CSC 252: Computer Organization
Spring 2020: Lecture 21

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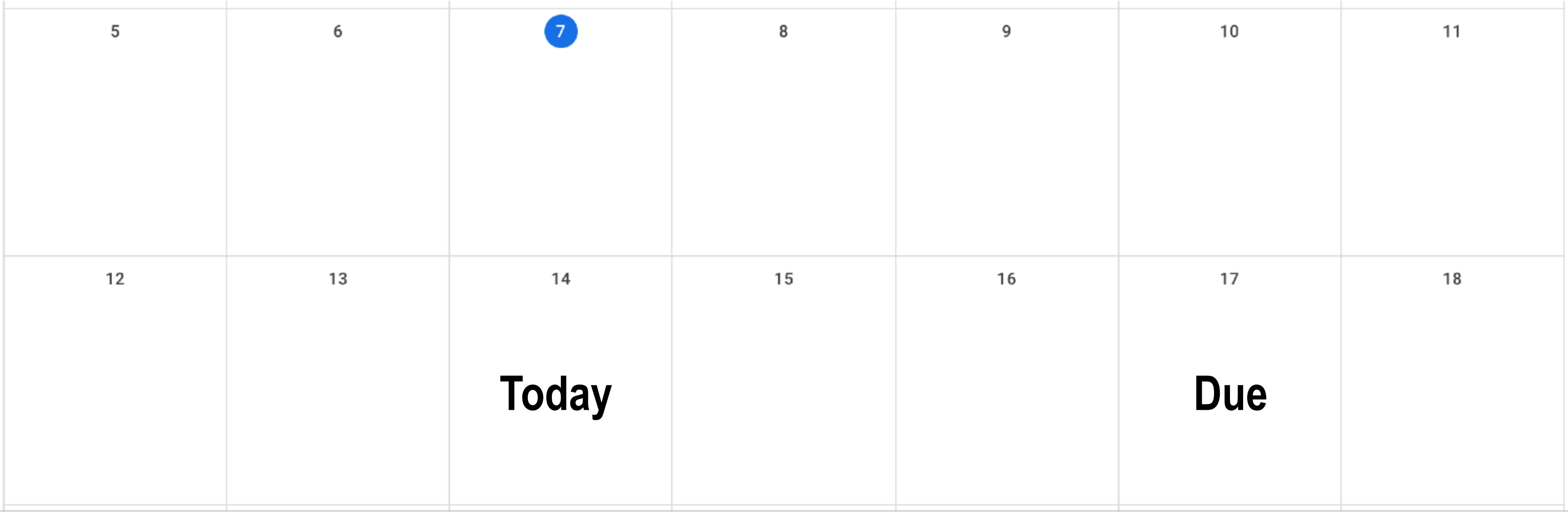
Announcement

- Programming assignment 4 is out
  - Details: https://www.cs.rochester.edu/courses/252/spring2020/labs/assignment4.html
  - Due on **Apr. 17**, 11:59 PM
  - You (may still) have 3 slip days



5	6	7	8	9	10	11
12	13	14 **Today**	15	16	17 **Due**	18

Another Unsafe Signal Handler Example

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- Assume a program wants to do the following:
  - The parent creates multiple child processes
  - When each child process is created, add the child PID to a queue
  - When a child process terminates, the parent process removes the child PID from the queue

Another Unsafe Signal Handler Example

- Assume a program wants to do the following:
  - The parent creates multiple child processes
  - When each child process is created, add the child PID to a queue
  - When a child process terminates, the parent process removes the child PID from the queue
- One possible implementation:
  - An array for keeping the child PIDs
  - Use a loop to fork child, and add PID to the array after fork
  - Install a handler for SIGCHLD in parent process
  - The SIGCHLD handler removes the child PID

First Attempt

```
void handler(int sig)
{
    pid_t pid;

    while ((pid = wait(NULL)) > 0) { /* Reap child */
        /* Delete the child from the job list */
        deletejob(pid);
    }
}

int main(int argc, char **argv)
{
    int pid;

    Signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (1) {
        if ((pid = Fork()) == 0) { /* Child */
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The following can happen:

- Child runs, and terminates
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- Context switch to parent, but before it can run, kernel has to handle SIGCHLD first
- The handler deletes the job, which does nothing

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```

The following can happen:

- Child runs, and terminates
- Kernel sends SIGCHLD
- Context switch to parent, but before it can run, kernel has to handle SIGCHLD first
- The handler deletes the job, which does nothing
- The parent process resumes and adds a terminated child to job list

Second Attempt

```
void handler(int sig)
{
    sigset_t mask_all, prev_all;
    pid_t pid;

    sigfillset(&mask_all);
    while ((pid = wait(NULL)) > 0) {
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        deletejob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
}
int main(int argc, char **argv)
{
    int pid;
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    sigfillset(&mask_all);
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    while (1) {
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        }
        sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        addjob(pid);
        sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
    exit(0);
}
```
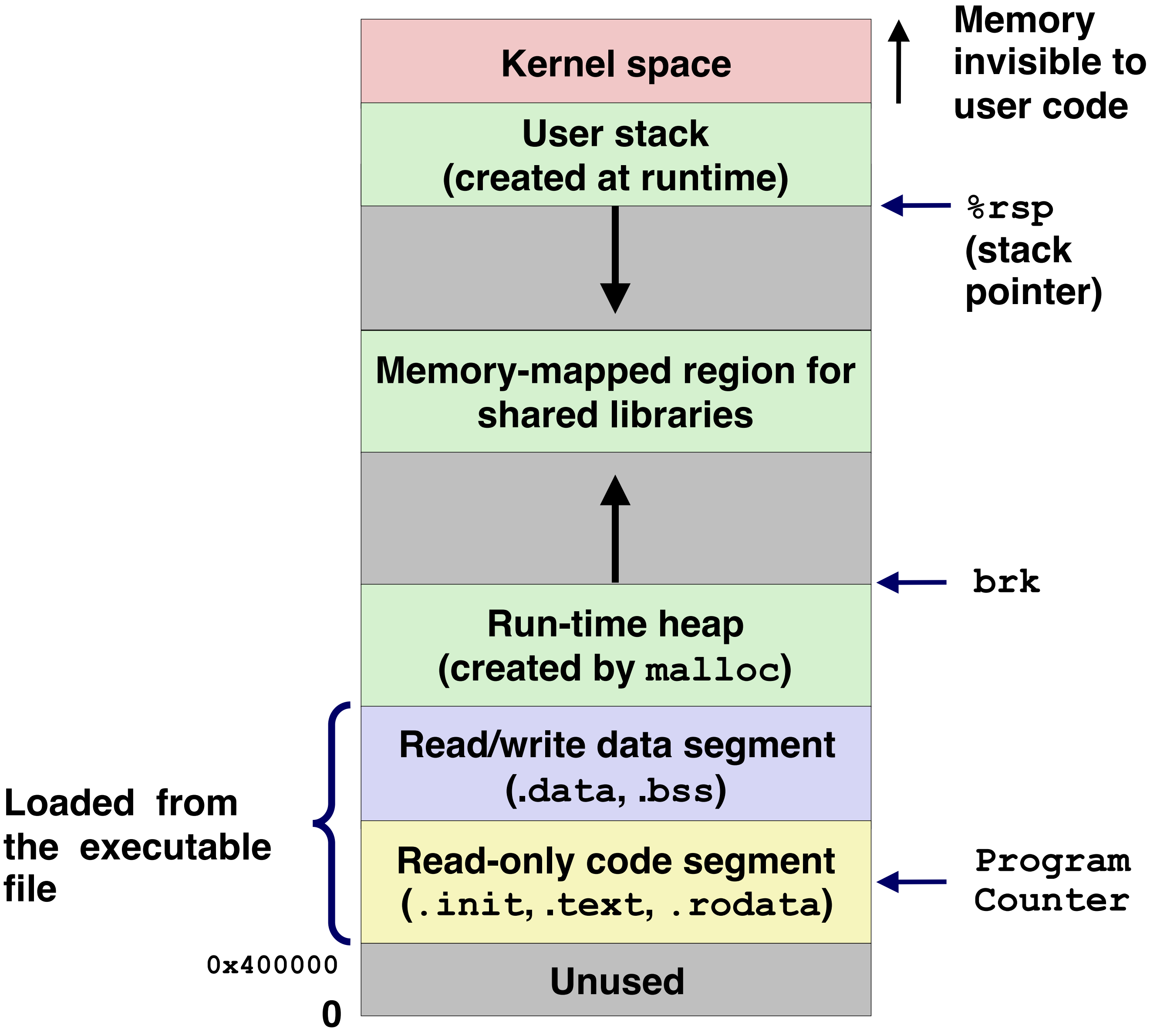
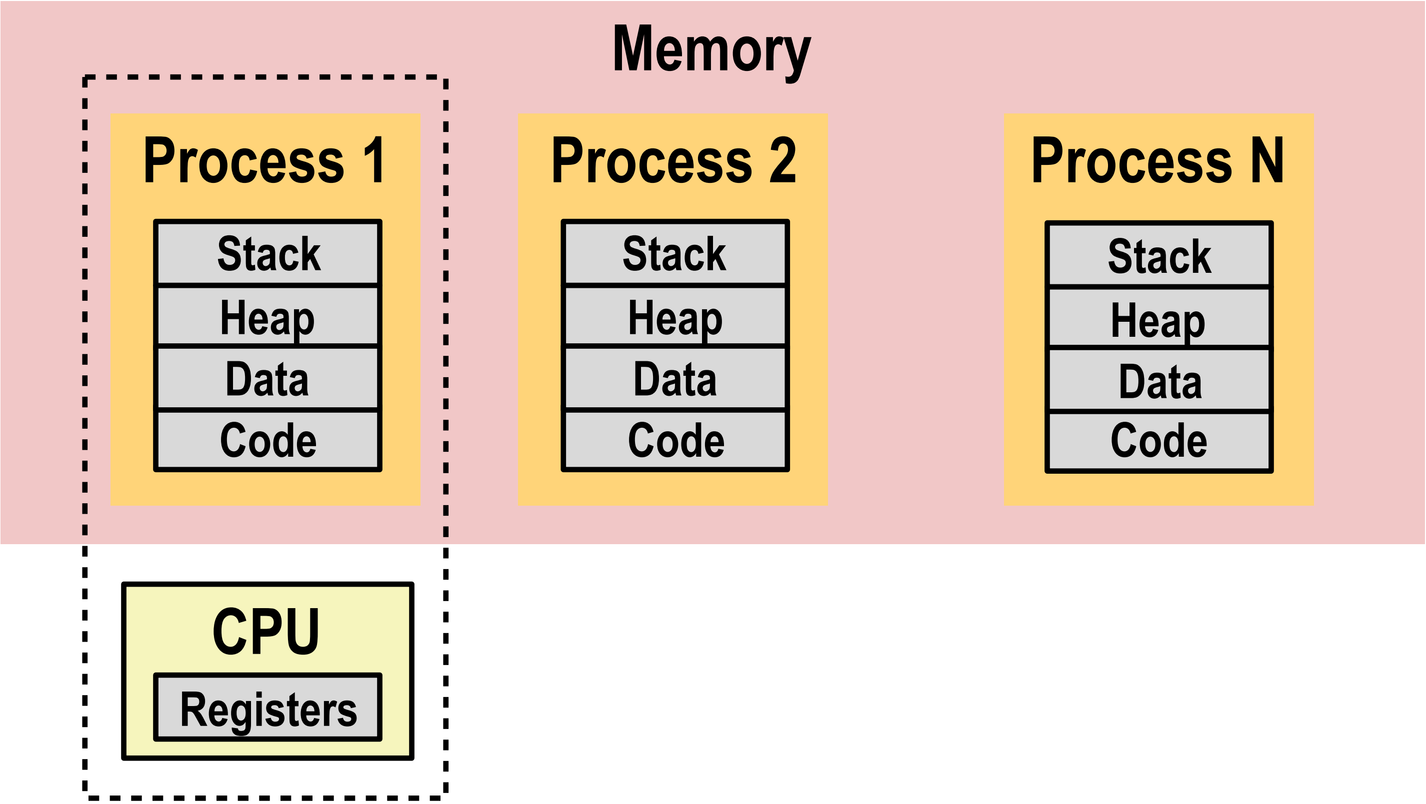

Third Attempt (The Correct One)

```
int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, mask_one, prev_one;

    Sigfillset(&mask_all);
    Sigemptyset(&mask_one);
    Sigaddset(&mask_one, SIGCHLD);
    Signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (1) {
        Sigprocmask(SIG_BLOCK, &mask_one, &prev_one); /* Block SIGCHLD */
        if ((pid = Fork()) == 0) { /* Child process */
            Sigprocmask(SIG_SETMASK, &prev_one, NULL); /* Unblock SIGCHLD */
            Execve("/bin/date", argv, NULL);
        }
        addjob(pid);  /* Add the child to the job list */
        Sigprocmask(SIG_SETMASK, &prev_one, NULL);  /* Unblock SIGCHLD */
    }
    exit(0);
}
```

Process Address Space



Multiprocessing Illustration



Memory

Process 1

Stack

Heap

Data

Code

Process 2

Stack

Heap

Data

Code

Process N

Stack

Heap

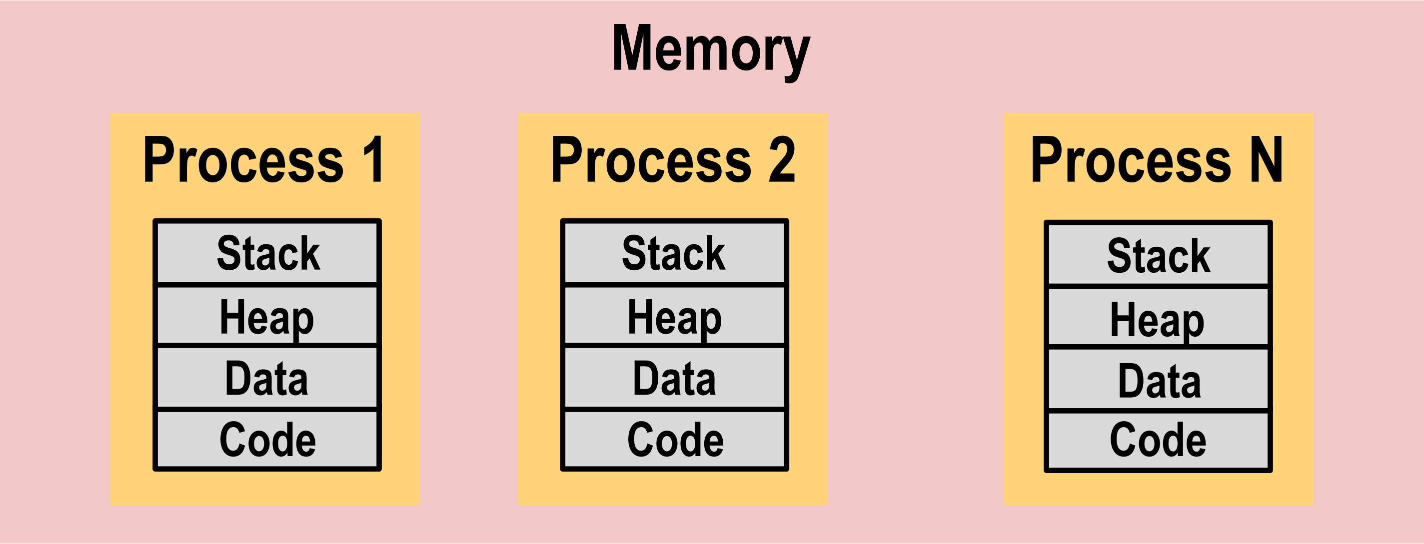
Data

Code

CPU

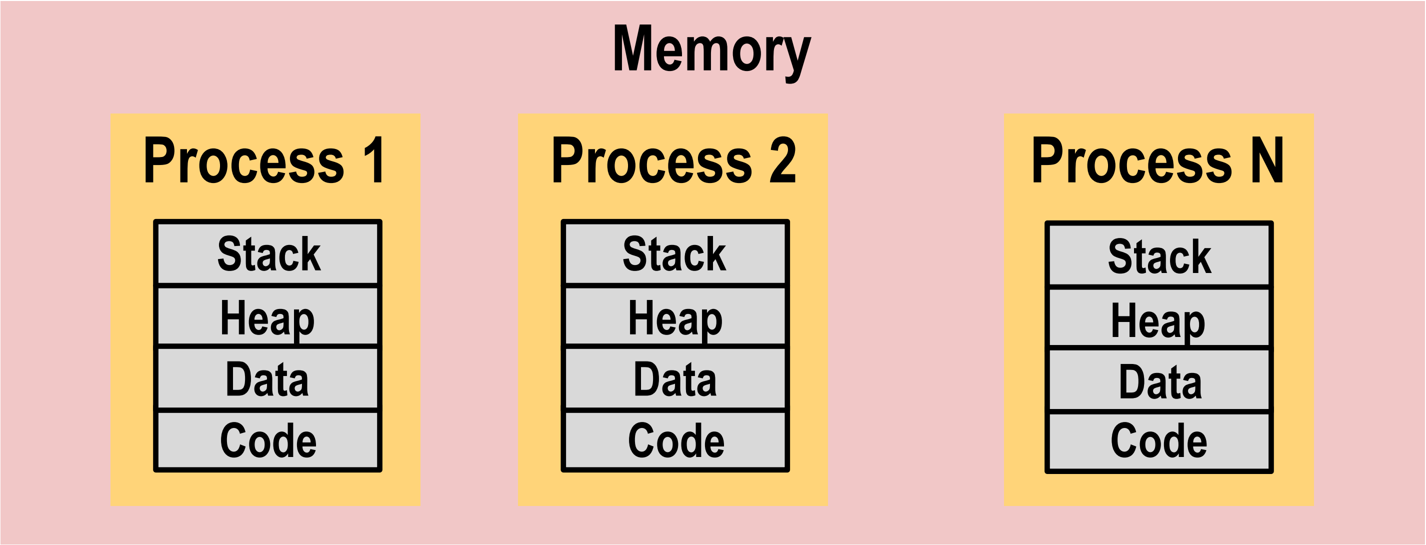
Registers

Problem



- Space:
  - Each process's address space is huge (64-bit): can memory hold it (16GB is just 34-bit)?
  - 2^48 bytes is about 282 TB
  - There are multiple processes, increasing the overhead further

Problem



- Space:
  - Each process's address space is huge (64-bit): can memory hold it (16GB is just 34-bit)?
  - 2^48 bytes is about 282 TB
  - There are multiple processes, increasing the overhead further
- Solution: store all the data in disk, and use memory only for most recently used data
  - Does this sound similar?

The Big Idea: Virtual Memory

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- What Does a Programmer Want?

