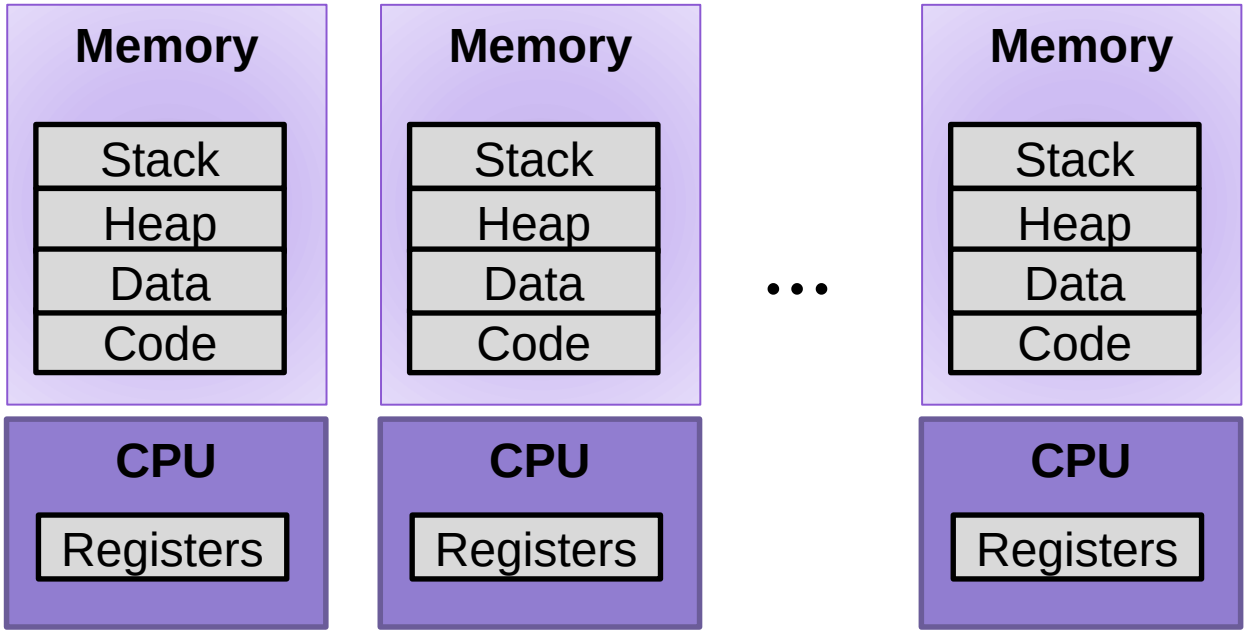
Lecture 16: Virtual Memory

CS 105

Spring 2025

Multiprocessing: The Illusion



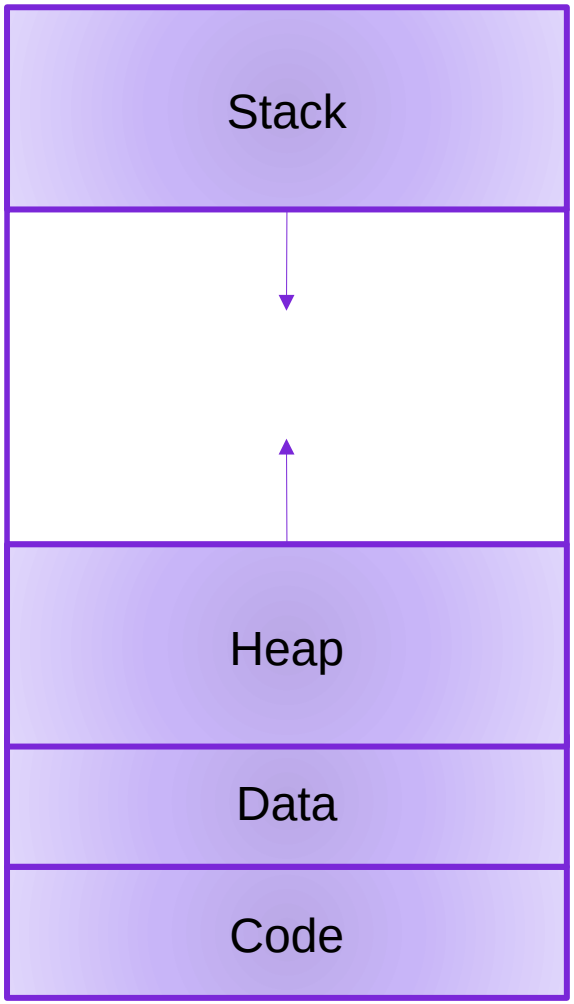
- Process provides each program with two key abstractions:
  - ***Logical control flow***
    - Each program seems to have exclusive use of the CPU
    - Provided by kernel mechanism called ***context switching***
  - ***Private address space***
    - Each program seems to have exclusive use of main memory.
    - Provided by kernel mechanism called ***virtual memory***

Multiprocessing: The Reality

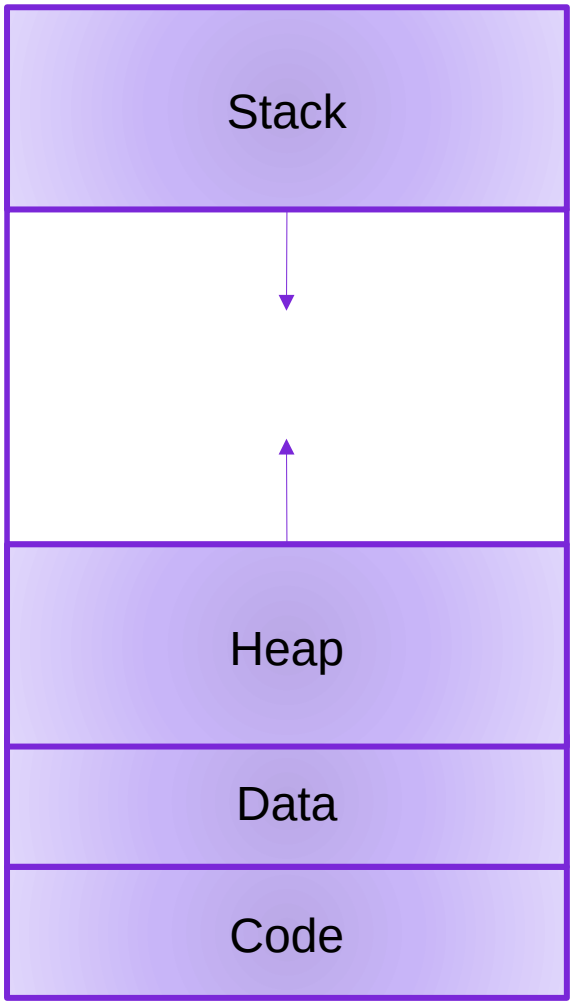
- Computer runs many processes simultaneously
- Running program “top” on Linux/Mac
  - E.g., system has 558 processes, 2 of which are active
  - Identified by Process ID (PID)

```
top - 11:35:22 up  3:38,  1 user,  load average: 1.11, 0.68, 1.10
Tasks: 560 total,   2 running, 558 sleeping,   0 stopped,   0 zombie
%Cpu(s):  0.4 us,  1.5 sy,  0.8 ni, 97.3 id,  0.0 wa,  0.0 hi,  0.0 si,  0.0 st
```

Virtual Memory Goals

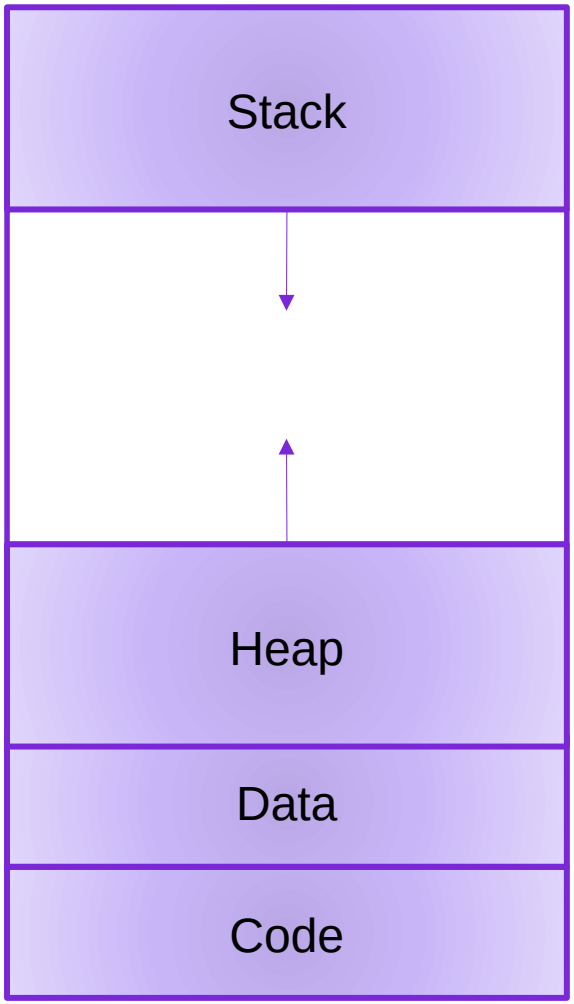


Virtual Memory Goals



- **Isolation:** don’t want different process states collided in physical memory

Virtual Memory Goals



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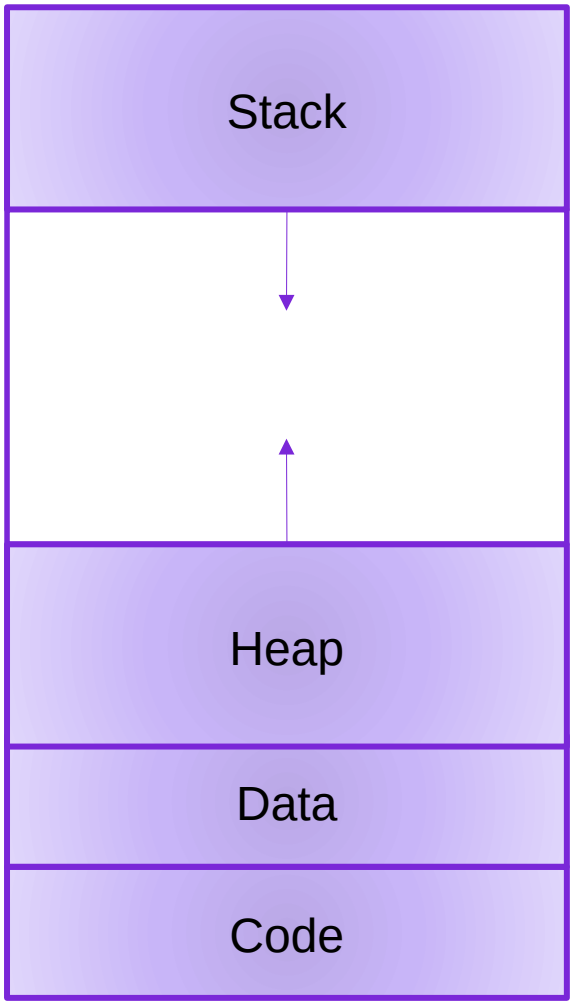
- **Efficiency:** want fast reads/writes to memory

Virtual Memory Goals



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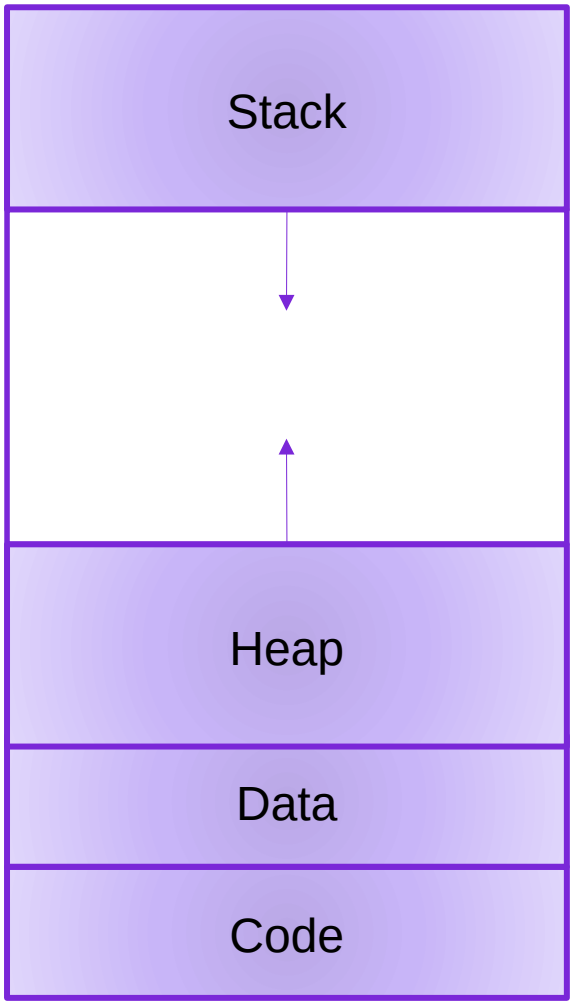
- **Sharing:** want option to overlap for communication

Virtual Memory Goals



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- **Sharing:** want option to overlap for communication
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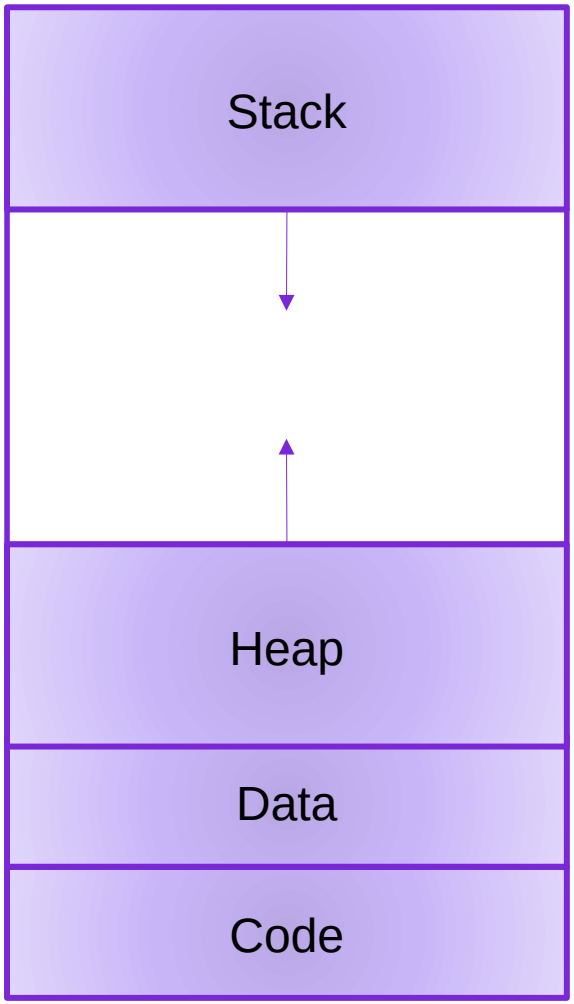
Virtual Memory Goals



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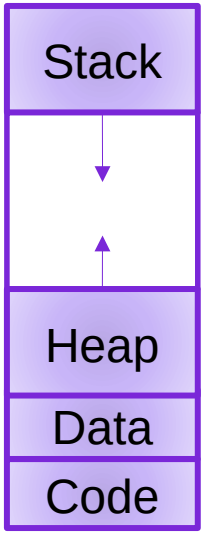
Address Translation



Address Translation

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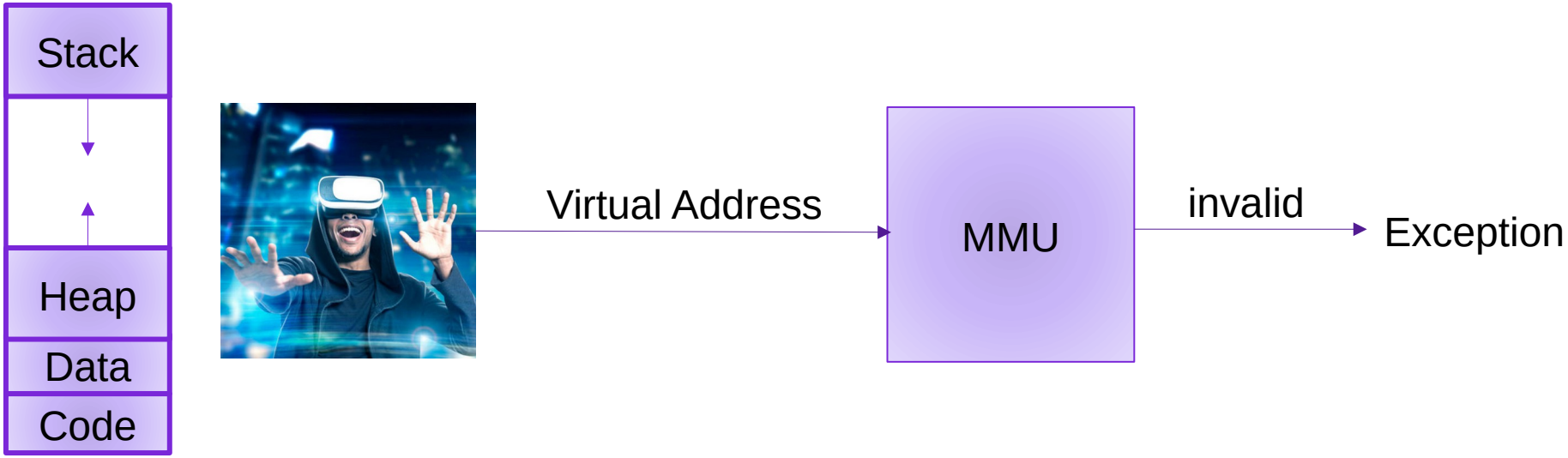

