CSCI 509

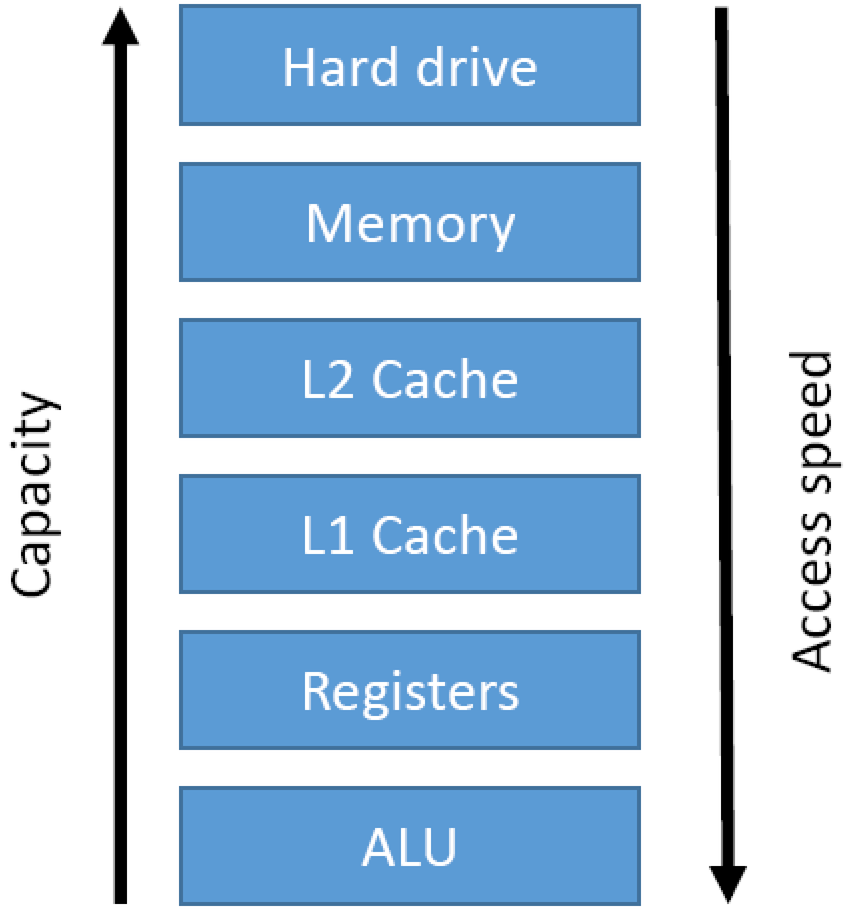
OPERATING SYSTEMS INTERNALS

PART 3: MEMORY MANAGEMENT

Chapter 9: Main Memory

MEMORY HIERARCHY

- When we talk about accessing memory, which memory are we talking about?
- Addresses refer to what part of memory?



Hard drive

Memory

L2 Cache

L1 Cache

Registers

ALU

Capacity

Access speed

MEMORY HIERARCHY

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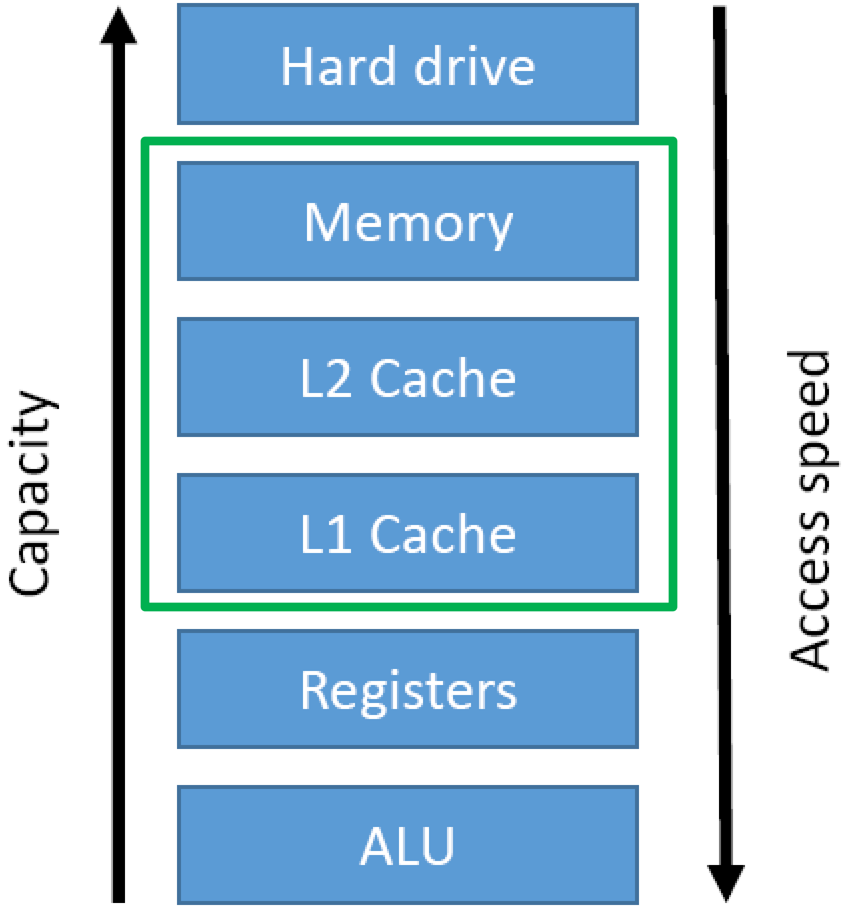

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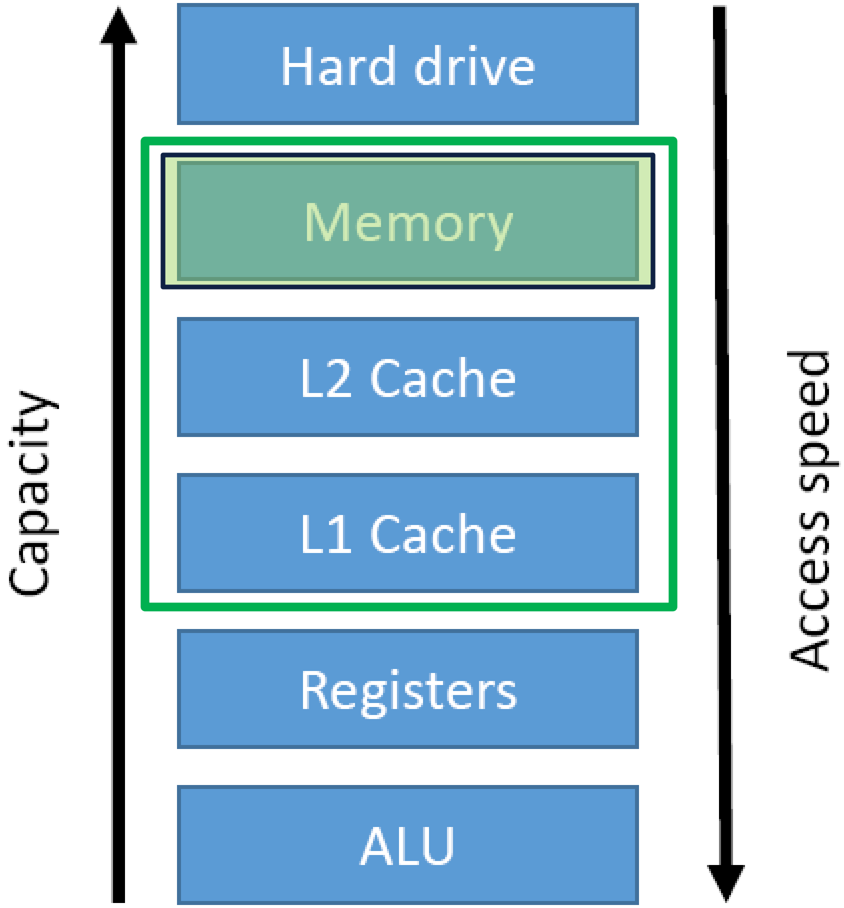
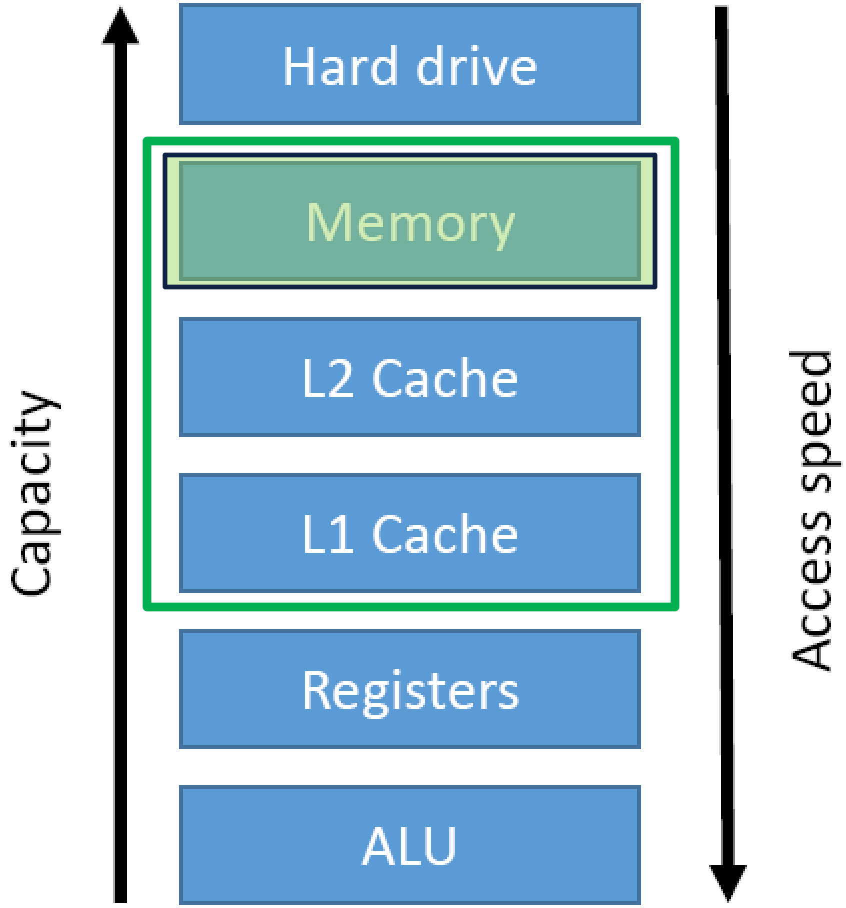
- A process/data is in memory if it's in main memory.