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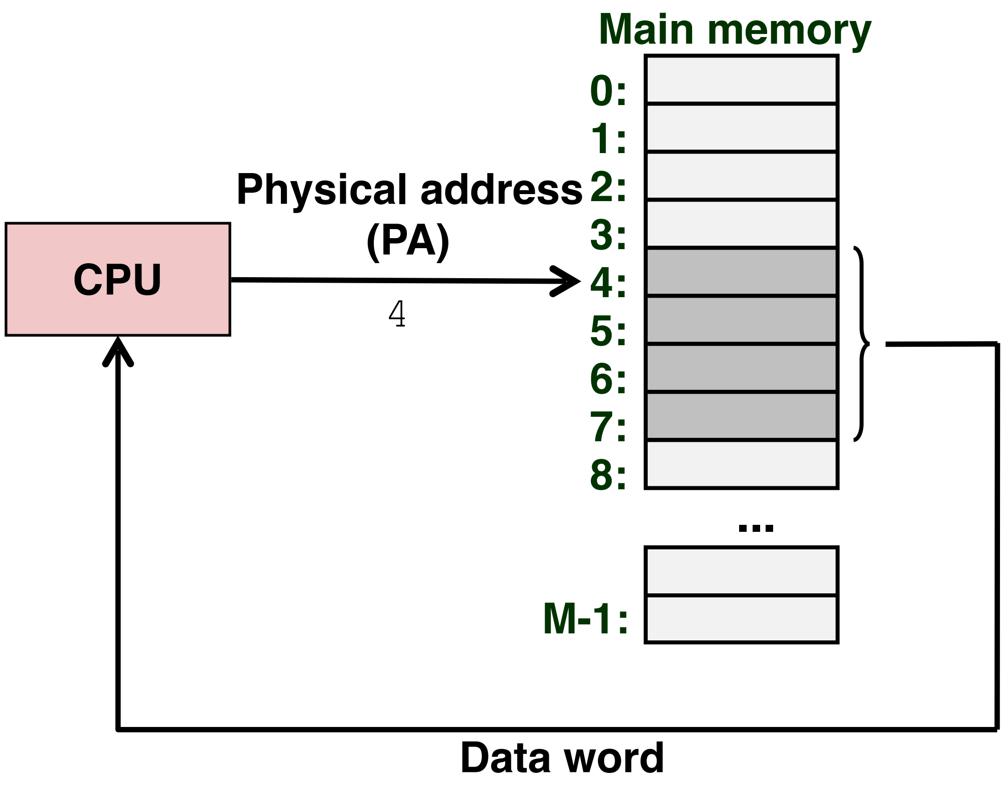
The Big Idea: Virtual Memory

- What Does a Programmer Want?
- Infinitely large, infinitely fast memory
  - Preferably automatically moved to where it is needed
- Virtual memory to the rescue
  - Present a large, uniform memory to programmers
  - Data in virtual memory by default stays in disk
  - Data moves to physical memory (DRAM) “**on demand**”
  - Disks (~TBs) are much larger than DRAM (~GBs), but 10,000x slower.
  - Effectively, virtual memory system transparently share the physical memory across different processes
  - Manage the sharing automatically: hardware-software collaborative strategy (too complex for hardware alone)

Today

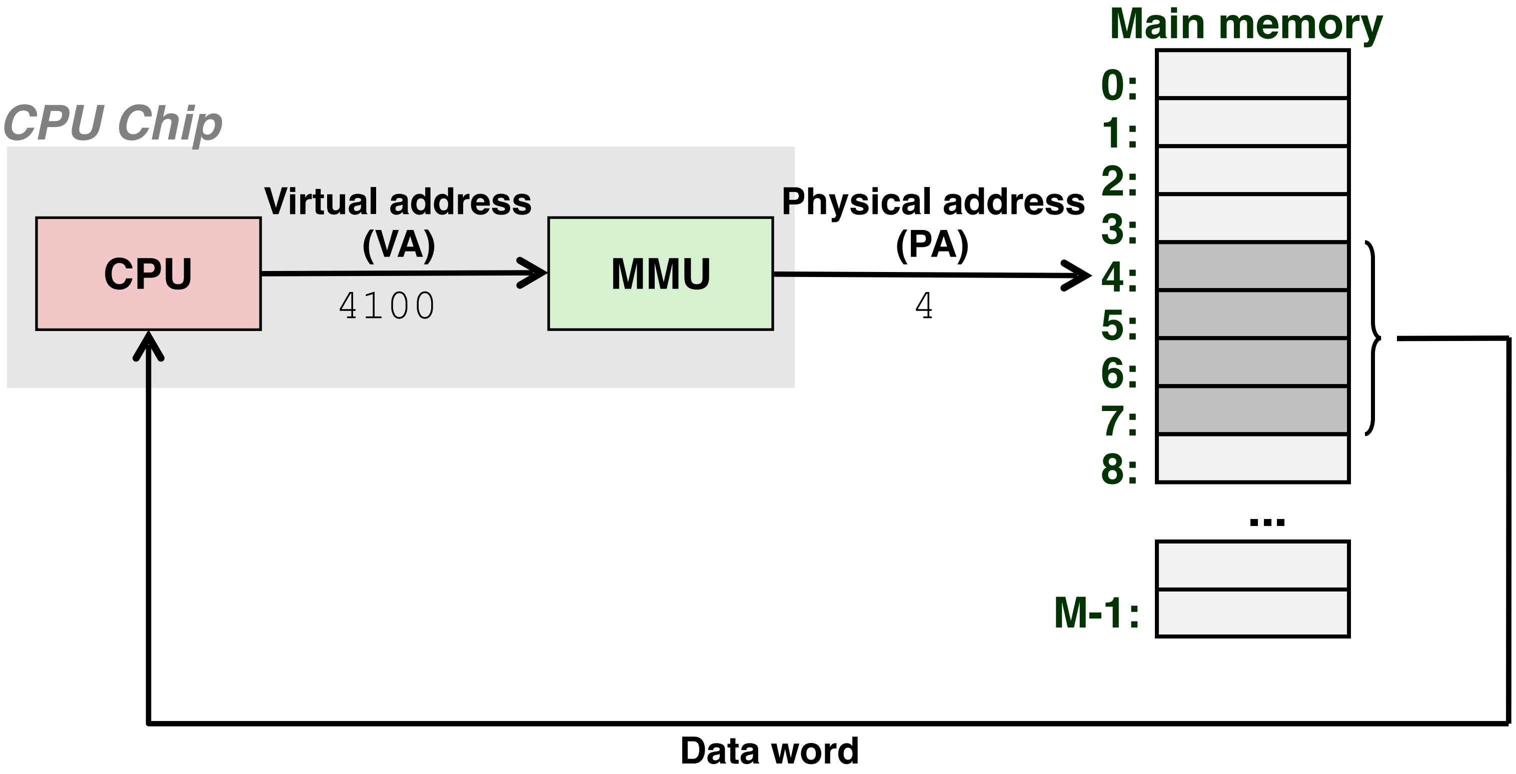
- Virtual memory (VM) illustration
- VM basic concepts and operation
- Other critical benefits of VM
- Address translation

A System Using Physical Addressing



- Used in “simple” systems like embedded microcontrollers in devices like cars, elevators, and digital picture frames

A System Using Virtual Addressing



- Used in all modern servers, laptops, and smart phones
- One of the great ideas in computer science
- MMU: Memory Management Unit

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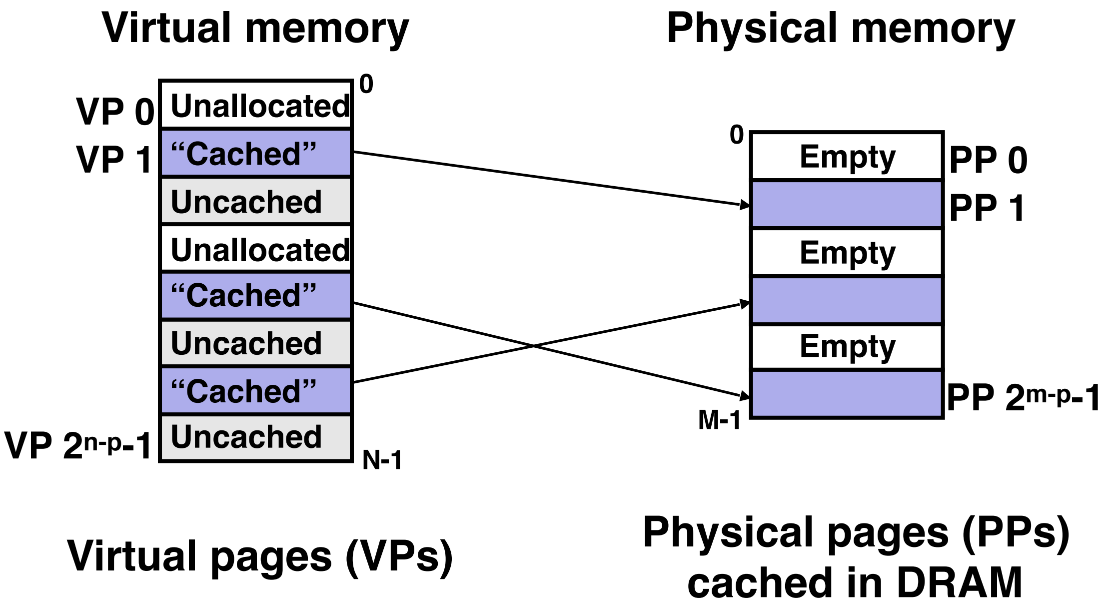
VM Concepts

- Conceptually, *virtual memory* is an array of N contiguous *pages* (page size $P = 2^p$ bytes)
- Physical memory is also divided into pages. Each physical page (sometimes called *frames*) has the same size as a virtual page. Physical memory has way fewer pages.
- A page can either be on the (“uncached”) disk or in the physical memory (“cached”).



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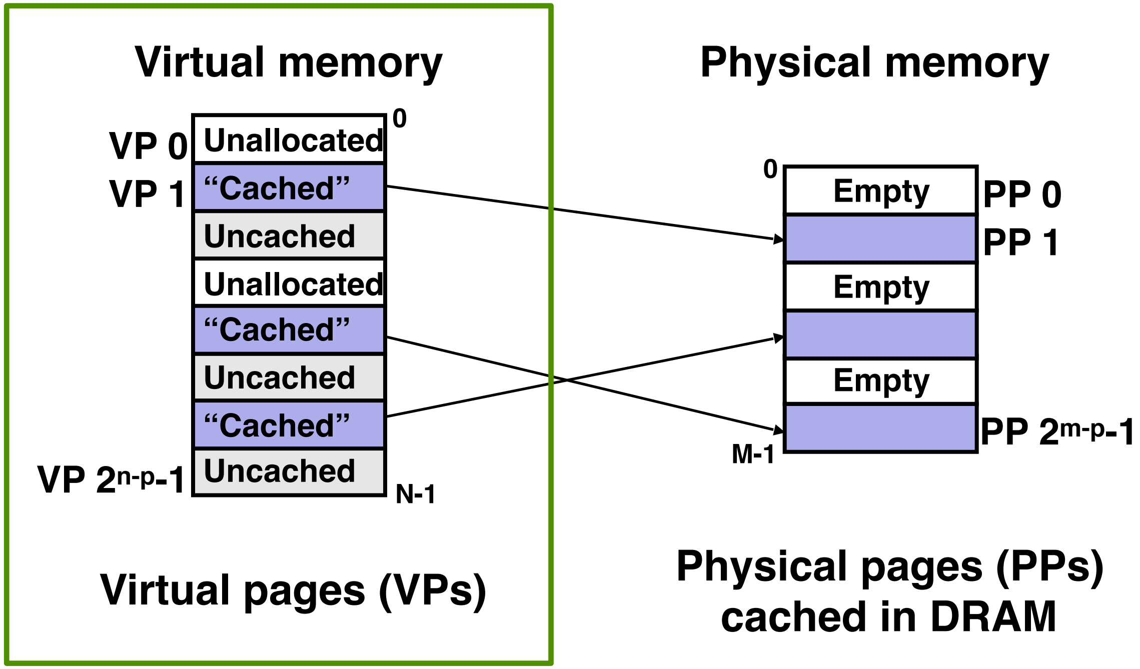

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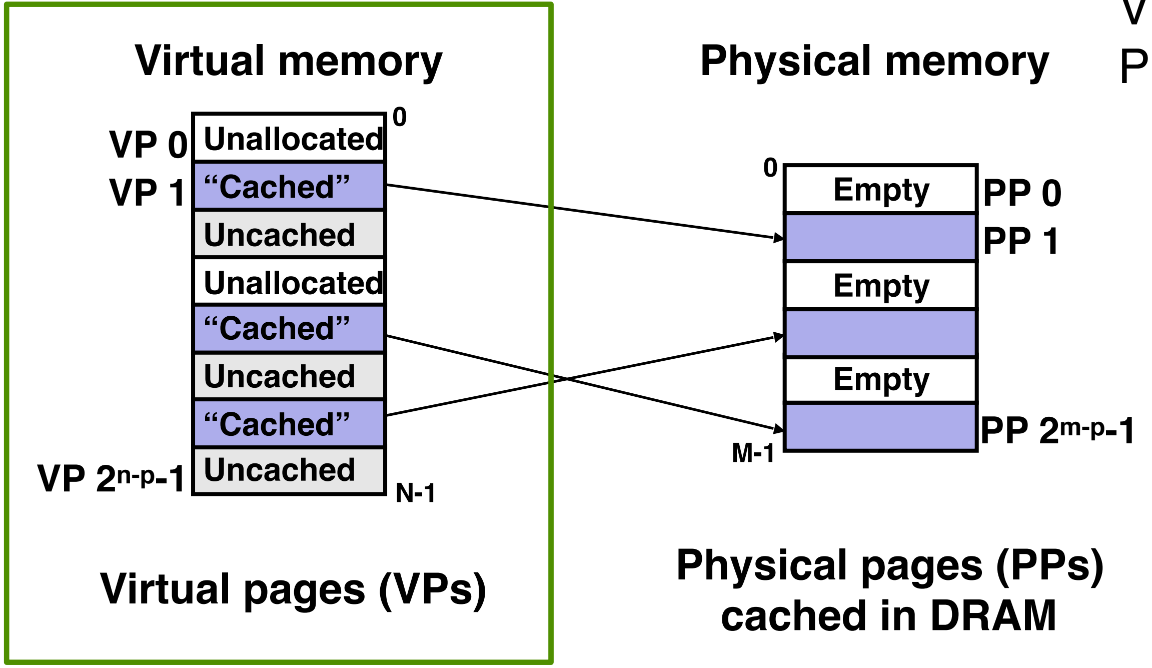
Assuming page size is 4K.
Virtual memory size is 4GB
Physical memory size is 1GB



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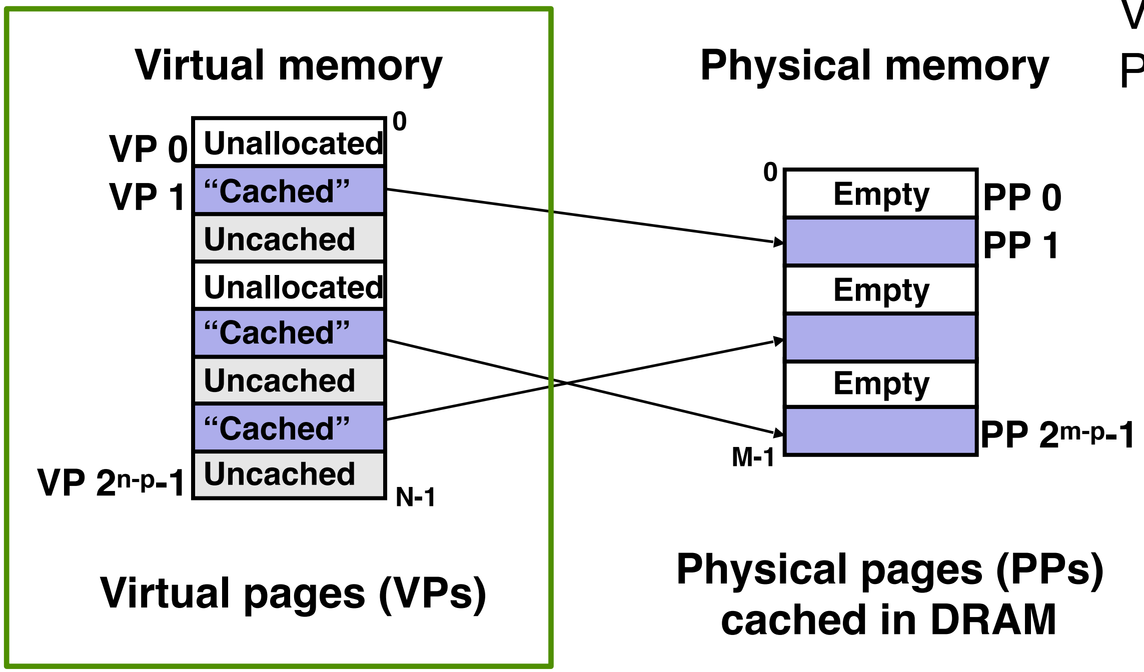

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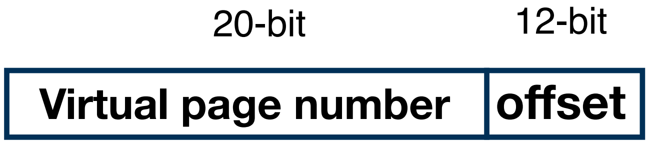

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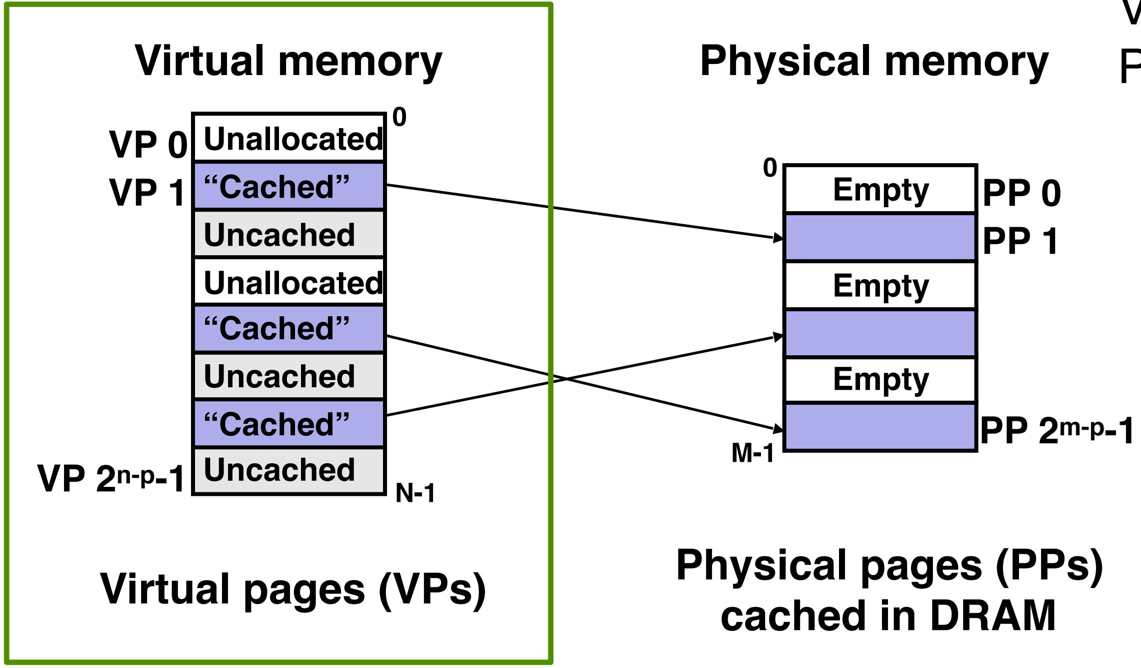

Virtual memory

VP 0 **Unallocated** **0**
VP 1 **"Cached"**
Uncached
Unallocated
"Cached"
Uncached
"Cached"
VP 2^{n-p}-1 **Uncached** **N-1**

Virtual pages (VPs)

Physical memory

0 **Empty** **PP 0**
PP 1
Empty
Empty
M-1 **PP 2^{m-p}-1**

Physical pages (PPs) cached in DRAM

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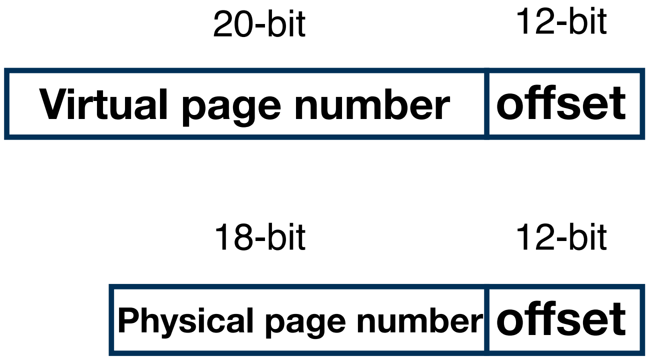

20-bit 12-bit
Virtual page number | **offset**

18-bit 12-bit
Physical page number | **offset**

Analogy for Address Translation: A Secure Hotel

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- Call a hotel looking for a guest; what happens?