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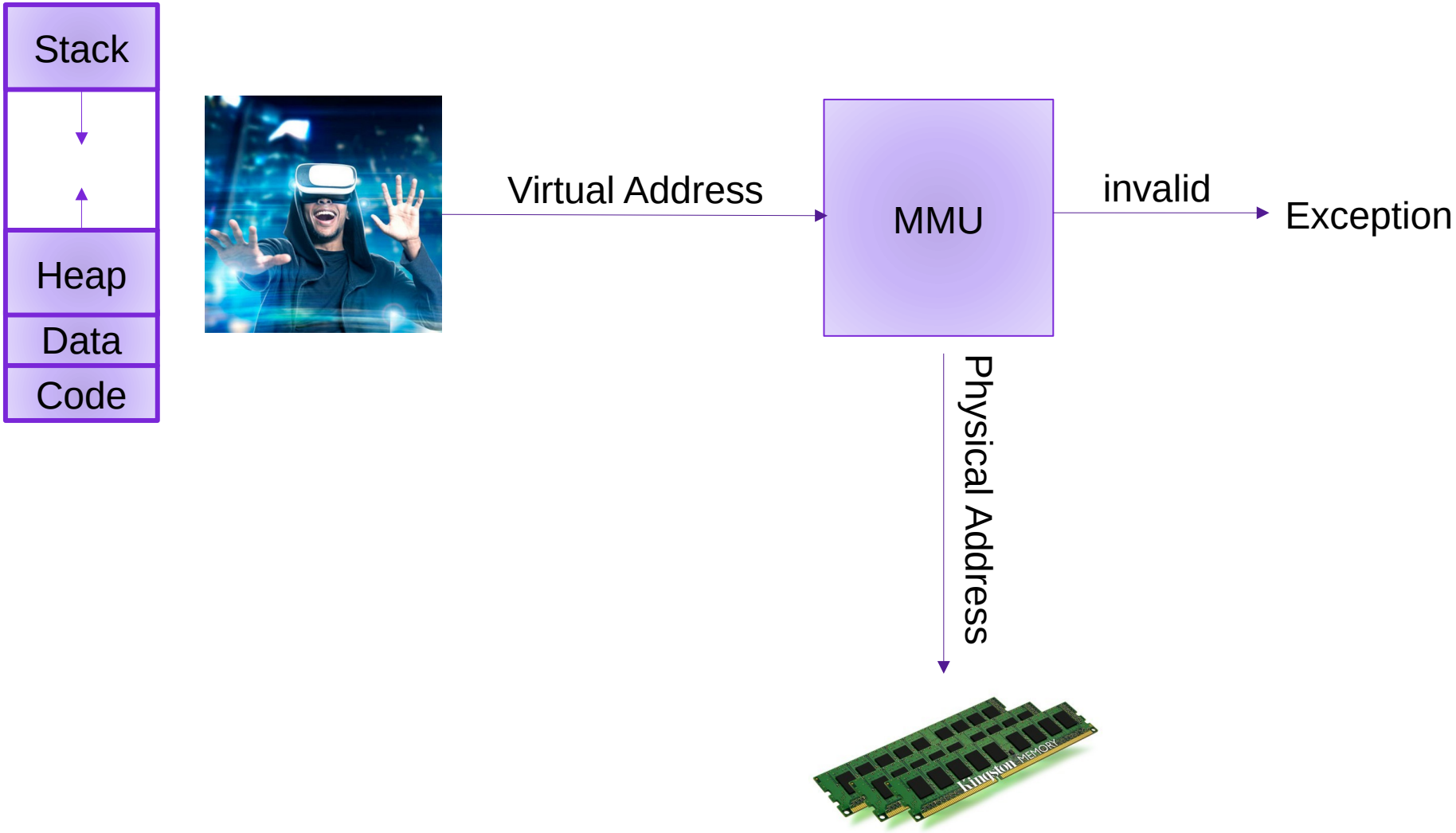

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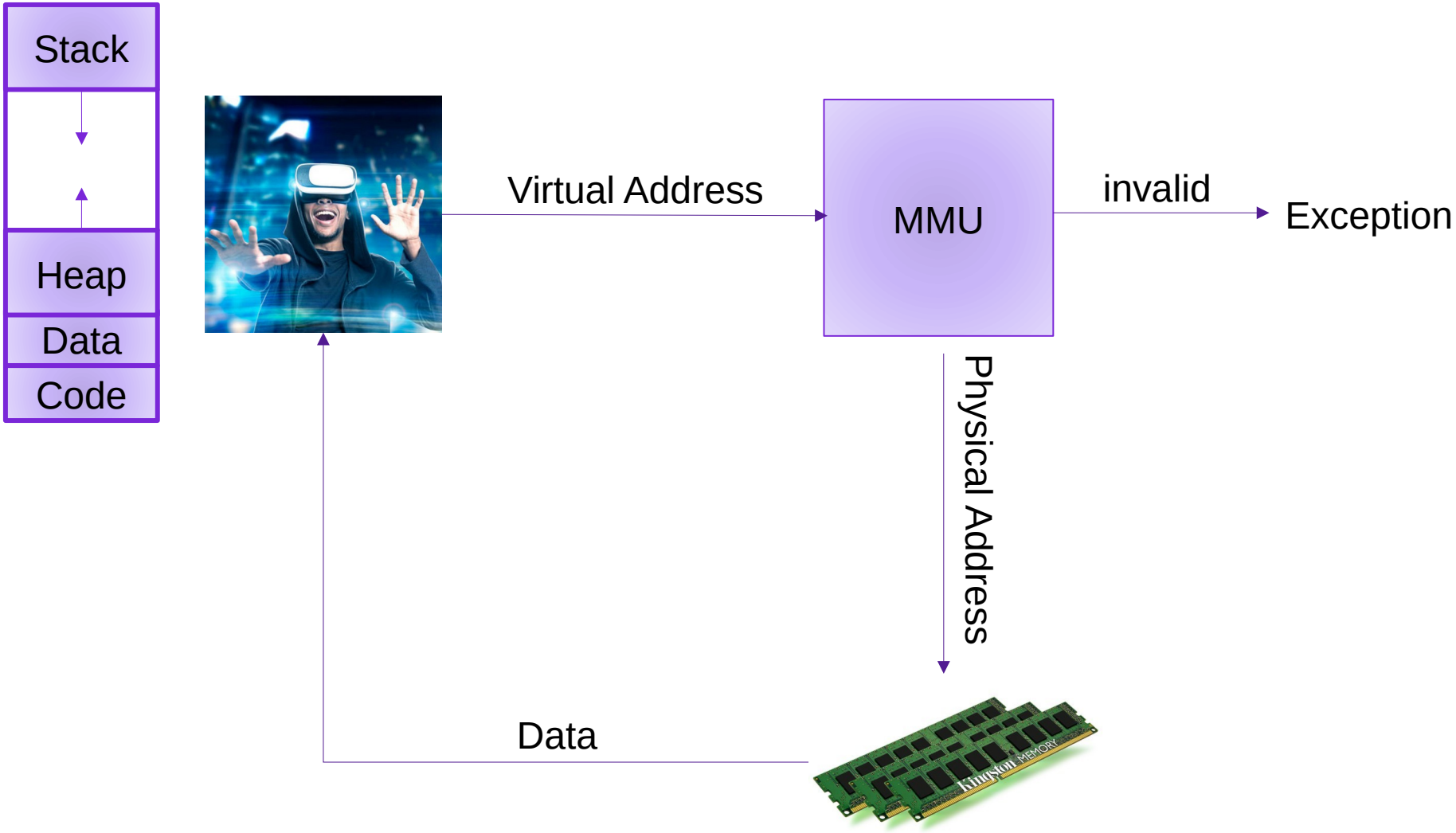
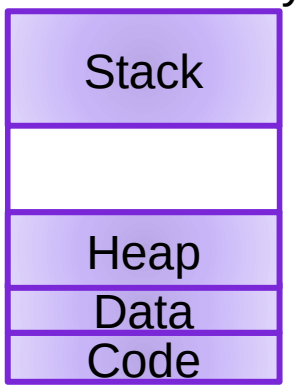
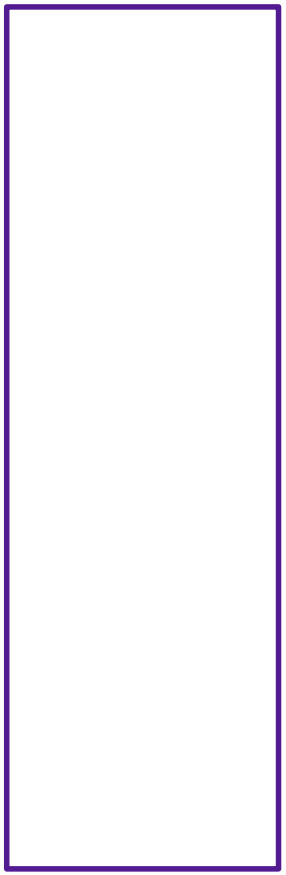


Base-and-Bound

Virtual Memory



Physical Memory



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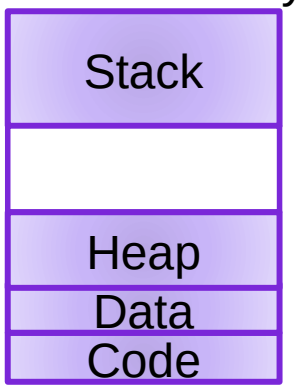

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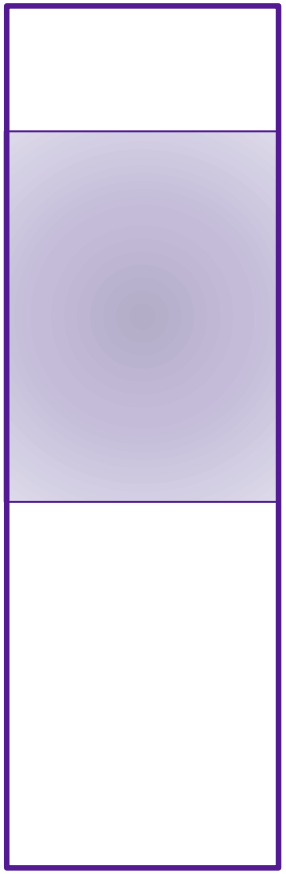
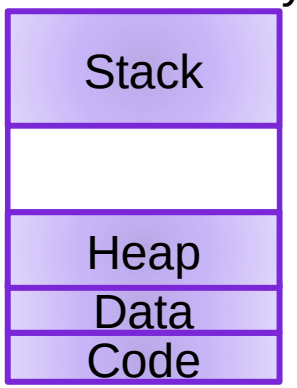


Base-and-Bound

Virtual Memory



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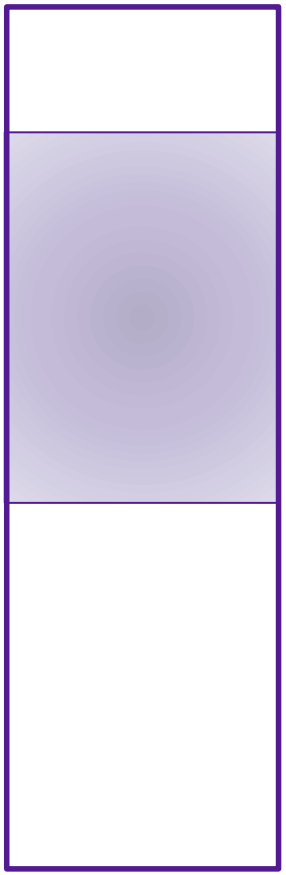
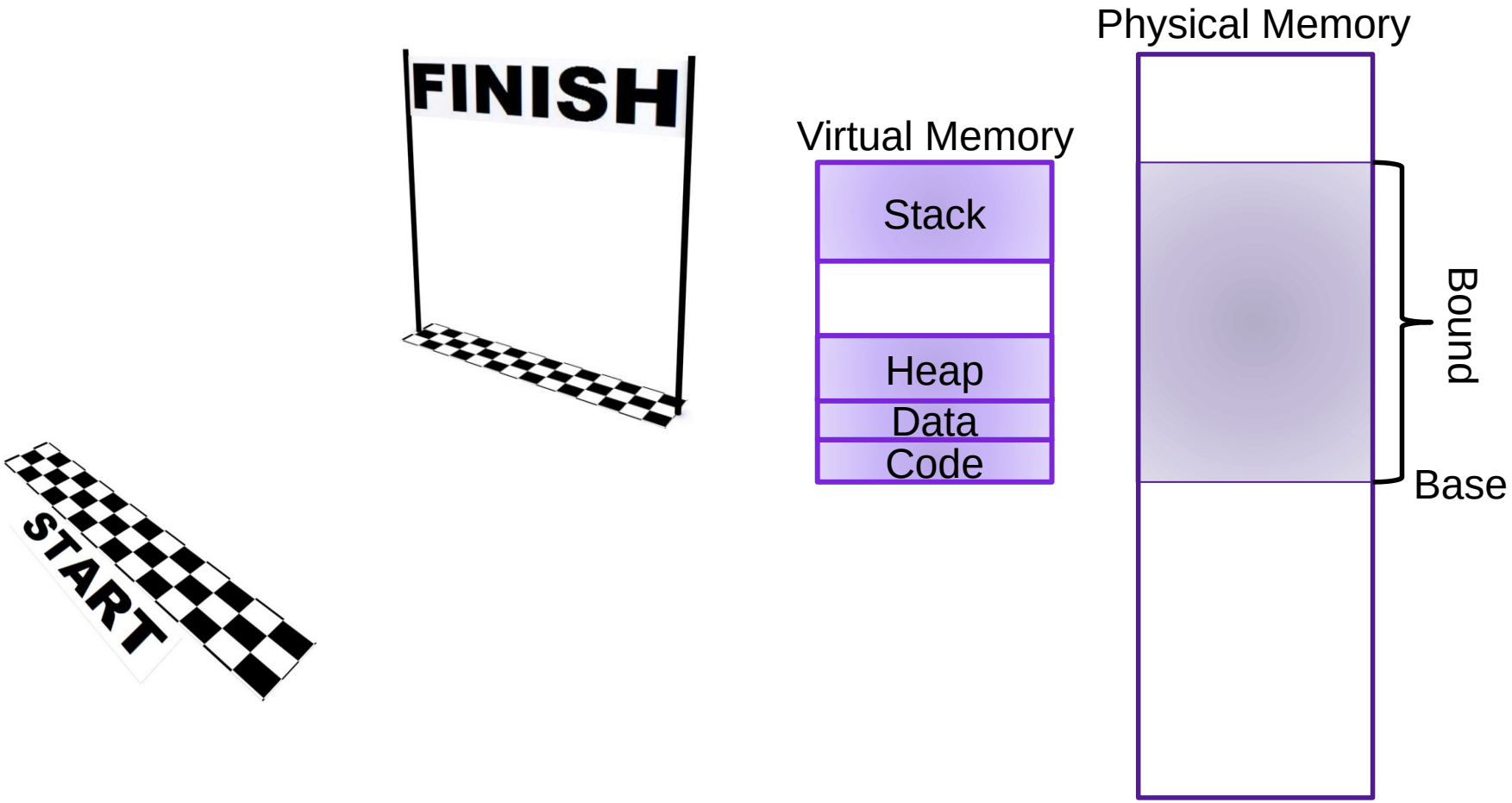
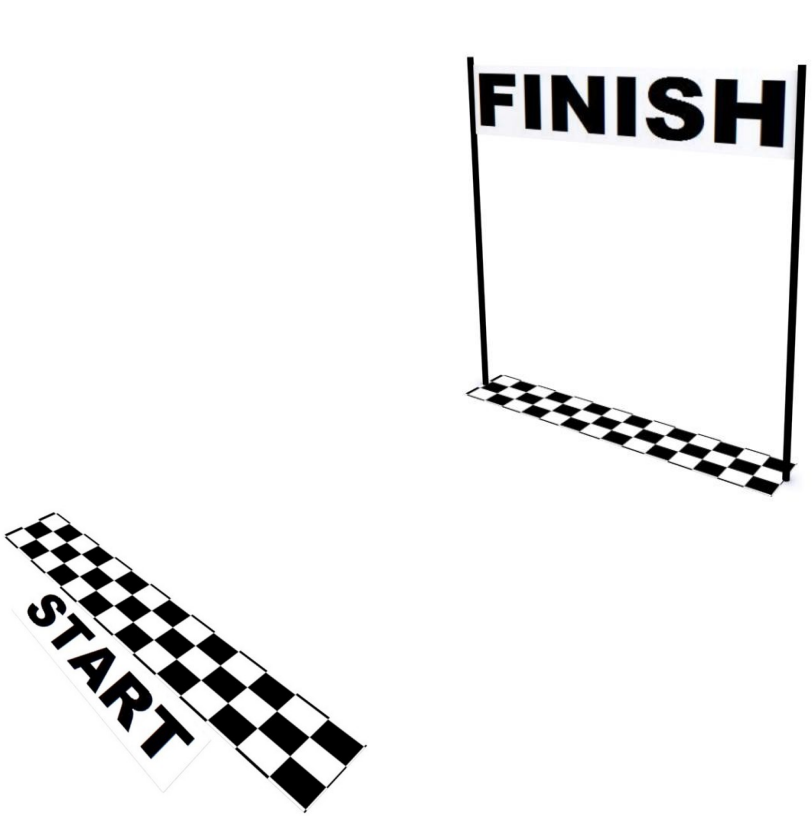