MEMORY HIERARCHY

- Hard drives are not considered part of memory, rather part of storage.
- A process/data is in memory if it's in main memory.
- Addresses refer to memory locations in Main Memory (RAM)
- L1 and L2 can be considered an extension of Main Memory.



MEMORY HIERARCHY

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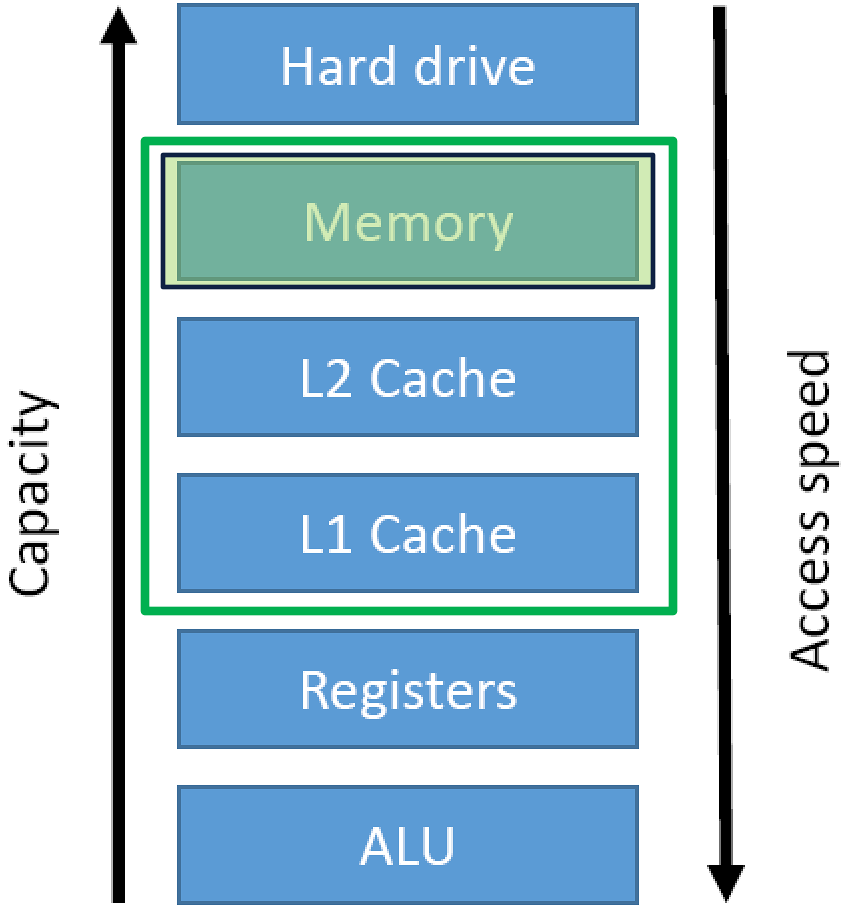
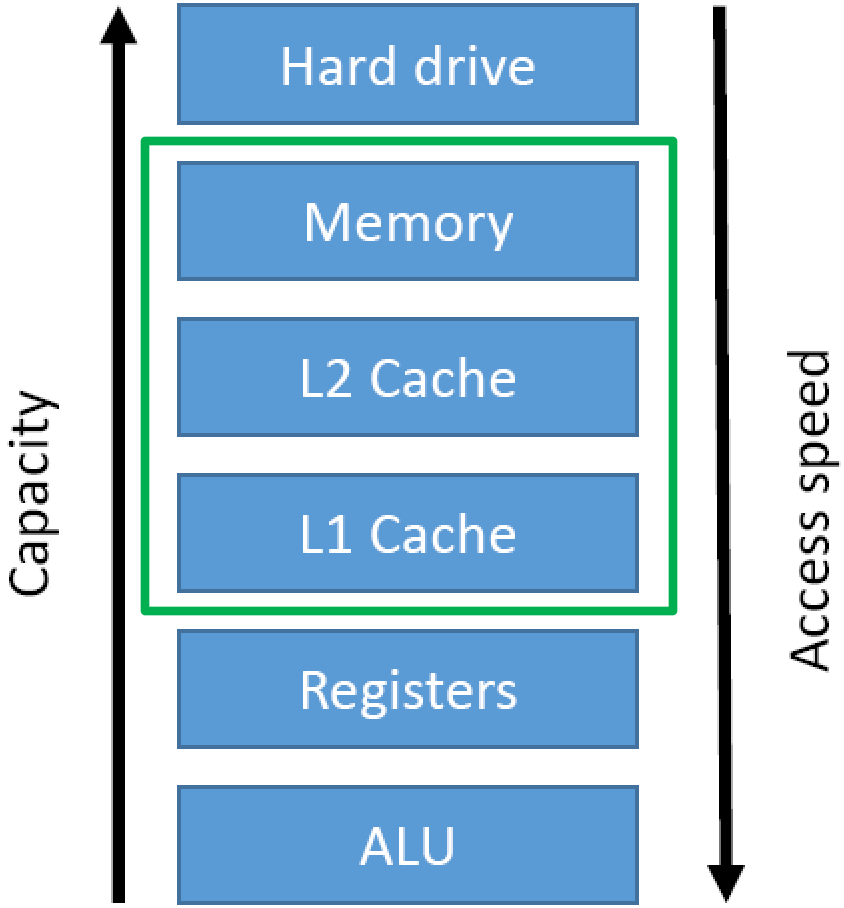
- A process/data is in memory if it's in main memory.
- Addresses refer to memory locations in Main Memory (RAM)
- L1 and L2 can be considered an extension of Main Memory.
- Main memory would also contain a copy of L1 and L2 Cache
- However, the Main memory copy may not be updated, it will be flagged non the less.



PROCESS MEMORY

- Each Process has its own memory space.
- Why?



PROCESS MEMORY

- Each Process has its own memory space.
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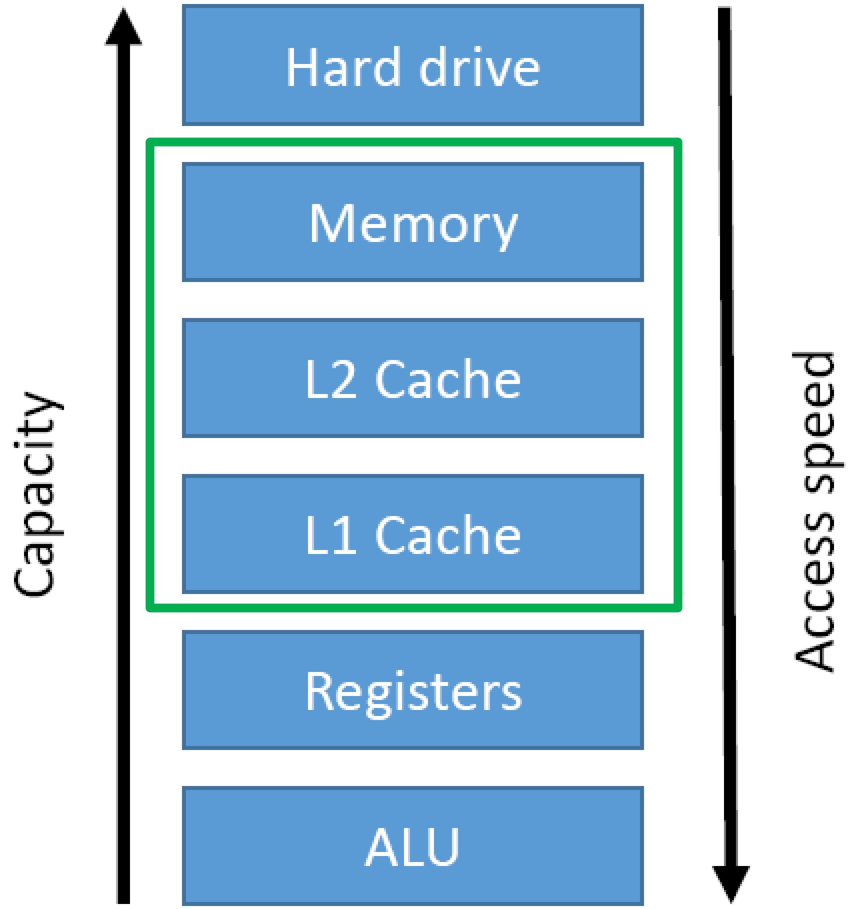
  - Protection
  - Modularity



