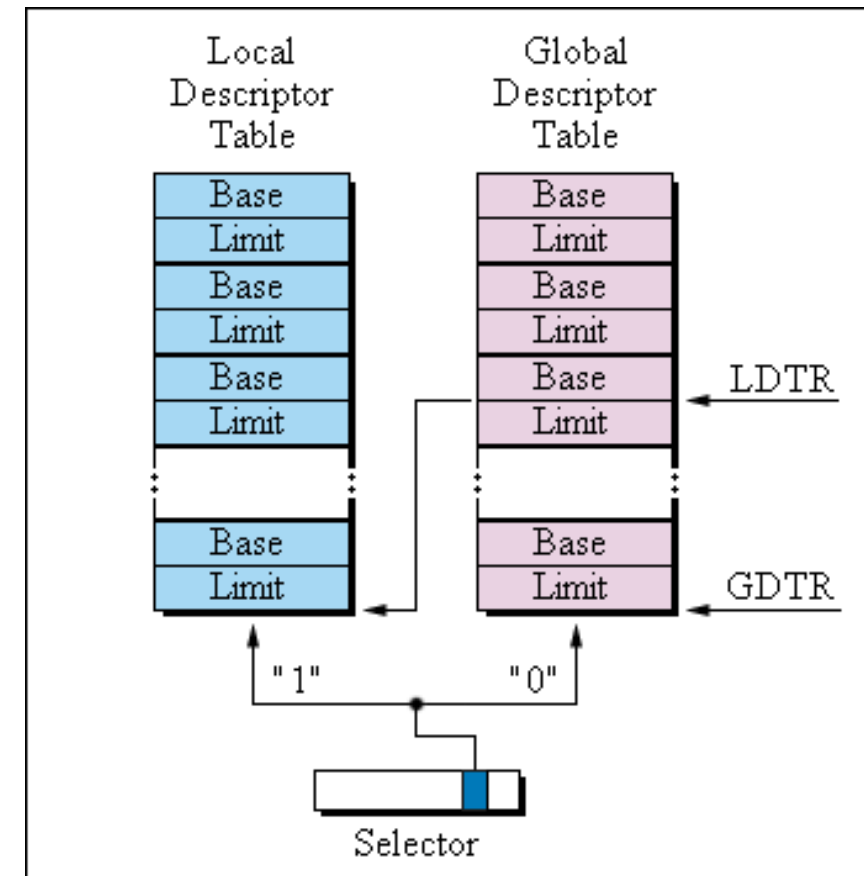
# Segmented Memory

- An x86 view of memory segmentation
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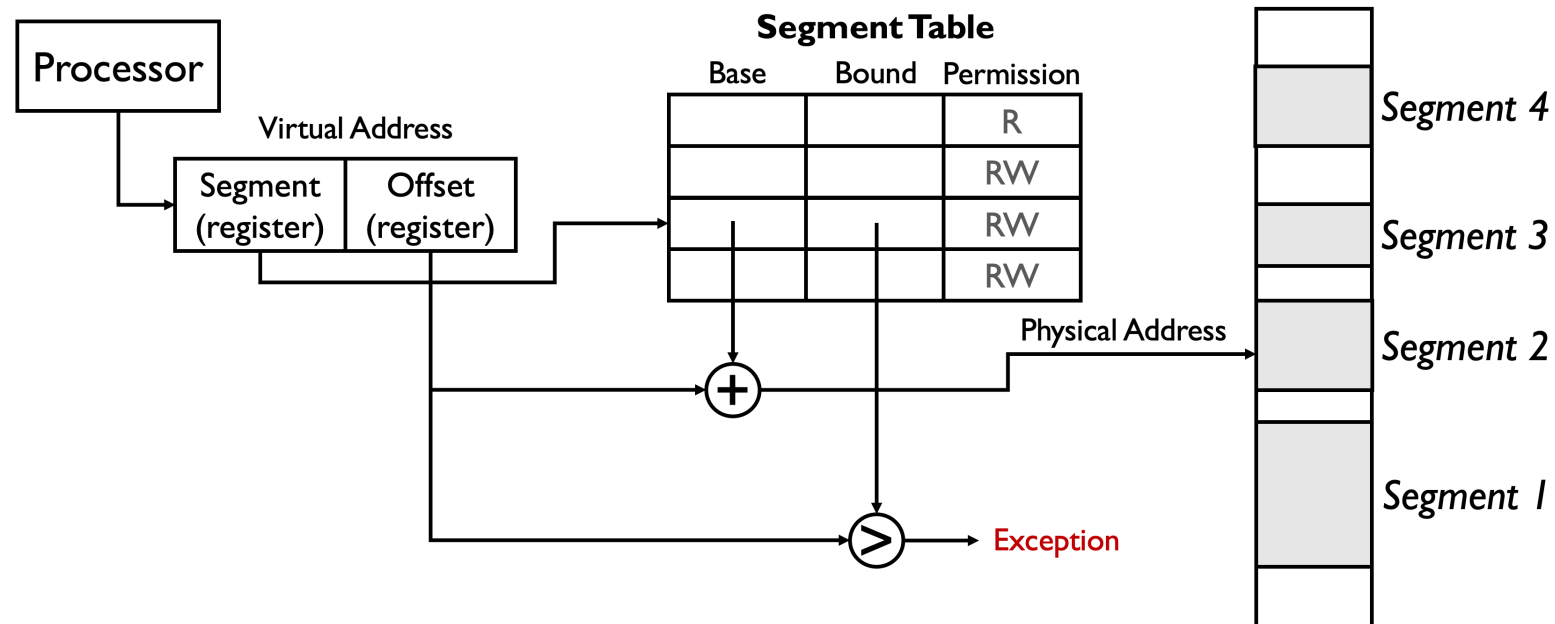
151 // Segment Descriptors
152 struct Segdesc {
153     unsigned sd_lim_15_0 : 16; // Low bits of segment limit
154     unsigned sd_base_15_0 : 16; // Low bits of segment base address
155     unsigned sd_base_23_16 : 8; // Middle bits of segment base address
156     unsigned sd_type : 4; // Segment type (see STS_constants)
157     unsigned sd_s : 1; // 0 = system, 1 = application
158     unsigned sd_dpl : 2; // Descriptor Privilege Level
159     unsigned sd_p : 1; // Present
160     unsigned sd_lim_19_16 : 4; // High bits of segment limit
161     unsigned sd_avl : 1; // Unused (available for software use)
162     unsigned sd_rsv1 : 1; // Reserved
163     unsigned sd_db : 1; // 0 = 16-bit segment, 1 = 32-bit segment
164     unsigned sd_g : 1; // Granularity: limit scaled by 4K when set
165     unsigned sd_base_31_24 : 8; // High bits of segment base address
166 };

```



# Segmented Memory

- The power of segmentation
  - Access control
  - Code sharing (library routines)
  - Inter-process communication
  - Efficient management of dynamically allocated memory



# Segmented Memory

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- The principle downside of segmentation: overhead of managing a large number of variable size and dynamically growing memory segments.