Base

Base-and-Bound



Base-and-Bound



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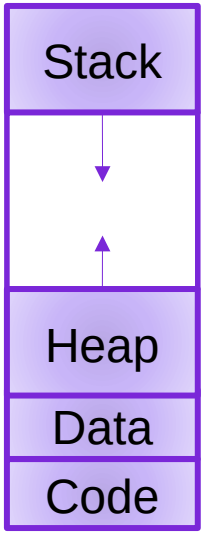

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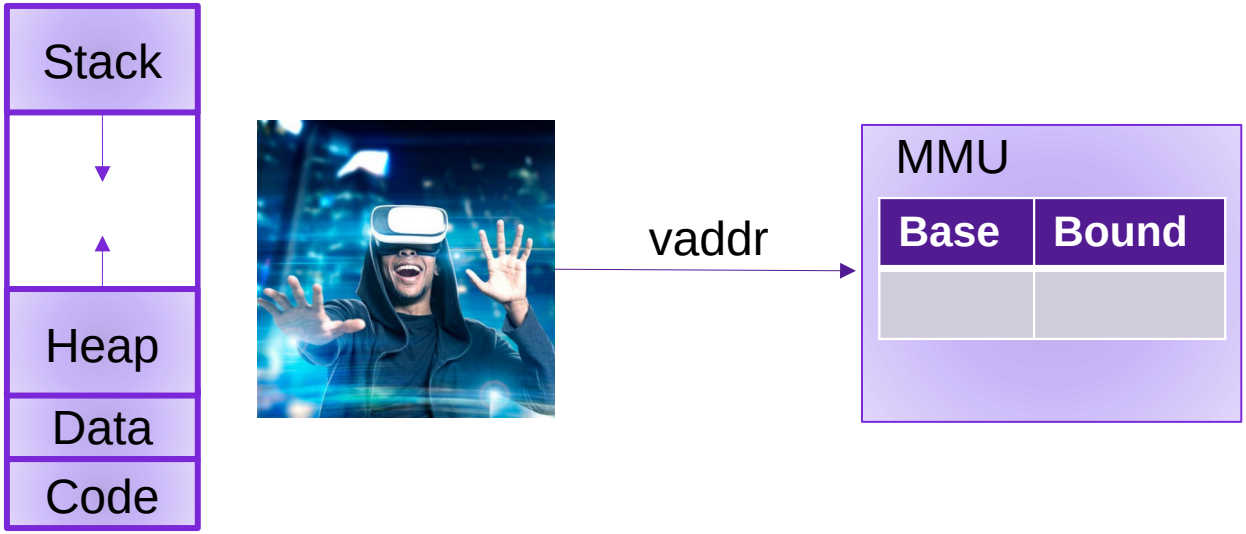

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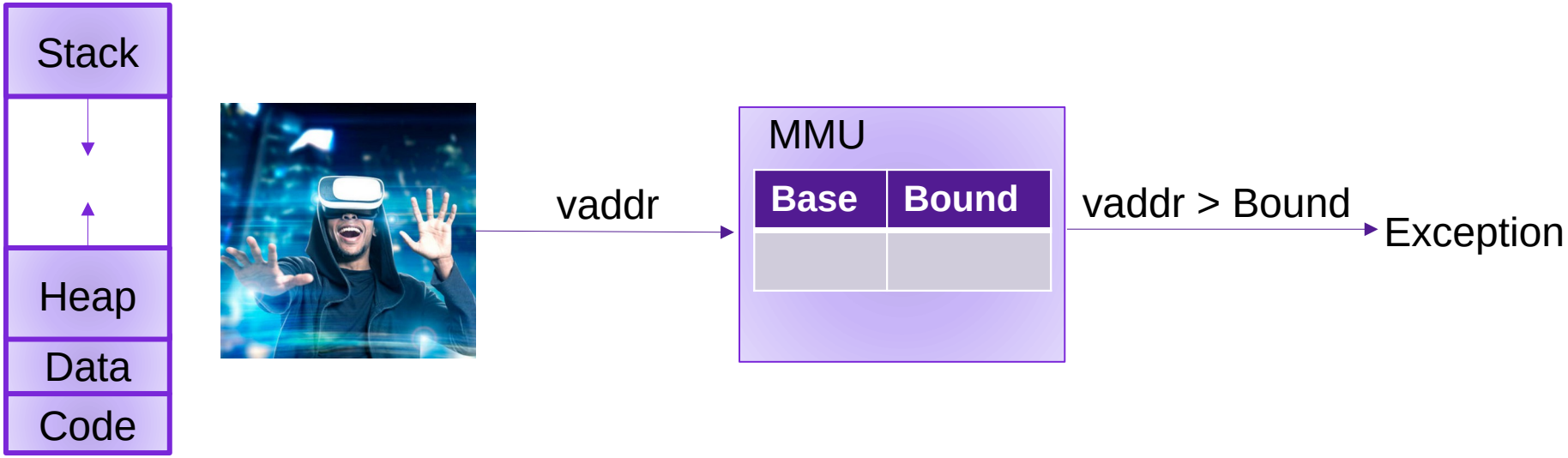

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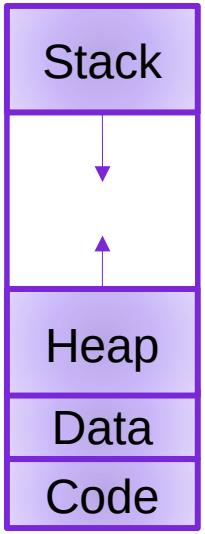
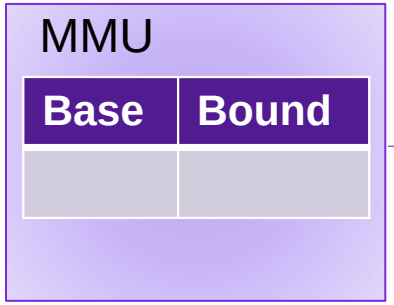


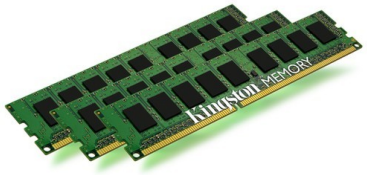
vaddr



vaddr > Bound

Exception

paddr = vaddr + Base



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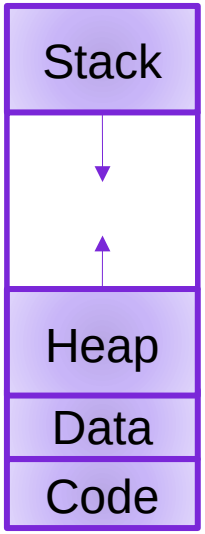

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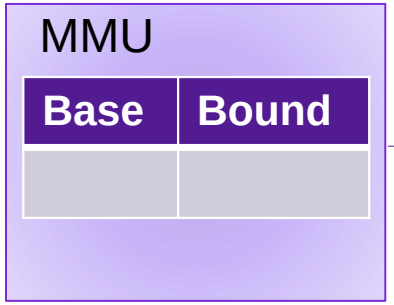

vaddr > Bound

Exception

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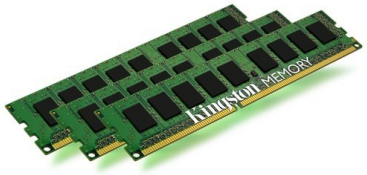
Data



Exercise 1: Base-and-Bound

Assume that you are currently executing a process P with Base 0x1234 and Bound 0x100.

- What is the physical address that corresponds to the virtual address 0x47?
- What is the physical address that corresponds to the virtual address 0x123?

Exercise 1: Base-and-Bound

Assume that you are currently executing a process P with Base 0x1234 and Bound 0x100.

- What is the physical address that corresponds to the virtual address 0x47? **0x127b**
- What is the physical address that corresponds to the virtual address 0x123?

Exercise 1: Base-and-Bound

Assume that you are currently executing a process P with Base 0x1234 and Bound 0x100.

- What is the physical address that corresponds to the virtual address 0x47? **0x127b**
- What is the physical address that corresponds to the virtual address 0x123? **invalid**

Evaluating Base-and-Bound

- **Isolation:** don't want different process states collided in physical memory
- **Efficiency:** want fast reads/writes to memory
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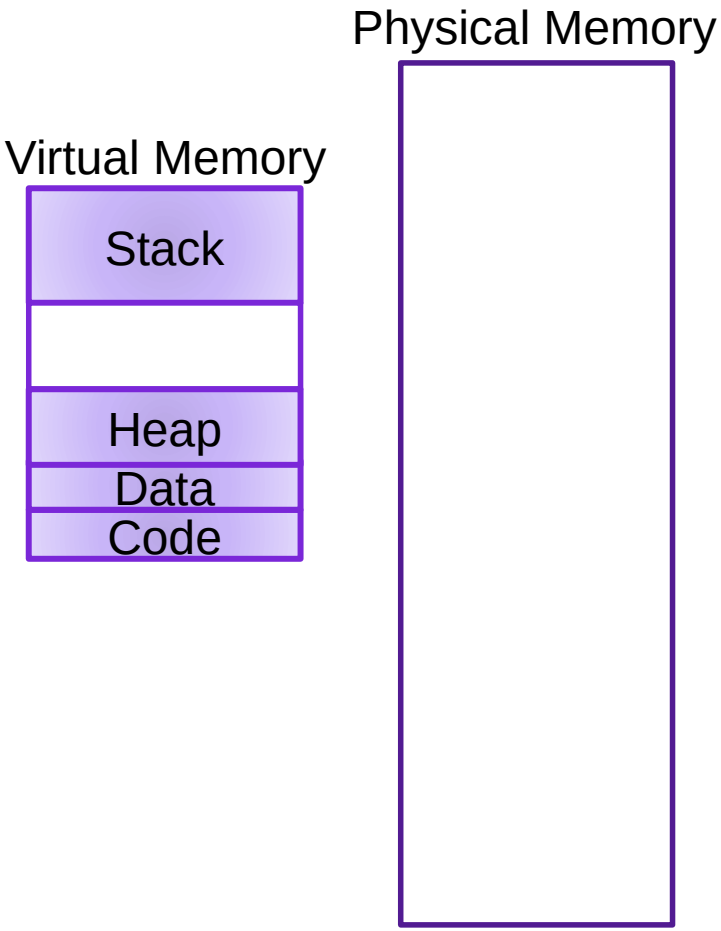
Segmentation



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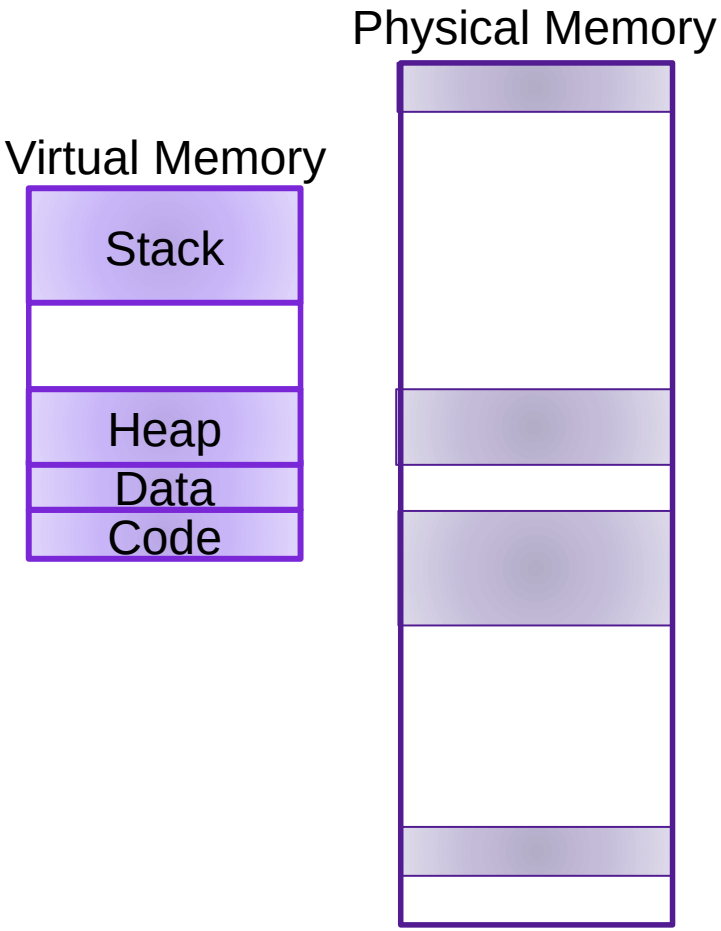

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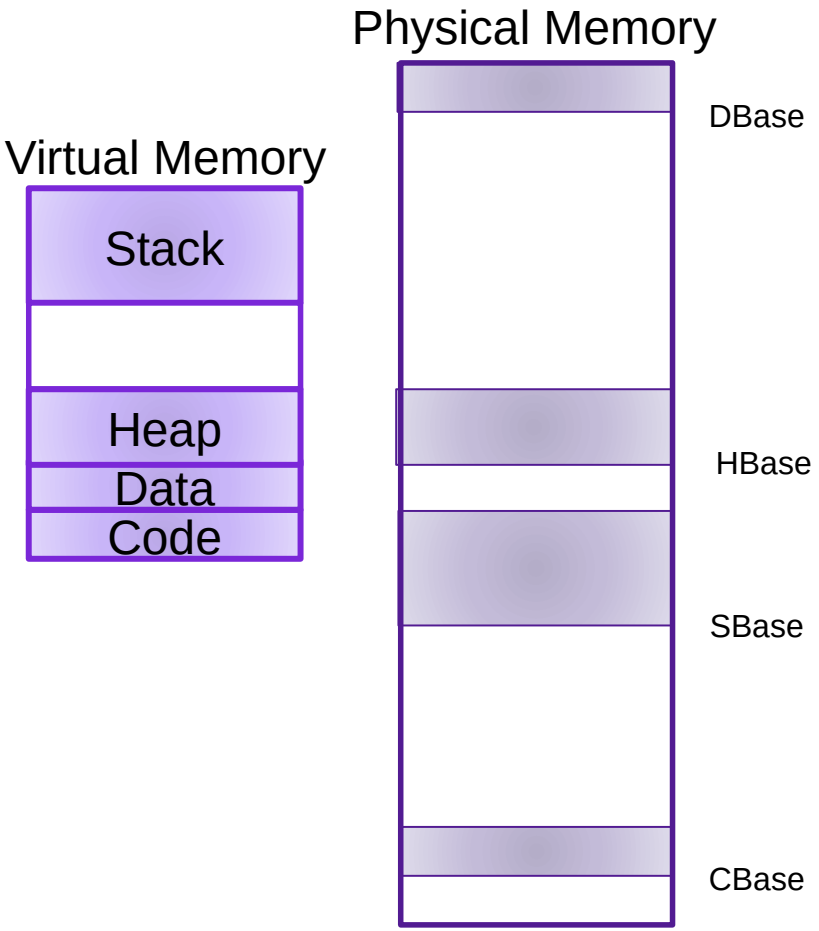

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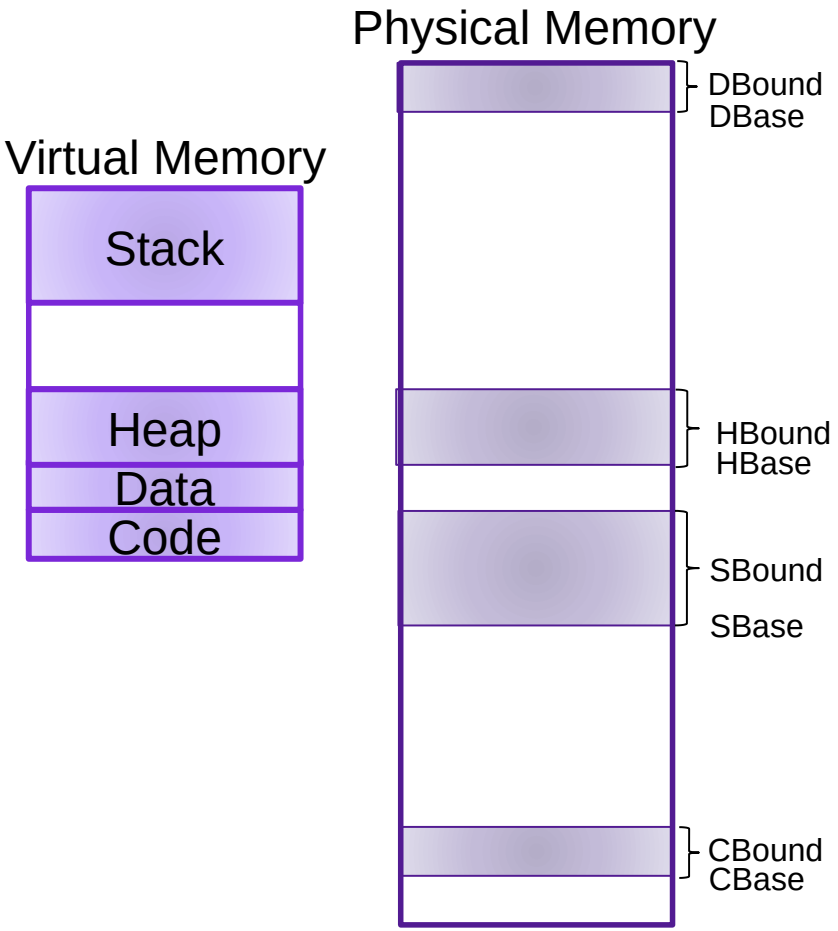