PROCESS MEMORY

- Each Process has its own memory space.
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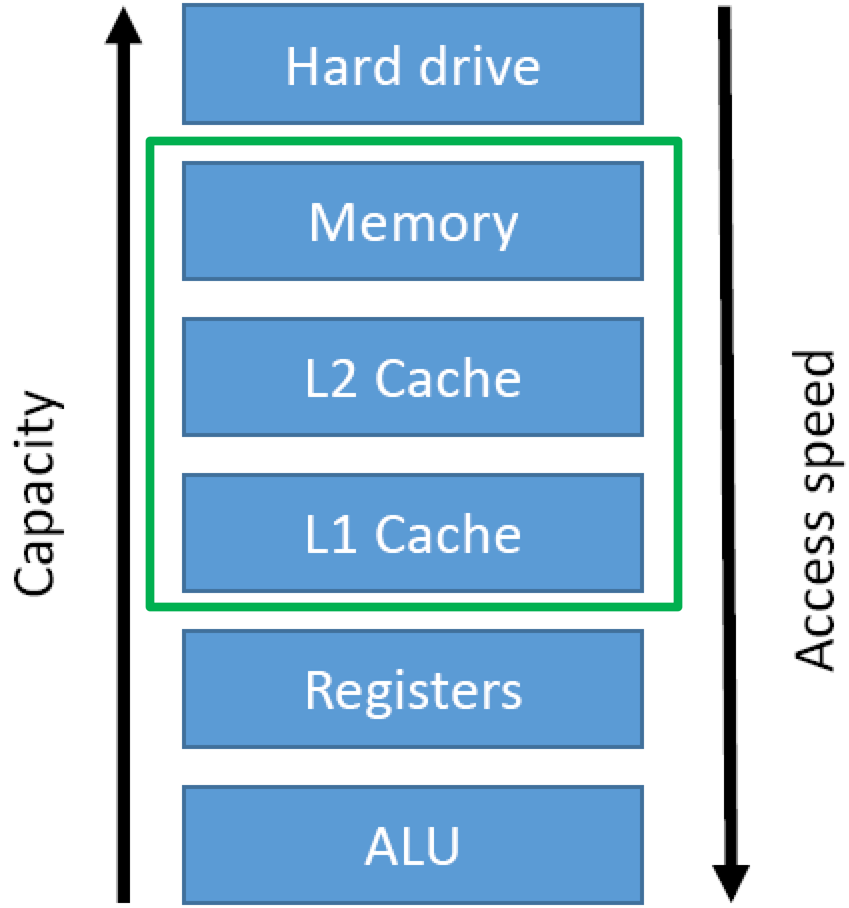

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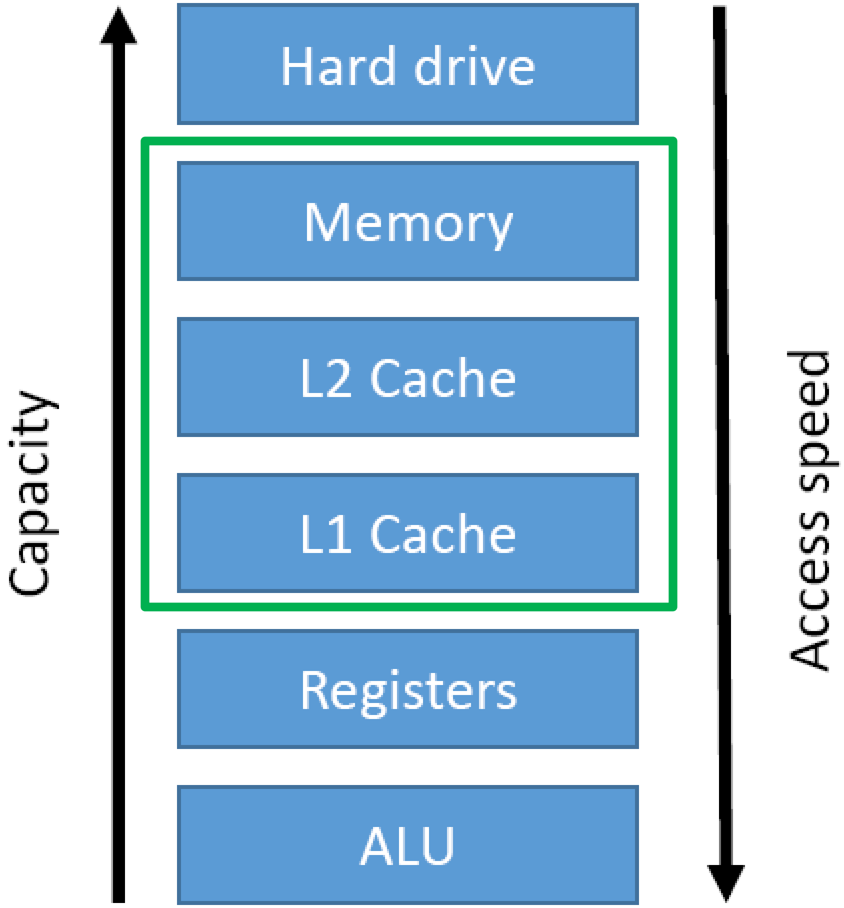
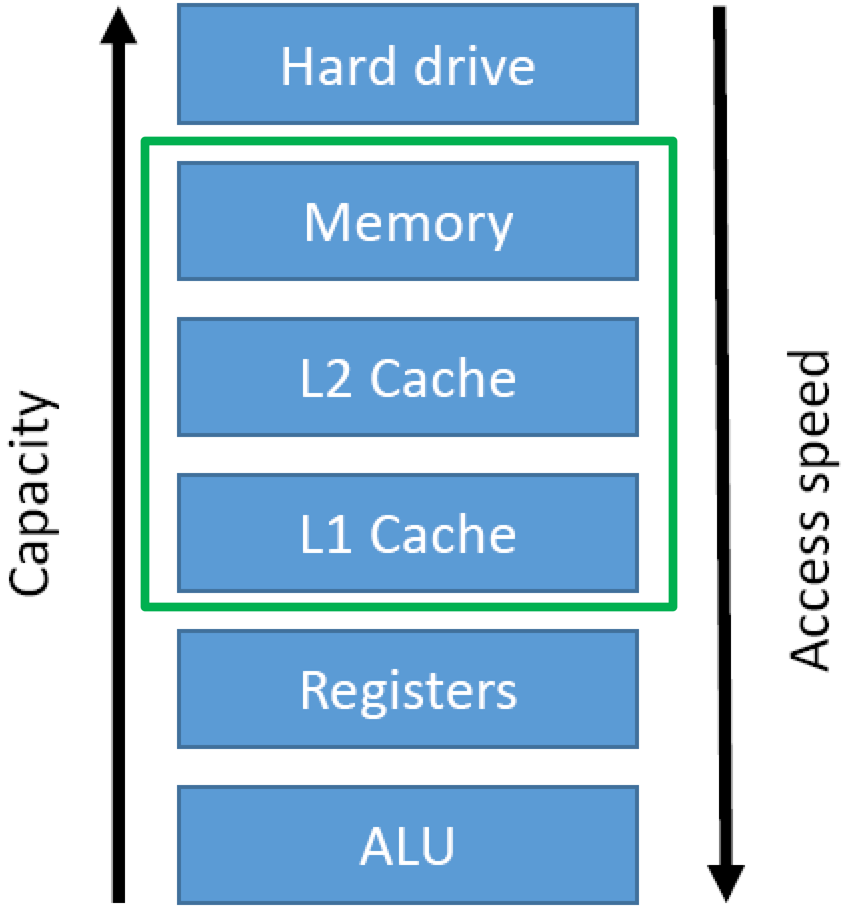


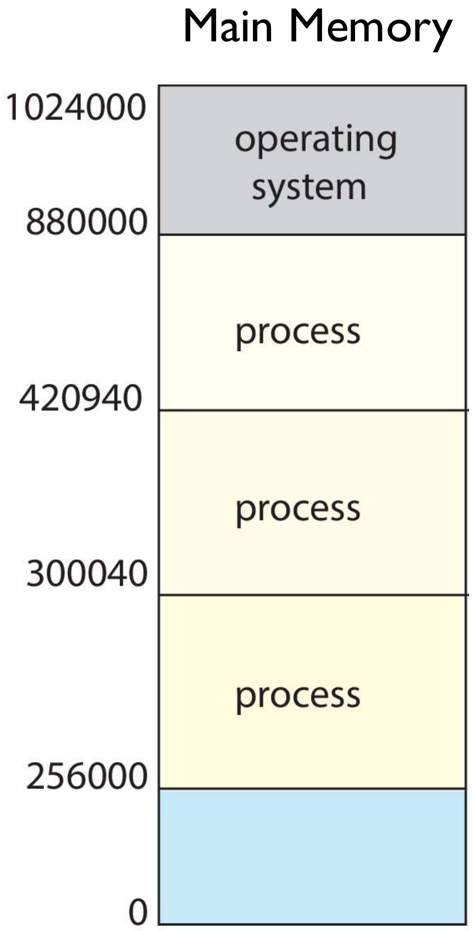
PROCESS MEMORY

- Each Process has its own memory space.
- Why?
  - Protection
  - Modularity
- Process A should not be able to access the memory of Process B.
- Exceptions?
- Except for shared memory segments, which are handled by OS).