  - Front desk routes call to room, does not give out room number
  - Guest’s name is a virtual address
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- Benefits
  - **Ease of management**: Guest could change rooms (physical address). You can still find her without knowing it
  - **Protection**: Guest could have block on calls, block on calls from specific callers (permissions)
  - **Sharing**: Multiple guests (virtual addresses) can share the same room (physical address)

Different Names in Different Places

Symbolic
address

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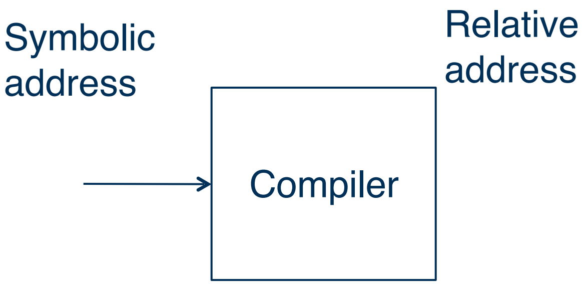

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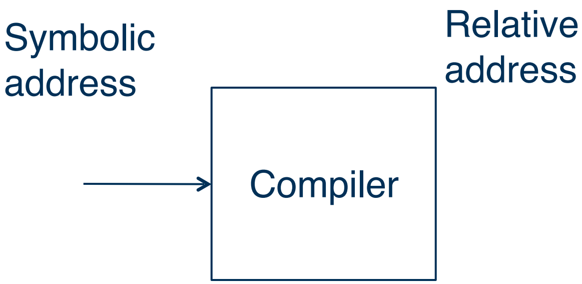

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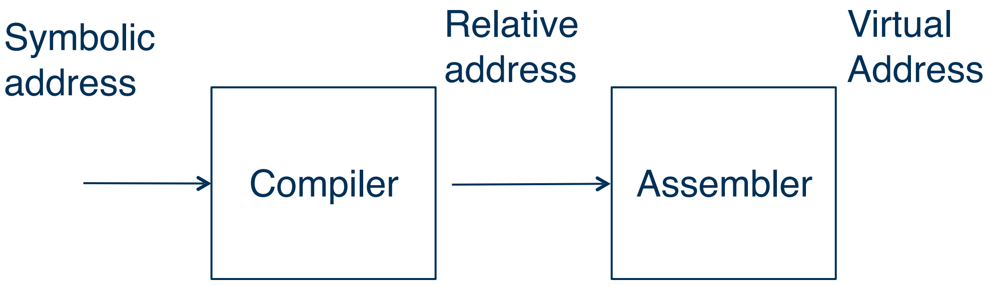

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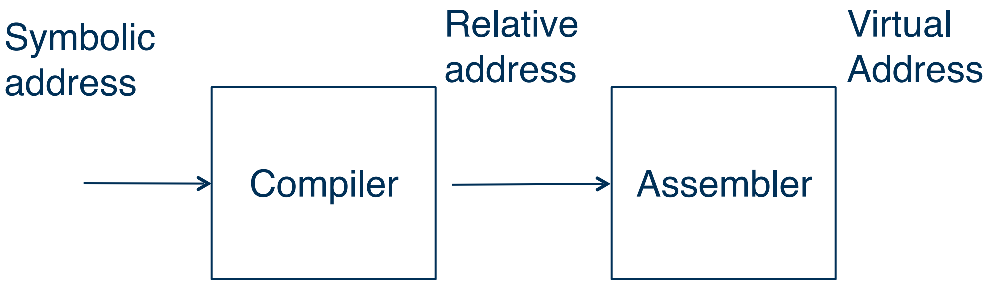

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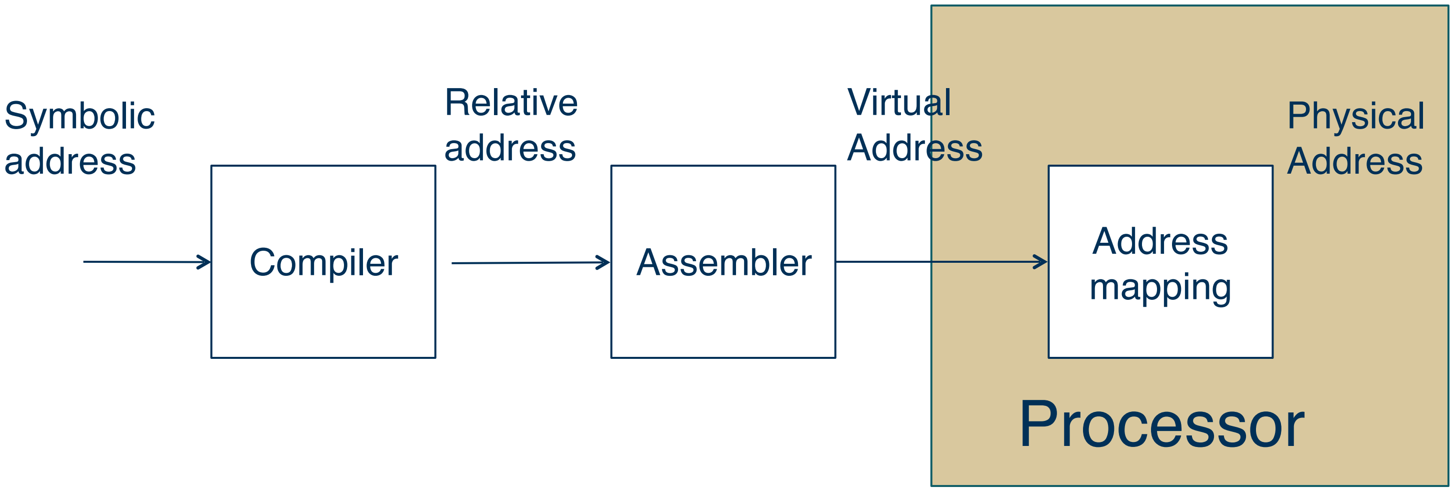

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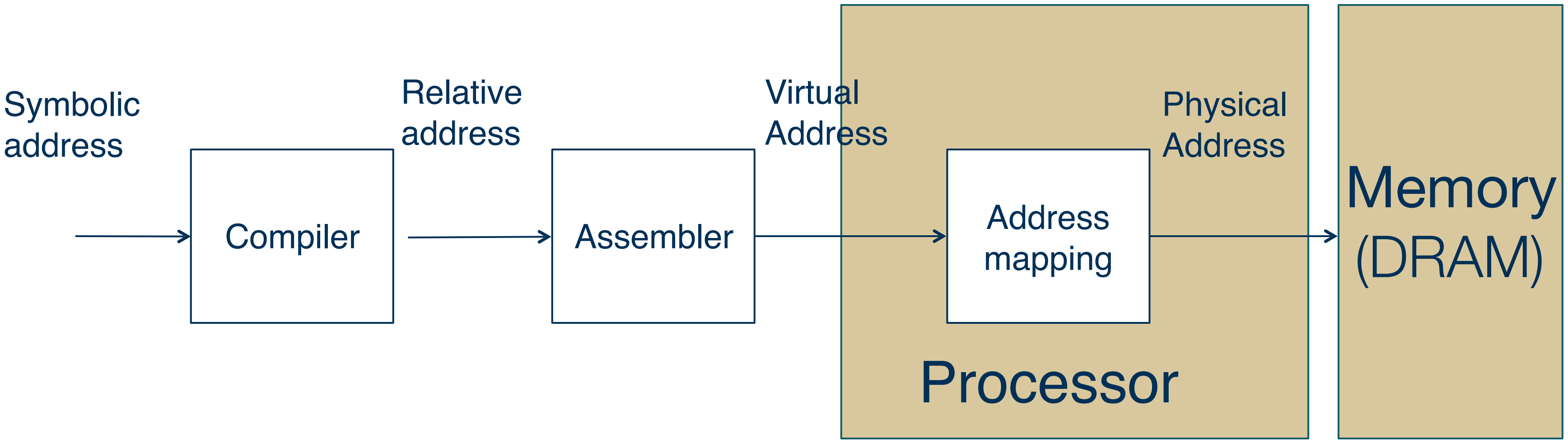

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- Do you need a page table for each process?
  - Per-process data structure; managed by the OS kernel

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Virtual memory (disk)

VP 1
VP 2
VP 3
VP 4
VP 6
VP 7

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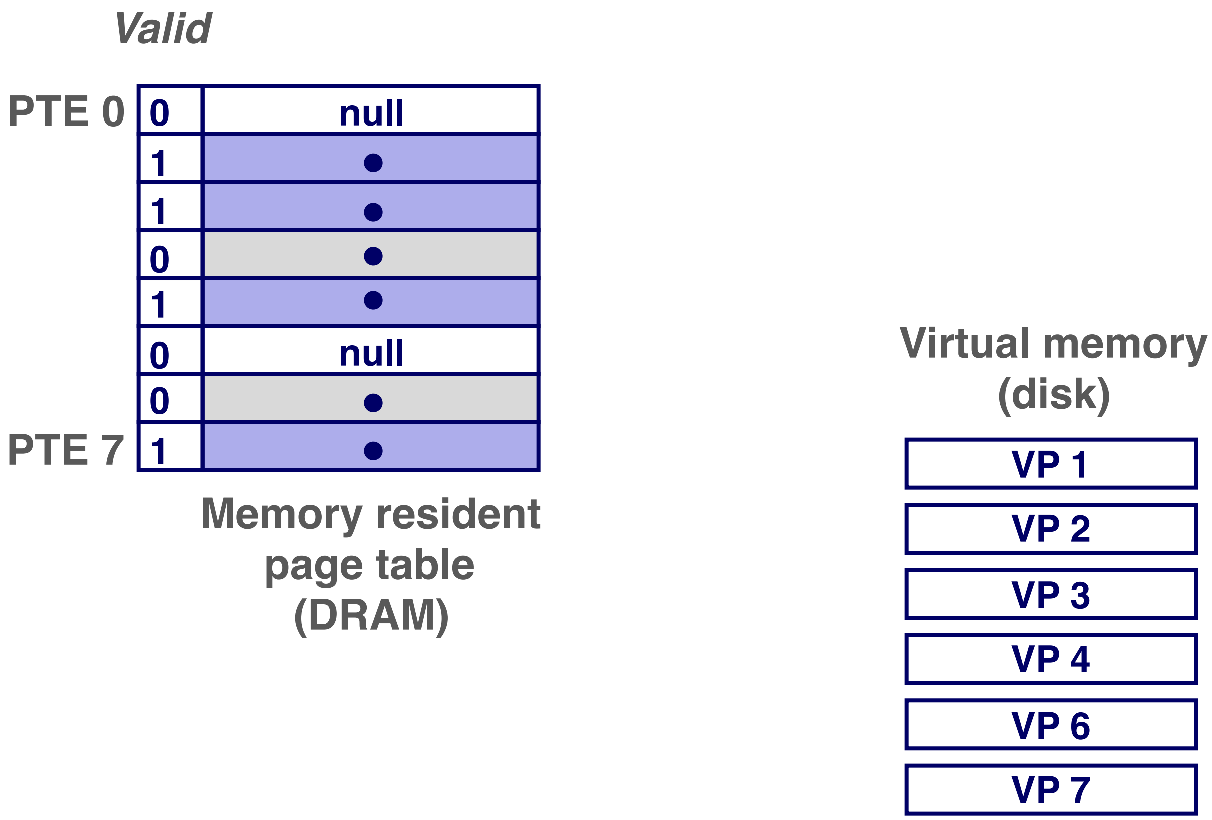

	Valid	
PTE 0	0	null
	1	●
	1	●
	0	●
	1	●
	0	null
	0	●
PTE 7	1	●

Memory resident page table (DRAM)

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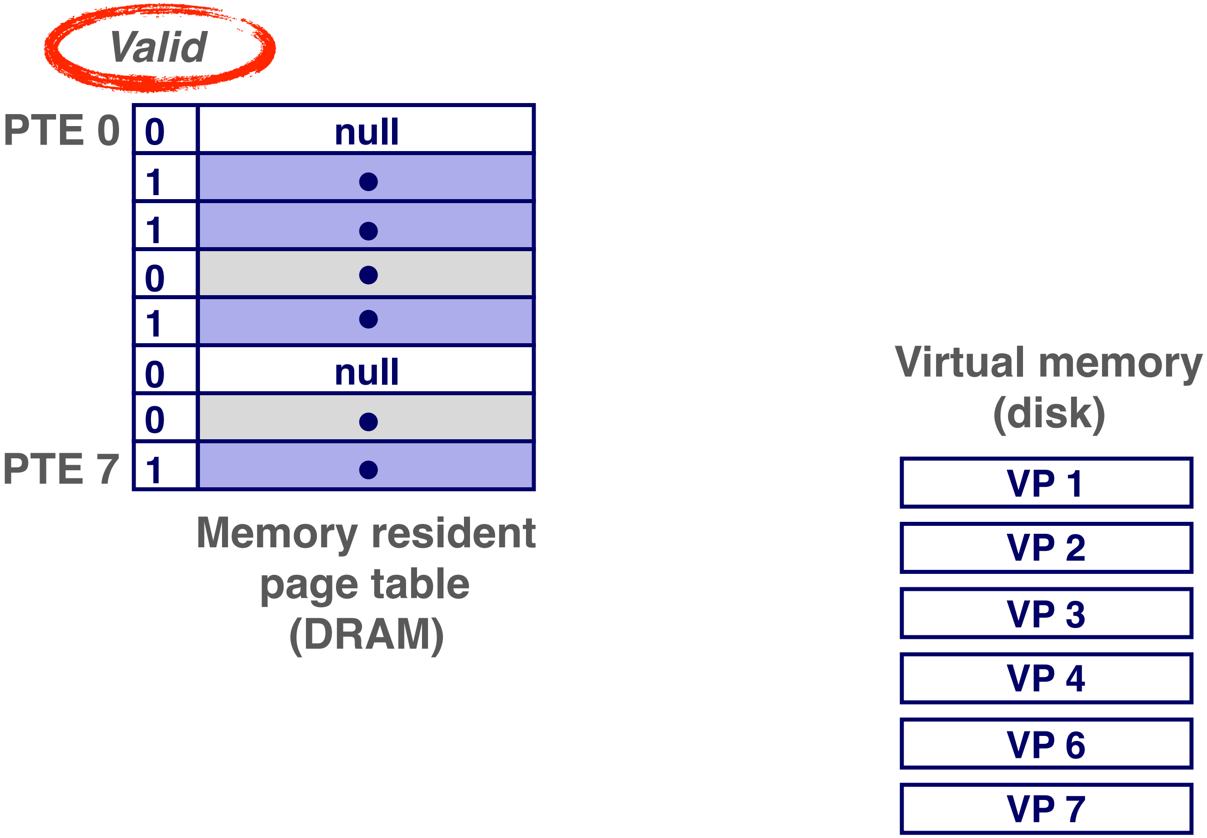

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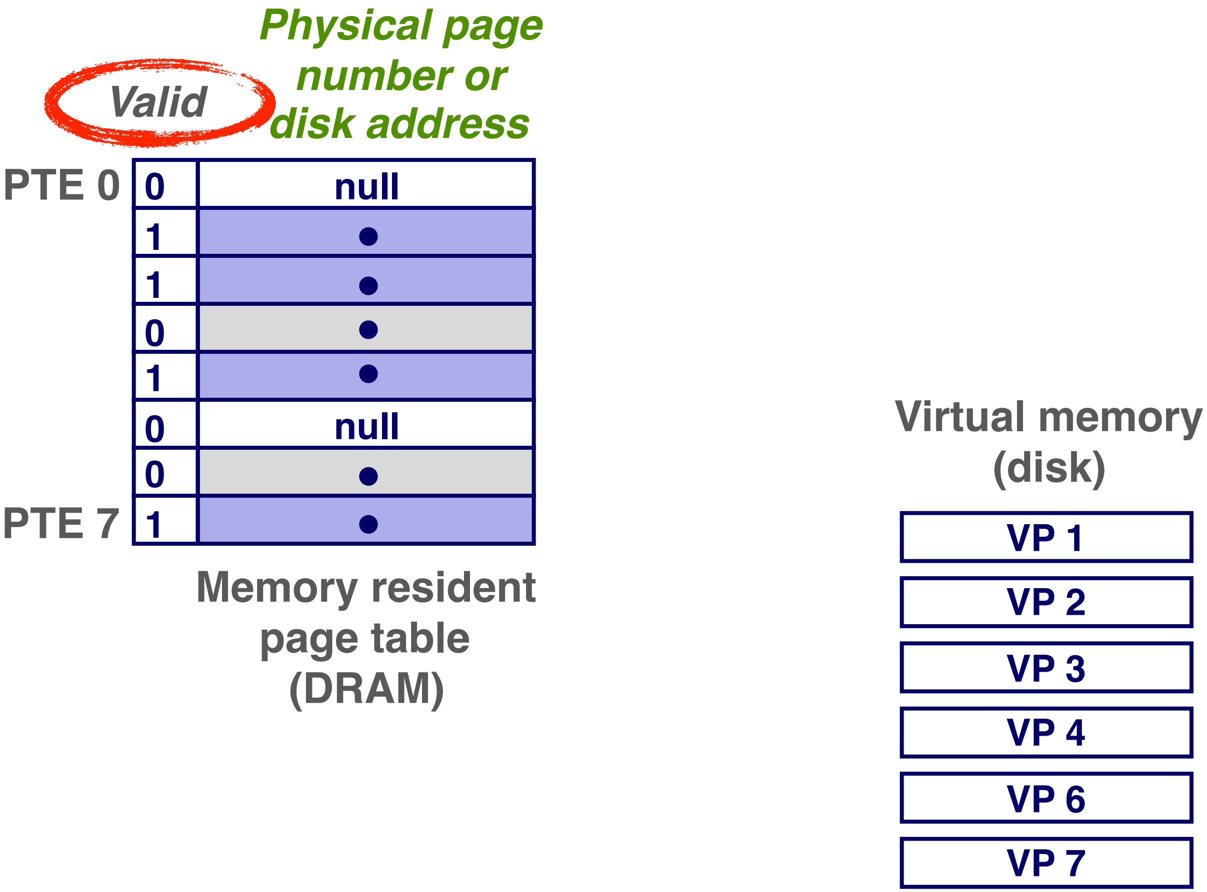


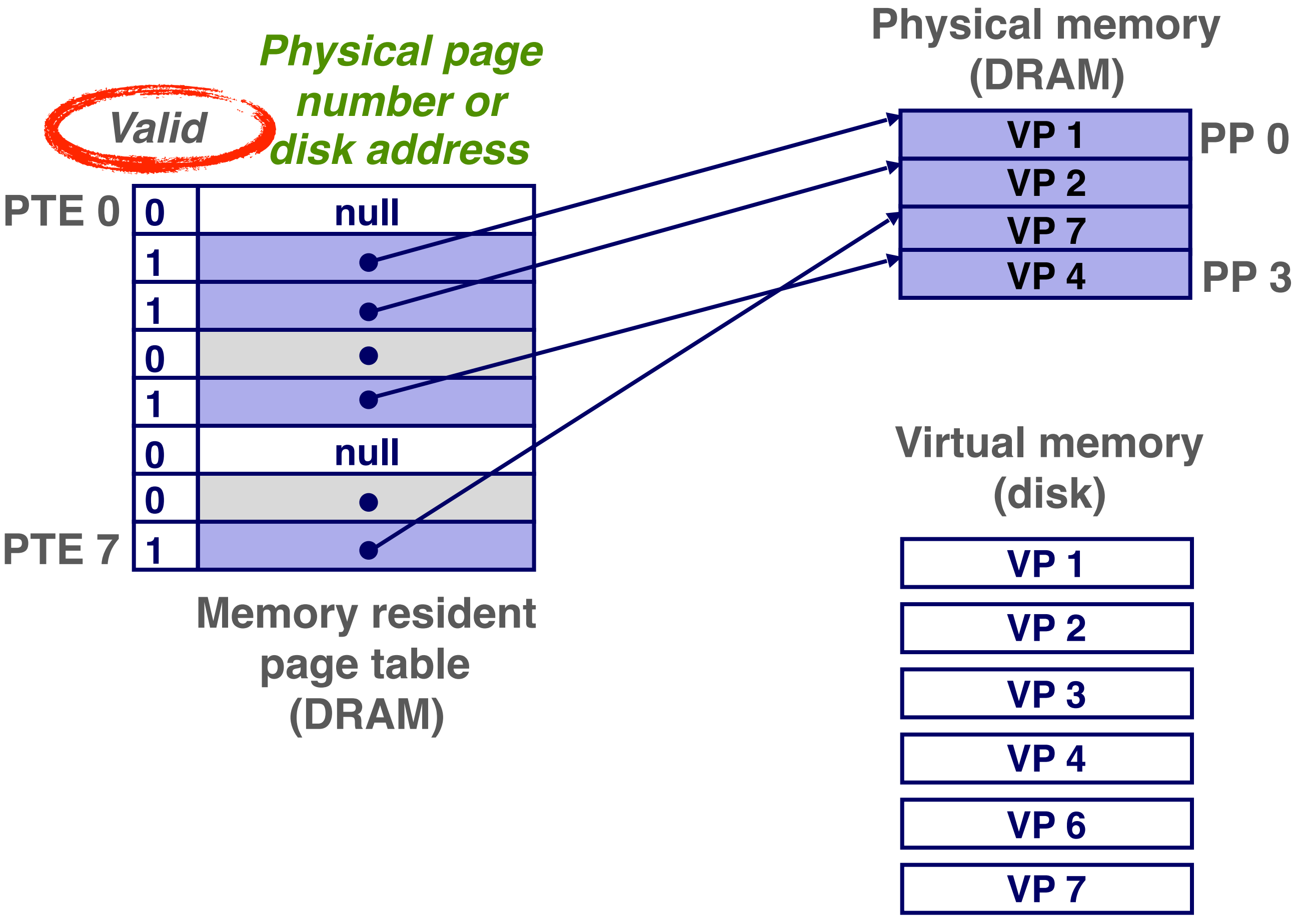
	Valid	*Physical page number or disk address*
PTE 0	0	null
	1	●
	1	●
	0	●
	1	●
	0	null
	0	●
PTE 7	1	●

Memory resident page table (DRAM)

Virtual memory (disk)

Enabling Data Structure: Page Table

- A page table is an array of page table entries (PTEs) that maps every virtual page to its physical page.