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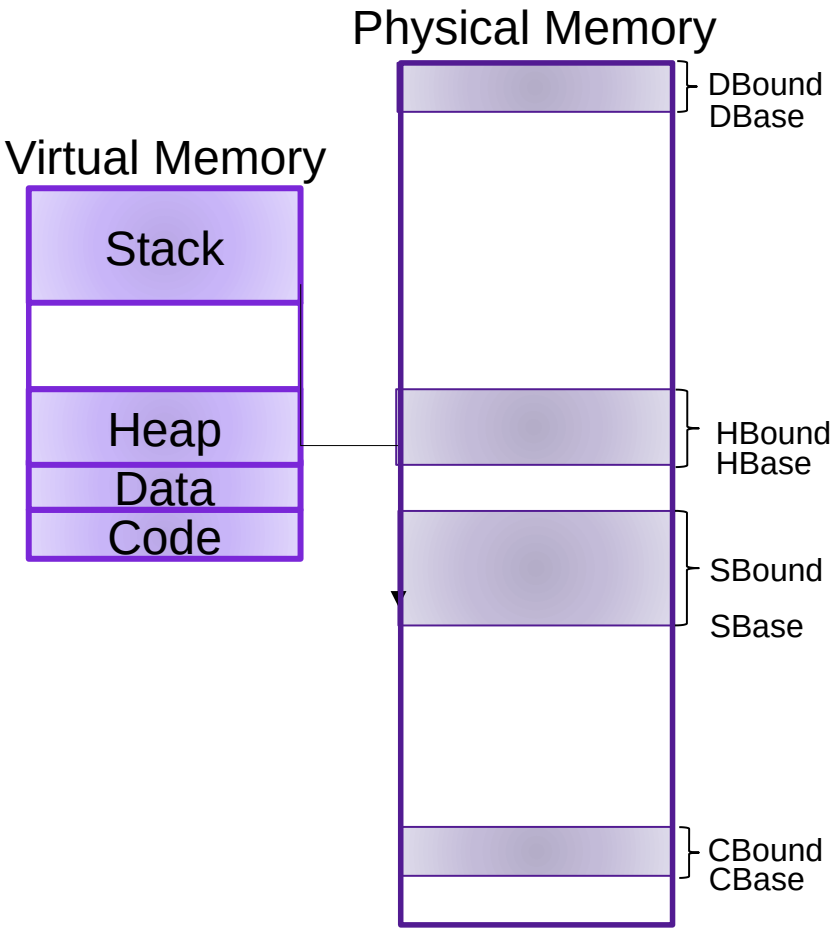

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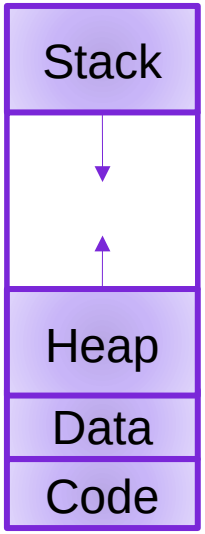

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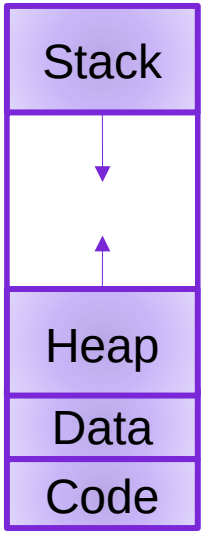
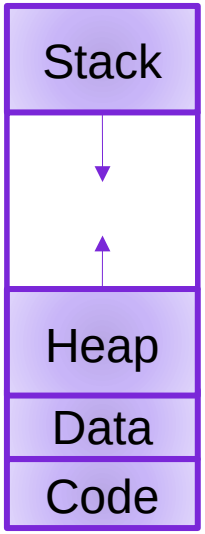


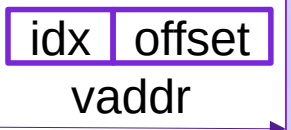
vaddr

MMU

Base	Bound	Access
		R,W
		R,W
		R,W
		R,X

Segmentation





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Base	Bound	Access
		R,W
		R,W
		R,W
		R,X

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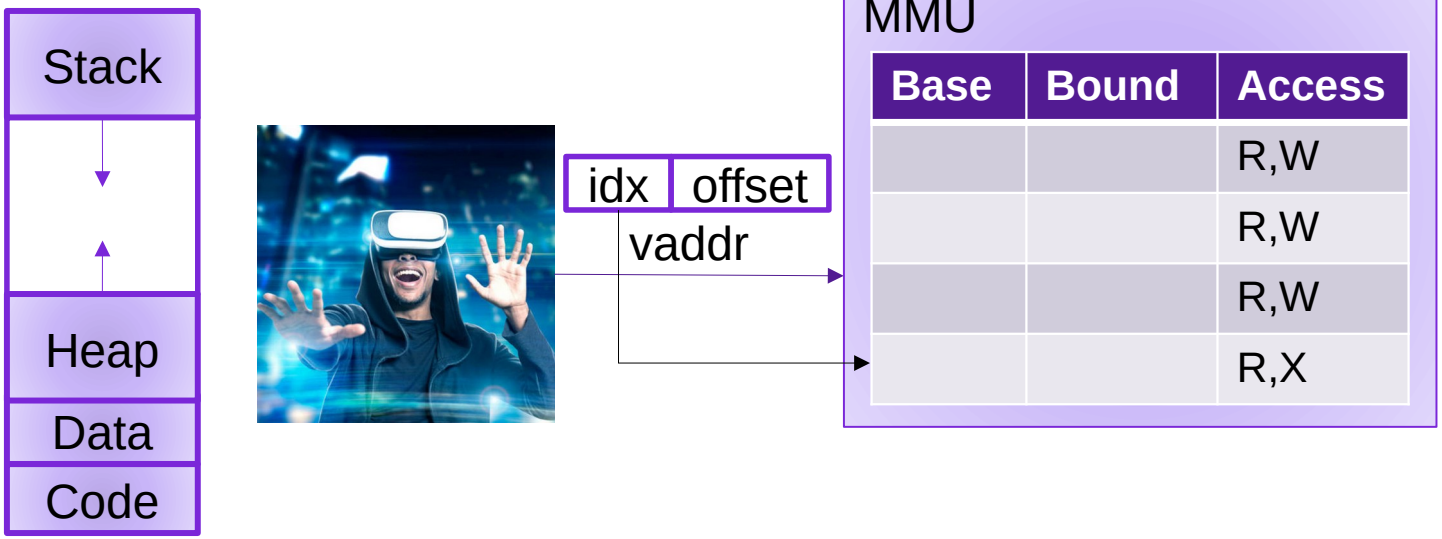

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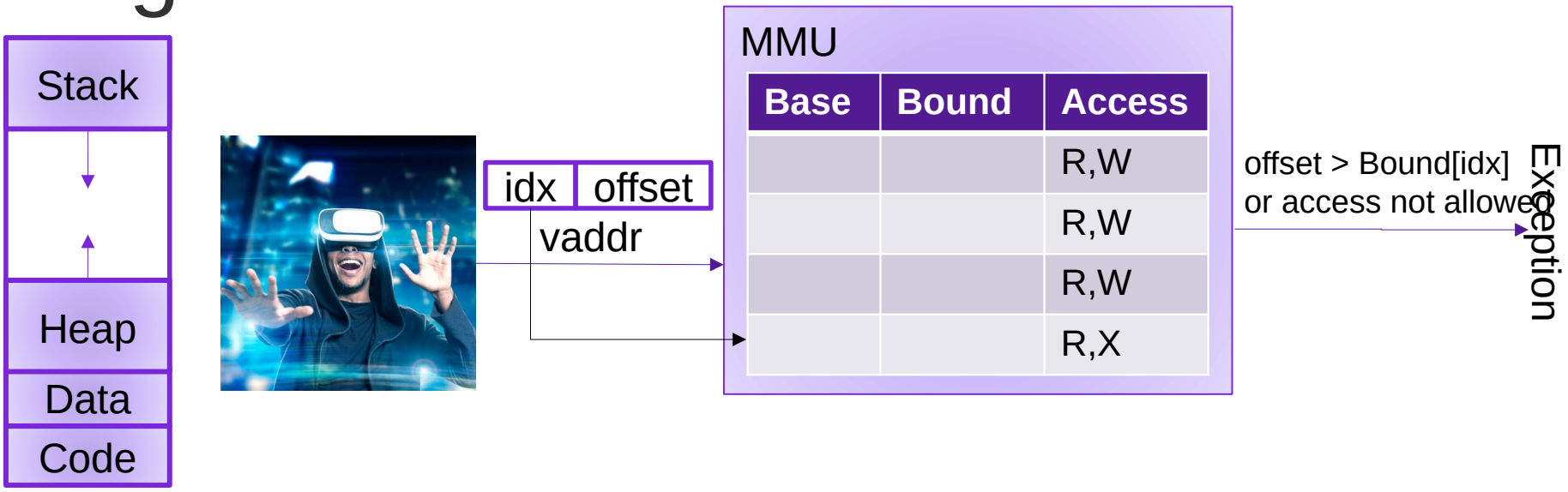

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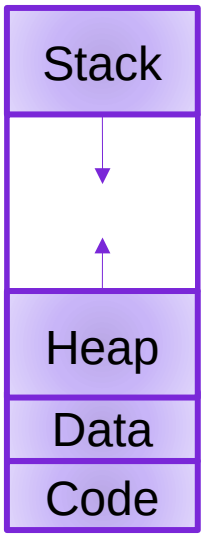


idx | offset

vaddr

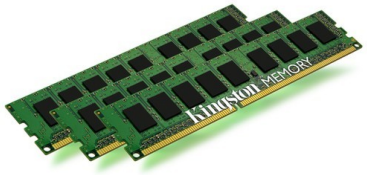
MMU

Base	Bound	Access
		R,W
		R,W
		R,W
		R,X

offset > Bound[idx]
or access not allowed

Exception

paddr = Base[idx] + offset



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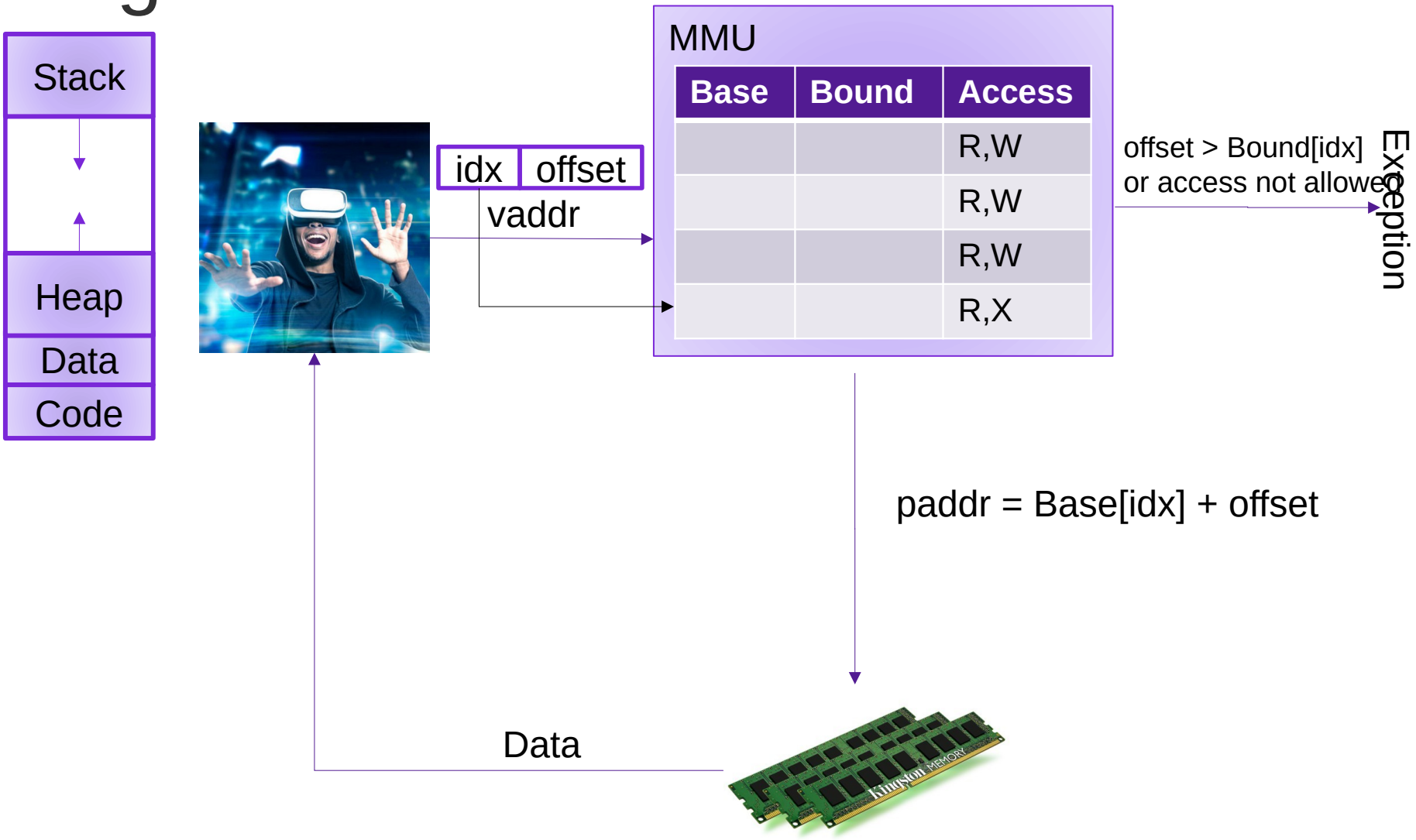

Exercise 2: Segmentation

Assume that you are currently executing a process P with the following segment table:

Base	Bound	Access
0x4747	0x80	R,W
0x2424	0x40	R,W
0x0023	0x80	R,W
0x1000	0x200	R,X

- What is the physical address that corresponds to the virtual address 0x001?
- What is the physical address that corresponds to the virtual address 0xD47?

Exercise 2: Segmentation

Assume that you are currently executing a process P with the following segment table:

Base	Bound	Access
0x4747	0x80	R,W
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0x0023	0x80	R,W
0x1000	0x200	R,X

- What is the physical address that corresponds to the virtual address 0x001?

- What is the physical address that corresponds to the virtual address 0xD47?

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Base	Bound	Access
0x4747	0x80	R,W
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0x0023	0x80	R,W
0x1000	0x200	R,X

- What is the physical address that corresponds to the virtual address 0x001?

0x4748

- What is the physical address that corresponds to the virtual address 0xD47?

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0x4747	0x80	R,W
0x2424	0x40	R,W
0x0023	0x80	R,W
0x1000	0x200	R,X

- What is the physical address that corresponds to the virtual address 0x001?

00	0000000001

0x4748

- What is the physical address that corresponds to the virtual address 0xD47?

11	0101000111

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Assume that you are currently executing a process P with the following segment table:

Base	Bound	Access
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0x2424	0x40	R,W
0x0023	0x80	R,W
0x1000	0x200	R,X

- What is the physical address that corresponds to the virtual address 0x001?

00	0000000001

0x4748

- What is the physical address that corresponds to the virtual address 0xD47?