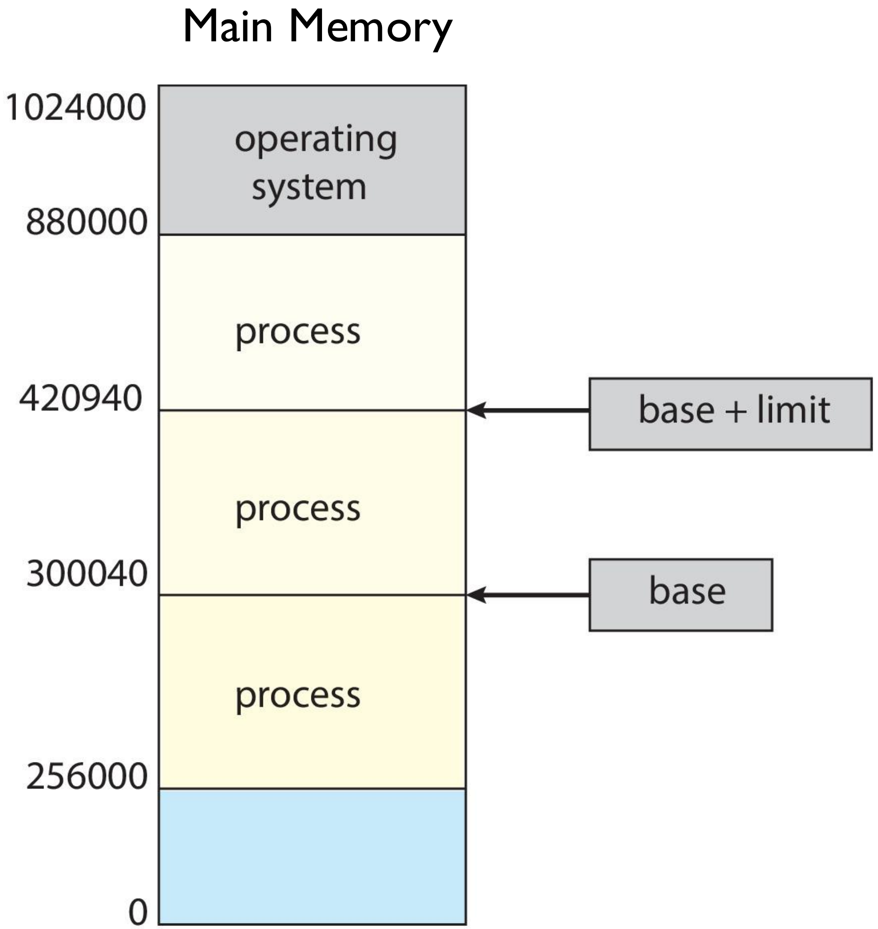
PROCESS MEMORY BOUNDARIES

Q: How to enforce memory protection and process memory?



PROCESS MEMORY BOUNDARIES

Two register values, **base** and **limit**, are used to hold the starting and end memory addresses of a process.



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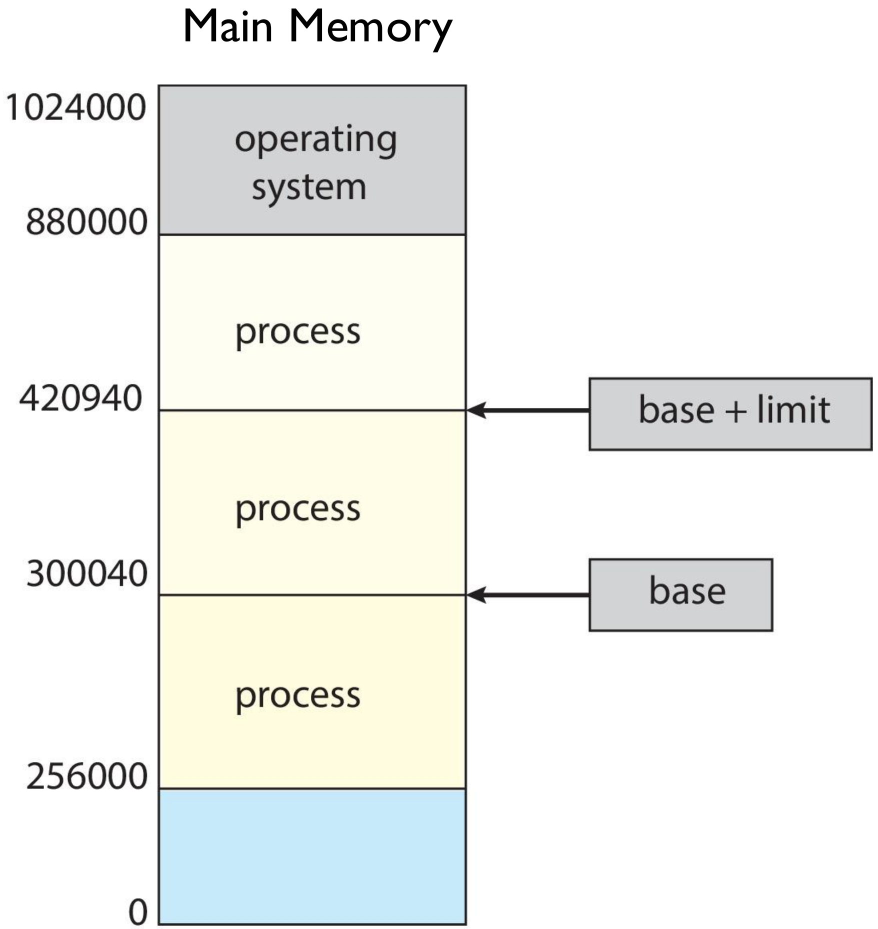
Q: Who has access to the base and limit registers?



PROCESS MEMORY BOUNDARIES

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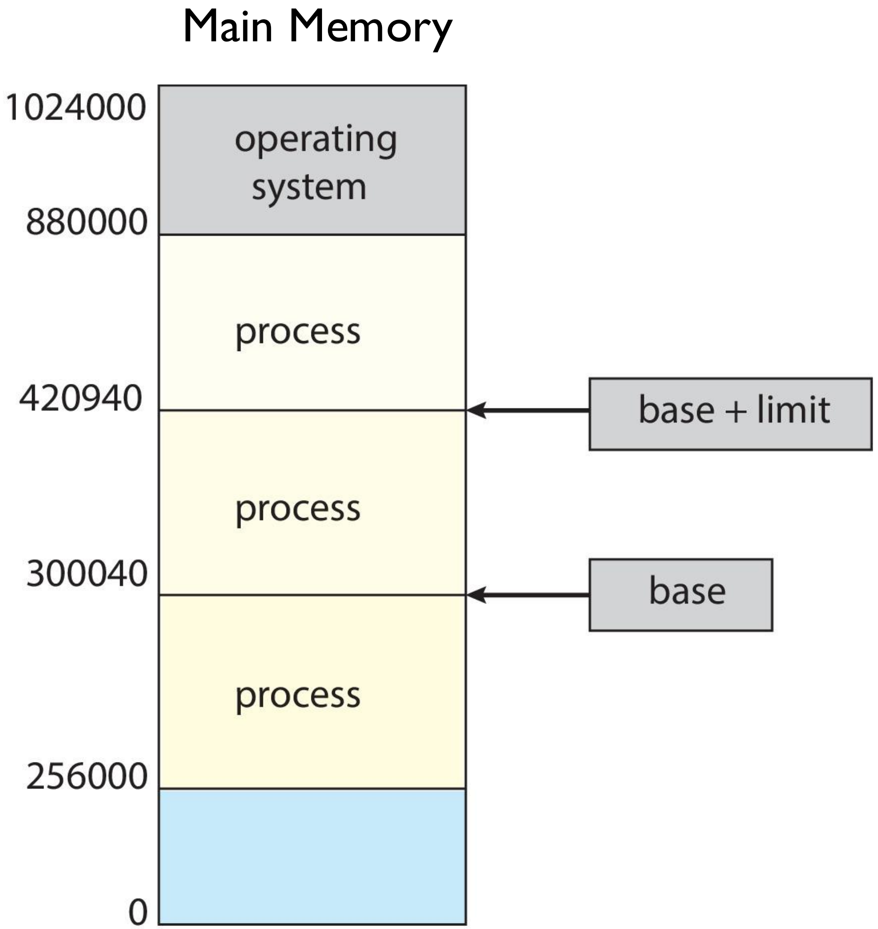
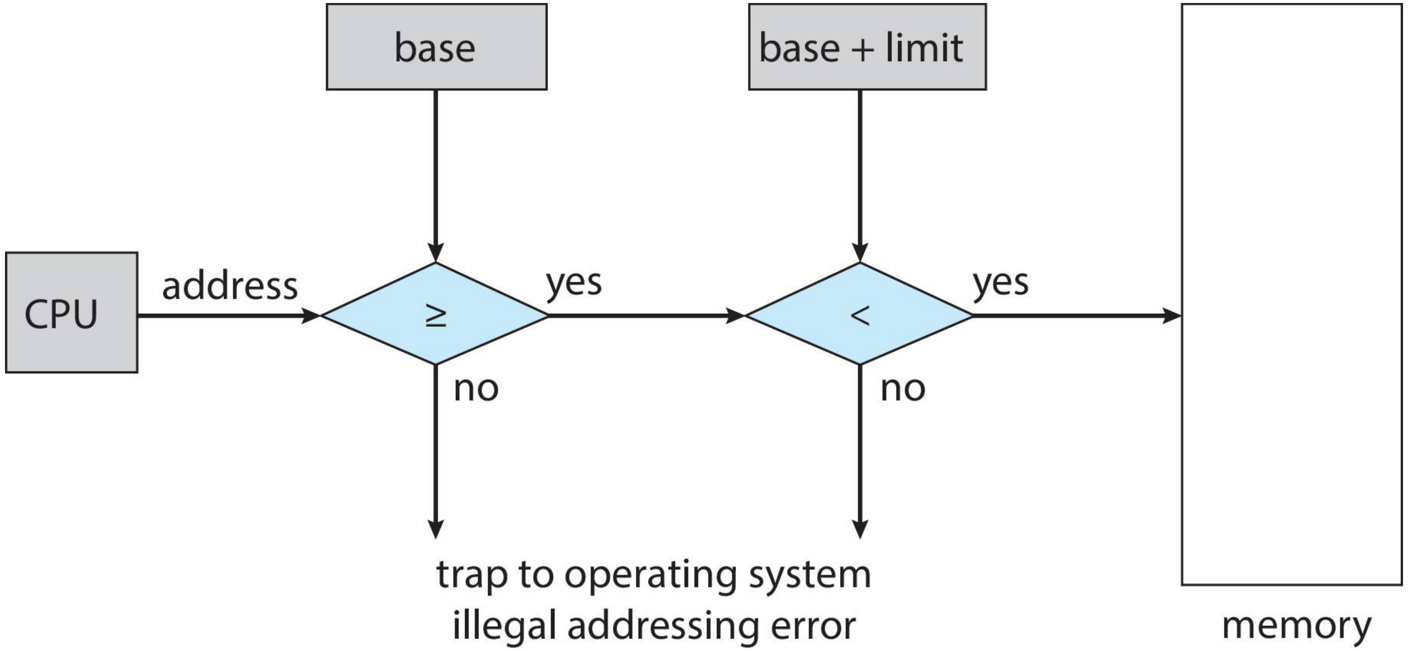
Only the kernel (in kernel mode) can access the values of these two registers