  - *External fragmentation*: free space becomes noncontiguous
  - Compacting the memory is very slow
  - It becomes even more complex if the segments can grow (like heap)

# Goals for Today

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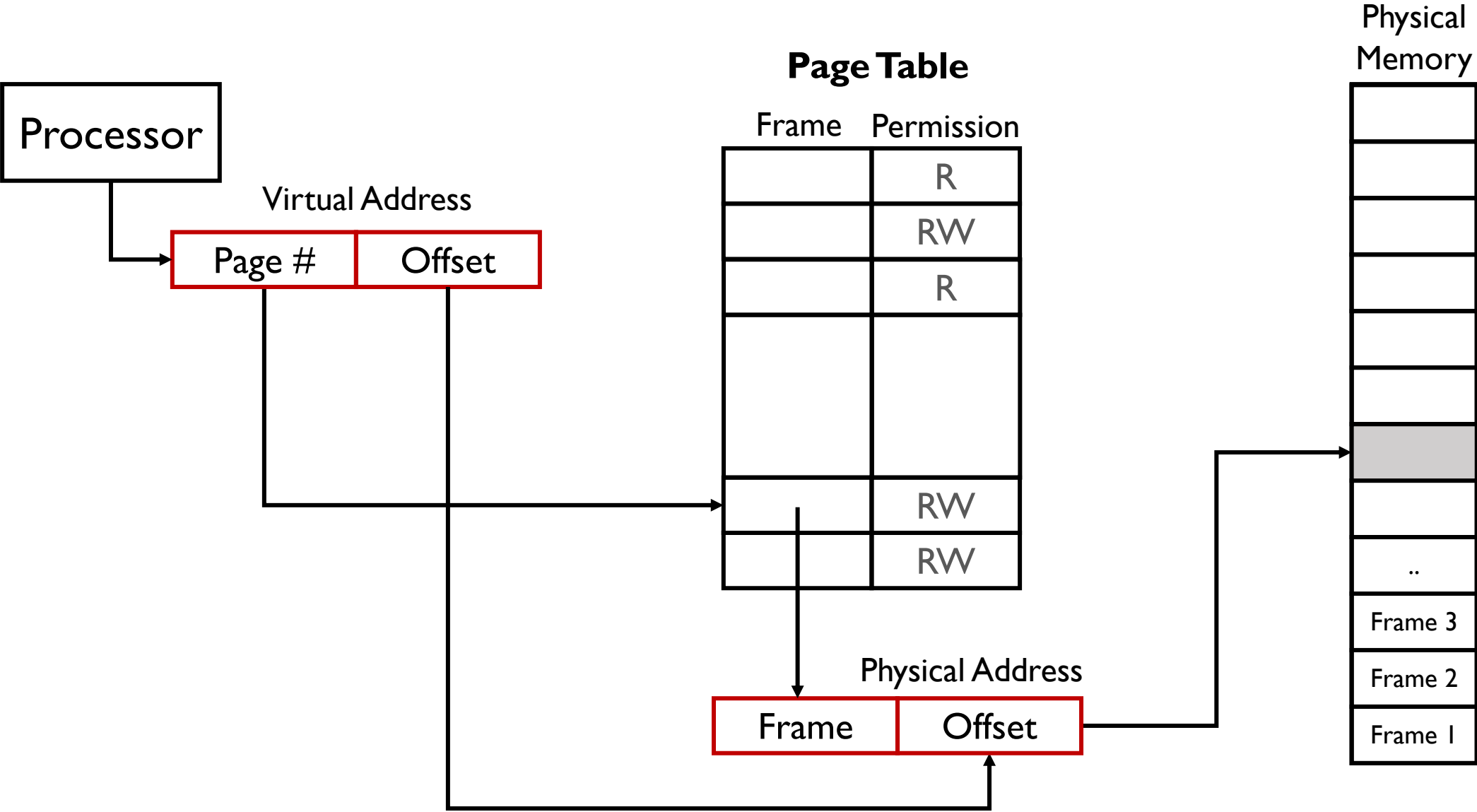
- Address Translation Concept
- Segmentation (分段)
- Paging (分页)

# Paged Memory

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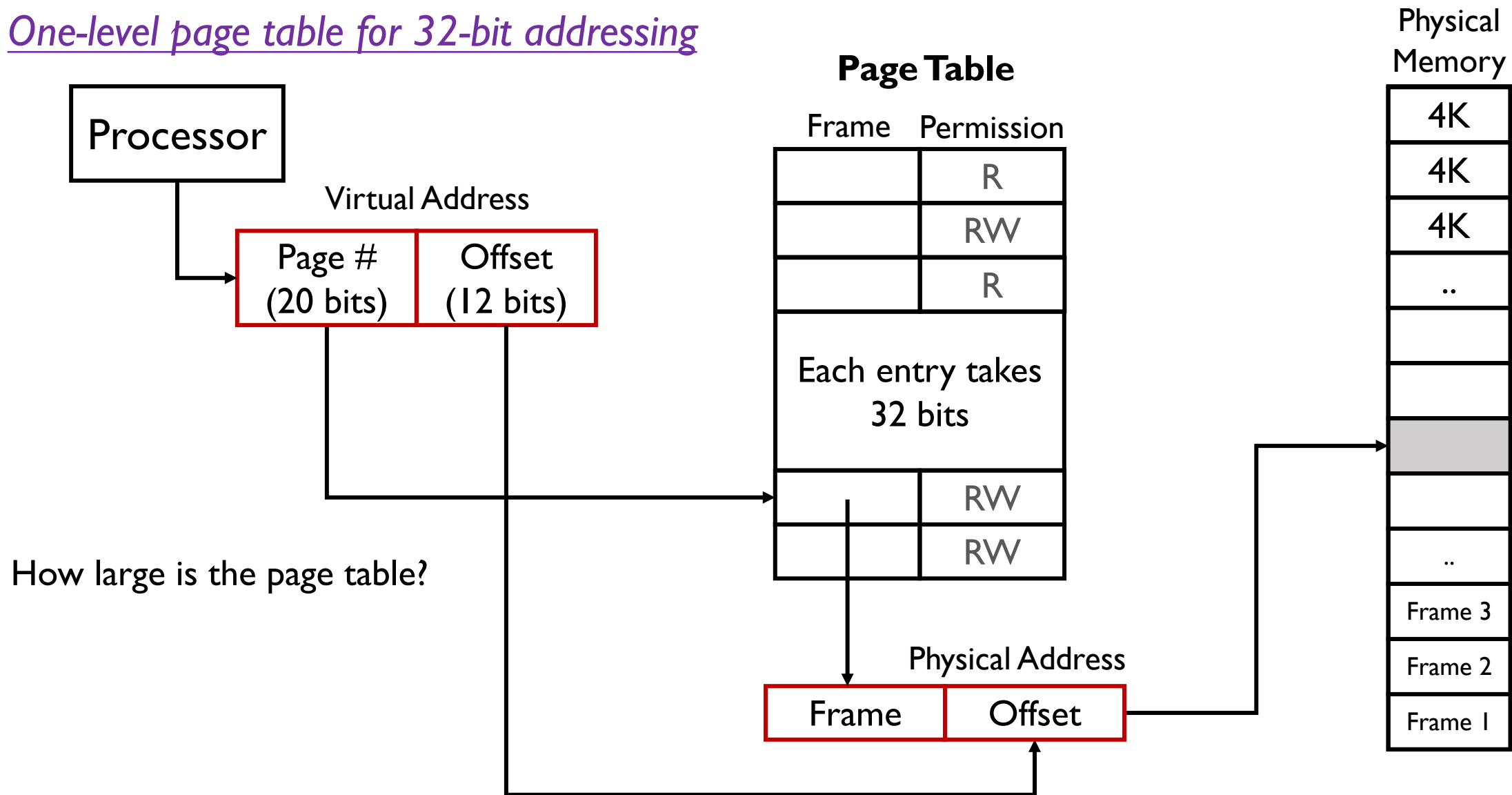
- Paging (分页): allocating memory in fixed-sized chunks called page frames (页框)