11	0101000111

0x1147

Evaluating Segmentation

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- **Utilization:** want best use of limited resource
- **Virtualization:** want to create illusion of more resources

Evaluating Segmentation

- **Isolation:** don't want different process states collided in physical memory
- **Efficiency:** want fast reads/writes to memory
- **Sharing:** want option to overlap for communication
- **Utilization:** want best use of limited resource
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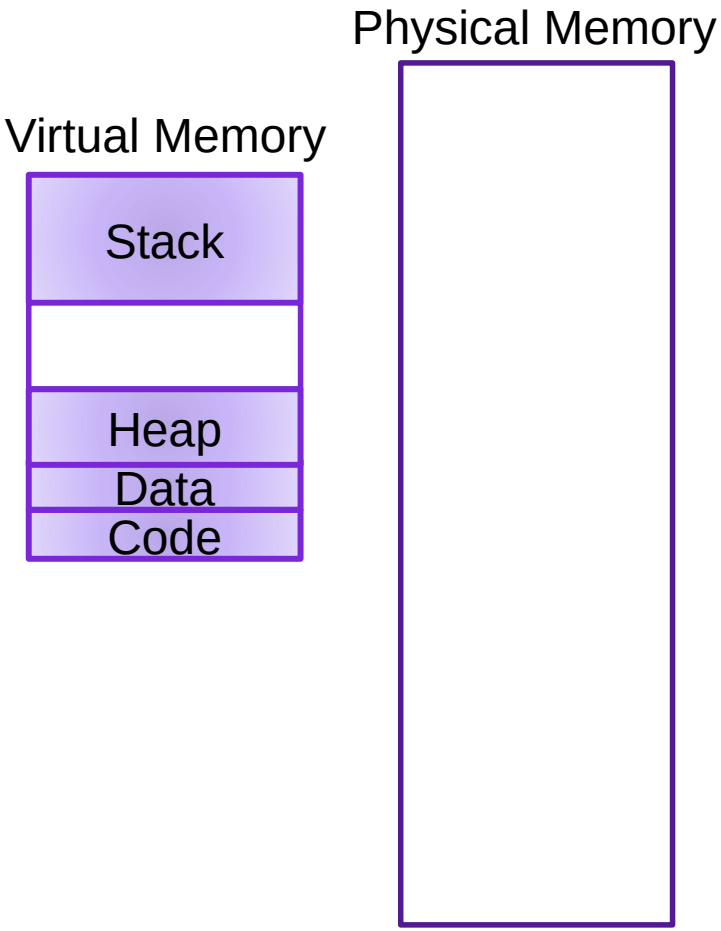
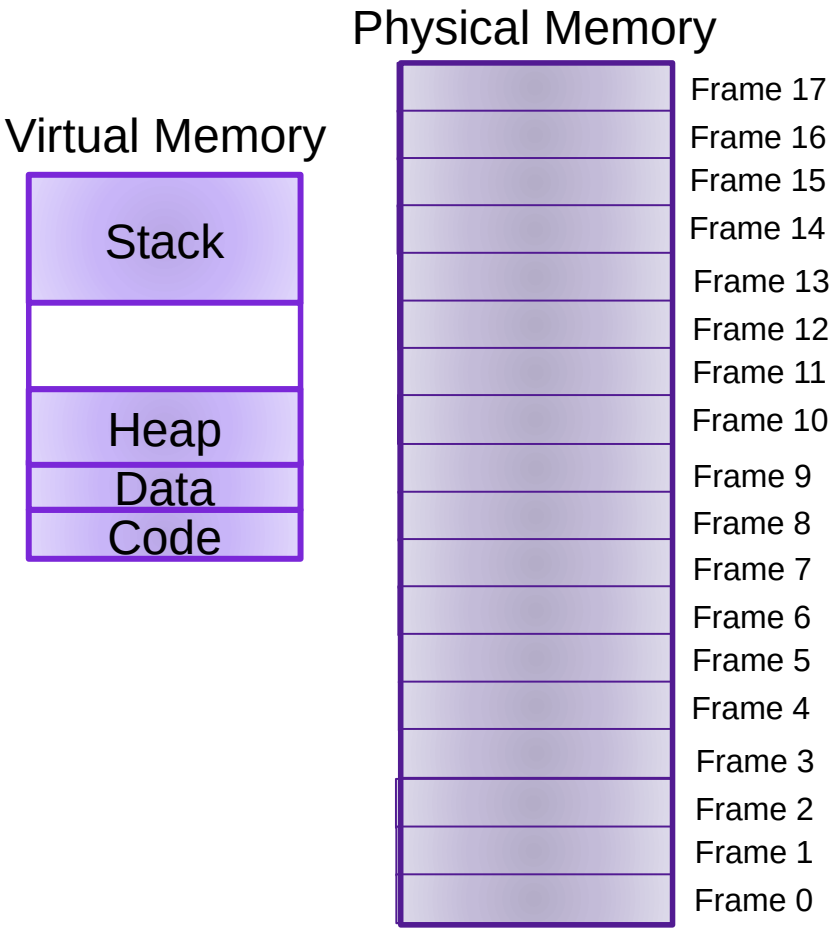
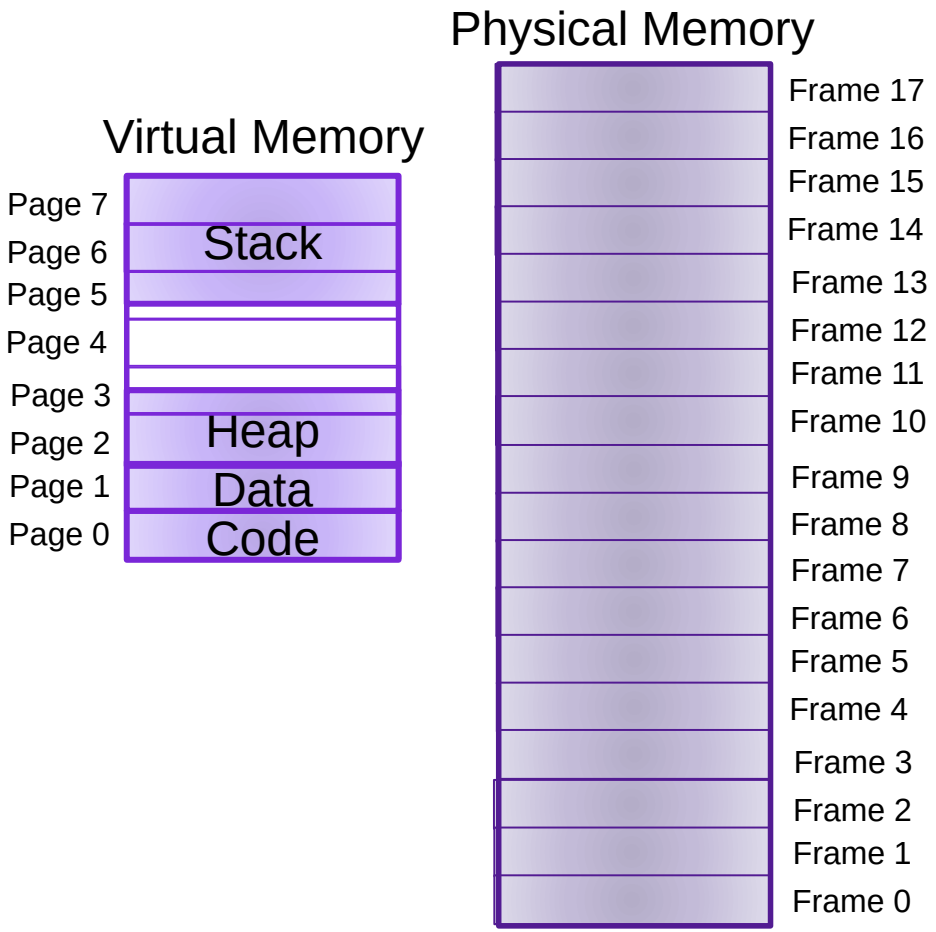
Paging



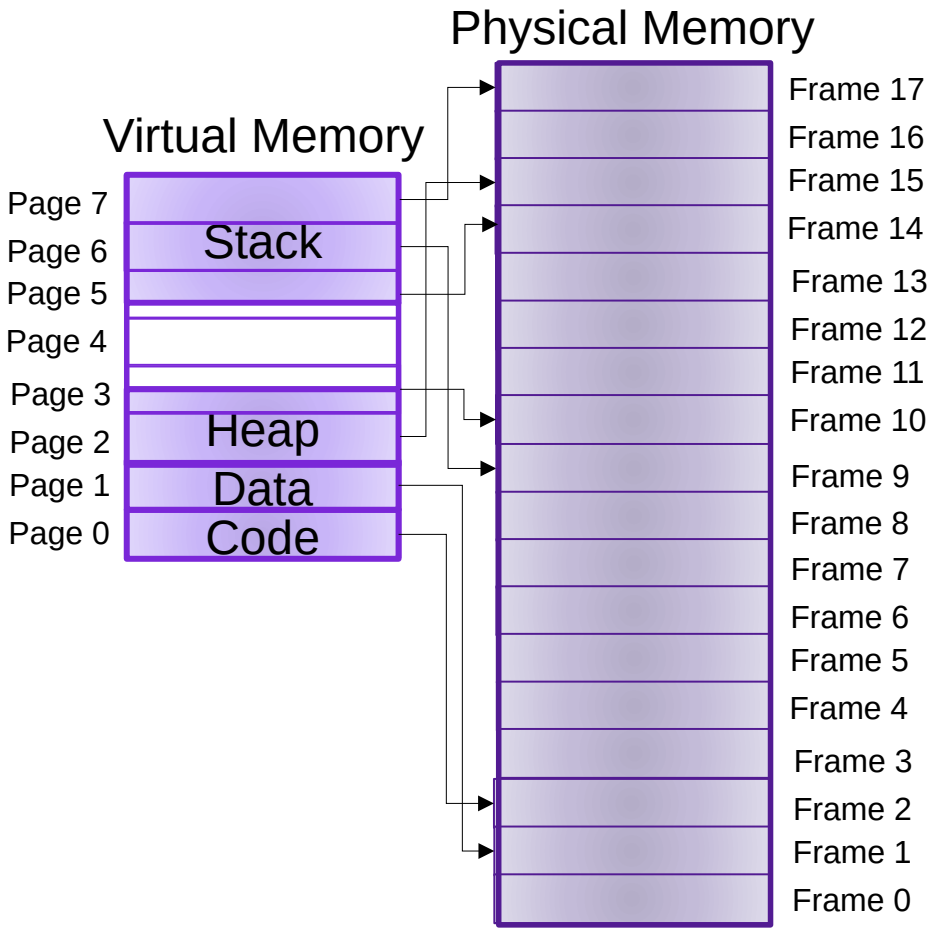
Paging


Physical Memory
Virtual Memory
Stack
Heap
Data
Code
Frame 17
Frame 16
Frame 15
Frame 14
Frame 13
Frame 12
Frame 11
Frame 10
Frame 9
Frame 8
Frame 7
Frame 6
Frame 5
Frame 4
Frame 3
Frame 2
Frame 1
Frame 0

Paging


Virtual Memory
Page 7
Page 6
Page 5
Page 4
Page 3
Page 2
Page 1
Page 0
Stack
Heap
Data
Code
Physical Memory
Frame 17
Frame 16
Frame 15
Frame 14
Frame 13
Frame 12
Frame 11
Frame 10
Frame 9
Frame 8
Frame 7
Frame 6
Frame 5
Frame 4
Frame 3
Frame 2
Frame 1
Frame 0

Paging


Physical Memory
Virtual Memory
Page 7
Page 6
Page 5
Page 4
Page 3
Page 2
Page 1
Page 0
Stack
Heap
Data
Code
Frame 17
Frame 16
Frame 15
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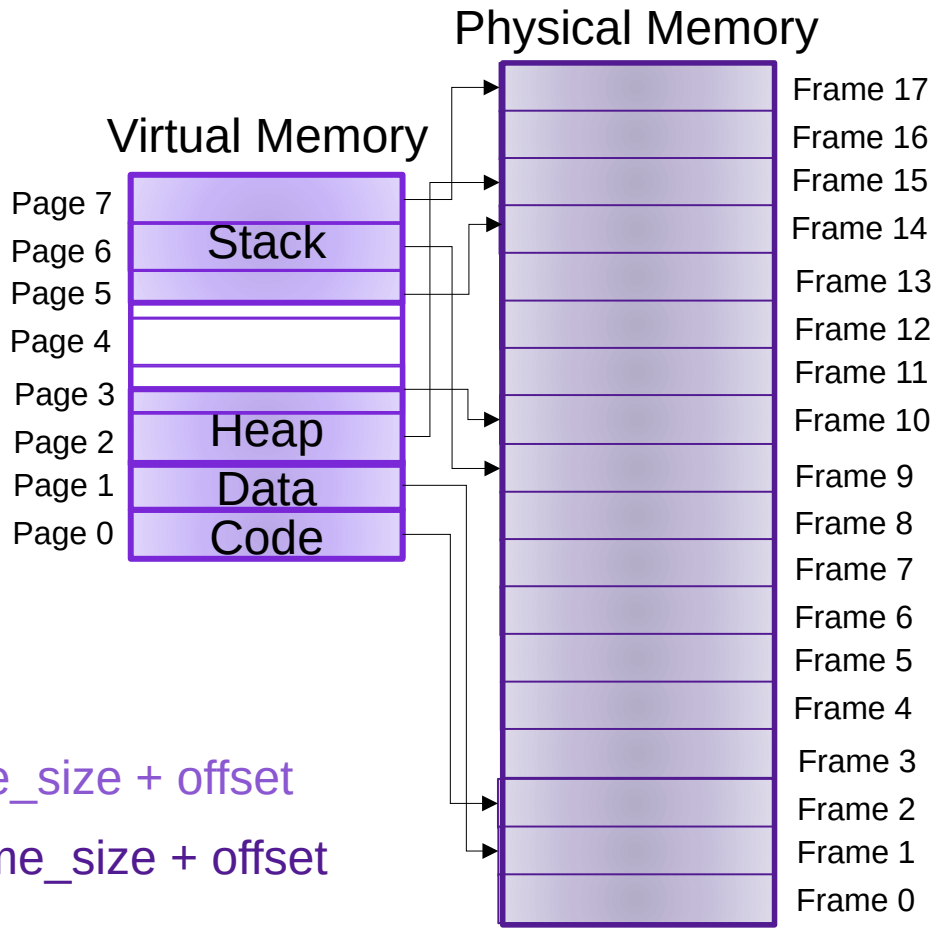
Frame 12
Frame 11
Frame 10
Frame 9
Frame 8
Frame 7
Frame 6
Frame 5
Frame 4
Frame 3
Frame 2
Frame 1
Frame 0