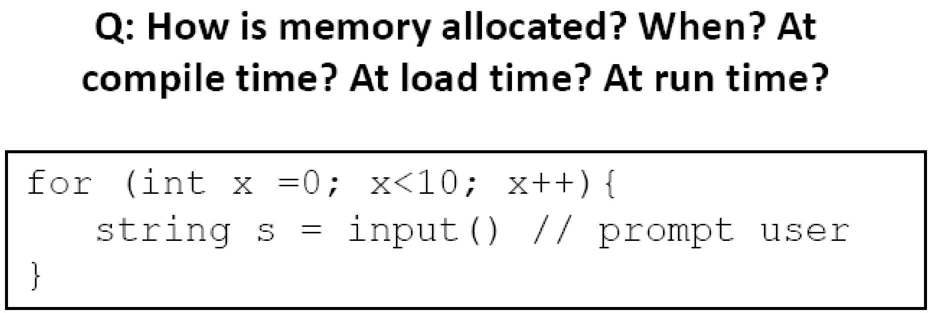


MEMORY PROTECTION

- CPU must check every memory access generated in user mode to be sure it is between base and limit for that user.
- The instructions to loading the base and limit registers are privileged.



ADDRESS IN CODE



Q: How is memory allocated? When? At compile time? At load time? At run time?

```
for (int x =0; x<10; x++){
   string s = input() // prompt user
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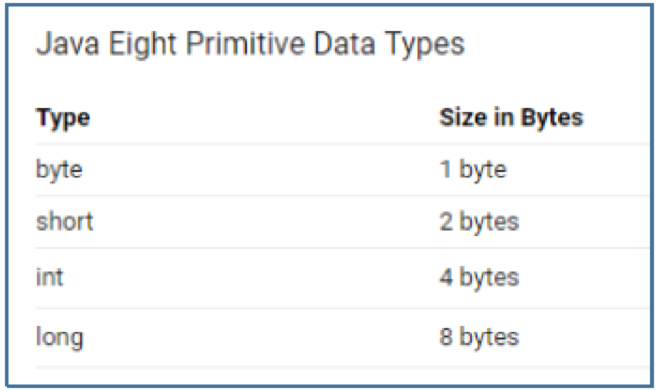
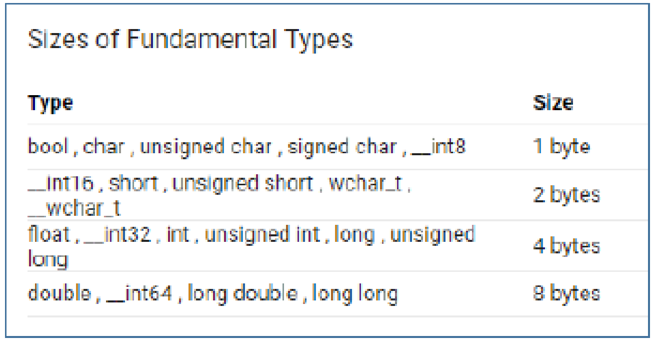


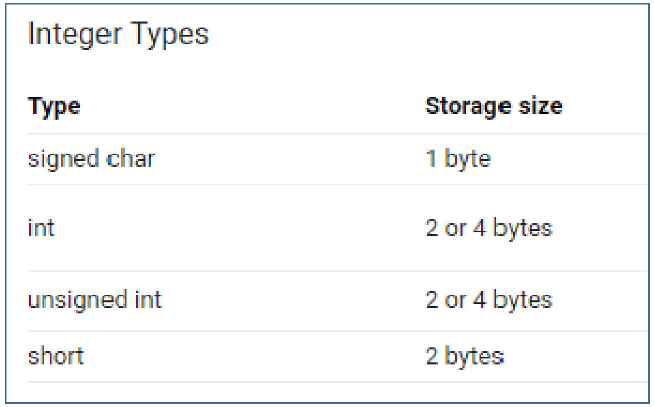
Java Eight Primitive Data Types

Type	Size in Bytes
byte	1 byte
short	2 bytes
int	4 bytes
long	8 bytes



Sizes of Fundamental Types

Type	Size
bool , char , unsigned char , signed char , __int8	1 byte
__int16 , short , unsigned short , wchar_t , __wchar_t	2 bytes
float , __int32 , int , unsigned int , long , unsigned long	4 bytes
double , __int64 , long double , long long	8 bytes

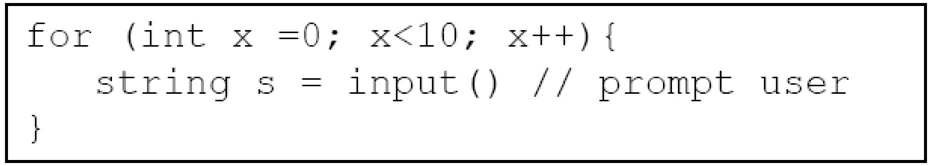


Integer Types

Type	Storage size
signed char	1 byte
int	2 or 4 bytes
unsigned int	2 or 4 bytes
short	2 bytes

ADDRESS BINDING

When you write a code, you don’t worry about memory addresses … but ultimately everything has to be bound to physical memory,.