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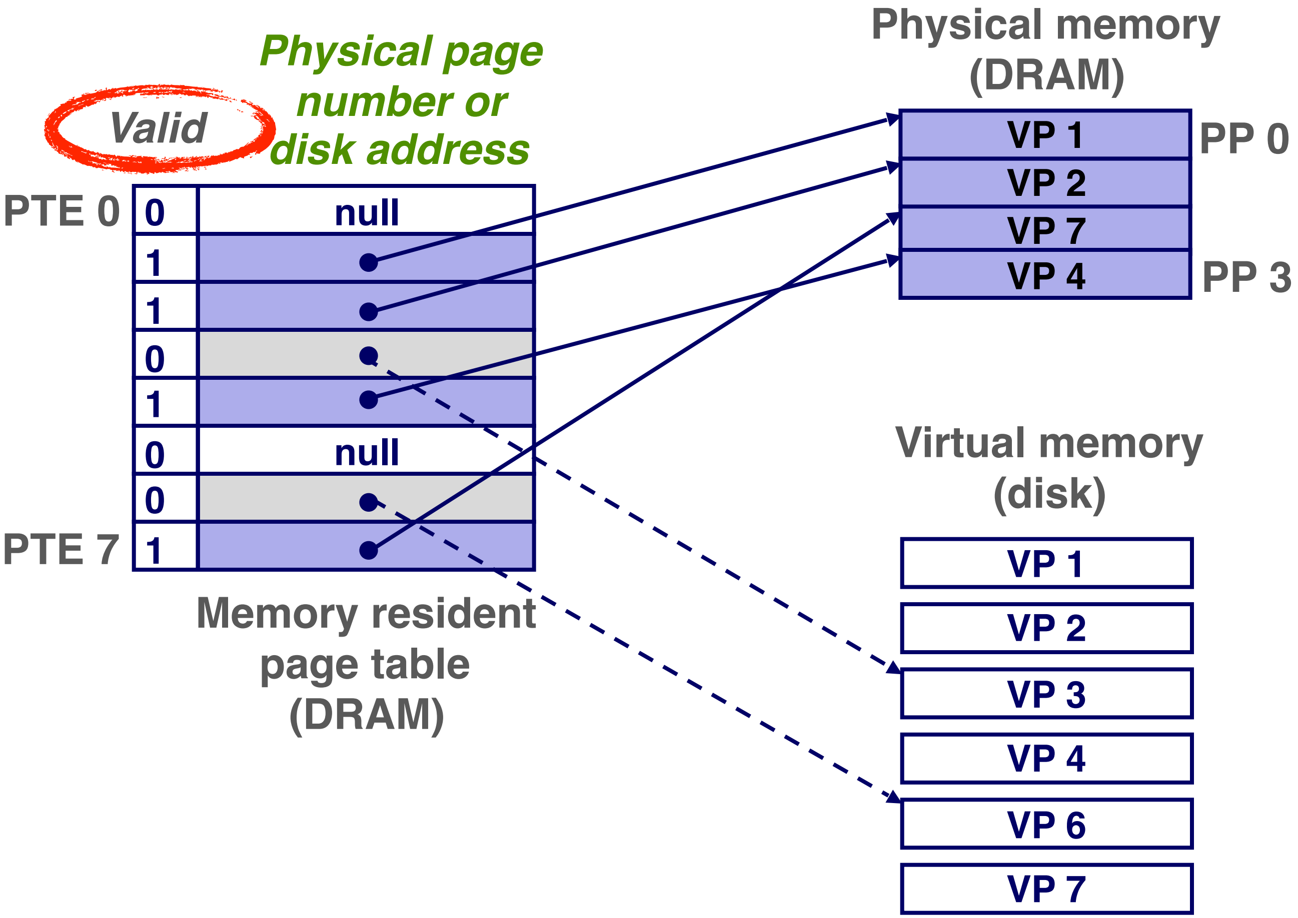
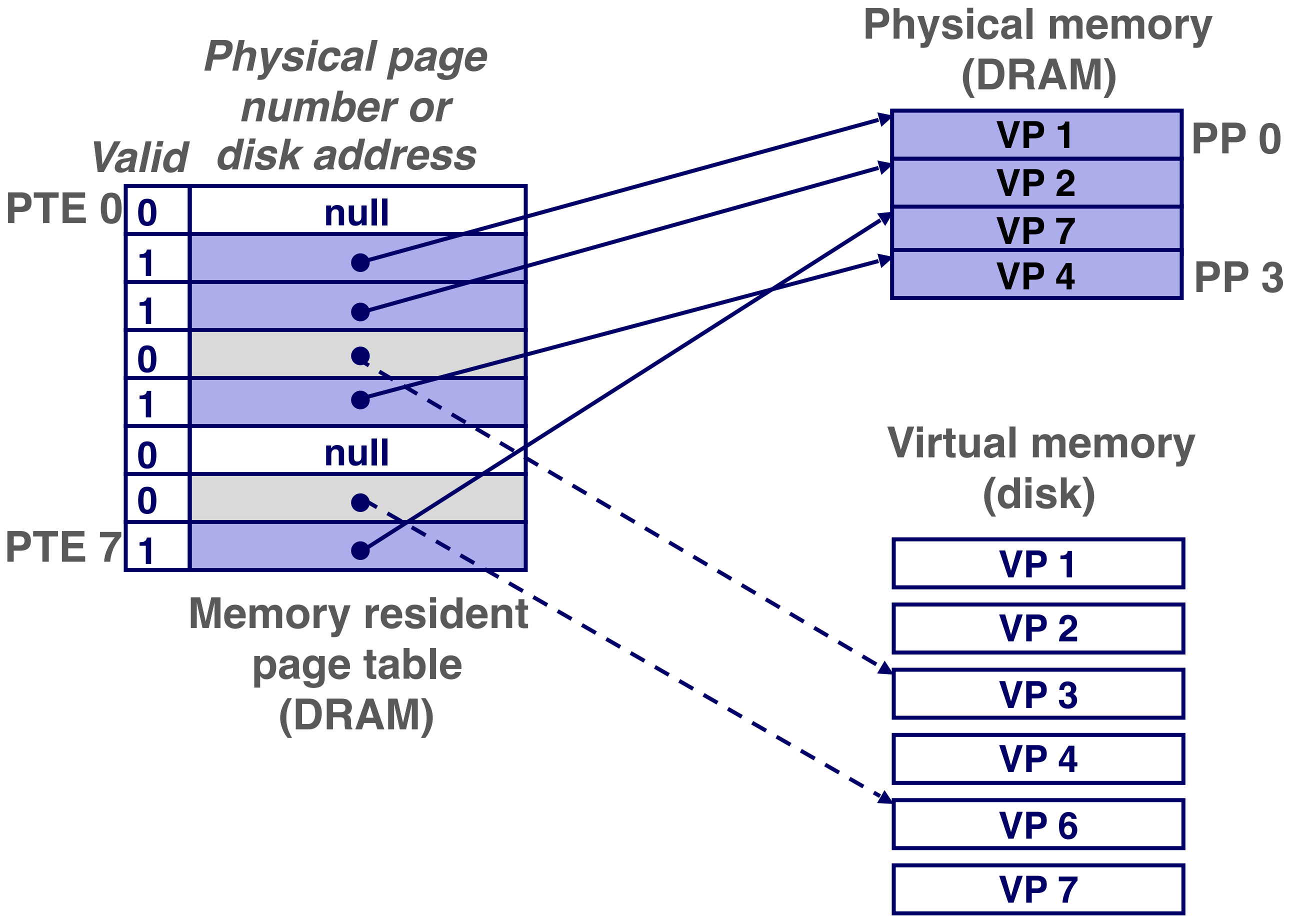


Page Hit

- *Page hit:* reference to VM word that is in physical memory



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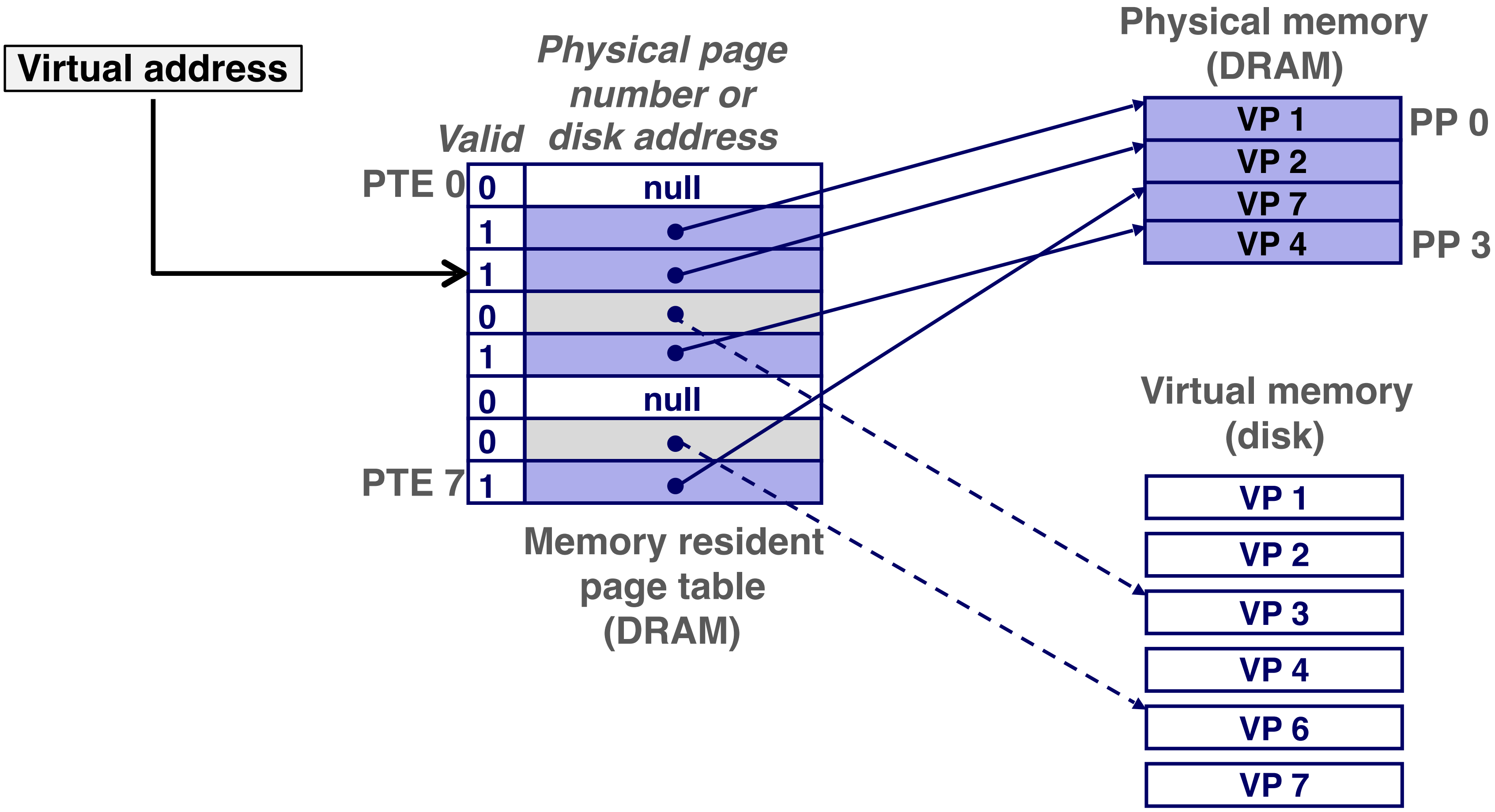
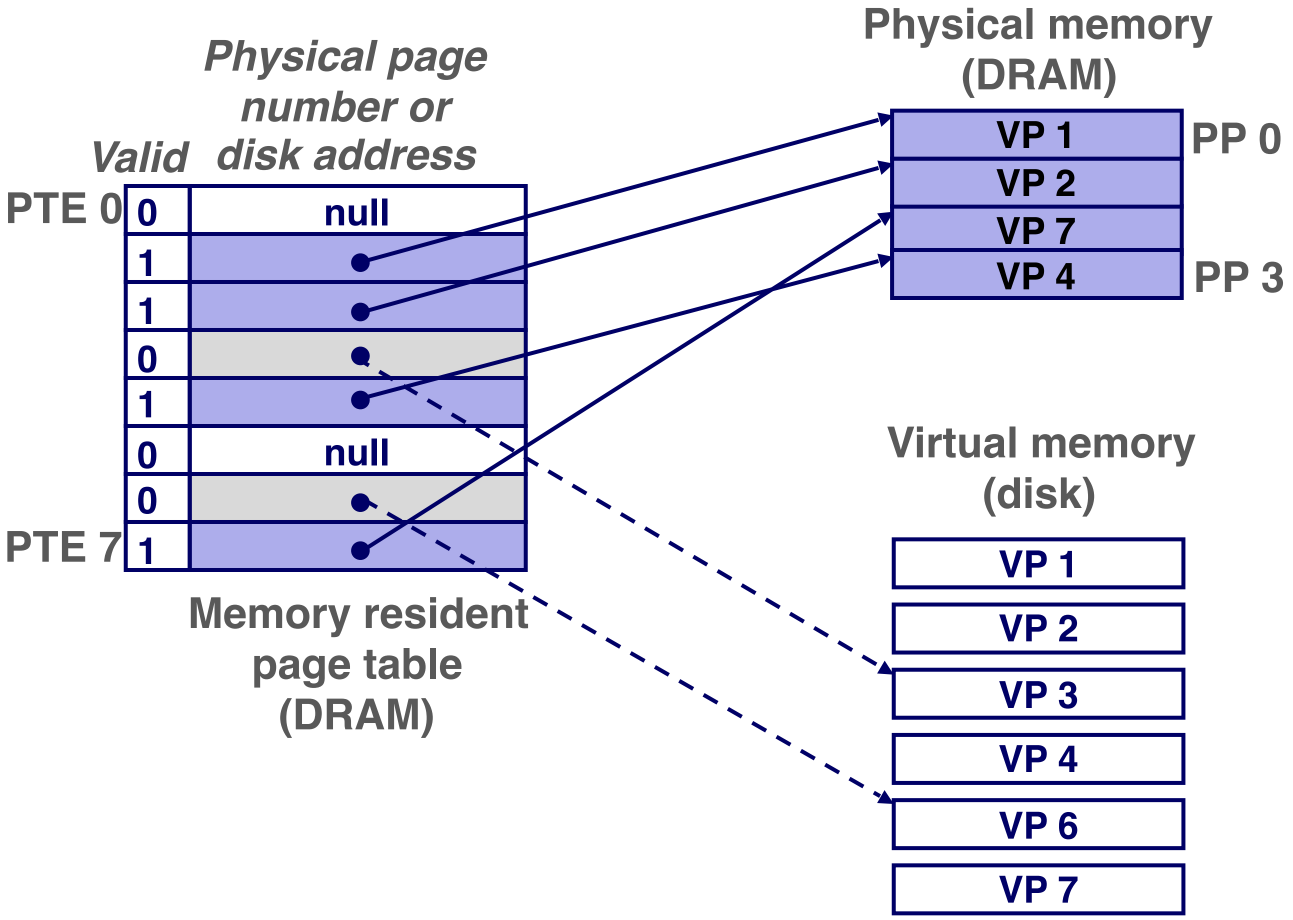


Page Fault

- *Page fault:* reference to VM word that is not in physical memory



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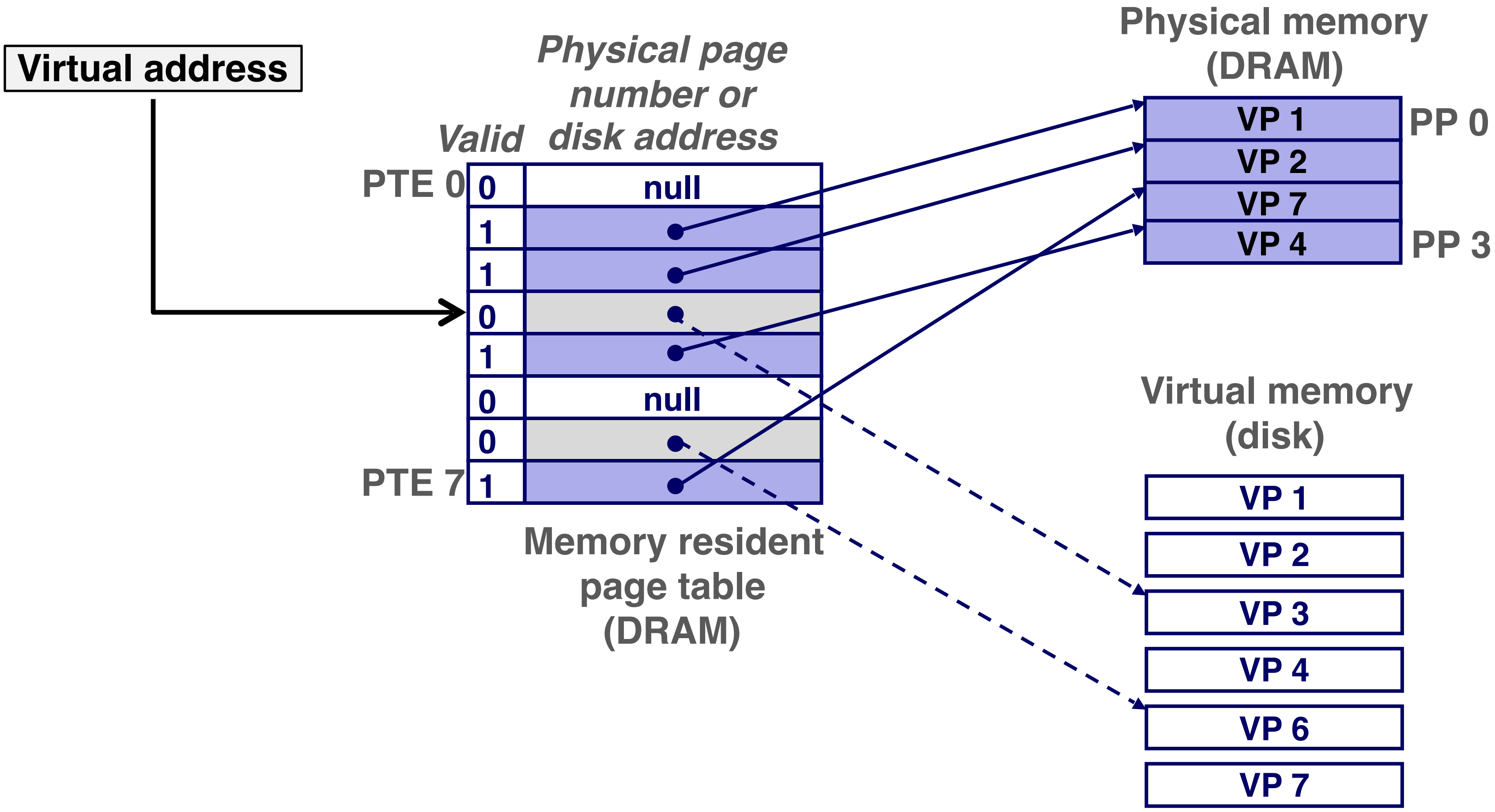
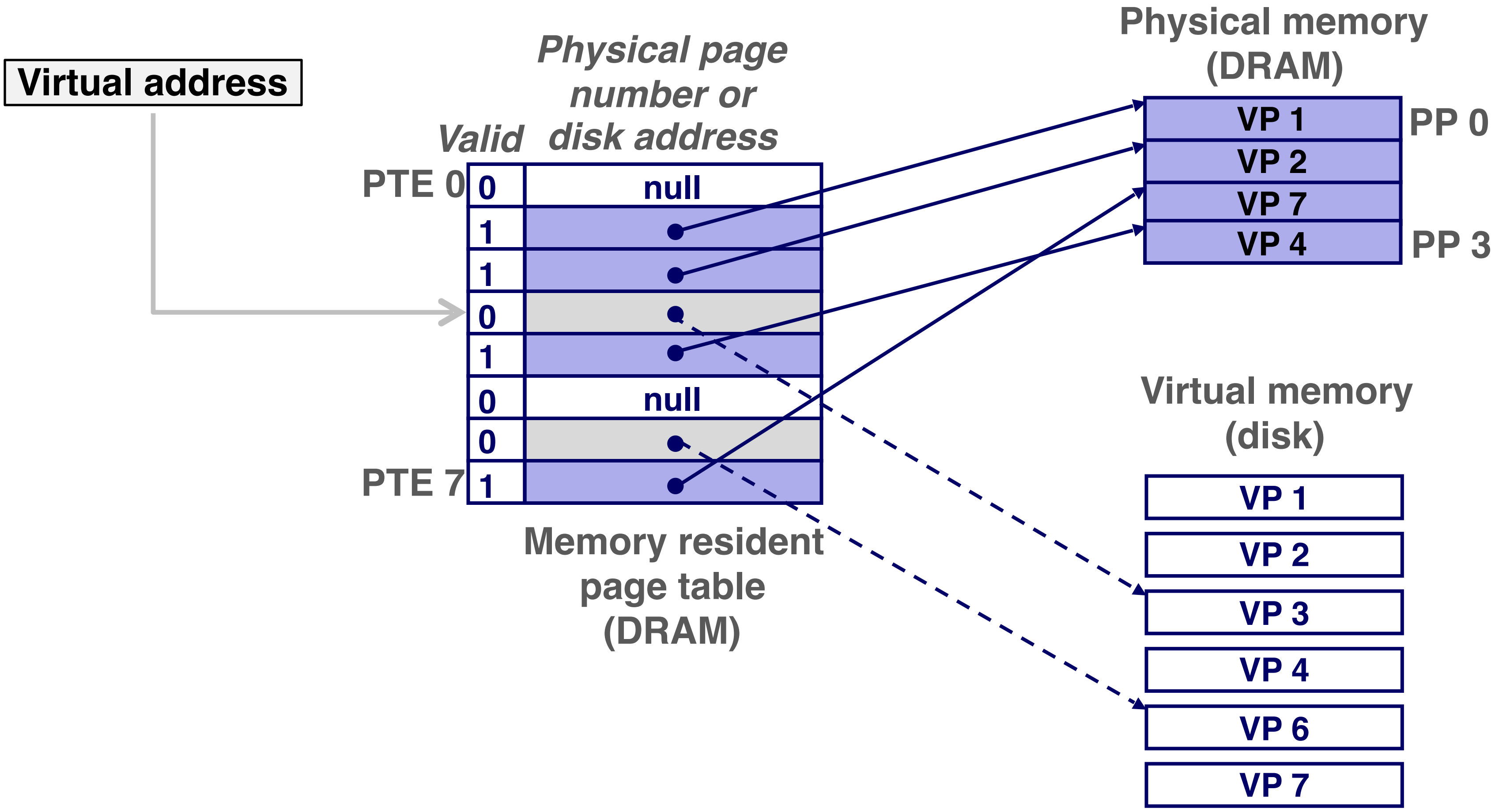


Handling Page Fault