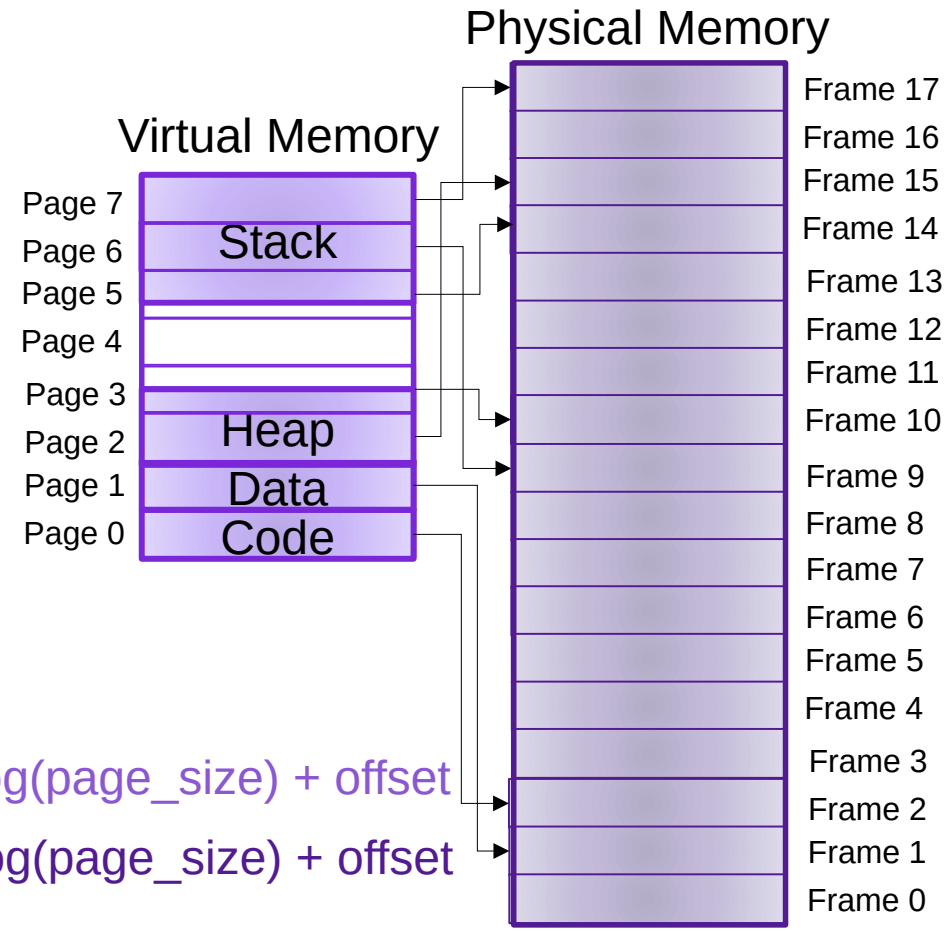
Paging



vaddr = page_num*page_size + offset

paddr = frame_num*frame_size + offset

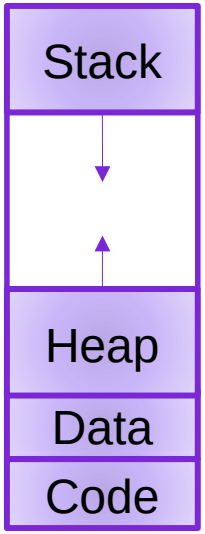
Paging



vaddr = page_num<< log(page_size) + offset

paddr = frame_num<<log(page_size) + offset

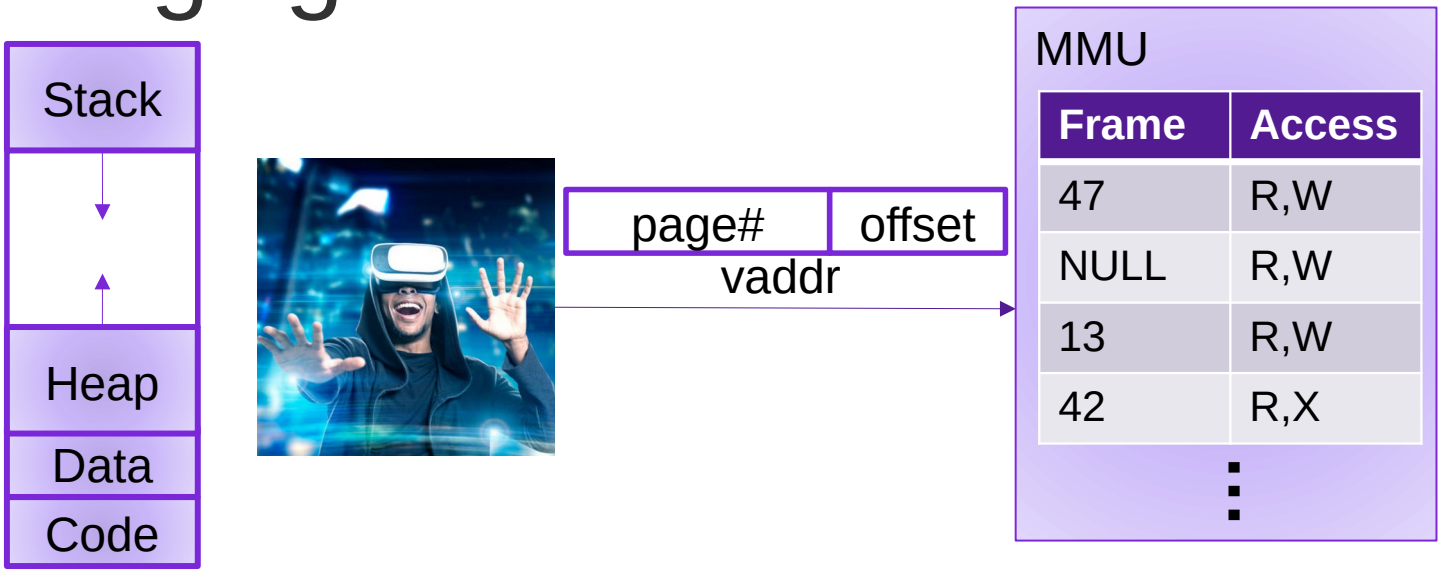
Paging



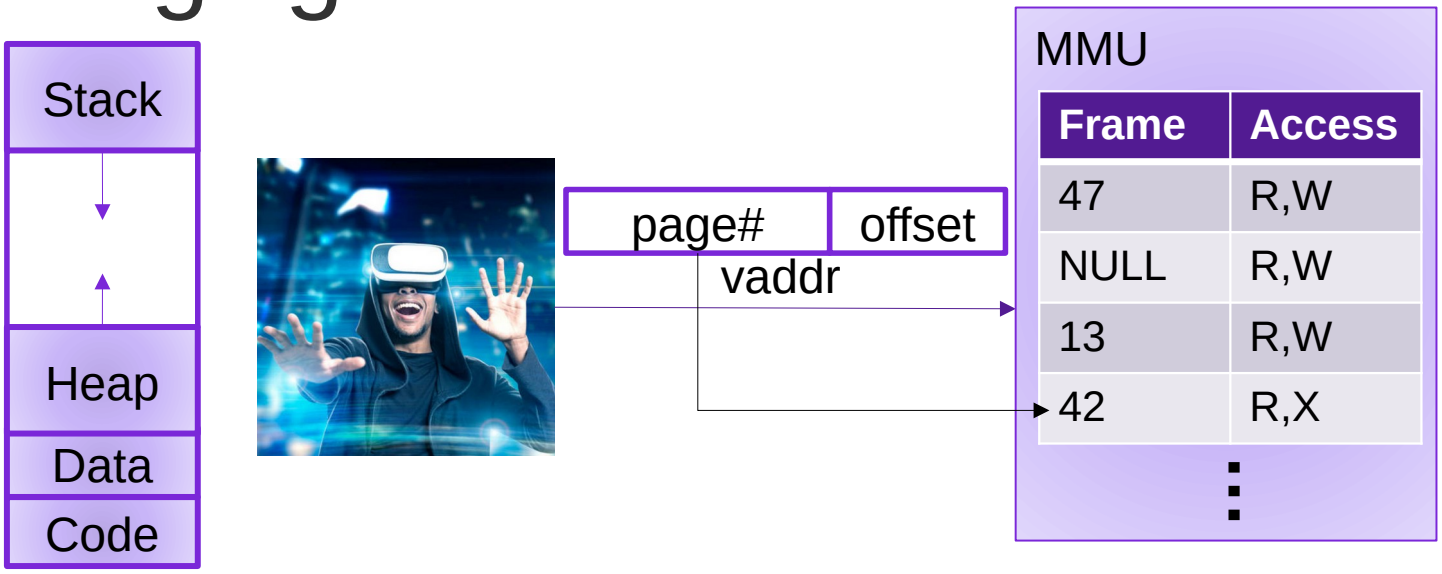
Paging


Stack
Heap
Data
Code
vaddr
MMU
Frame
Access
47
R,W
NULL
R,W
13
R,W
42
R,X

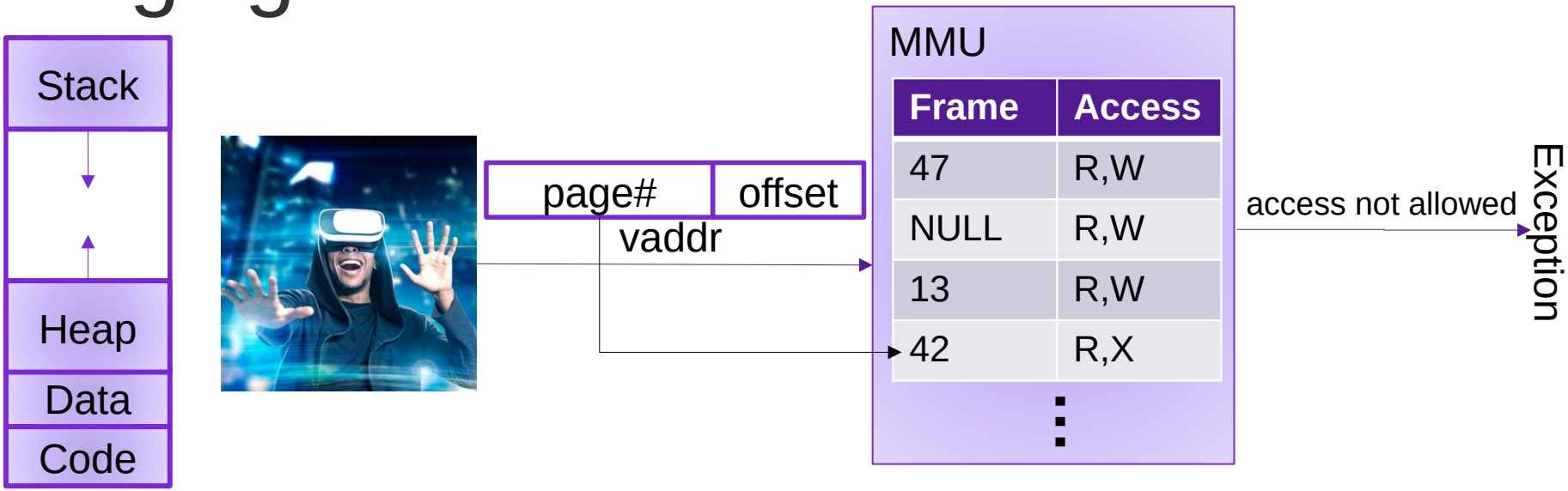
Paging


Stack
Heap
Data
Code
page#
offset
vaddr
MMU
Frame
Access
47
R,W
NULL
R,W
13
R,W
42
R,X

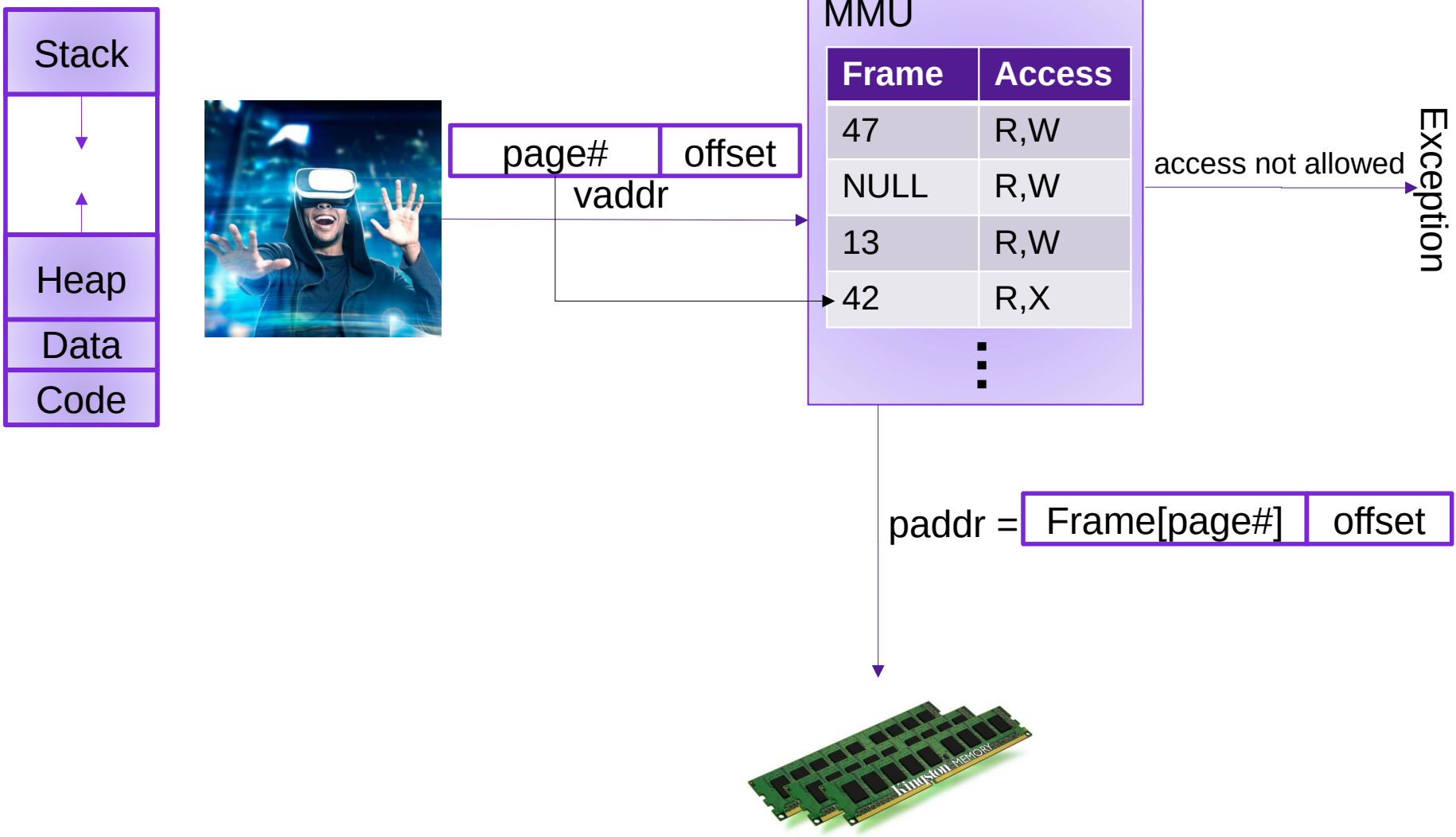
Paging


Stack
Heap
Data
Code
page#
offset
vaddr
MMU
Frame
Access
47
R,W
NULL
R,W
13
R,W
42
R,X

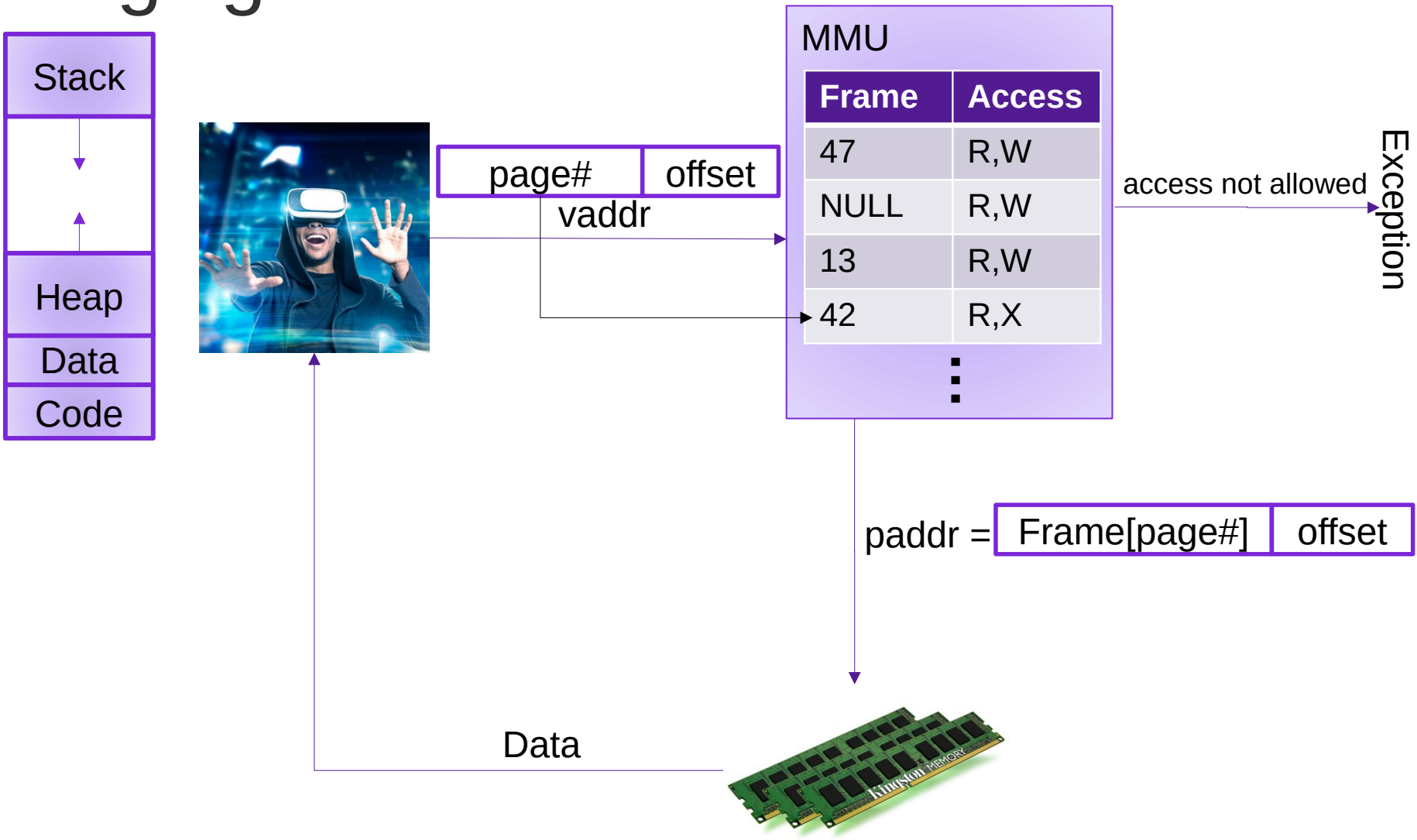
Paging


Stack
Heap
Data
Code
page#
offset
vaddr
MMU
Frame
Access
47
R,W
NULL
R,W
13
R,W
42
R,X
access not allowed
Exception

Paging


Stack
Heap
Data
Code
page#
offset
vaddr
MMU
Frame
Access
47
R,W
NULL
R,W
13
R,W
42
R,X
access not allowed
Exception
paddr =
Frame[page#]
offset
Kingston MEMORY

Paging


Stack
Heap
Data
Code
page#
offset
vaddr
MMU
Frame
Access
47
R,W
NULL
R,W
13
R,W
42
R,X
access not allowed
Exception
paddr =
Frame[page#]
offset
Data

Exercise 3: Paging

Assume that you are currently executing a process P with the following page table on a system with 16 byte pages:

	Frame	Access
⋮		
0x17	0x47	R,W
0x16	0xF4	R,W
0x15	NULL	R,W
0x14	0x23	R,X
⋮		

- What is the physical address that corresponds to the virtual address 0x147?
- What is the physical address that corresponds to the virtual address 0x16E?

Exercise 3: Paging

Assume that you are currently executing a process P with the following page table on a system with 16 byte pages:

	Frame	Access
⋮		
0x17	0x47	R,W
0x16	0xF4	R,W
0x15	NULL	R,W
0x14	0x23	R,X
⋮		

- What is the physical address that corresponds to the virtual address 0x147?
- What is the physical address that corresponds to the virtual address 0x16E?

Exercise 3: Paging

Assume that you are currently executing a process P with the following page table on a system with 16 byte pages:

	Frame	Access
⋮		
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0x16	0xF4	R,W
0x15	NULL	R,W
0x14	0x23	R,X
⋮		

- What is the physical address that corresponds to the virtual address 0x147?

- What is the physical address that corresponds to the virtual address 0x16E?

Exercise 3: Paging

Assume that you are currently executing a process P with the following page table on a system with 16 byte pages:

	Frame	Access
⋮		
0x17	0x47	R,W
0x16	0xF4	R,W
0x15	NULL	R,W
0x14	0x23	R,X
⋮		

- What is the physical address that corresponds to the virtual address 0x147?