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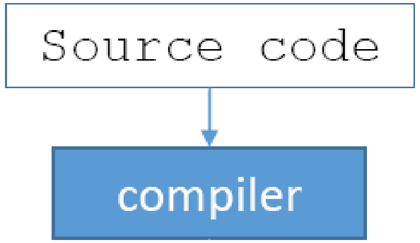
PROGRAM LOADING

`Source code`

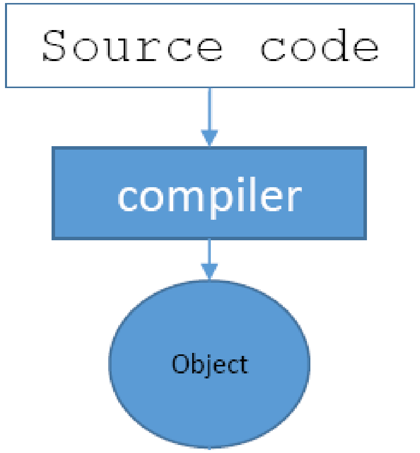
PROGRAM LOADING



Source code

compiler

PROGRAM LOADING

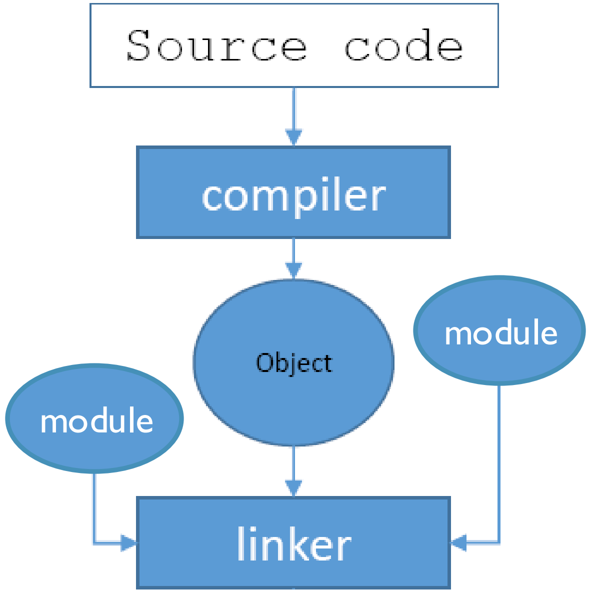


Source code

compiler

Object

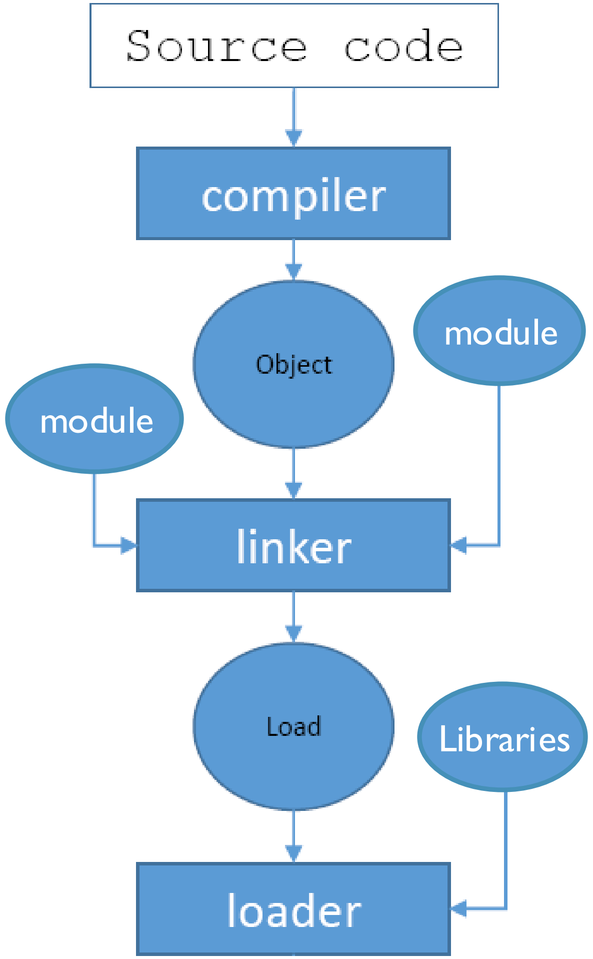
PROGRAM LOADING



- Usually a Linker is needed to incorporate other object modules which the source code is dependent on.

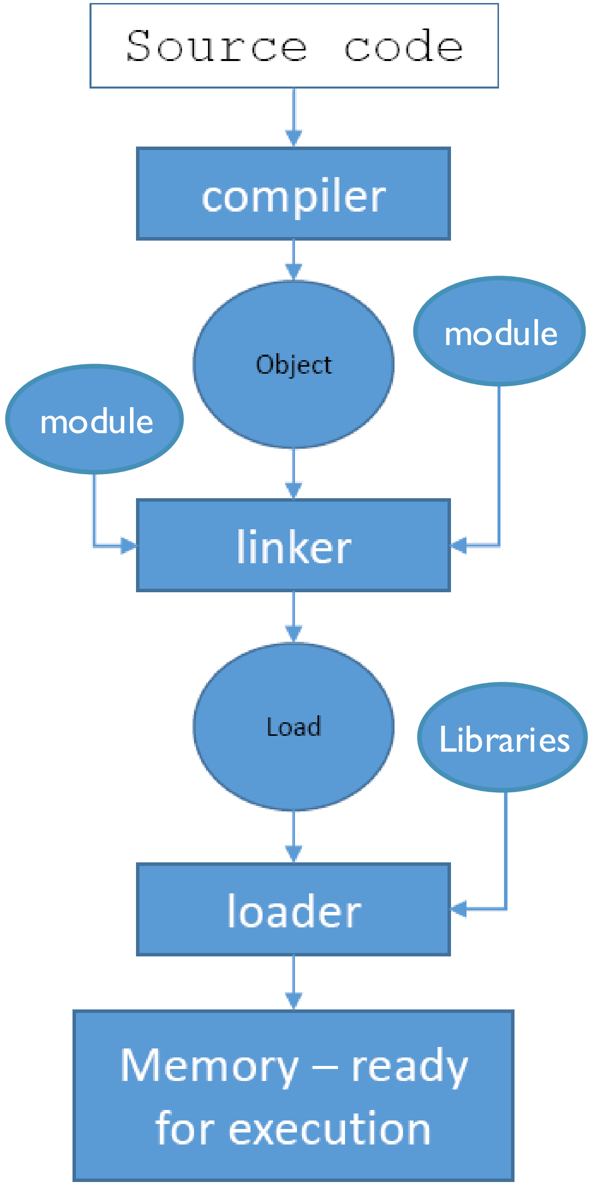
PROGRAM LOADING

- Library calls might be needed as well



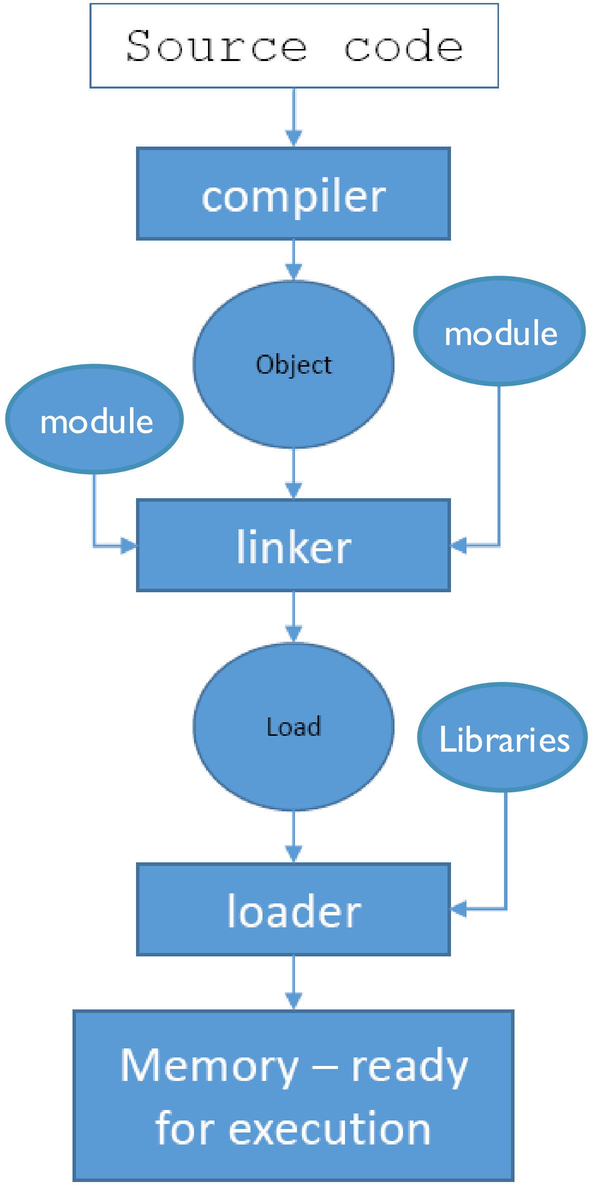
PROGRAM LOADING

- After loading, the program is in memory and ready for execution.



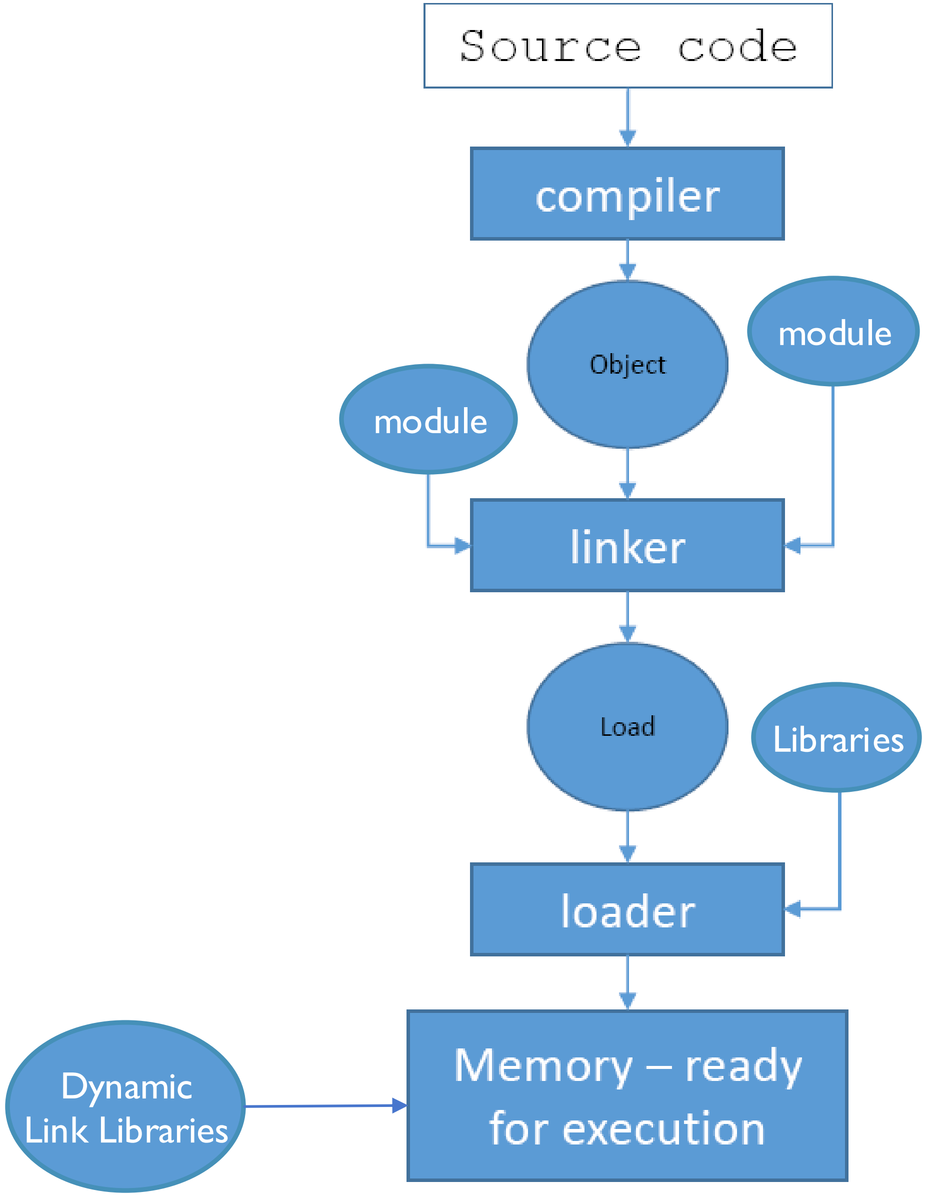
PROGRAM LOADING

- Can you load libraries during execution?



PROGRAM LOADING

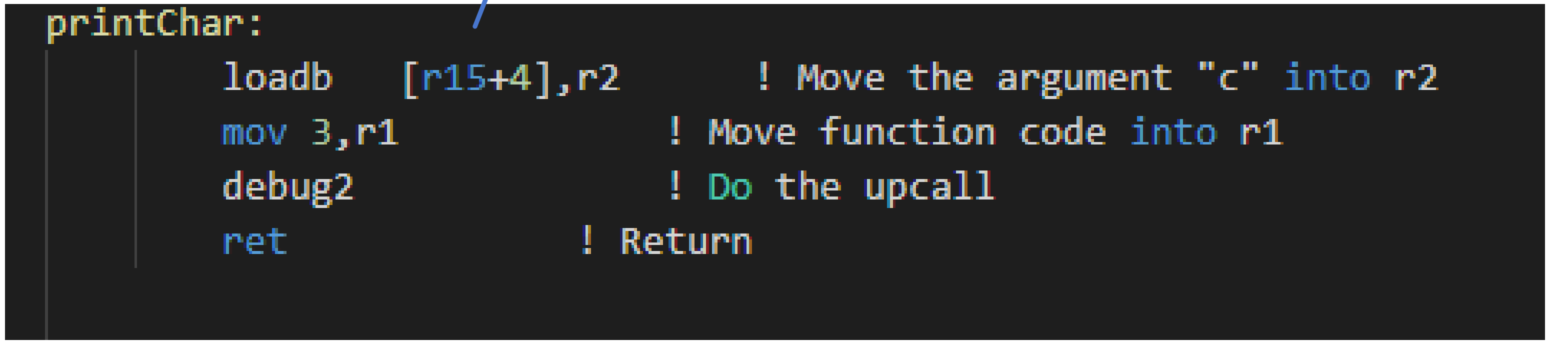
- Can you load libraries during execution?
- Yes: Dynamic Link Libraries; used extensively in modern operating systems.



ADDRESS BINDING

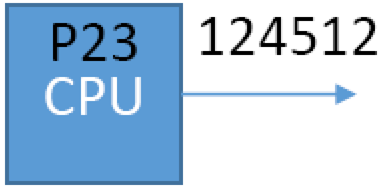
- With address binding done at runtime … the address run by each instruction is a logical address, not a physical one!

[r15+4] is not a real/physical memory address ..

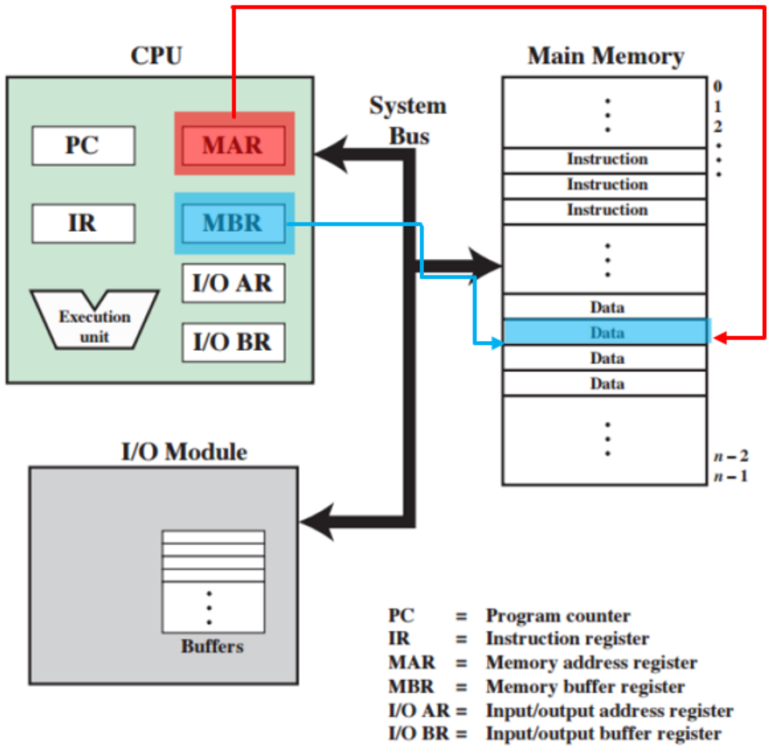