- Page miss causes page fault (an exception)



Handling Page Fault

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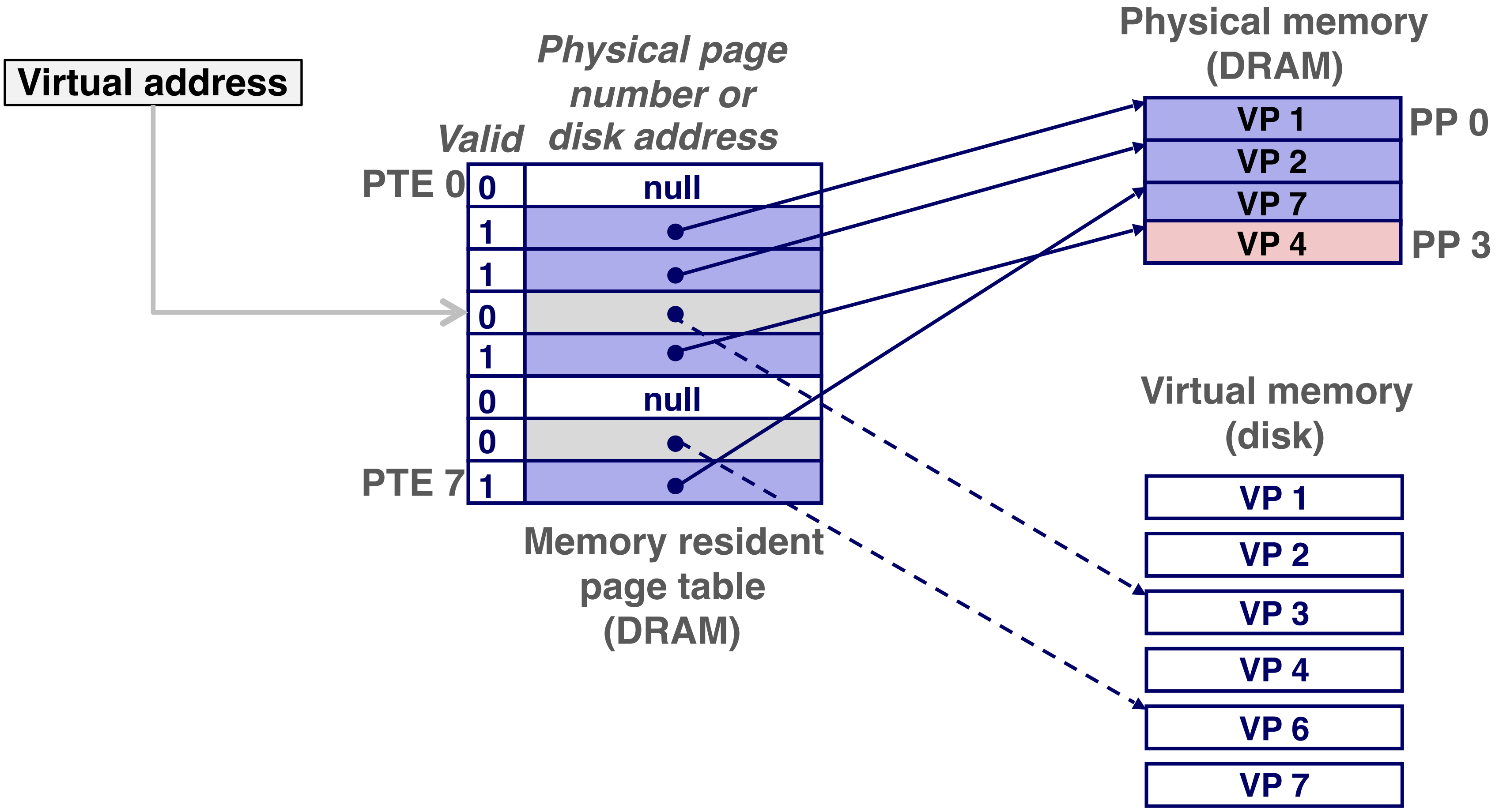
- Page fault handler selects a victim to be evicted (here VP 4)



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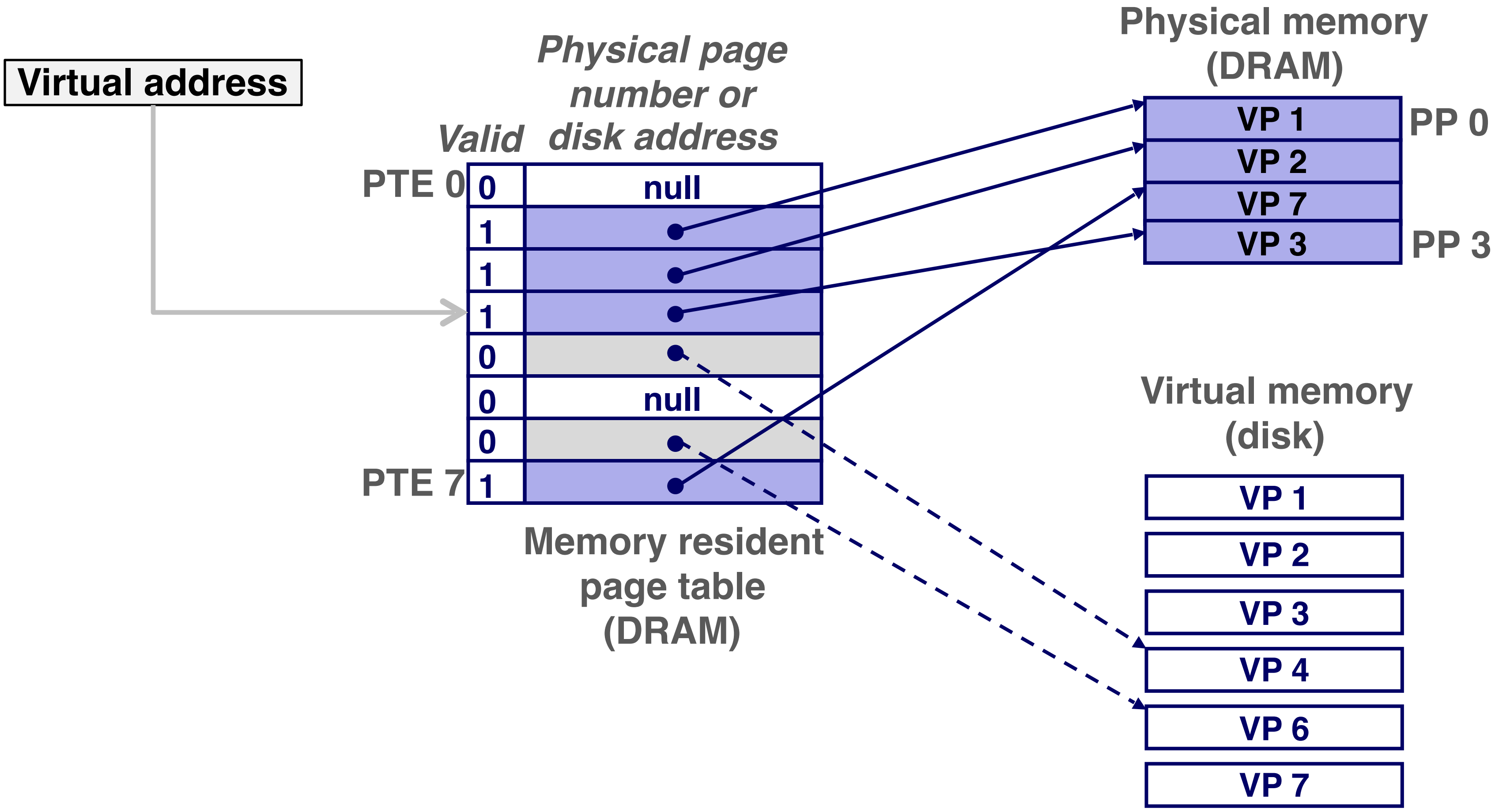
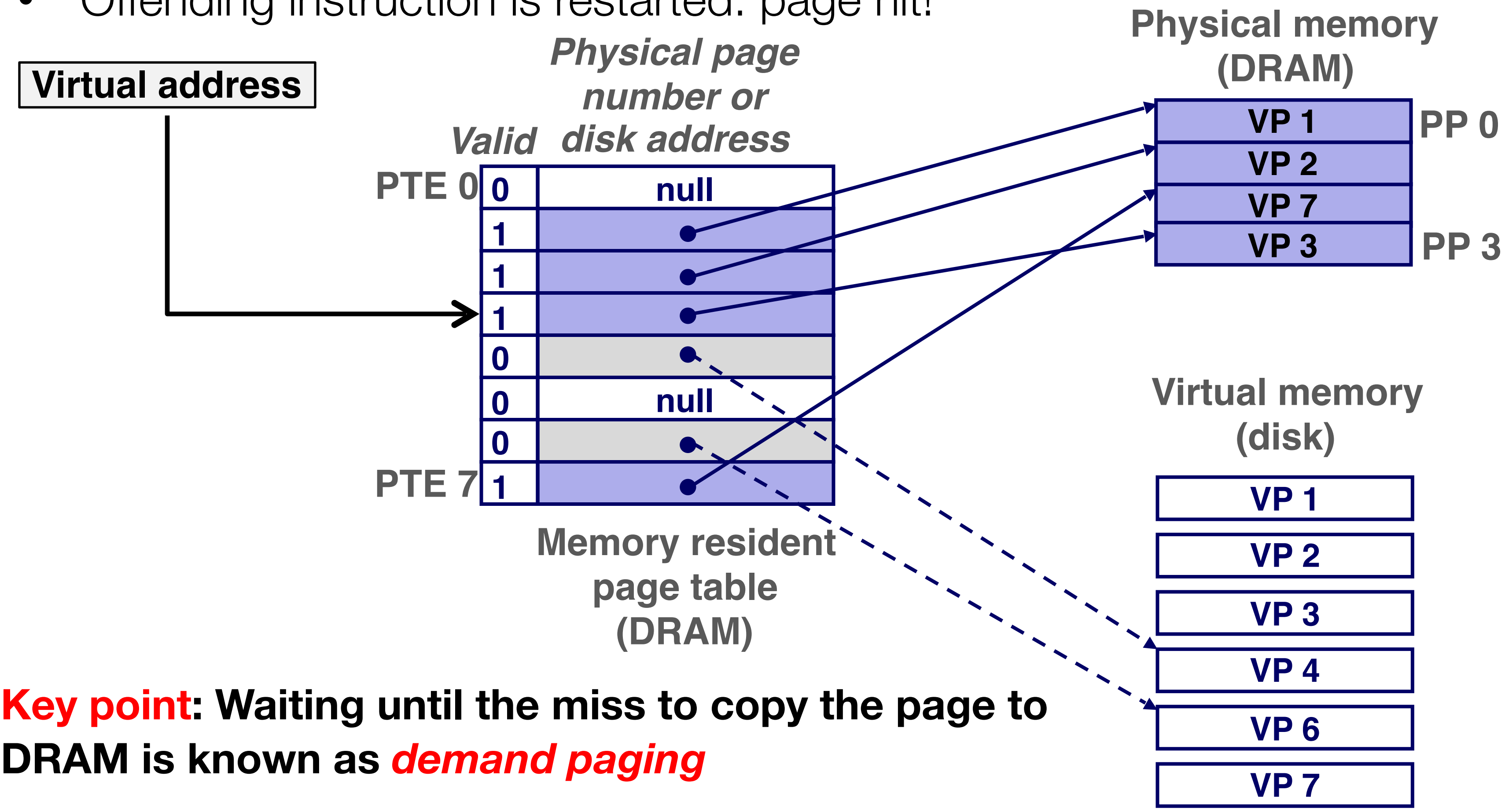


Handling Page Fault

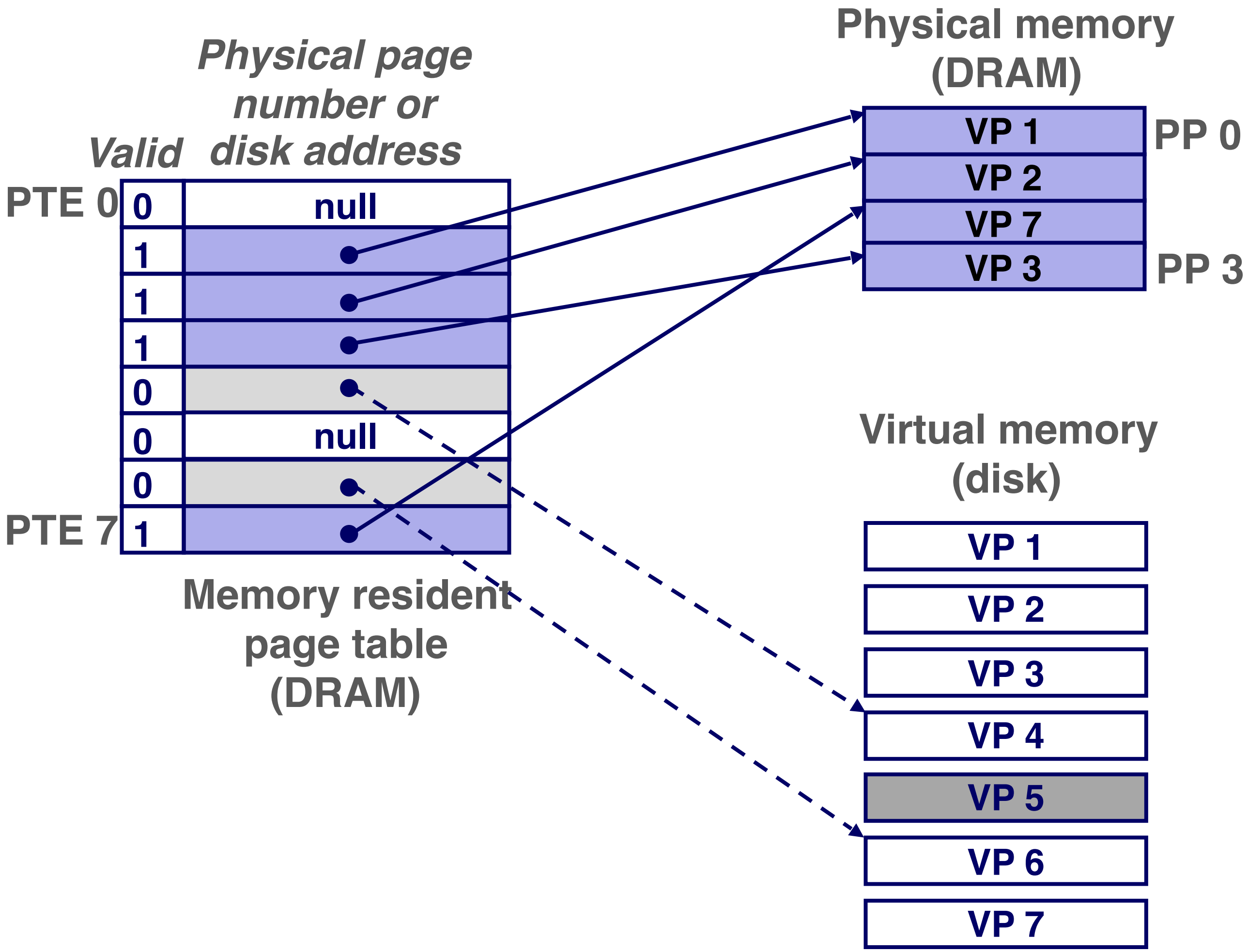
- Page miss causes page fault (an exception)
- Page fault handler selects a victim to be evicted (here VP 4)
- Offending instruction is restarted: page hit!