0x237

- What is the physical address that corresponds to the virtual address 0x16E?

Exercise 3: Paging

Assume that you are currently executing a process P with the following page table on a system with 16 byte pages:

	Frame	Access
⋮		
0x17	0x47	R,W
0x16	0xF4	R,W
0x15	NULL	R,W
0x14	0x23	R,X
⋮		

- What is the physical address that corresponds to the virtual address 0x147?

00010100	0111

0x237

- What is the physical address that corresponds to the virtual address 0x16E?

00010110	1110

Exercise 3: Paging

Assume that you are currently executing a process P with the following page table on a system with 16 byte pages:

	Frame	Access
⋮		
0x17	0x47	R,W
0x16	0xF4	R,W
0x15	NULL	R,W
0x14	0x23	R,X
⋮		

- What is the physical address that corresponds to the virtual address 0x147?

00010100	0111

0x237

- What is the physical address that corresponds to the virtual address 0x16E?

00010110	1110

0xF4E

Exercise 3: Paging

Assume that you are currently executing a process P with the following page table on a system with 16 byte pages:

	Frame	Access
⋮		
0x17	0x47	R,W
0x16	0xF4	R,W
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⋮		

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Assume that you are currently executing a process P with the following page table on a system with 16 byte pages:

	Frame	Access
⋮		
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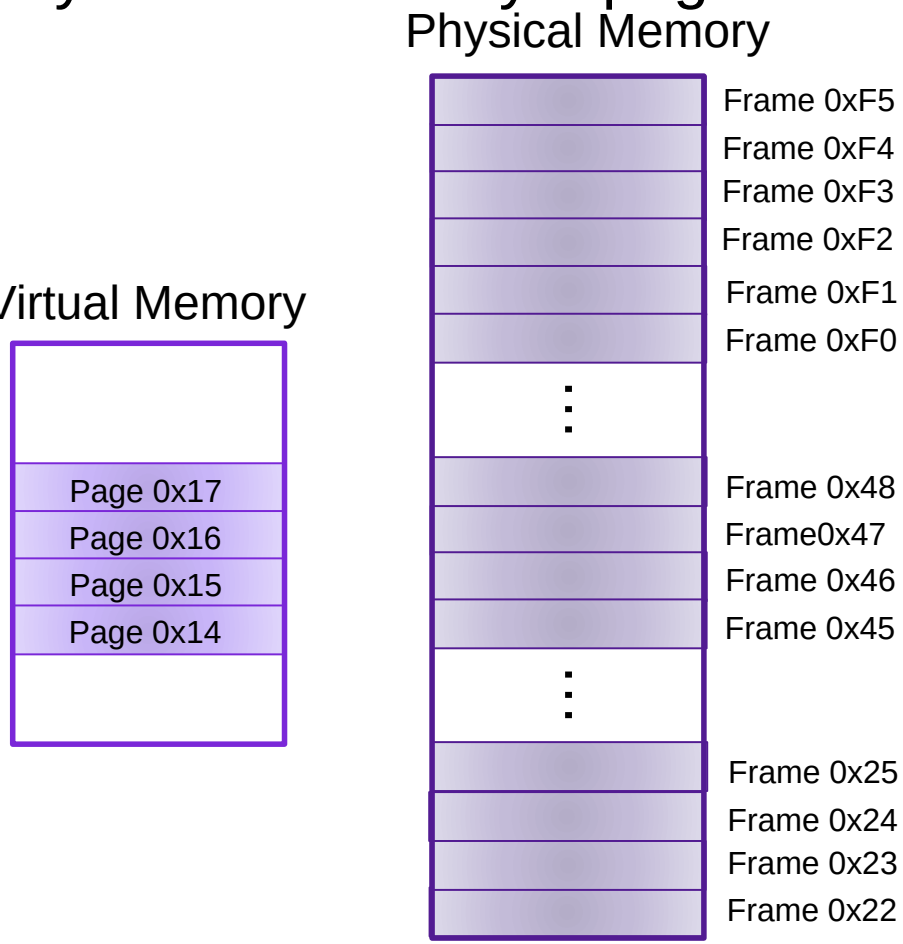
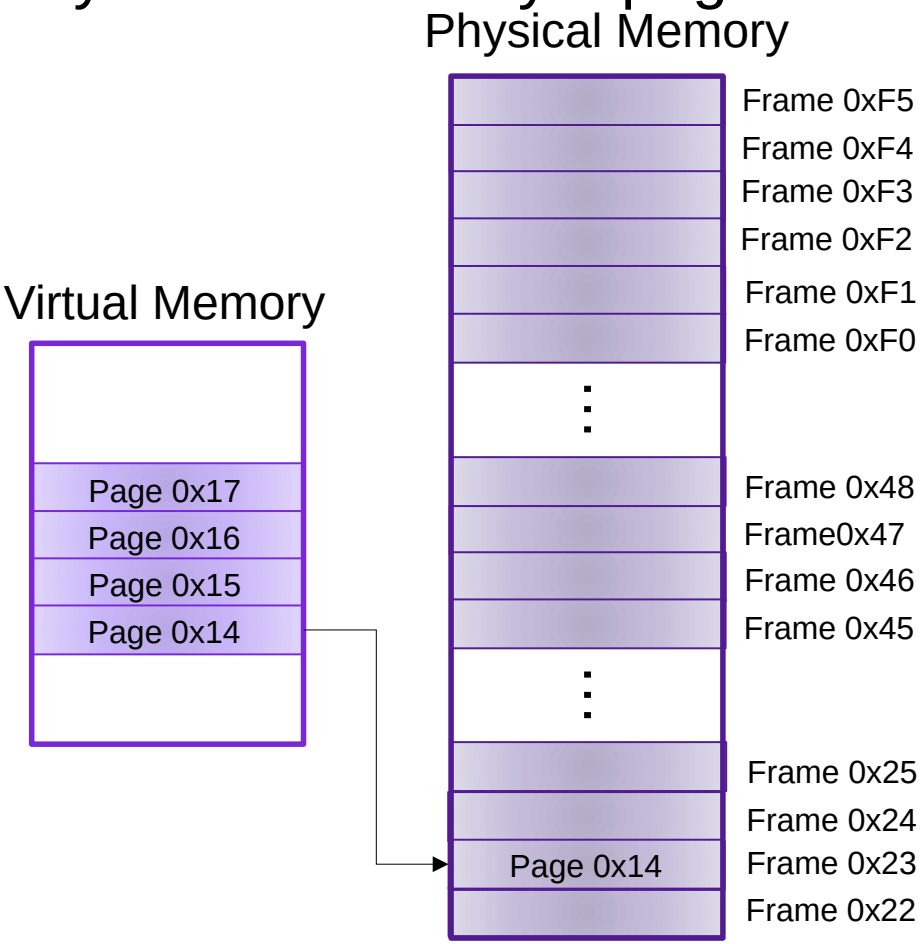
0x16	0xF4	R,W
0x15	NULL	R,W
0x14	0x23	R,X
⋮		



Exercise 3: Paging

Assume that you are currently executing a process P with the following page table on a system with 16 byte pages:

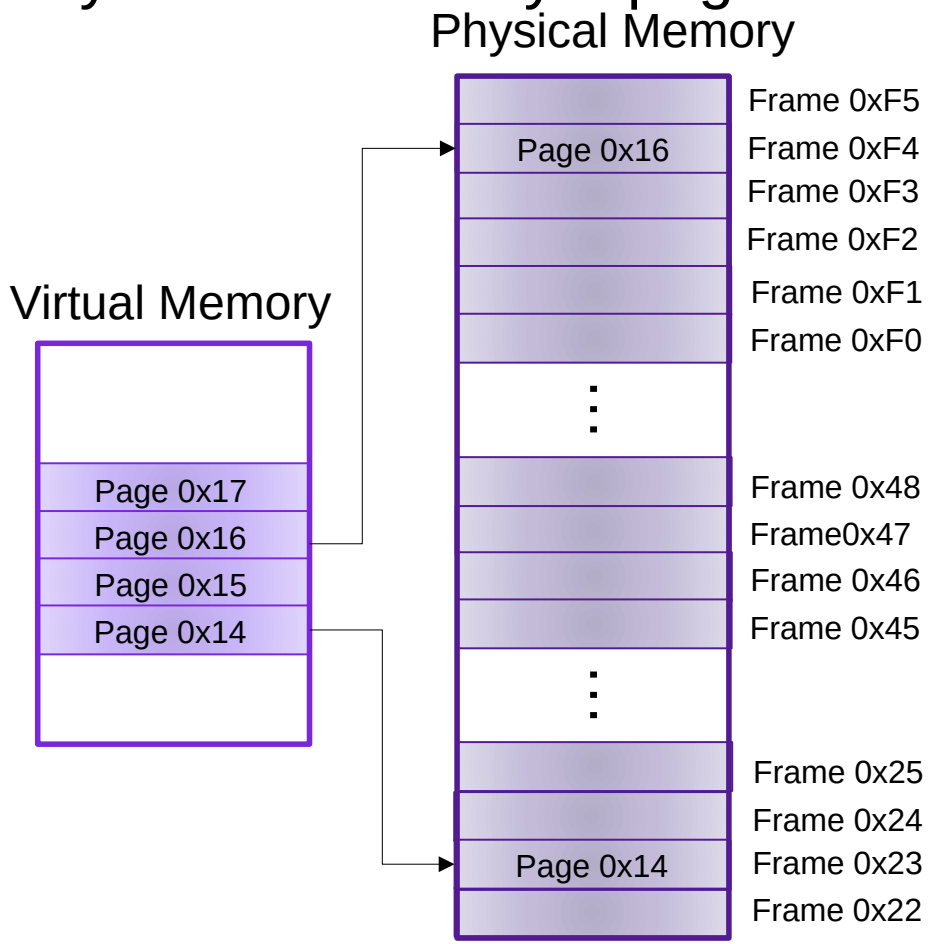
	Frame	Access
⋮		
0x17	0x47	R,W
0x16	0xF4	R,W
0x15	NULL	R,W
0x14	0x23	R,X
⋮		



Exercise 3: Paging

Assume that you are currently executing a process P with the following page table on a system with 16 byte pages:

	Frame	Access
⋮		
0x17	0x47	R,W
0x16	0xF4	R,W
0x15	NULL	R,W
0x14	0x23	R,X
⋮		



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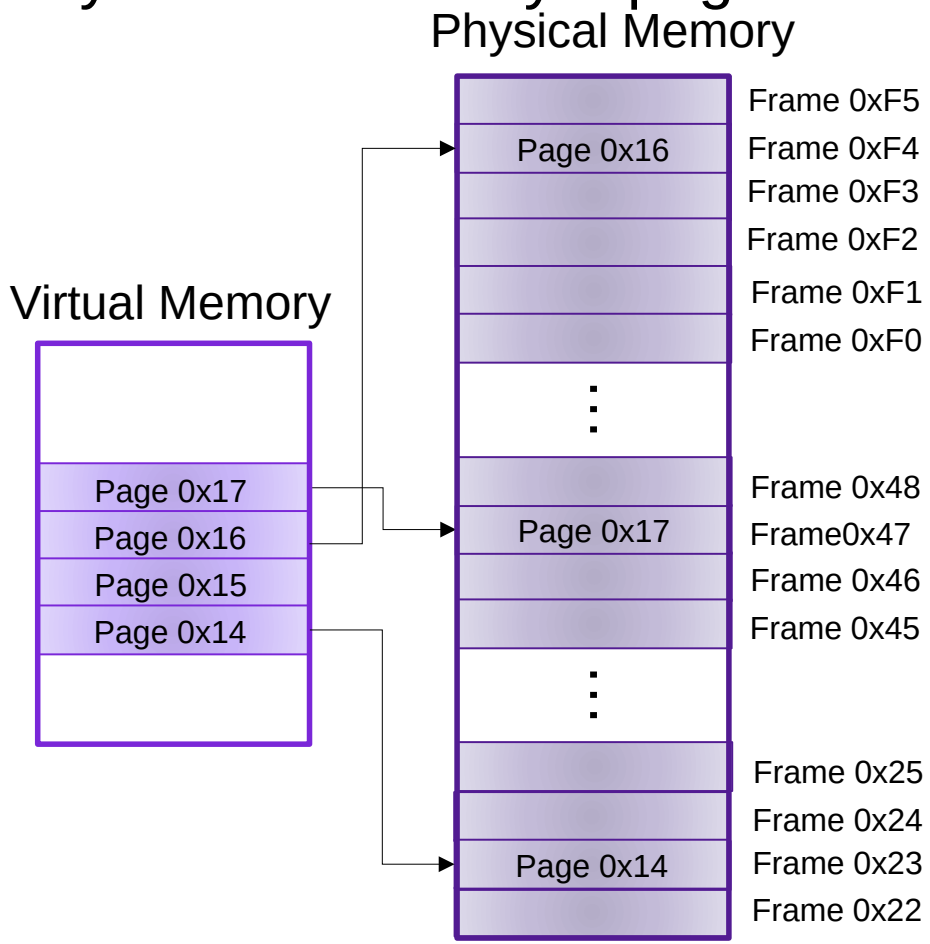
Assume that you are currently executing a process P with the following page table on a system with 16 byte pages:

	Frame	Access
⋮		
0x17	0x47	R,W
0x16	0xF4	R,W
0x15	NULL	R,W
0x14	0x23	R,X
⋮		



Memory as a Cache

- each page table entry has a valid bit
- for valid entries, frame indicates physical address of page in memory
- a **page fault** occurs when a program requests a page that is not currently in memory
  - handled much like a cache miss

MMU

v	Frame	Access
1	0x47	R,W
0	NULL	R,W
0	0x13	R,W
1	0xF1	R,X
⋮		

Memory as a Cache

- each page table entry has a valid bit
- for valid entries, frame indicates physical address of page in memory
- a **page fault** occurs when a program requests a page that is not currently in memory
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  - evict another page in memory to make space (which one?)

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0	0x13	R,W
1	0xF1	R,X
⋮		

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- each page table entry has a valid bit
- for valid entries, frame indicates physical address of page in memory
- a **page fault** occurs when a program requests a page that is not currently in memory
  - handled much like a cache miss
  - evict another page in memory to make space (which one?)
  - takes time to handle, so context switch

MMU

v	Frame	Access
1	0x47	R,W
0	NULL	R,W
0	0x13	R,W
1	0xF1	R,X

Memory as a Cache

Assume that you are currently executing a process P with the following page table on a system with 16 byte pages:

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⋮			
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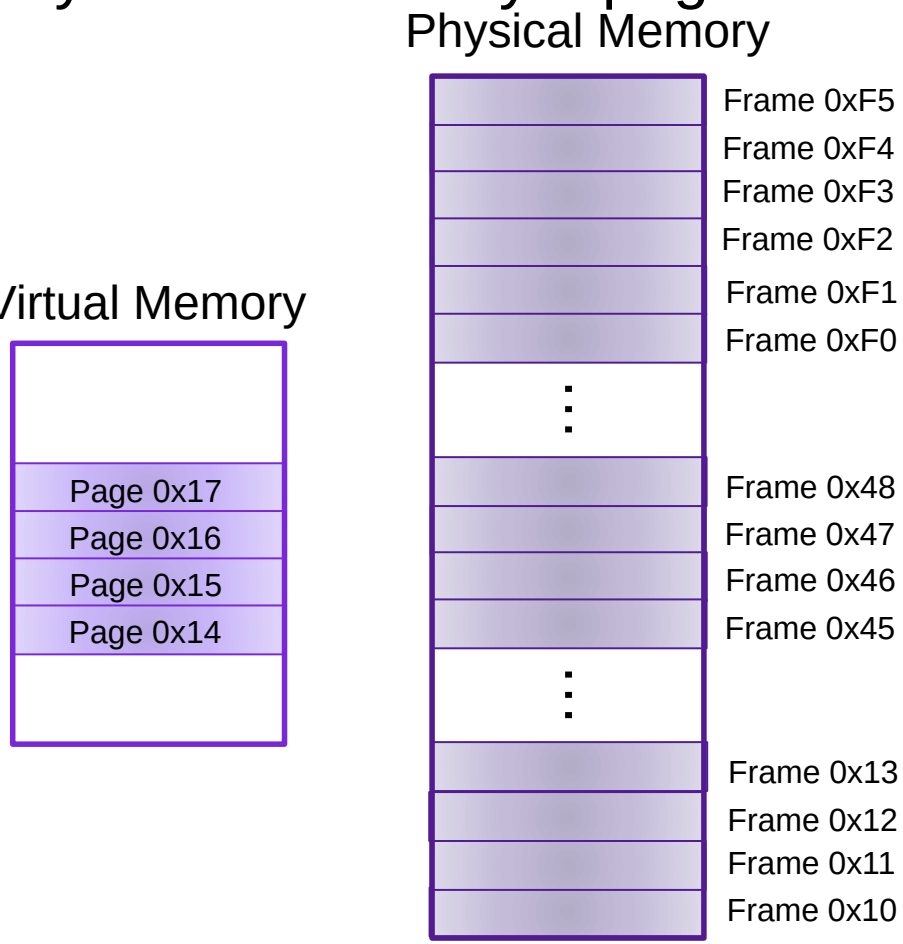
0x15	0	0x13	R,W
0x14	1	0xF1	R,X
⋮			