- A page table (页表) stores for each process whose entries contain pointers to the page frames.
  - More compact than segment table because it does not need to store "bound"
- What's cool: the pages are scattered across physical memory regions
  - Yet within a page, the memory access is contiguous
  - For instance, a large matrix might span many pages
- Memory allocation becomes very simple: find a page frame.

# Paged Memory



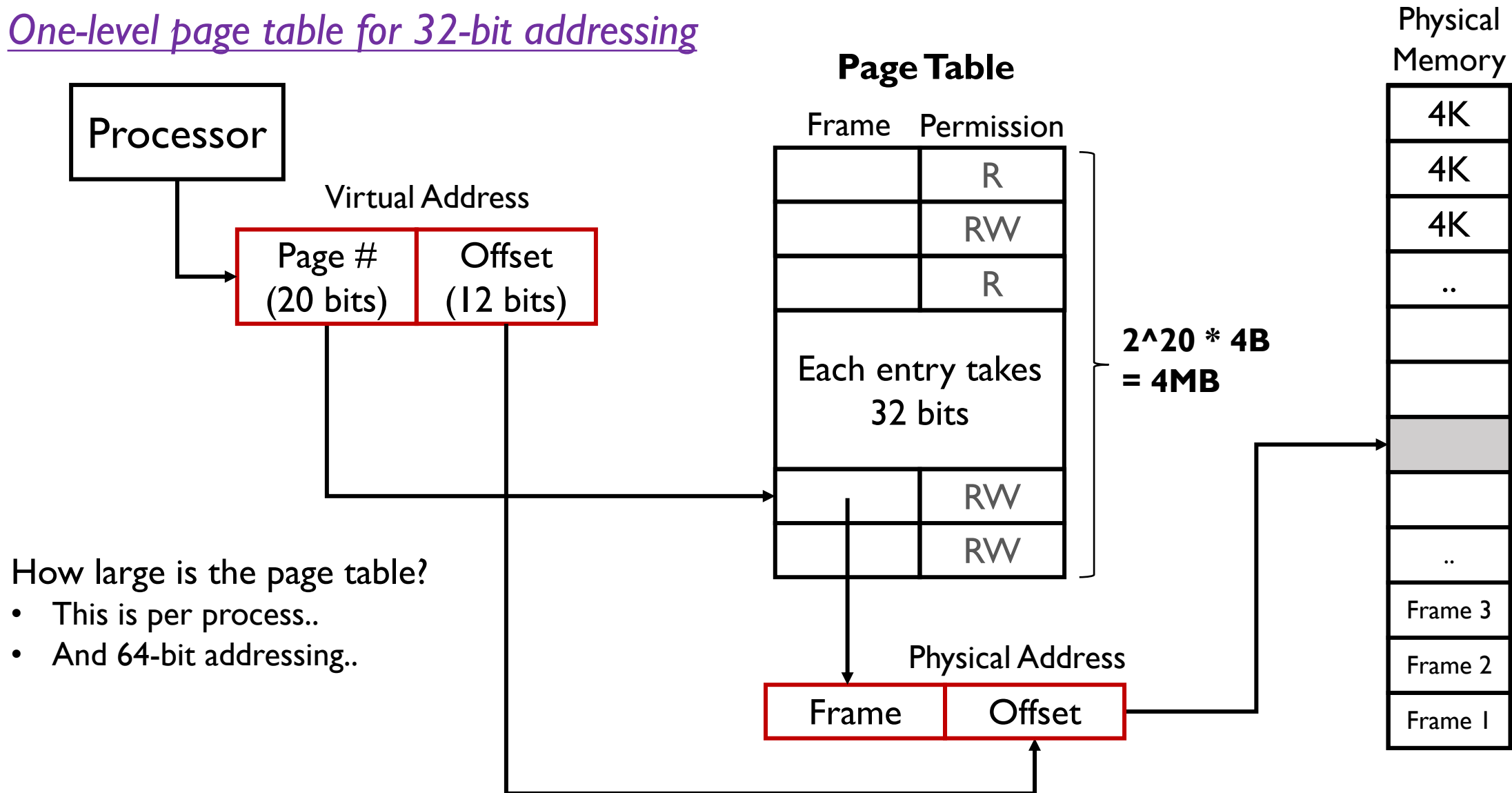
# Paged Memory

## One-level page table for 32-bit addressing



# Paged Memory

## One-level page table for 32-bit addressing





s large page  