Key point: **Waiting until the miss to copy the page to DRAM is known as *demand paging***

Allocating Pages

- Allocating a new page (VP 5) of virtual memory.



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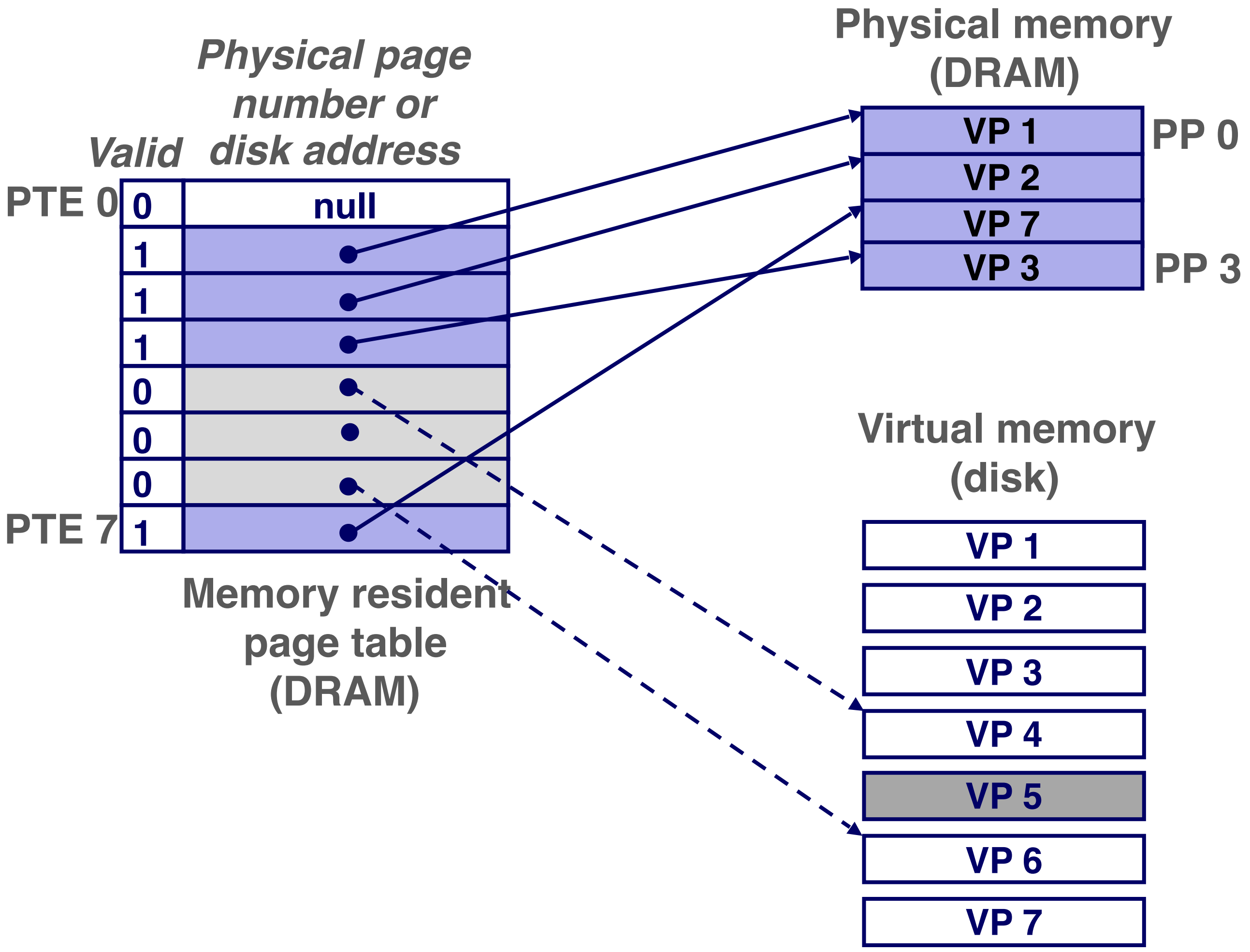

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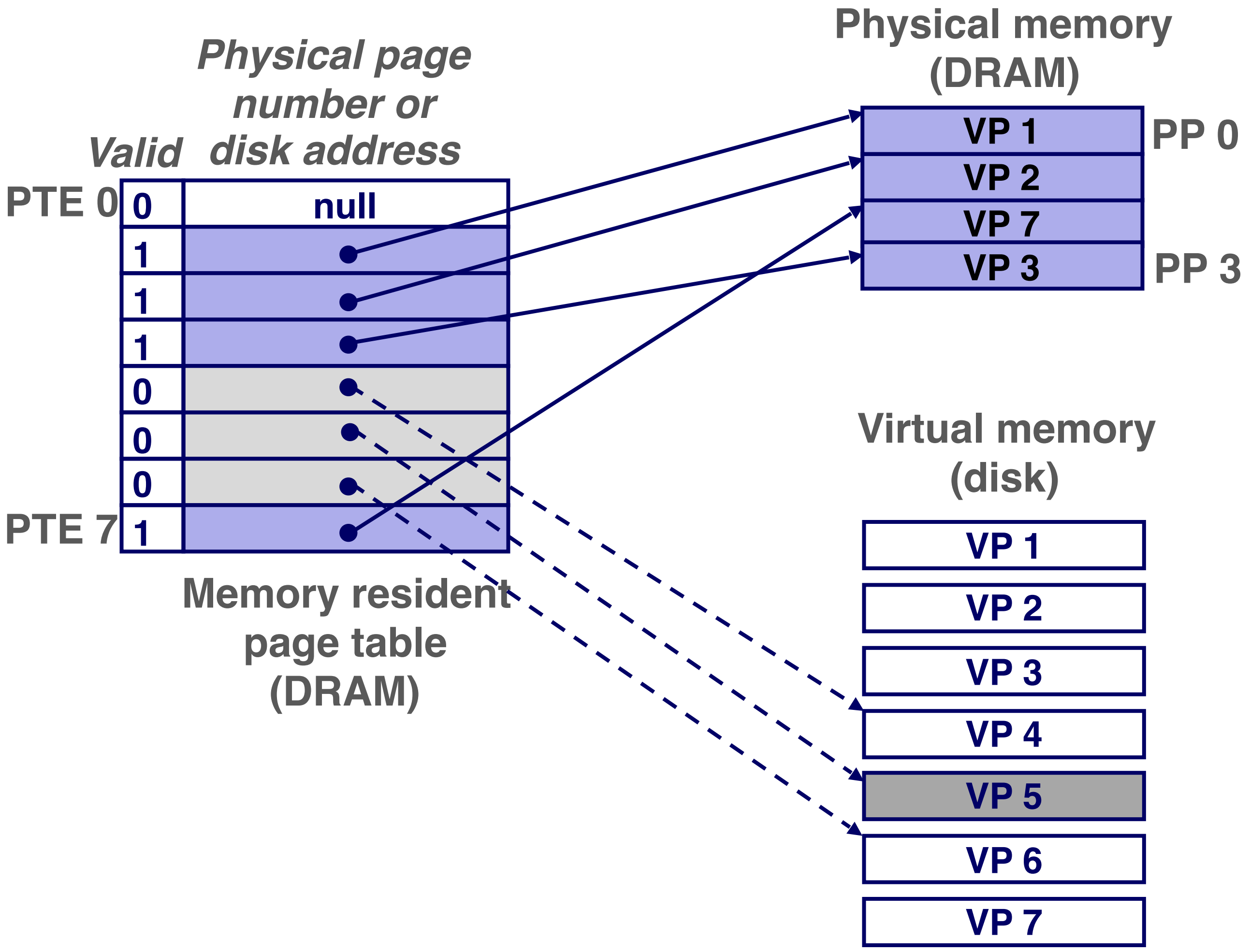

Virtual Memory Exploits Locality (Again!)

- Virtual memory seems terribly inefficient, but it works because of locality.

- At any point in time, programs tend to access a set of active virtual pages called the *working set*
  - Programs with better temporal locality will have smaller working sets

- If (working set size < main memory size)
  - Good performance for one process after initial misses

- If (SUM(working set sizes) > main memory size)
  - *Thrashing:* Performance meltdown where pages are swapped (copied) in and out continuously

Where Does Page Table Live?

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- It needs to be at a specific location where we can find it
  - Some special SRAM?
  - In main memory?
  - On disk?

Where Does Page Table Live?

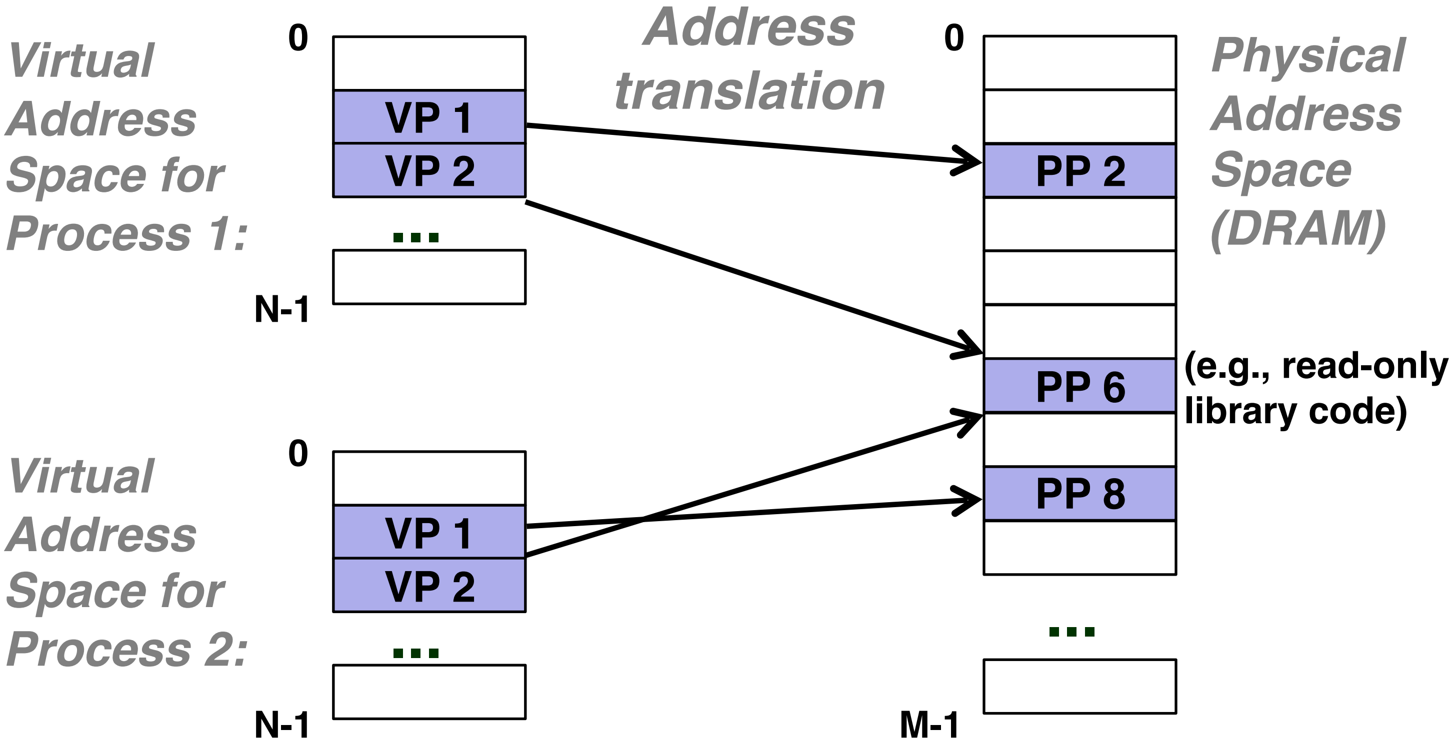
- It needs to be at a specific location where we can find it
  - Some special SRAM?
  - In main memory?
  - On disk?
- Assume 4KB page, 4GB main memory, each PTE is 8 Bytes
  - 1M PTEs in a page table
  - 8MB total size per page table
  - Too big for on-chip SRAM
  - Too slow to access in disk
  - Put the page table in DRAM, with its start address stored in a special register (Page Table Base Register)

Today

- Virtual memory (VM) illustration
- VM basic concepts and operation
- Other critical benefits of VM
- Address translation

VM as a Tool for Memory Management

- Key idea: each process has its own virtual address space
  - It can view memory as a simple linear array
  - Mapping scatters addresses through physical memory
    - Well-chosen mappings can improve locality



Virtual Memory Enables Isolations

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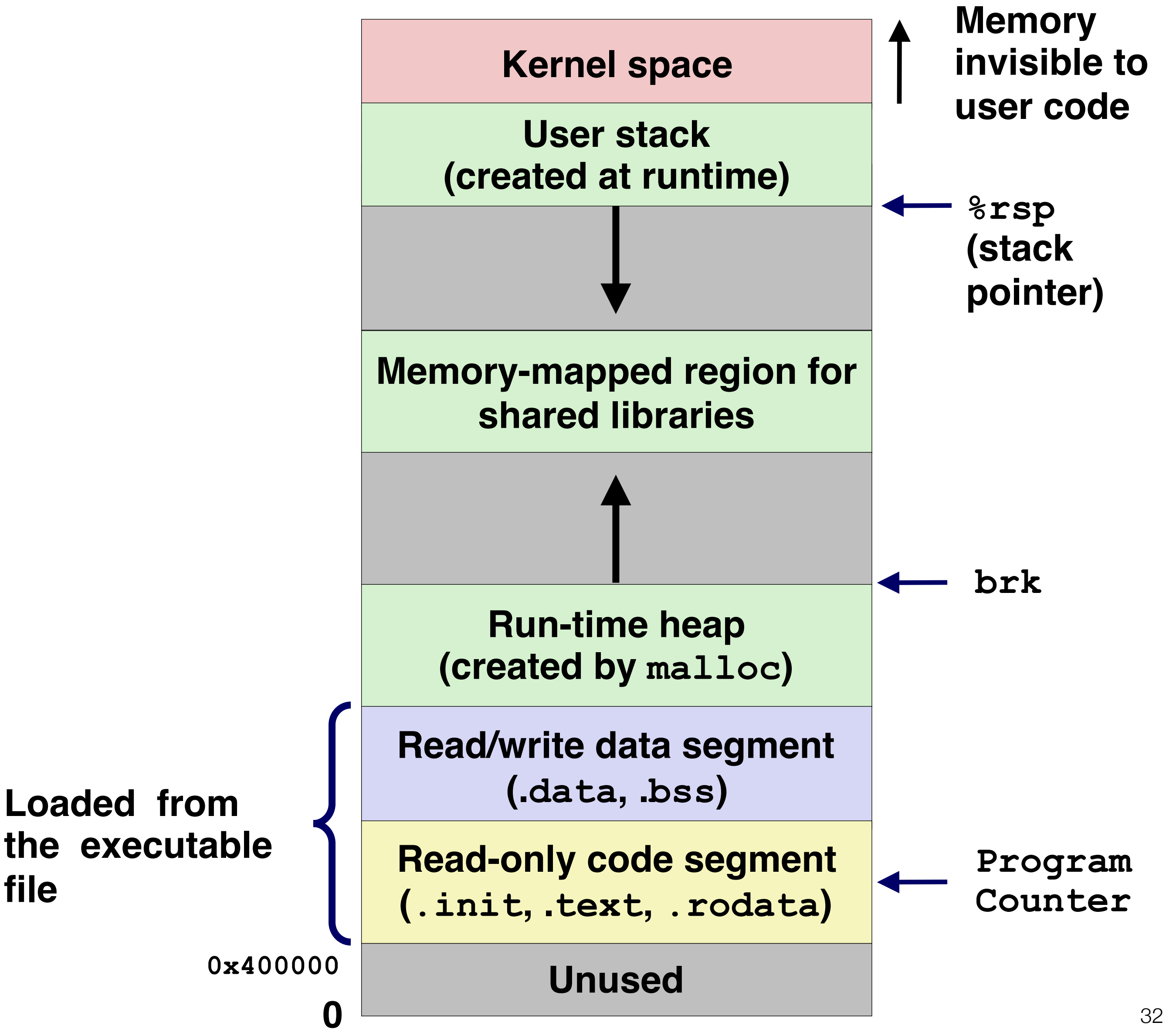
  - not ideal: address in programs depend on where the program is loaded in memory
- With virtual memory, addresses used by program are not the same as what the processor uses to actually access memory. This naturally isolates/protect programs.