```
printChar:
        loadb   [r15+4],r2      ! Move the argument "c" into r2
        mov 3,r1                ! Move function code into r1
        debug2                  ! Do the upcall
        ret                 ! Return
```

LOGICAL TO PHYSICAL ADDRESS

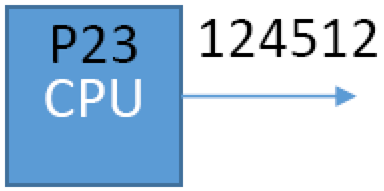


The address generated by a CPU is called a logical address, and most often referred to as virtual address



PC	=	Program counter
IR	=	Instruction register
MAR	=	Memory address register
MBR	=	Memory buffer register
I/O AR	=	Input/output address register
I/O BR	=	Input/output buffer register

LOGICAL TO PHYSICAL ADDRESS



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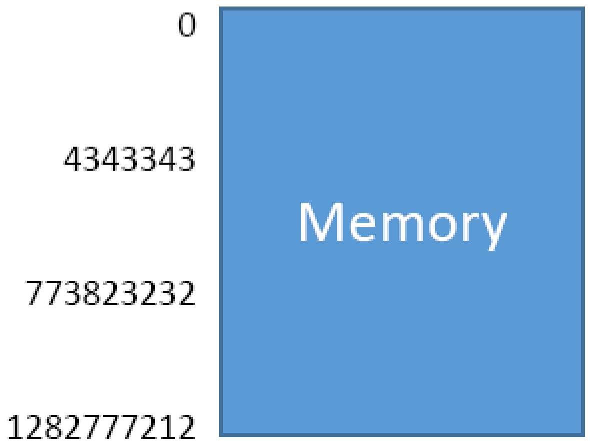
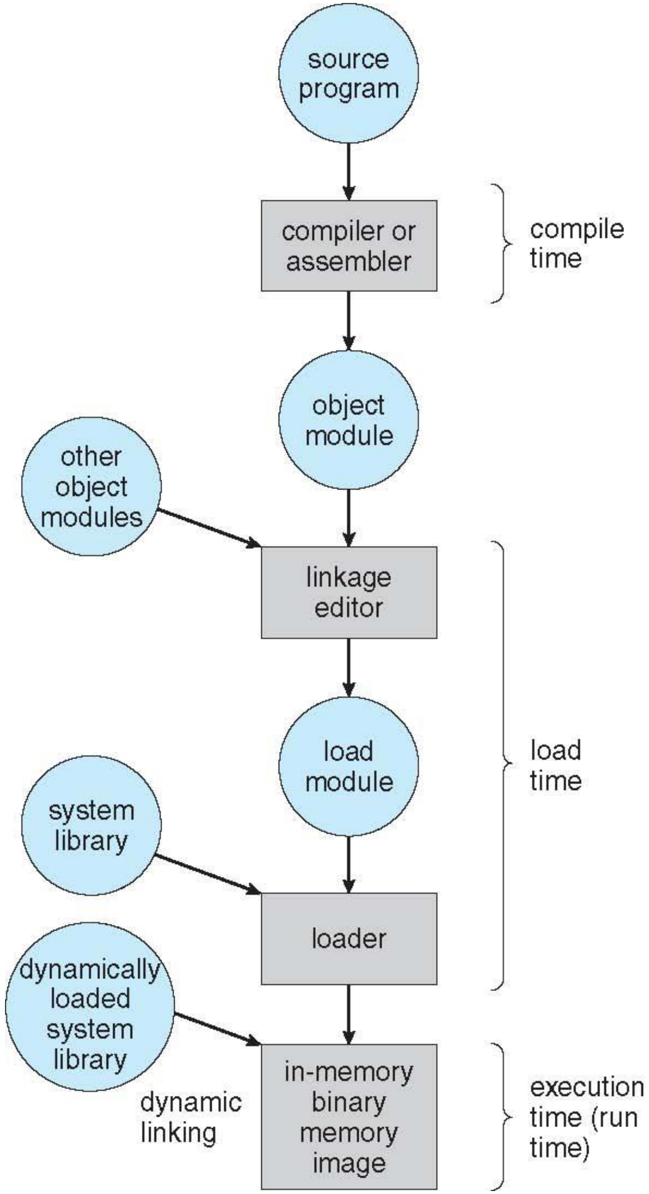


The address that the memory unit (memory) reasons about is referred to as <u>physical</u> address

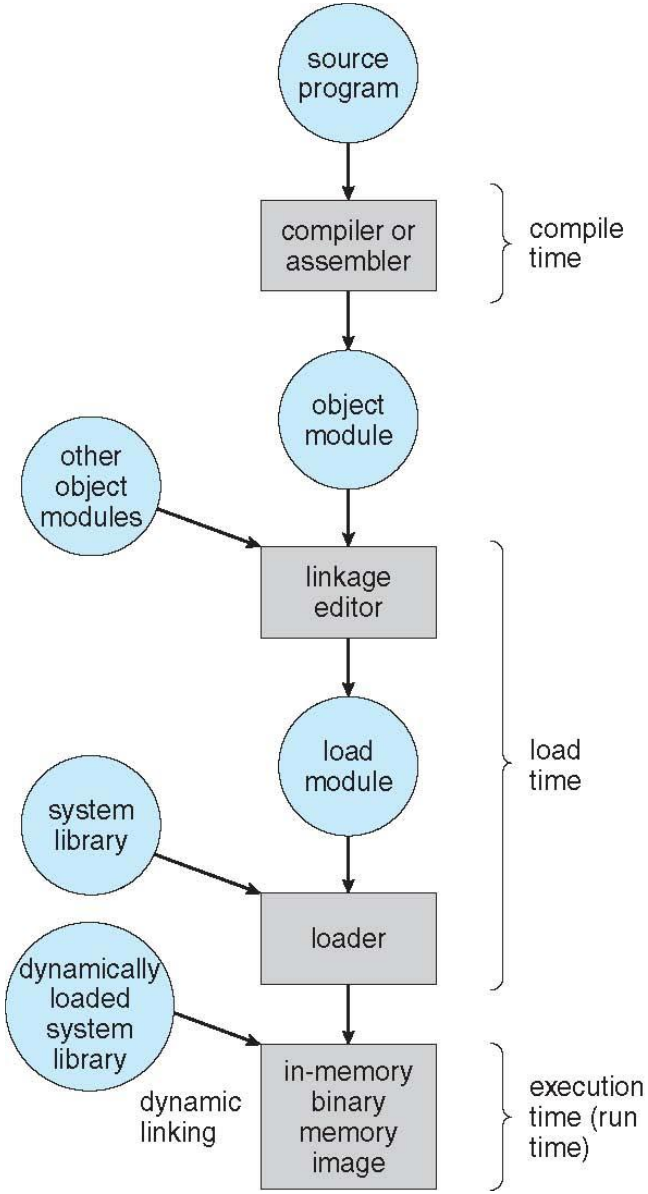
ADDRESS BINDING

- When do we bind source address values to physical memory?



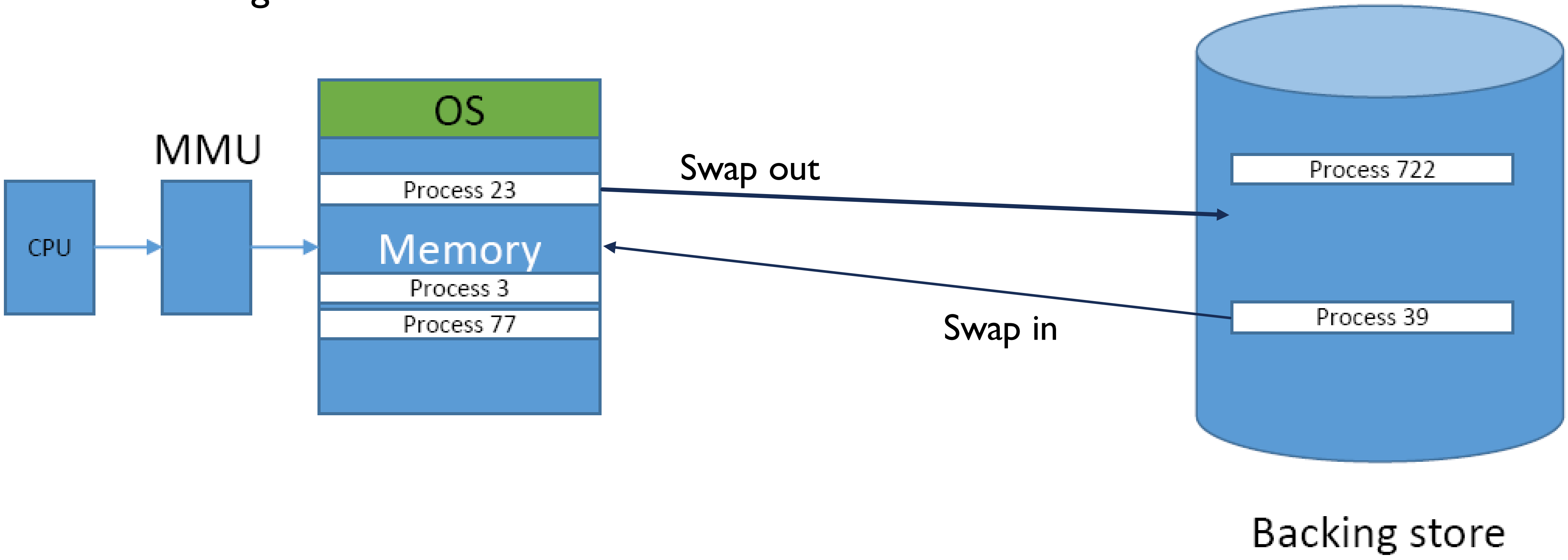