an the memory

**Page Table #1**

Frame	Permission
	R
	RW
	R
	RW
	RW

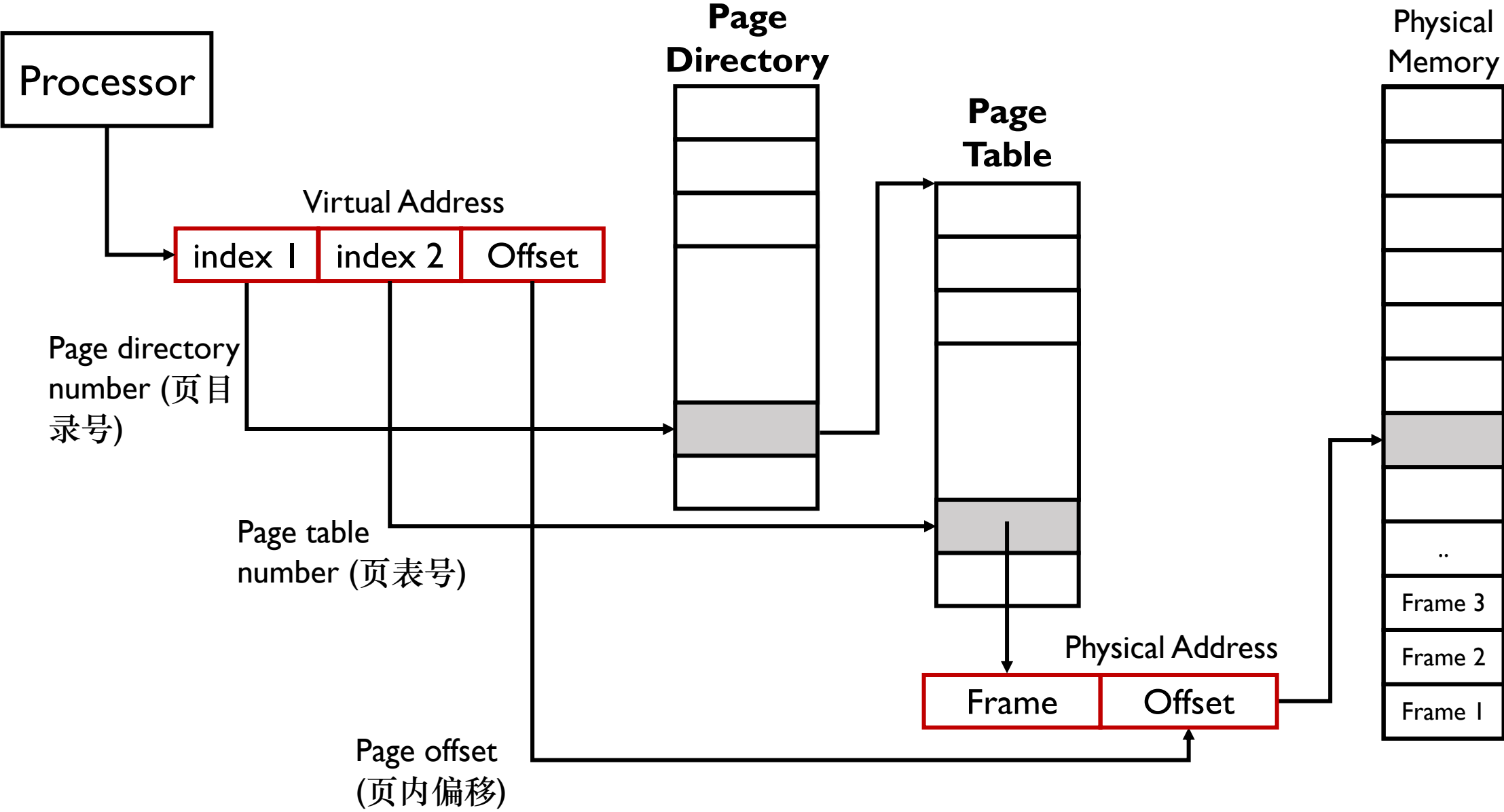
**Physical Memory**

..
Shared
..

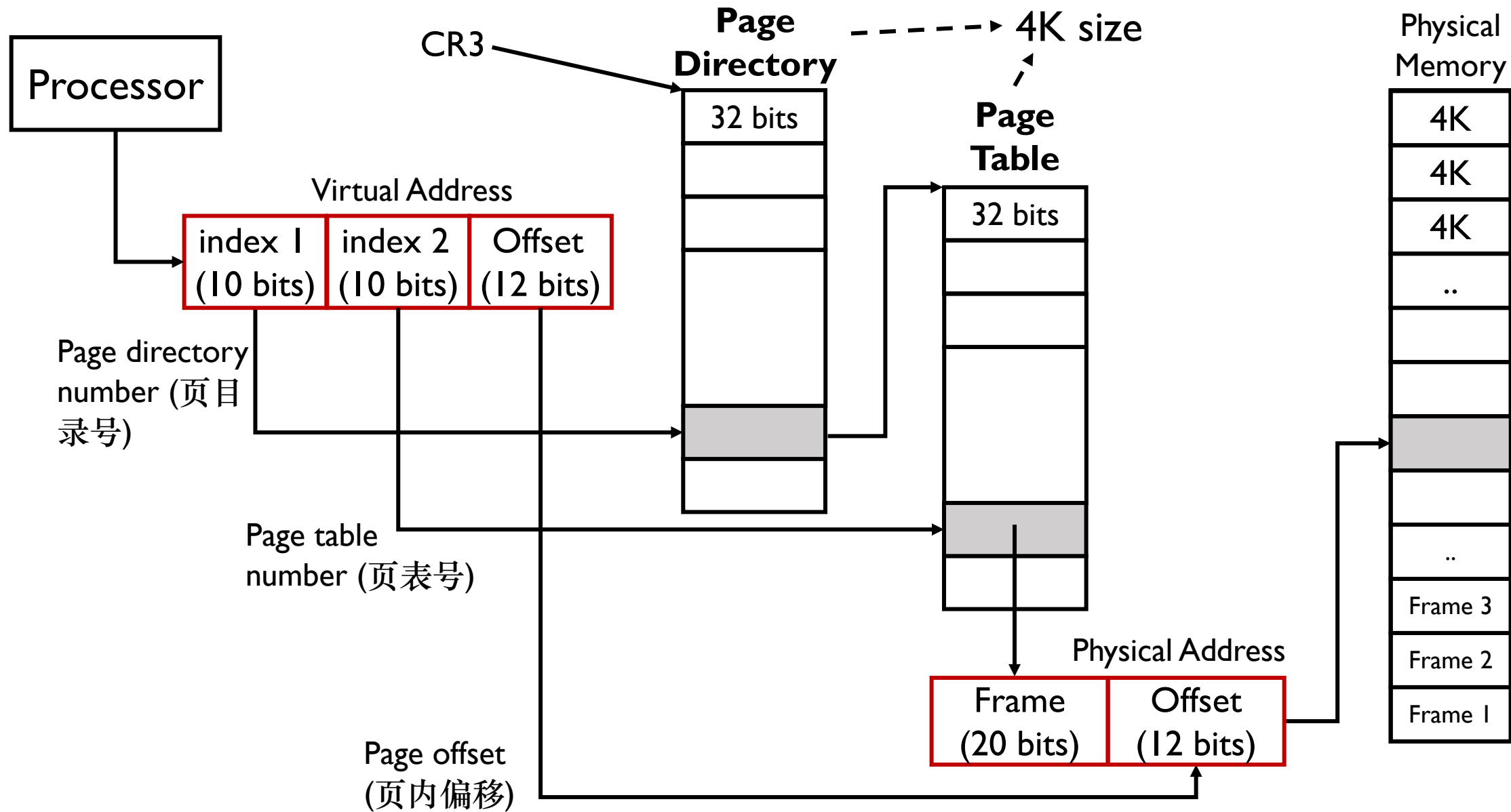
**Page Table #2**

Frame	Permission
	R
	RW
	RW
	R
	R

# Multi-level Paging

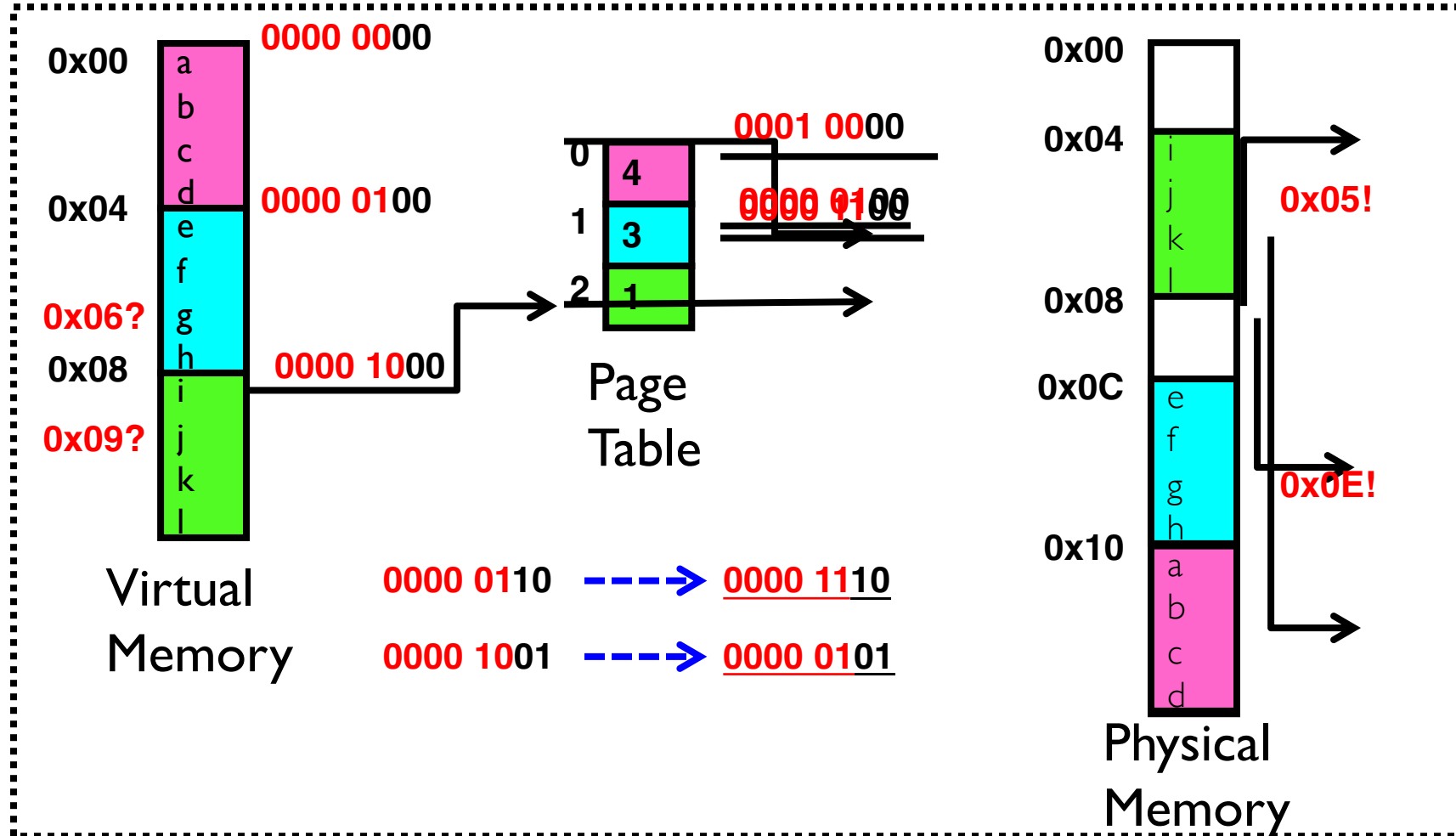


# x86 Multi-level Paging



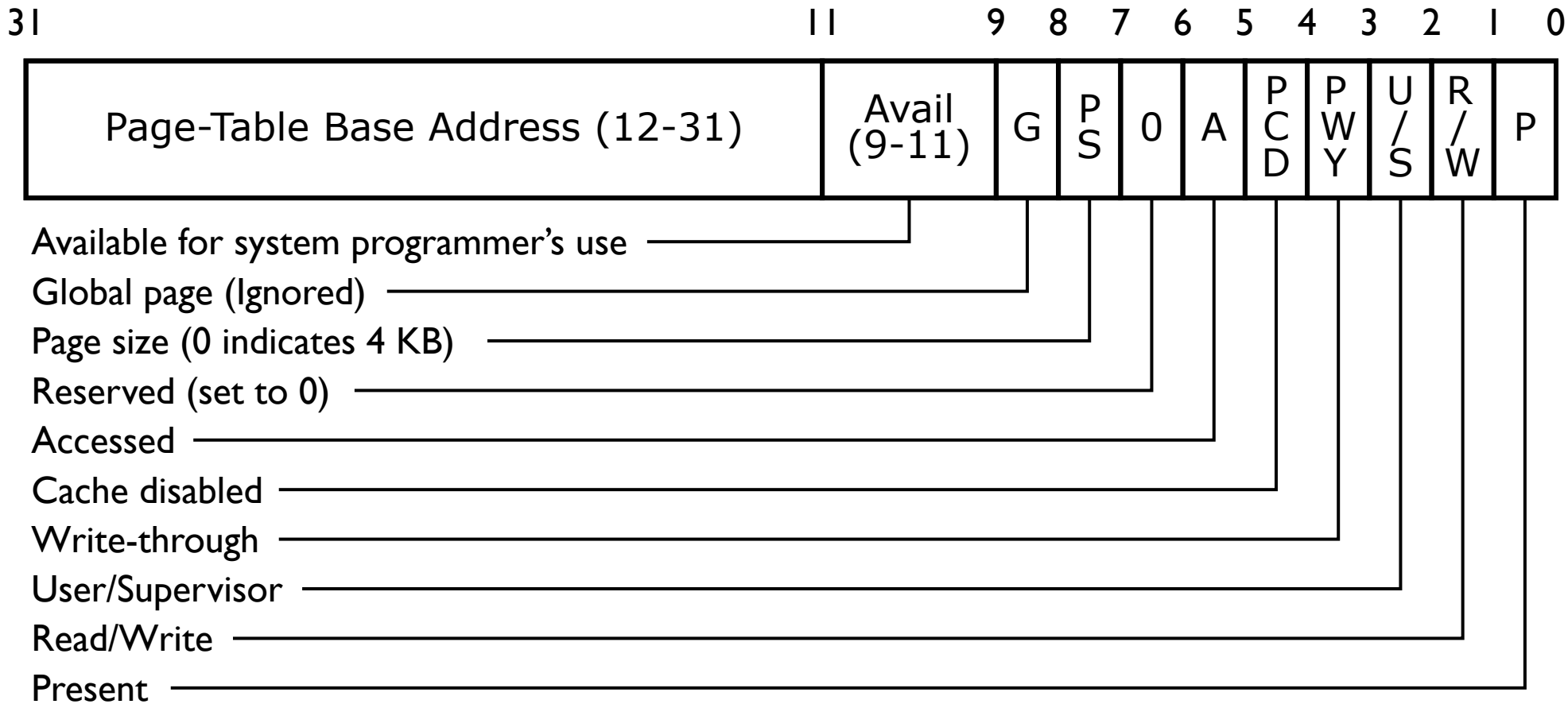
# x86 Multi-level Paging

Example (4 byte pages)



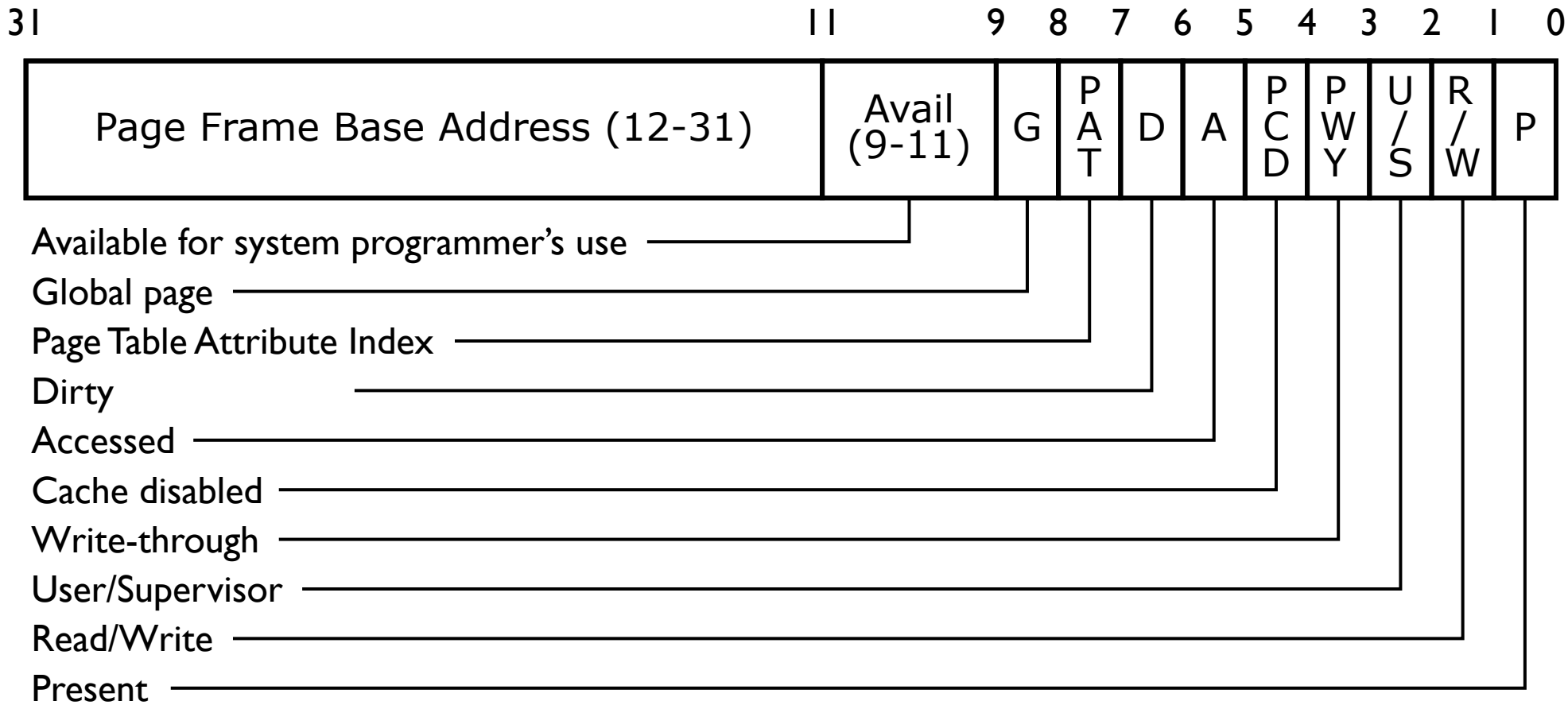
# x86 Multi-level Paging

- Each page directory entry (PDE, 页目录项) is 32-bits long.