Simplifying Linking and Loading



Kernel space

User stack
(created at runtime)

Memory-mapped region for
shared libraries

Run-time heap
(created by `malloc`)

Read/write data segment
(`.data`, `.bss`)

Read-only code segment
(`.init`, `.text`, `.rodata`)

Unused

Memory invisible to user code

`%rsp` (stack pointer)

`brk`

`Program Counter`

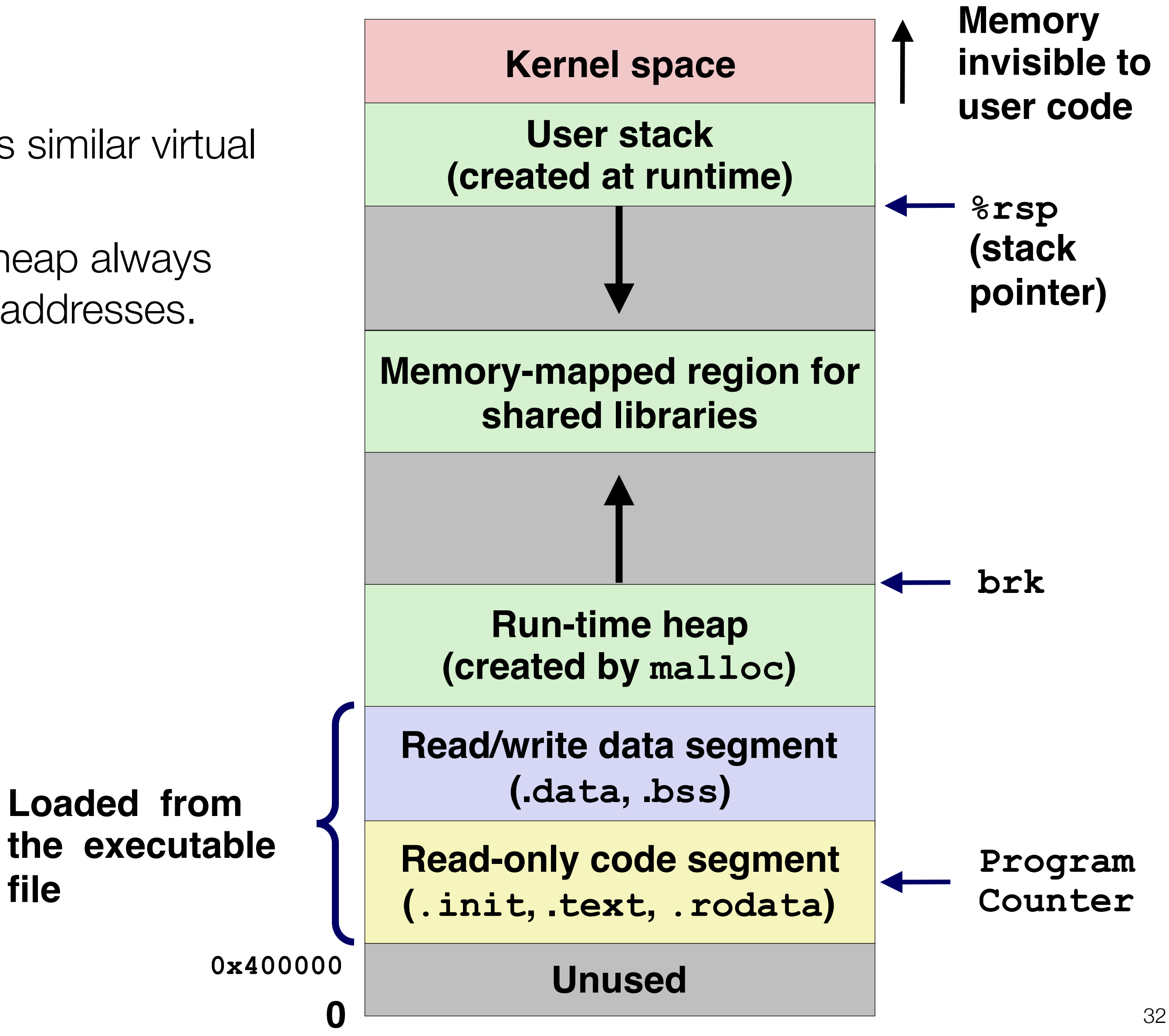
Loaded from the executable file

`0x400000`

0

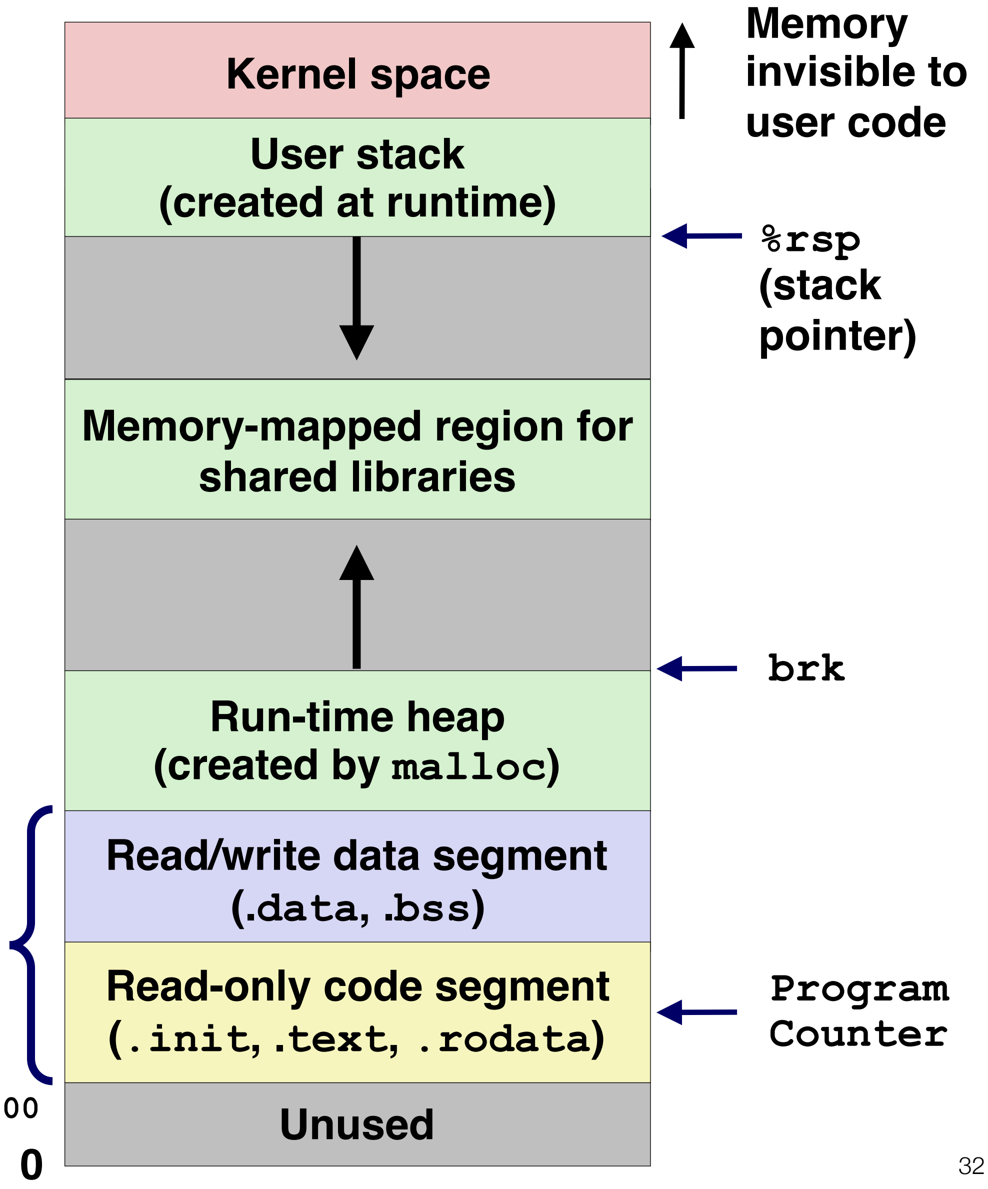
Simplifying Linking and Loading

- Linking
  - Each program has similar virtual address space
  - Code, data, and heap always start at the same addresses.



Simplifying Linking and Loading

- Linking
  - Each program has similar virtual address space
  - Code, data, and heap always start at the same addresses.
- Loading
  - `execve` allocates virtual pages for `.text` and `.data` sections & creates PTEs marked as invalid
  - The `.text` and `.data` sections are copied, page by page, on demand by the VM system



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`Program Counter`

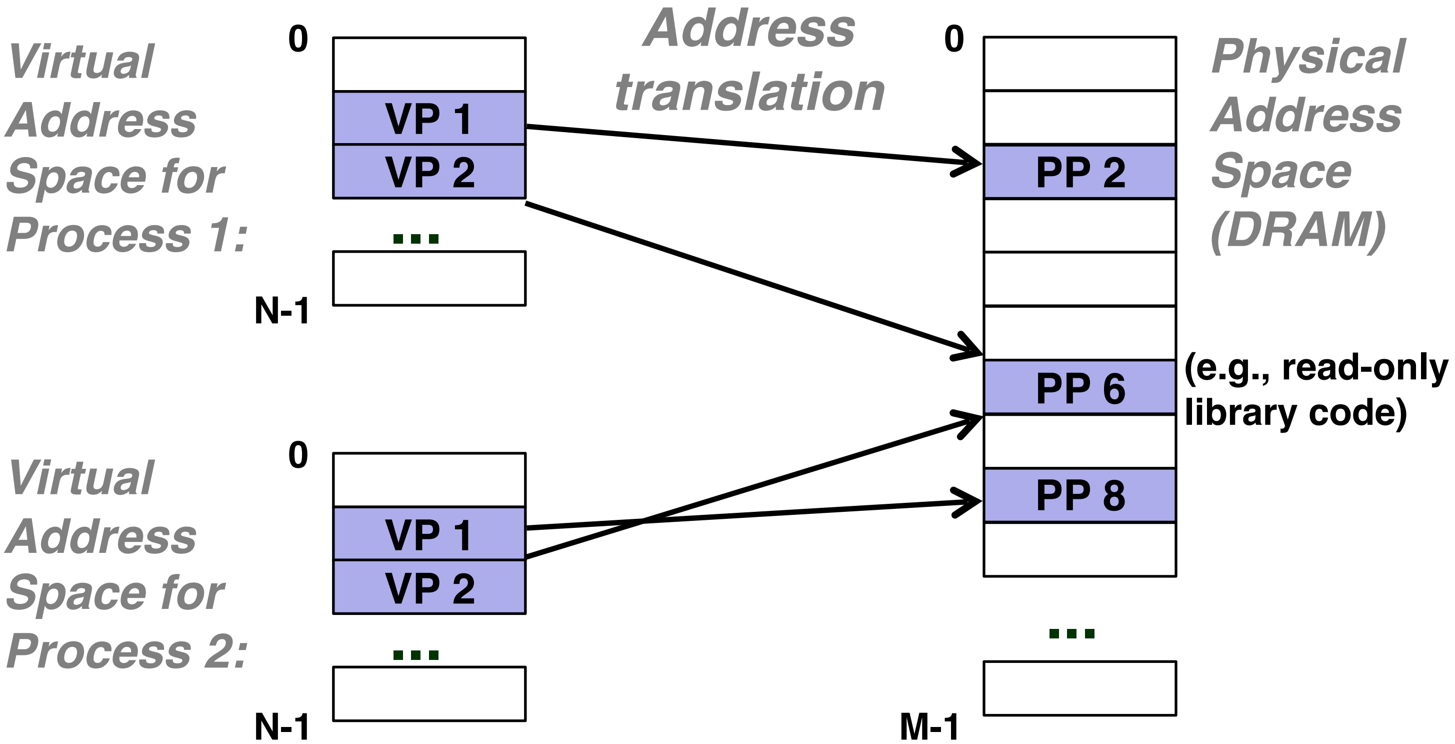
Loaded from the executable file

`0x400000`

0

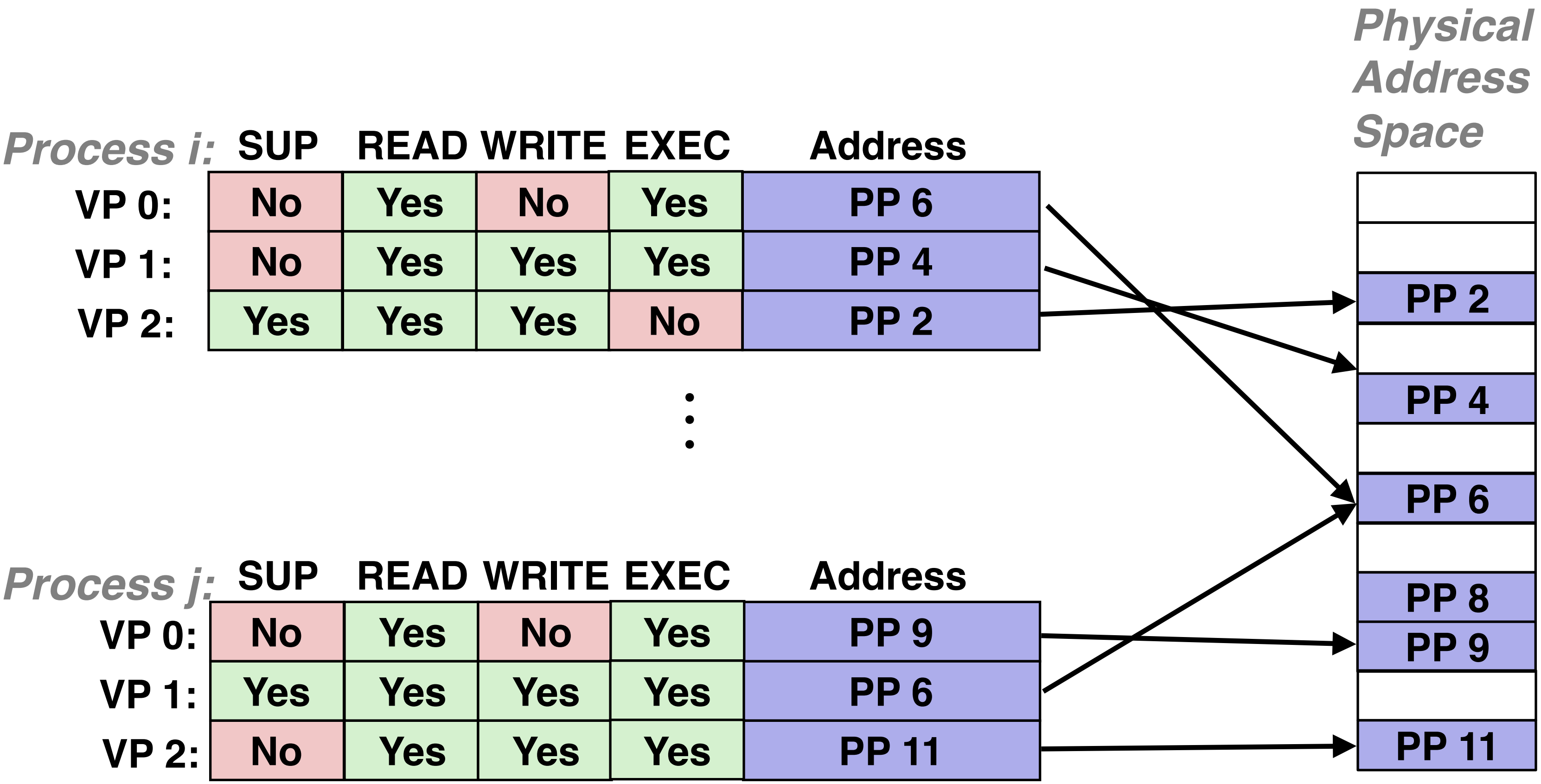
Virtual Memory Enables Sharing

- Simplifying memory allocation
  - Each virtual page can be mapped to any physical page
  - A virtual page can be stored in different physical pages at different times
- Sharing code and data among processes
  - Map virtual pages to the same physical page (here: PP 6)



VM Provides Further Protection Opportunities

- Extend PTEs with permission bits
- MMU checks these bits on each access



Process i:

	SUP	READ	WRITE	EXEC	Address
VP 0:	No	Yes	No	Yes	PP 6
VP 1:	No	Yes	Yes	Yes	PP 4
VP 2:	Yes	Yes	Yes	No	PP 2

⋮

Process j:

	SUP	READ	WRITE	EXEC	Address
VP 0:	No	Yes	No	Yes	PP 9
VP 1:	Yes	Yes	Yes	Yes	PP 6
VP 2:	No	Yes	Yes	Yes	PP 11

Today

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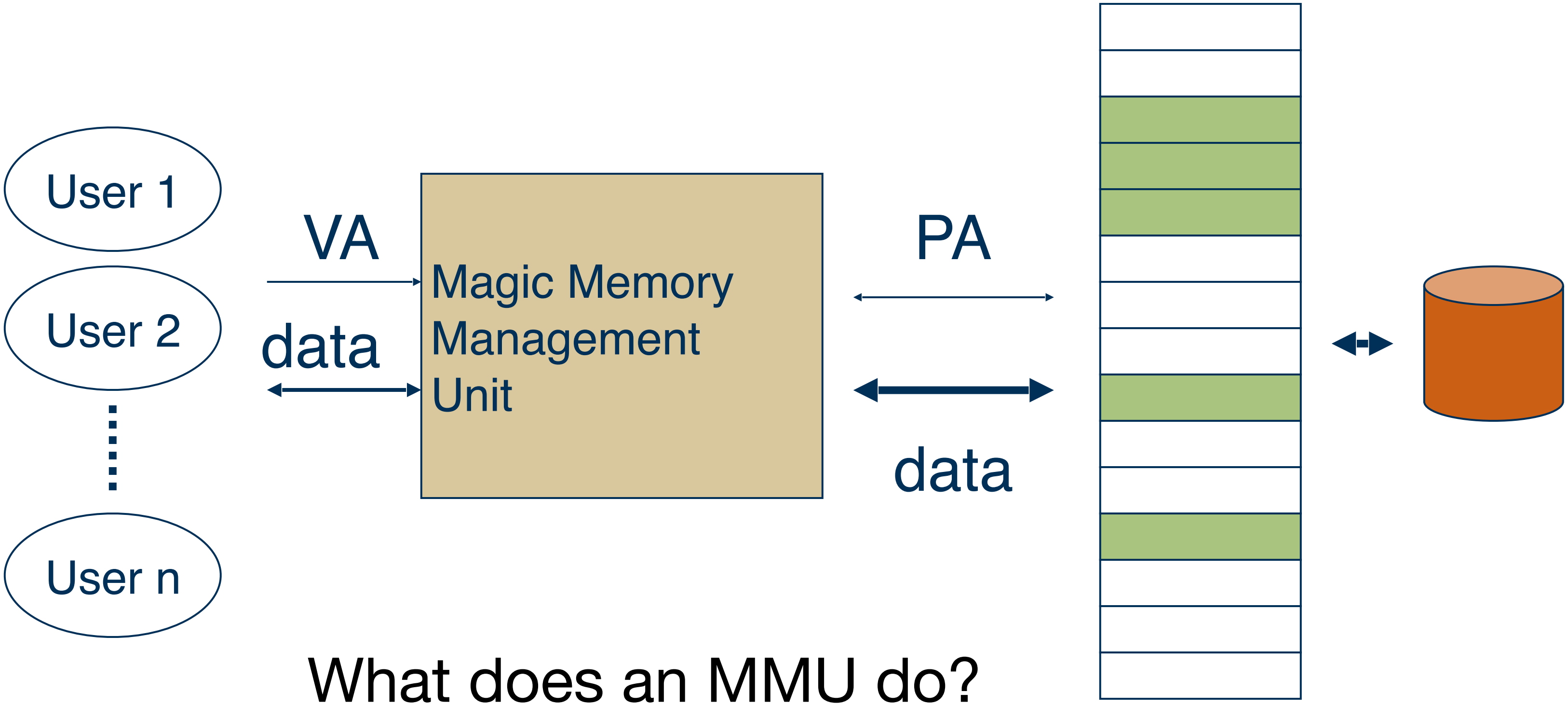
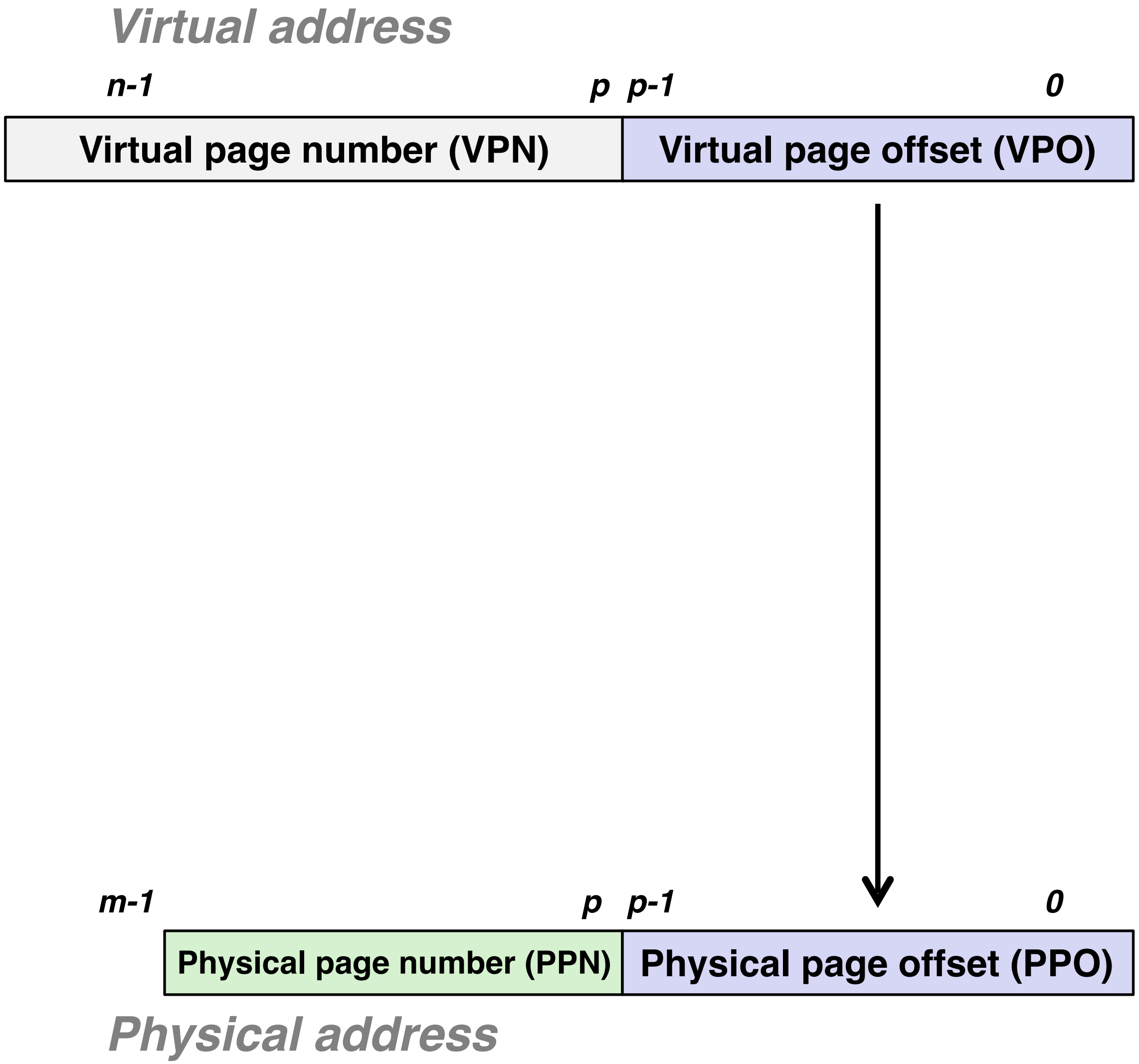
So Far…



What does an MMU do?