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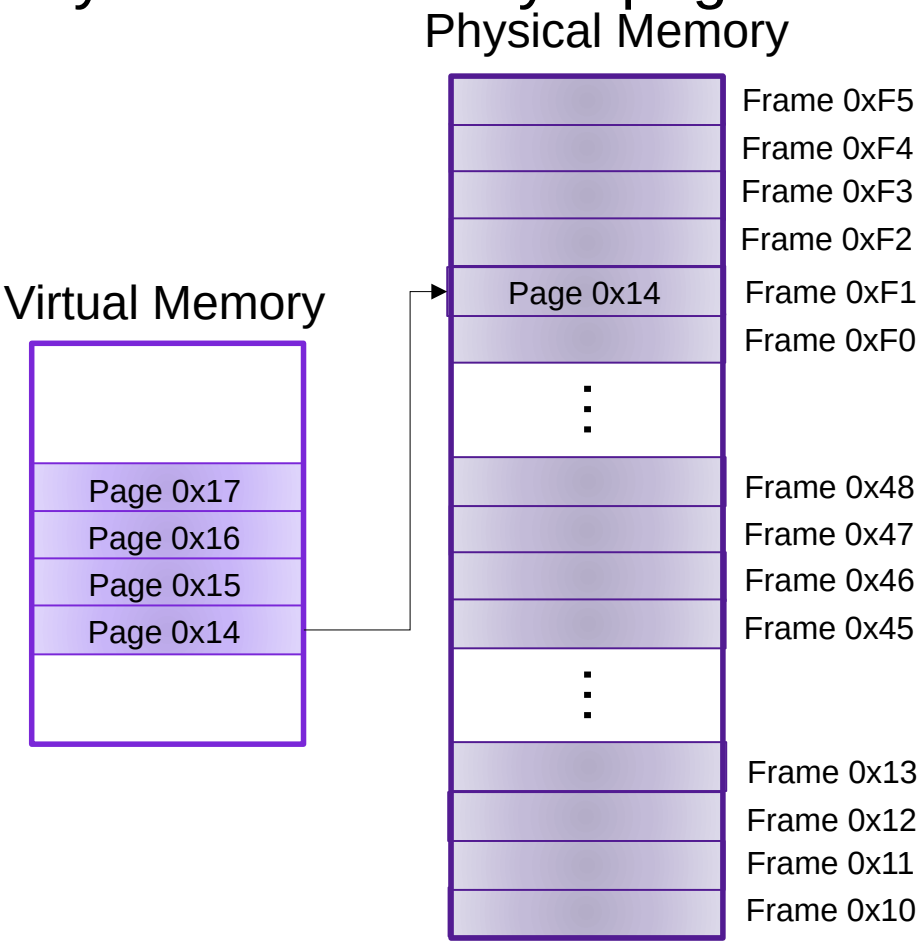
0x16	0	NULL	R,W
0x15	0	0x13	R,W
0x14	1	0xF1	R,X
⋮			



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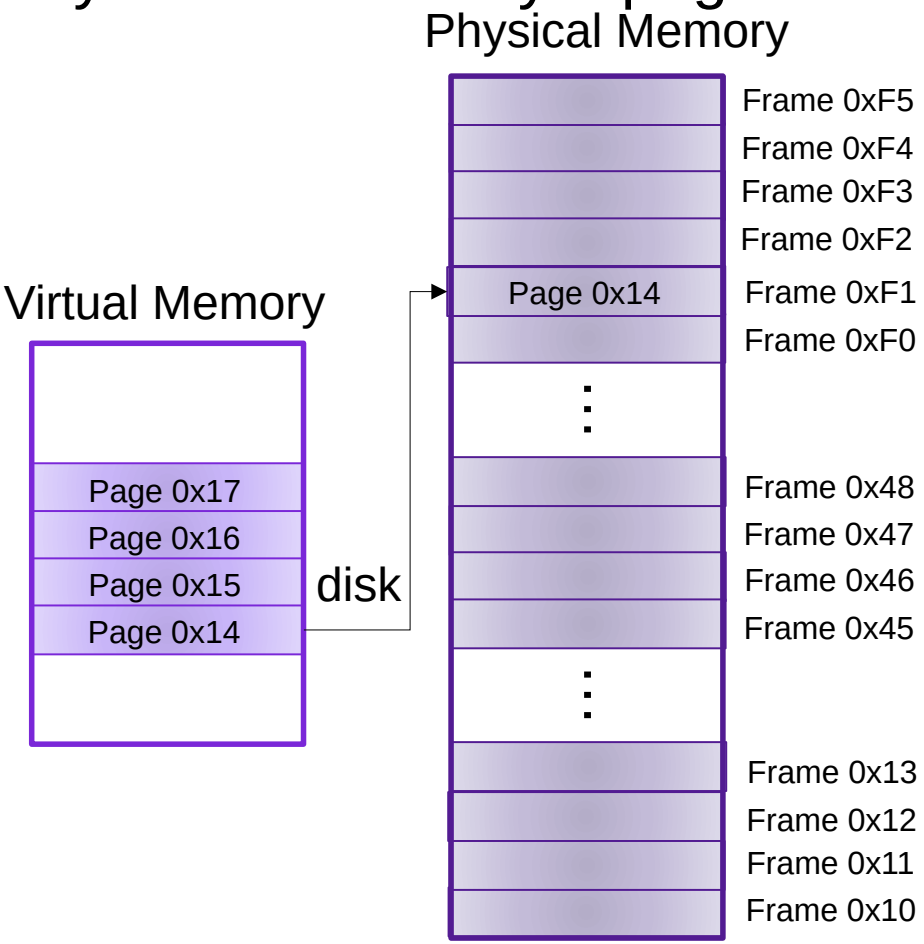
0x16	0	NULL	R,W
0x15	0	0x13	R,W
0x14	1	0xF1	R,X
⋮			



Memory as a Cache

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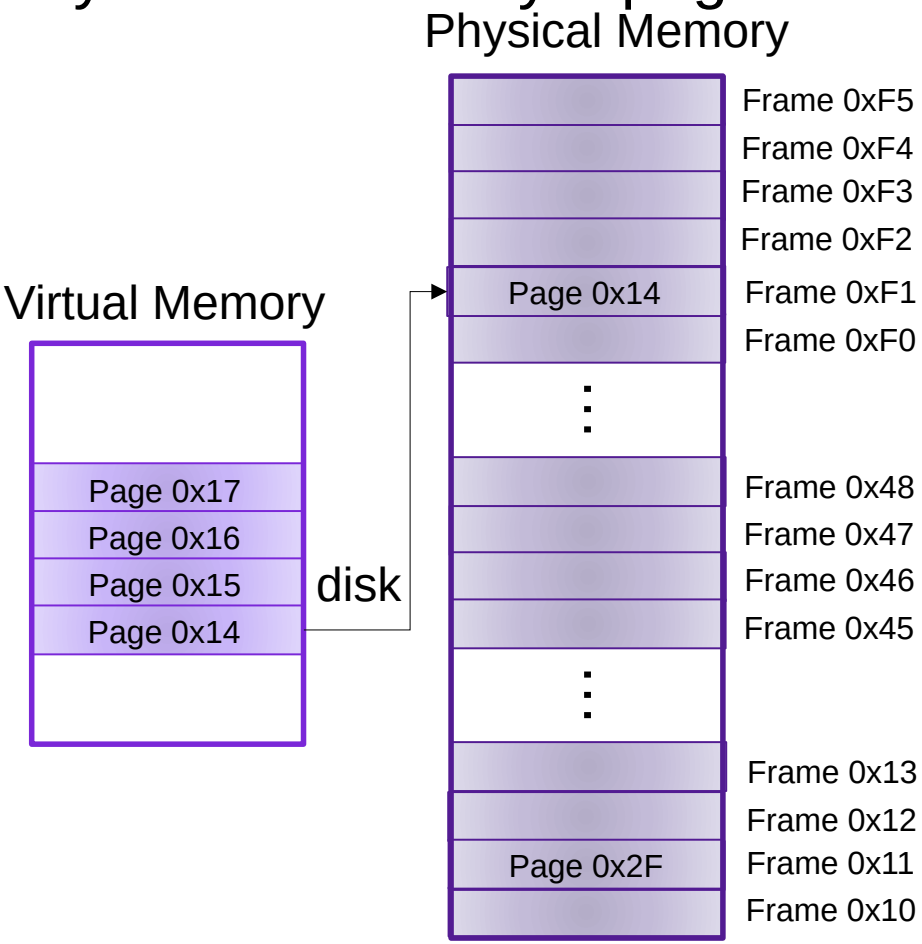
0x15	0	0x13	R,W
0x14	1	0xF1	R,X
⋮			



Memory as a Cache

Assume that you are currently executing a process P with the following page table on a system with 16 byte pages:

	v	Frame	Access
⋮			
0x17	1	0x47	R,W
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0x15	0	0x13	R,W
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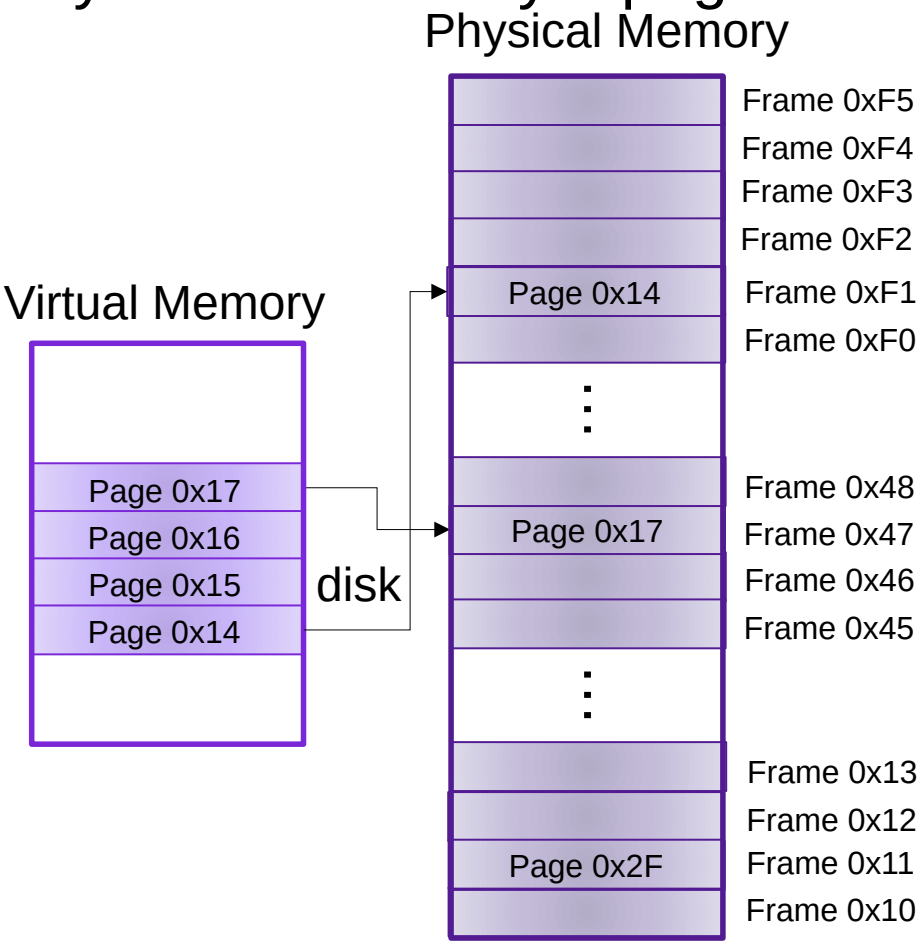
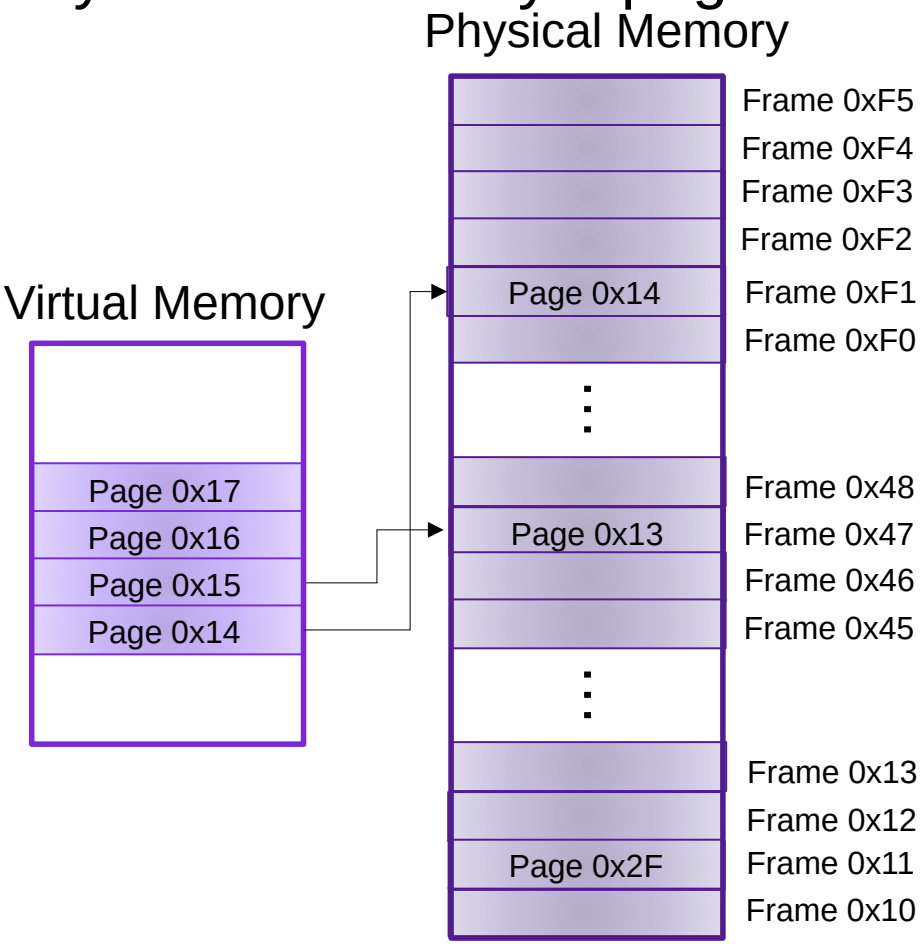
⋮			



Memory as a Cache

Assume that you are currently executing a process P with the following page table on a system with 16 byte pages:

	v	Frame	Access
⋮			
0x17	0	0x47	R,W
0x16	0	NULL	R,W
0x15	1	0x47	R,W
0x14	1	0xF1	R,X
⋮			



Exercise 4: Paging

Assume that you are currently executing a process P with the following page table on a system with 256 byte pages:

	v	Frame	Access
⋮			
0xFA	1	0x47	R,W
0xF9	1	0x24	R,W
0xF8	0	NULL	R,W
0xF7	0	0x23	R,X
⋮			

- What is the physical address that corresponds to the virtual address 0xF947?
- What is the physical address that corresponds to the virtual address 0xF700?
- What is the physical address that corresponds to the virtual address 0xF813?

Exercise 4: Paging

Assume that you are currently executing a process P with the following page table on a system with 256 byte pages:

	v	Frame	Access
⋮			
0xFA	1	0x47	R,W
0xF9	1	0x24	R,W
0xF8	0	NULL	R,W
0xF7	0	0x23	R,X
⋮			

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Assume that you are currently executing a process P with the following page table on a system with 256 byte pages:

	v	Frame	Access
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0xF9	1	0x24	R,W
0xF8	0	NULL	R,W
0xF7	0	0x23	R,X
⋮			

- What is the physical address that corresponds to the virtual address 0xF947?

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Assume that you are currently executing a process P with the following page table on a system with 256 byte pages:

	v	Frame	Access
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0xF9	1	0x24	R,W
0xF8	0	NULL	R,W
0xF7	0	0x23	R,X
⋮			

- What is the physical address that corresponds to the virtual address 0xF947?

0x2447

- What is the physical address that corresponds to the virtual address 0xF700?
- What is the physical address that corresponds to the virtual address 0xF813?

Exercise 4: Paging

Assume that you are currently executing a process P with the following page table on a system with 256 byte pages:

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⋮			

- What is the physical address that corresponds to the virtual address 0xF947?

0xF9	0x47

0x2447

- What is the physical address that corresponds to the virtual address 0xF700?

0xF7	0x00

- What is the physical address that corresponds to the virtual address 0xF813?

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0xF8	0	NULL	R,W
0xF7	0	0x23	R,X
⋮			

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0xF9	0x47

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- What is the physical address that corresponds to the virtual address 0xF700?

0xF7	0x00

page fault

- What is the physical address that corresponds to the virtual address 0xF813?

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- What is the physical address that corresponds to the virtual address 0xF947?

0xF9	0x47

0x2447

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page fault

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0xF7	0	0x23	R,X
⋮			

- What is the physical address that corresponds to the virtual address 0xF947?

0xF9	0x47

0x2447

- What is the physical address that corresponds to the virtual address 0xF700?

0xF7	0x00

page fault

- What is the physical address that corresponds to the virtual address 0xF813?

0xF8	0x13

segfault

Evaluating Paging

- **Isolation:** don't want different process states collided in physical memory
- **Efficiency:** want fast reads/writes to memory
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