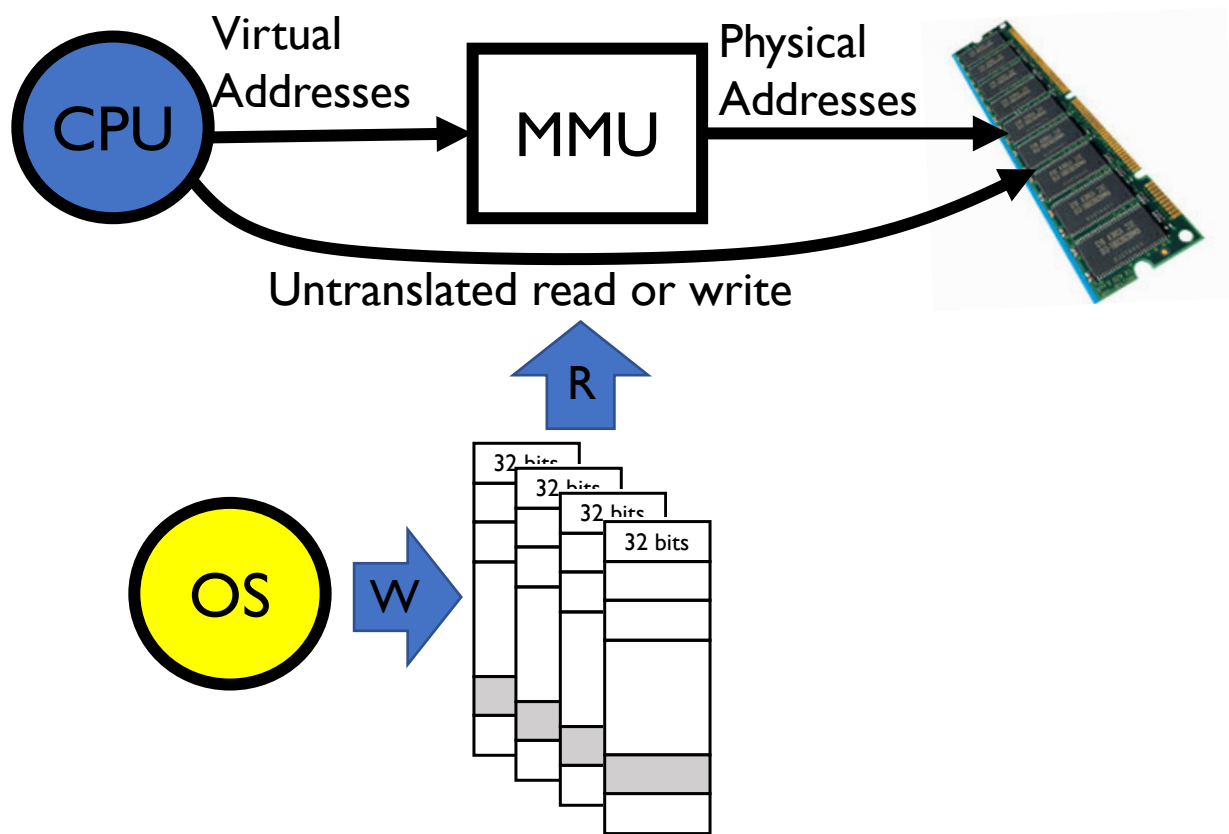
# x86 Multi-level Paging

- Each page table entry (PTE, 页表项) is 32-bits long.



# x86 Multi-level Paging

- Memory management unit (MMU, 分页内存管理单元): the hardware that actually does the translation
  - Usually located in CPU



# x86 Multi-level Paging

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- Memory management unit (MMU, 分页内存管理单元): the hardware that actually does the translation
- Page size shall be neither too small or too large
  - Too small: large page table sizes; low cache hit ratio
  - Too large: memory waste
  - Typical range: 512B to 8192B; default 4KB on Linux.



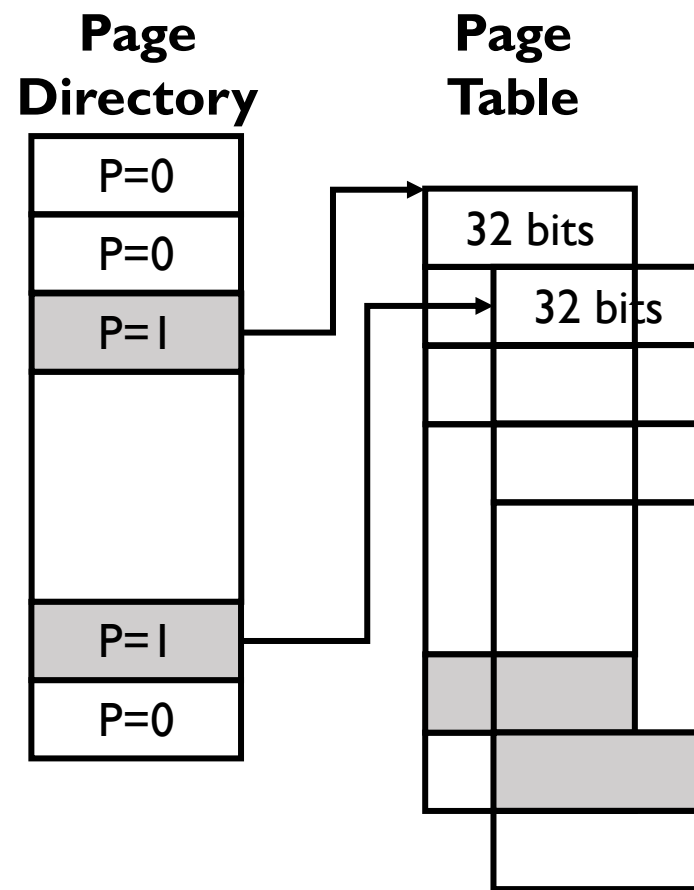
# x86 Multi-level Paging

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- Memory management unit (MMU, 分页内存管理单元): the hardware that actually does the translation
- Page size shall be neither too small or too large
- Each process ~~and kernel~~ has their own page table!
  - Not threads
  - The same address of different processes translate to different physical locations, unless the page is shared
  - A process can only access/modify its own page table! Otherwise..
  - In Linux, there is only one kernel space for all process

# x86 Multi-level Paging

- Memory management unit (MMU, 分页内存管理单元): the hardware that actually does the translation
- Page size shall be neither too small or too large
- Each process and kernel has their own page table!
- Page tables can be **sparse** (vs. single-level paging)
  - Not every PDE has a corresponding page table.
  - Saves a lot of space.
  - It's good to fit page table into one page.



# Page Fault

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- Page Fault (缺页中断) happens when CPU/MMU accesses a memory location that is not readily mapped
  - Pure: memory swapped out; shared pages; etc.
    - ☐ After handled, the access will be performed again
  - Invalid: write to read-only pages; access to pages not allocated; etc.
    - ☐ Segmentation fault!