- Translate address
  - Enforce permissions
  - Fetch from disk

Address Translation With a Page Table



Virtual address

n-1 *p* *p-1* *0*

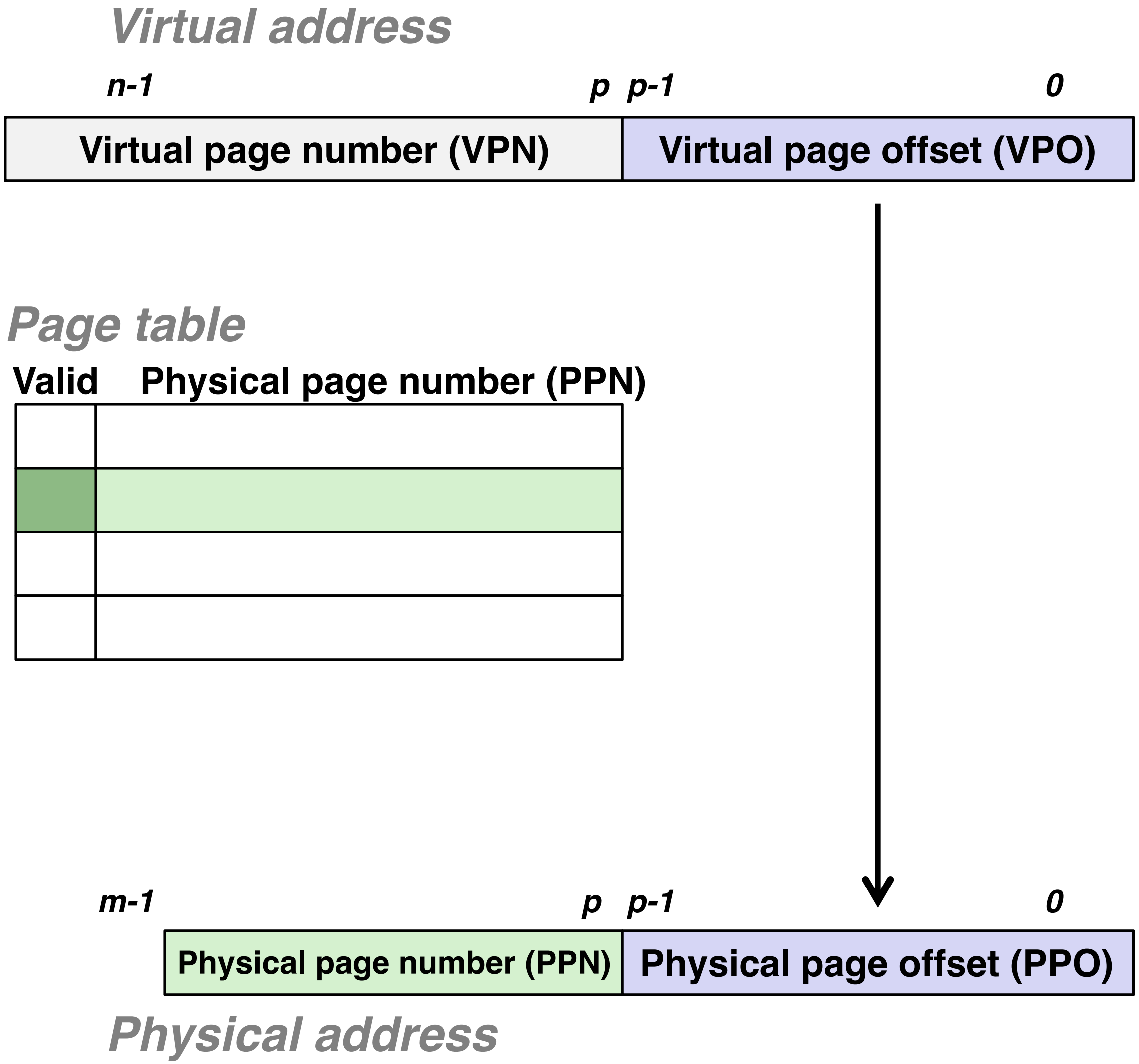
Virtual page number (VPN) | **Virtual page offset (VPO)**

m-1 *p* *p-1* *0*

Physical page number (PPN) | **Physical page offset (PPO)**

Physical address

Address Translation With a Page Table



Virtual address

n-1 *p* *p-1* *0*

Virtual page number (VPN) **Virtual page offset (VPO)**

Page table

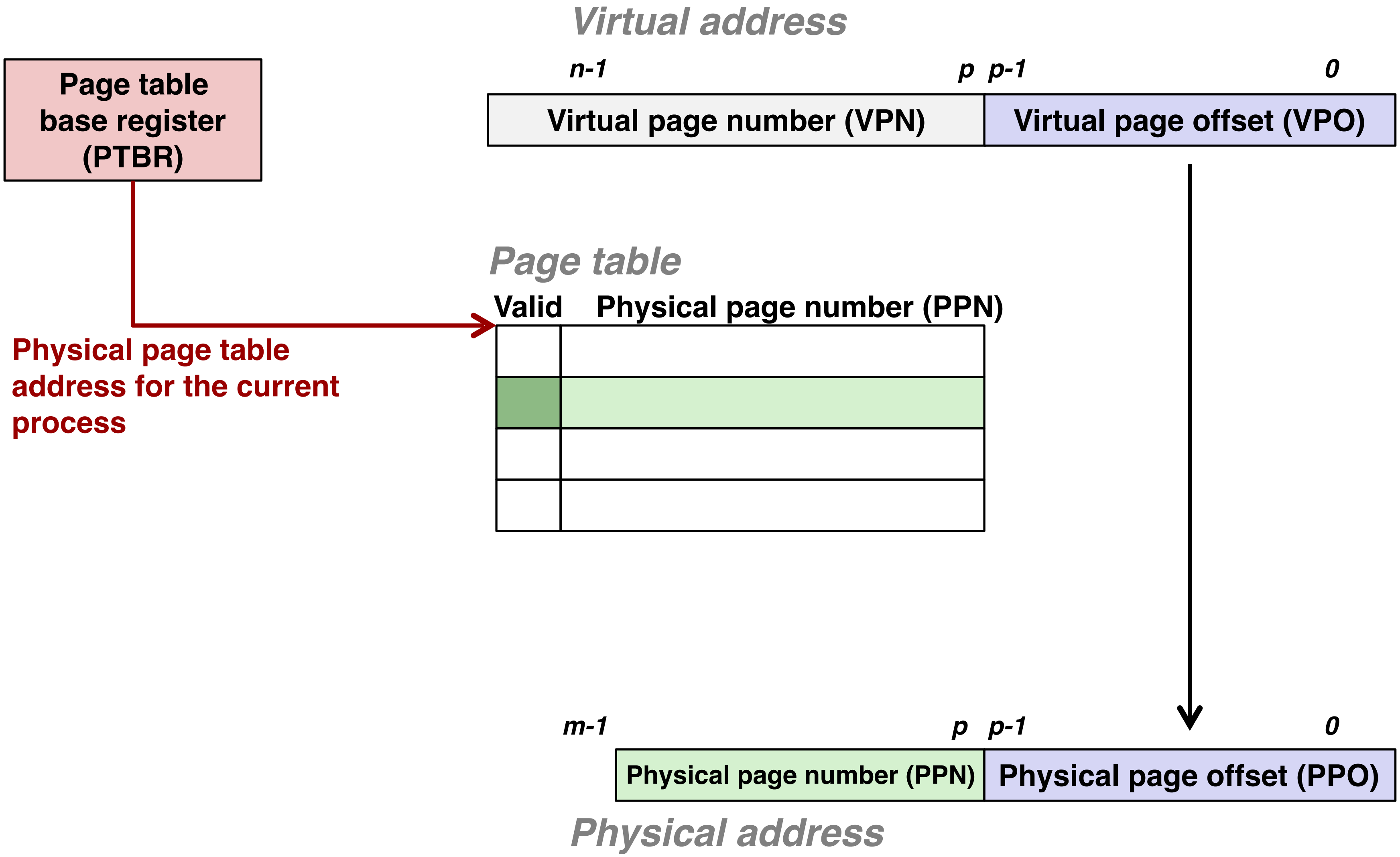
Valid **Physical page number (PPN)**

m-1 *p* *p-1* *0*

Physical page number (PPN) **Physical page offset (PPO)**

Physical address

Address Translation With a Page Table



Virtual address

n-1 *p* *p-1* *0*

Virtual page number (VPN) | Virtual page offset (VPO)

Page table base register (PTBR)

Physical page table address for the current process

Page table

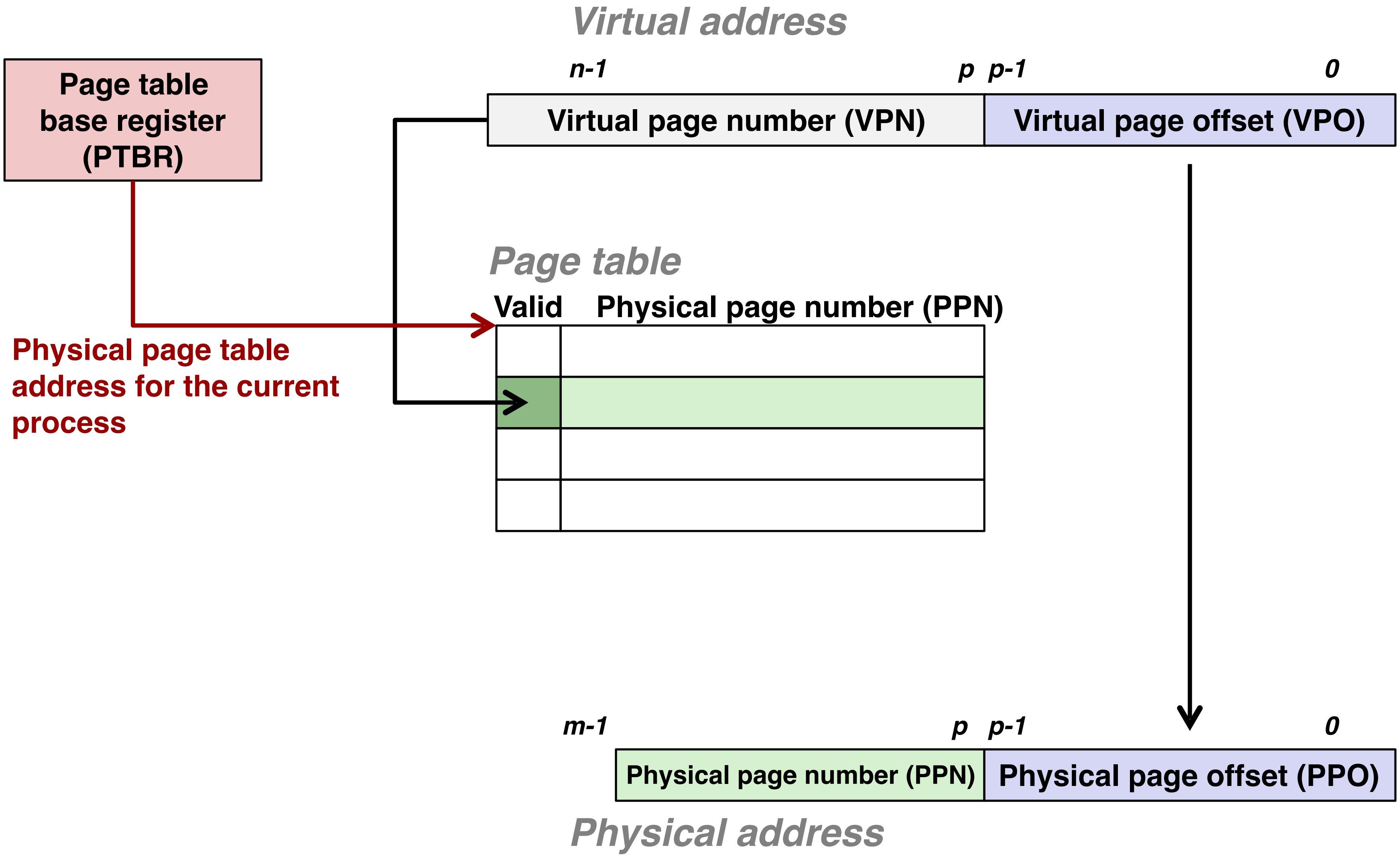
Valid Physical page number (PPN)

m-1 *p* *p-1* *0*

Physical page number (PPN) | Physical page offset (PPO)

Physical address

Address Translation With a Page Table



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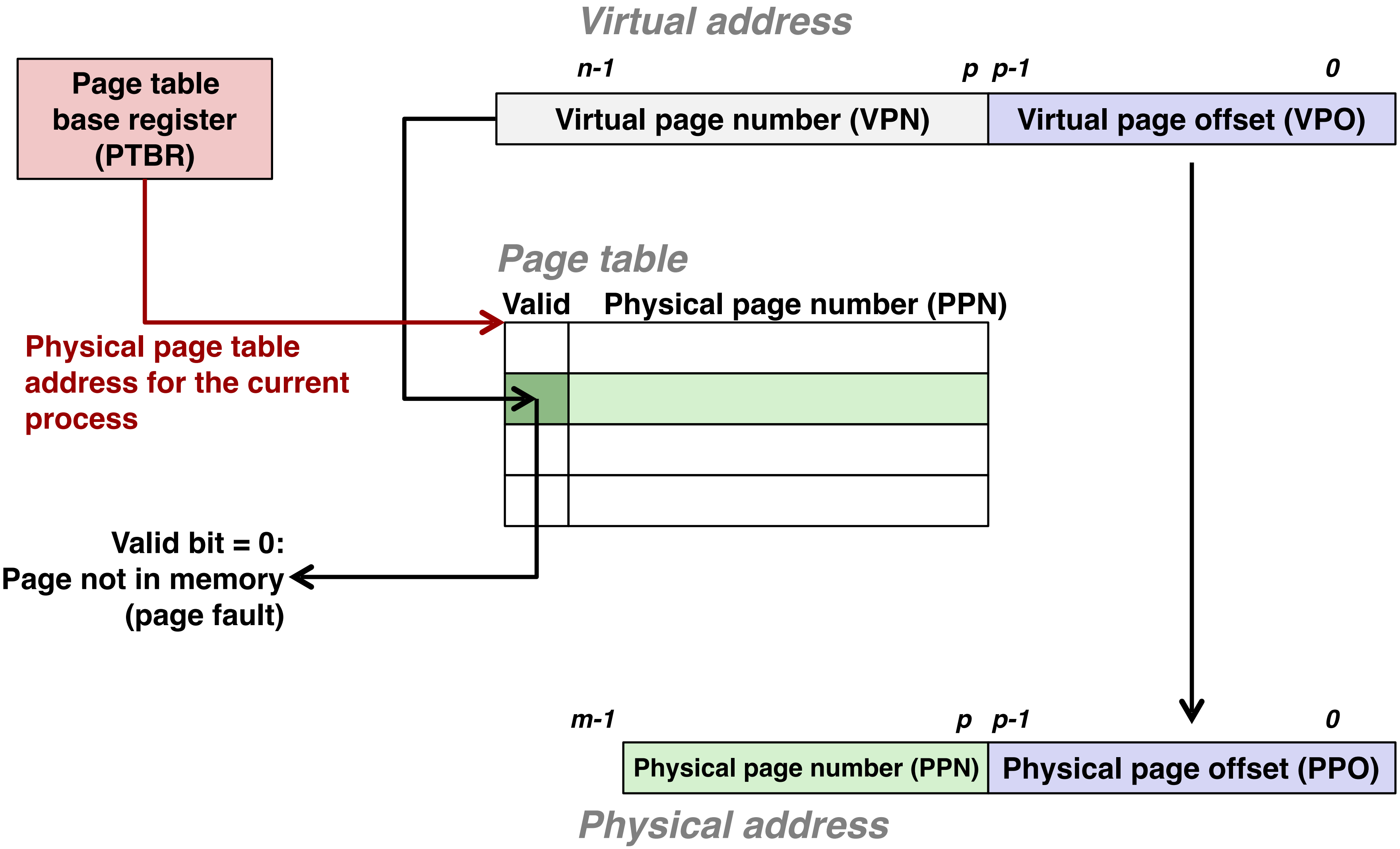

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Virtual page number (VPN)

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Page table base register (PTBR)

Page table

Valid

Physical page number (PPN)

Physical page table address for the current process

Valid bit = 0:
Page not in memory
(page fault)

m-1 *p* *p-1* *0*

Physical page number (PPN)

Physical page offset (PPO)

Physical address

Address Translation With a Page Table