# x86 Multi-level Paging

---

- Why PDE/PTE use 20 bits for addressing the next-level table or page?
- What needs to be switched on a context switch?
- If a process needs 1 page for its data, how many it will actually take?
- The largest address can be accessed in 2-level paging (32 bits address)?

# x86 Multi-level Paging

---

- Why PDE/PTE use 20 bits for addressing the next-level table or page?
  - Page directory/tables are always page-aligned ( $\% 4k = 0$ ).
- What needs to be switched on a context switch?
  - The page directory, stored in CR3
- If a process needs 1 page for its data, how many it will actually take?
  - 3 in total (1 page directory + 1 page table + 1 page for its data)
- The largest address can be accessed in 2-level paging (32 bits address)?
  - $4K * 2^{10} * 2^{10} = 4G$

# Virtual or Physical??

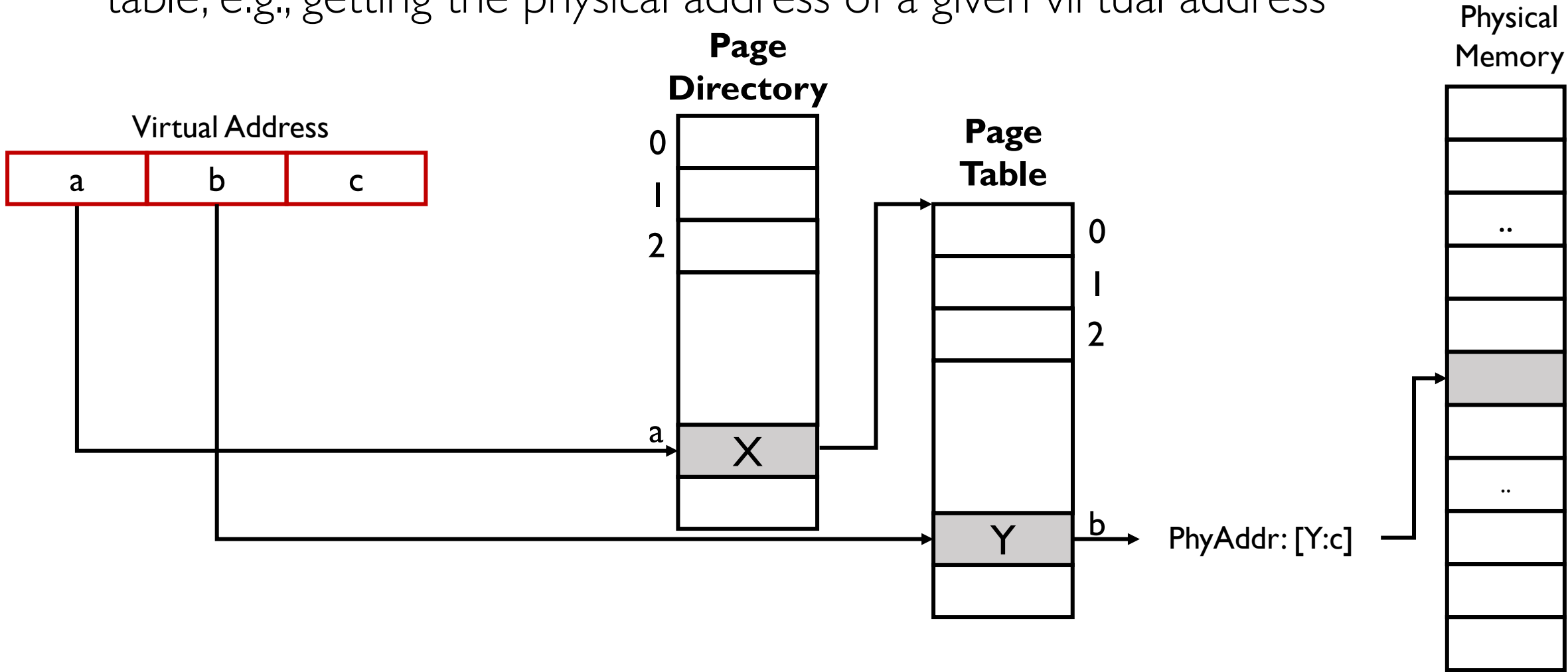
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- CR3 stores the virtual or physical address of the page directory?
- How about the PDE/PTE?
- The pointers used by kernel is virtual or physical?
- How can kernel manipulate the page directory/tables?

<https://wiki.osdev.org/Paging#Manipulation>

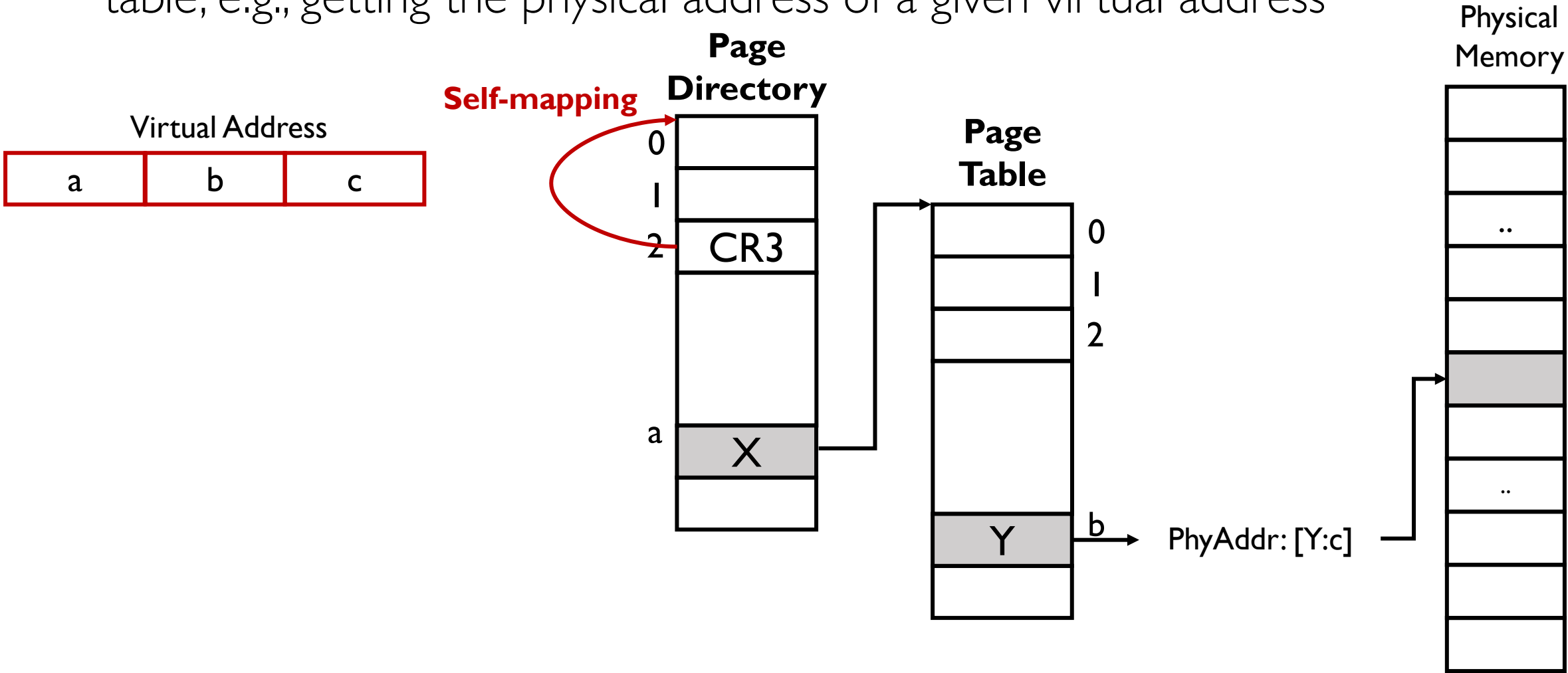
# Manipulating Page Table

- Since OS only sees the virtual address, how can it manipulate the page table, e.g., getting the physical address of a given virtual address



# Manipulating Page Table

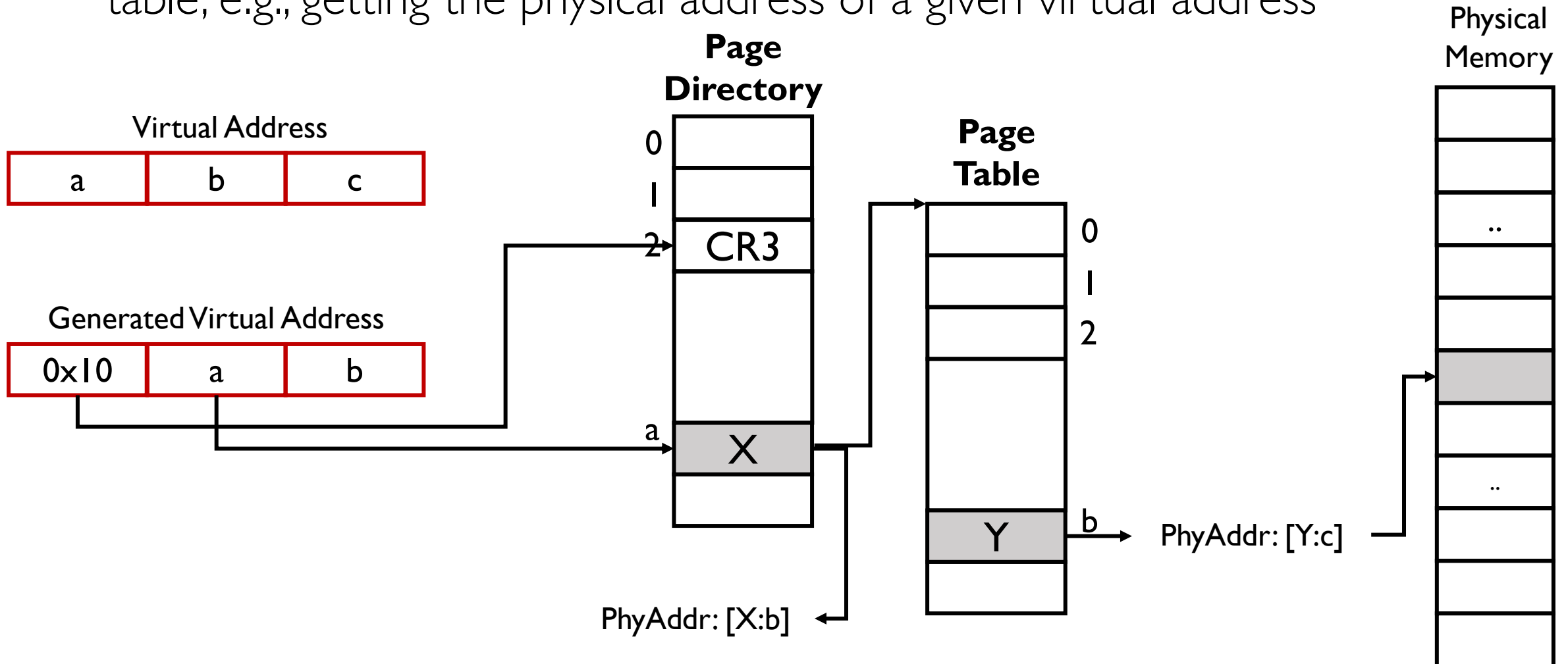
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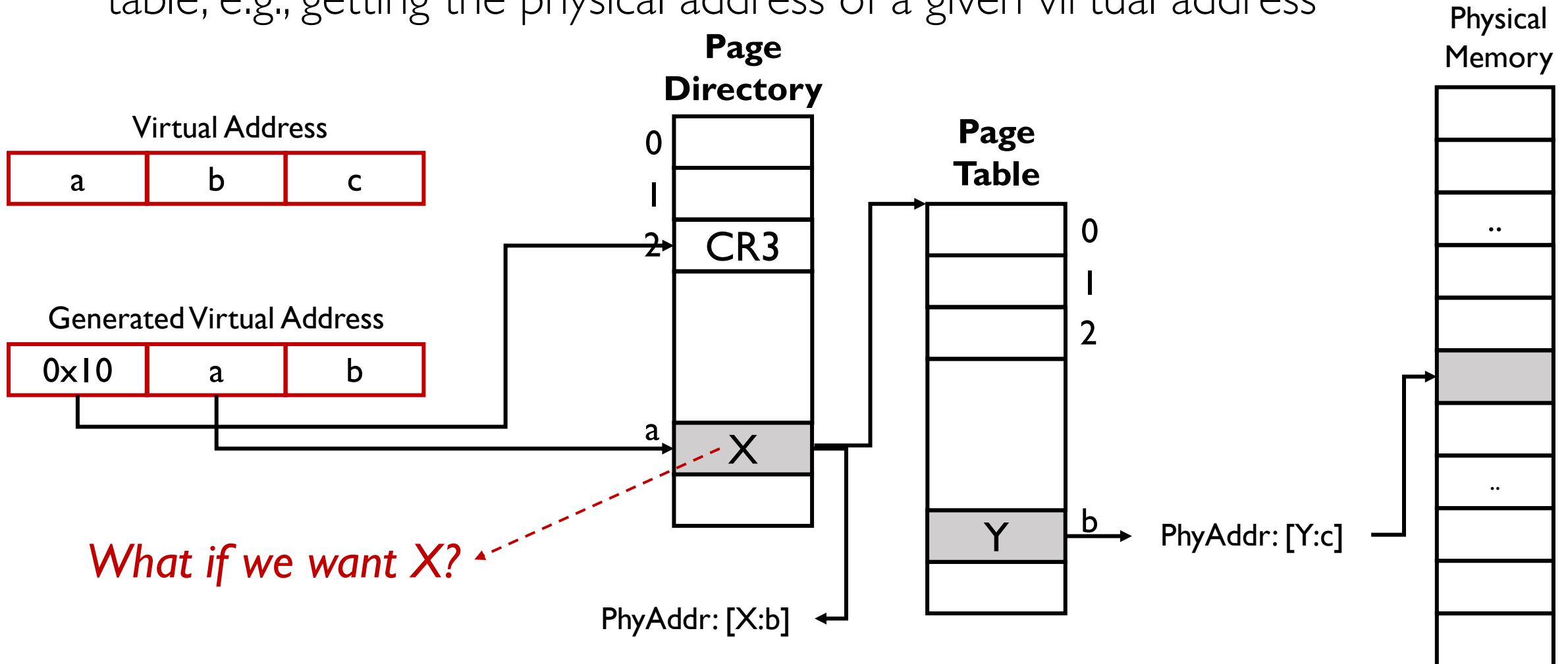
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# Manipulating Page Table

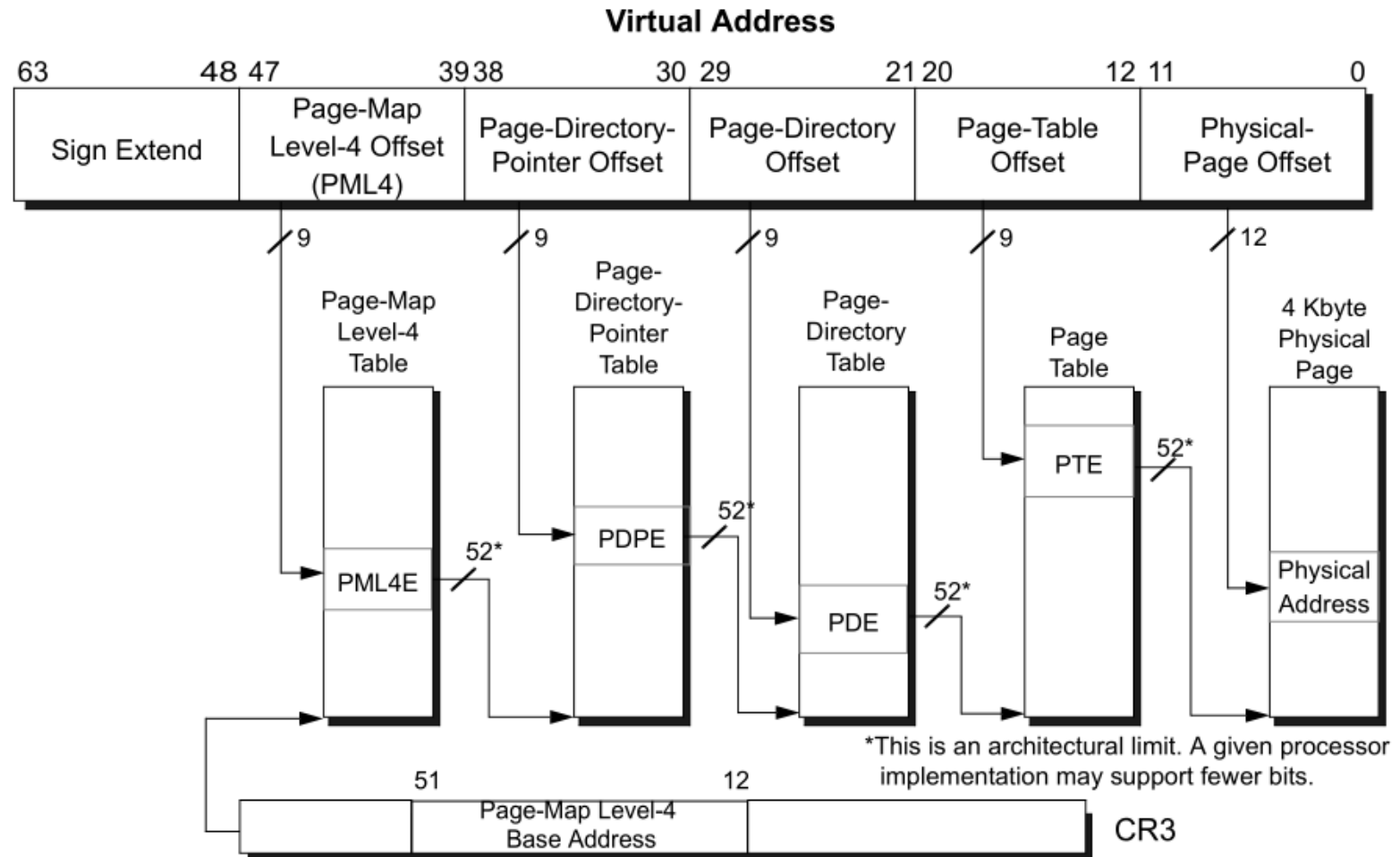
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- 59

# x86\_64 Multi-level Paging

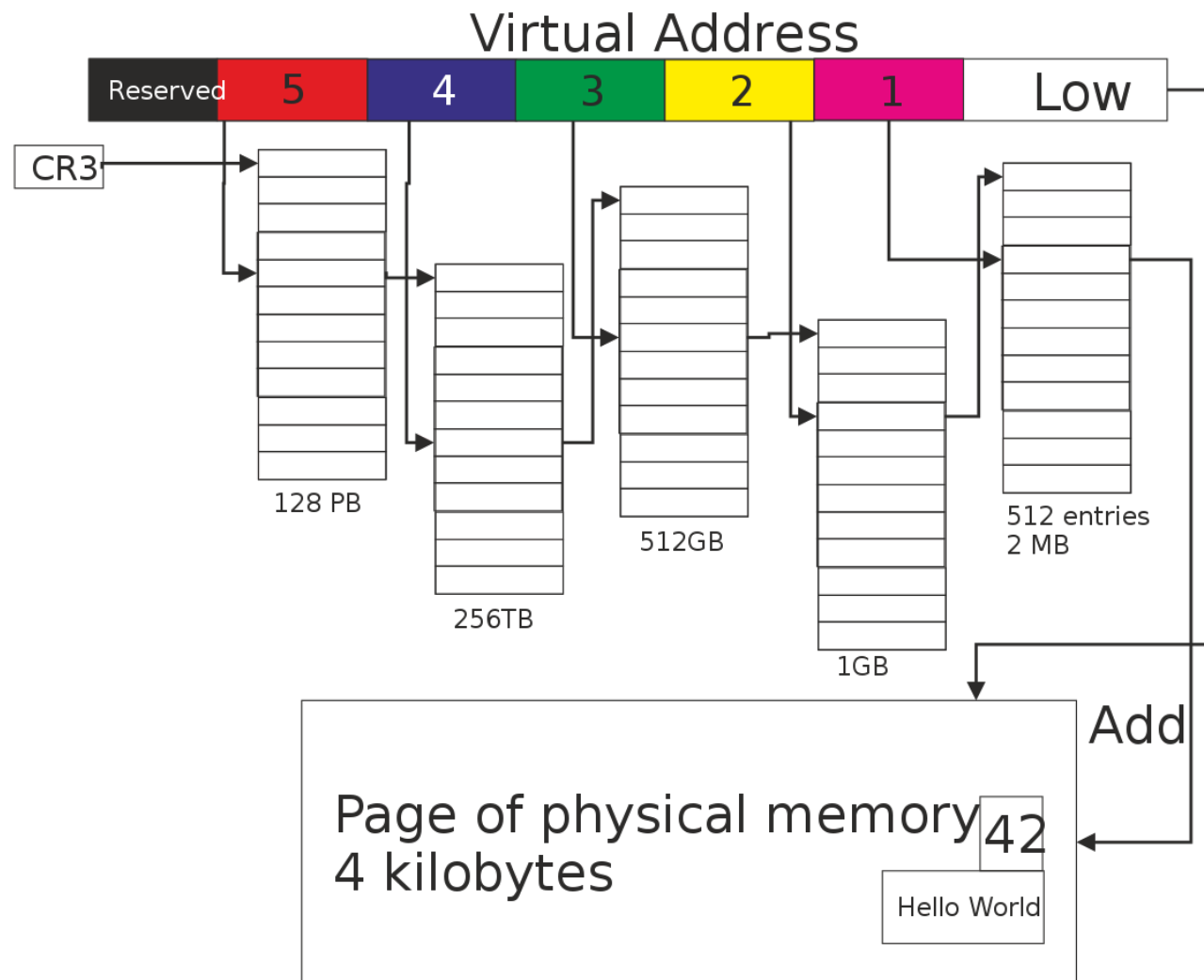
- 4-level: 48 bits



**Figure 5-17. 4-Kbyte Page Translation—Long Mode**

# x86\_64 Multi-level Paging

- 4-level: 48 bits
- 5-level: 64 bits



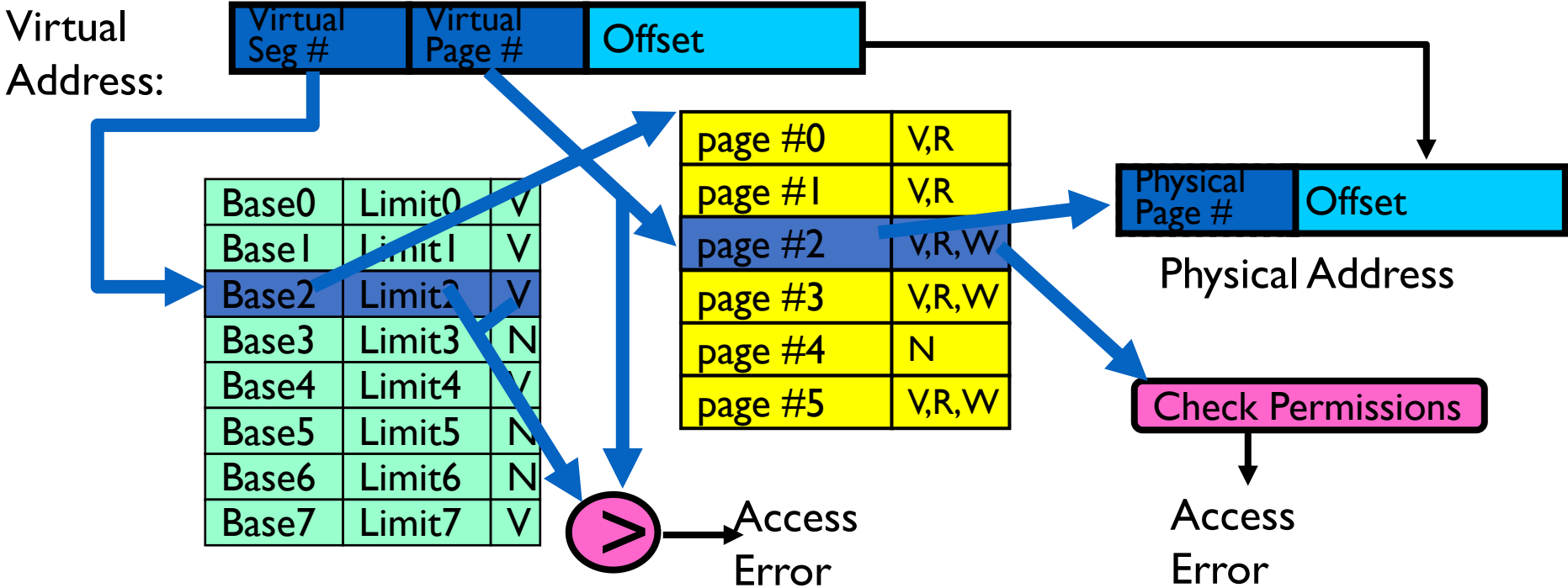
# Multi-level Paging Summary

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- Pros:
  - Only need to allocate as many page table entries as we need for application
    - ❑ In other words, sparse address spaces are easy
  - Easy memory allocation
  - Easy Sharing
    - ❑ Share at segment or page level (need additional reference counting)
- Cons:
  - One pointer per page (typically 4K – 16K pages today)
  - Page tables need to be contiguous
    - ❑ However, previous example keeps tables to exactly one page in size
  - Two (or more, if  $>2$  levels) lookups per reference
    - ❑ Seems very expensive!

# Segments + Paging

- What about a tree of tables?
  - Lowest level page table  $\Rightarrow$  memory still allocated with bitmap
  - Higher levels often segmented
- Could have any number of levels. Example (top segment):



# Segmentation vs. Paging

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- Intel x86 and Linux
  - 8086 era: segmentation and paging are both used
  - 80386 era: the segmentation is not really used
    - ❑ The processor provides 4 modes: none; paging only; segmentation only; both.
    - ❑ The `CS` is always set to 0 and the limit is  $2^{32}$ .
  - x86\_64 era: segmentation is considered as a legacy and not used in most OSes
- Now, everyone uses paging, few make any real use of segmentation.

<https://softwareengineering.stackexchange.com/questions/100047/why-not-segmentation>



# Copy-on-Write (COW)

---

- How to implement an efficient `fork()`?
  - Do not copy all contents immediately, but mark the page/segment tables of both child and parent processes as “read-only”
  - When a write (from either child or parent) happens, it traps into kernel through page fault, and a private page is copied.
- A `fork()` followed immediately by a `exec()`, how many pages are really copied?

# Homework

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- Look at the function `get_physaddr` in <https://wiki.osdev.org/Paging#Manipulation>, and explain how it works line by line.
- If the page size is 8K, how the address translation will work? Explain step by step in details, e.g., how the virtual address is splited, how large is the page directory and page table, etc..