ADDRESS BINDING

- Address binding of instructions and data to memory addresses can happen at three different stages
  - **Compile time**: If memory location known a priori, **absolute code** can be generated; must recompile code if starting location changes
  - **Load time**: Must generate **relocatable code** if memory location is not known at compile time
  - **Execution time**: Binding delayed until run time if the process can be moved during its execution from one memory segment to another
    - Need hardware support for address maps (e.g., base and limit registers)



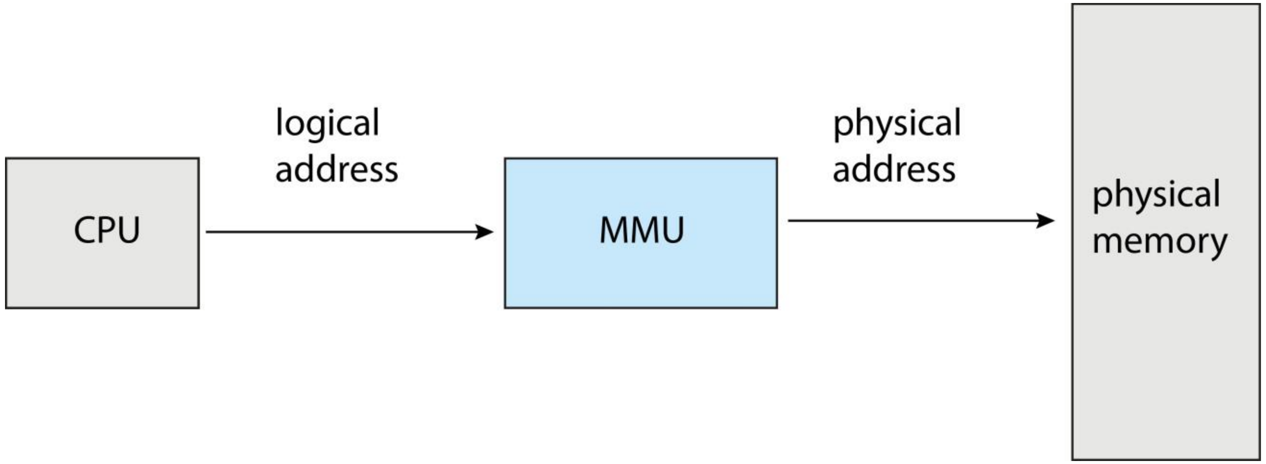
SWAPPING

- When process are swapped back, they don't necessary sit in the same place in memory!
- This is another reason why runtime address binding is beneficial.

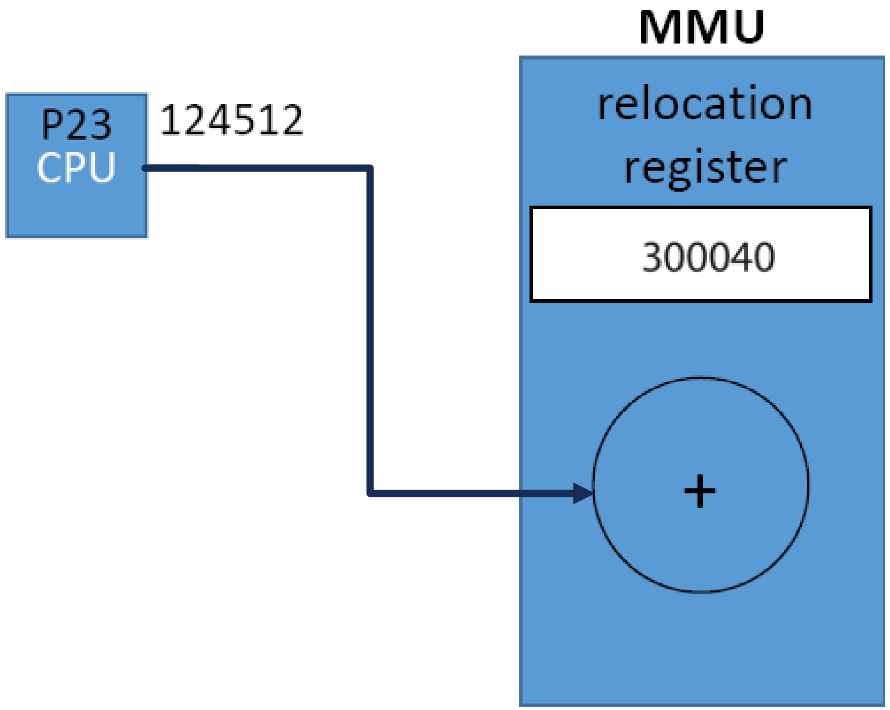


ADDRESS TRANSLATION

- Hardware device that at run time maps virtual to physical address



MEMORY MANAGEMENT UNIT



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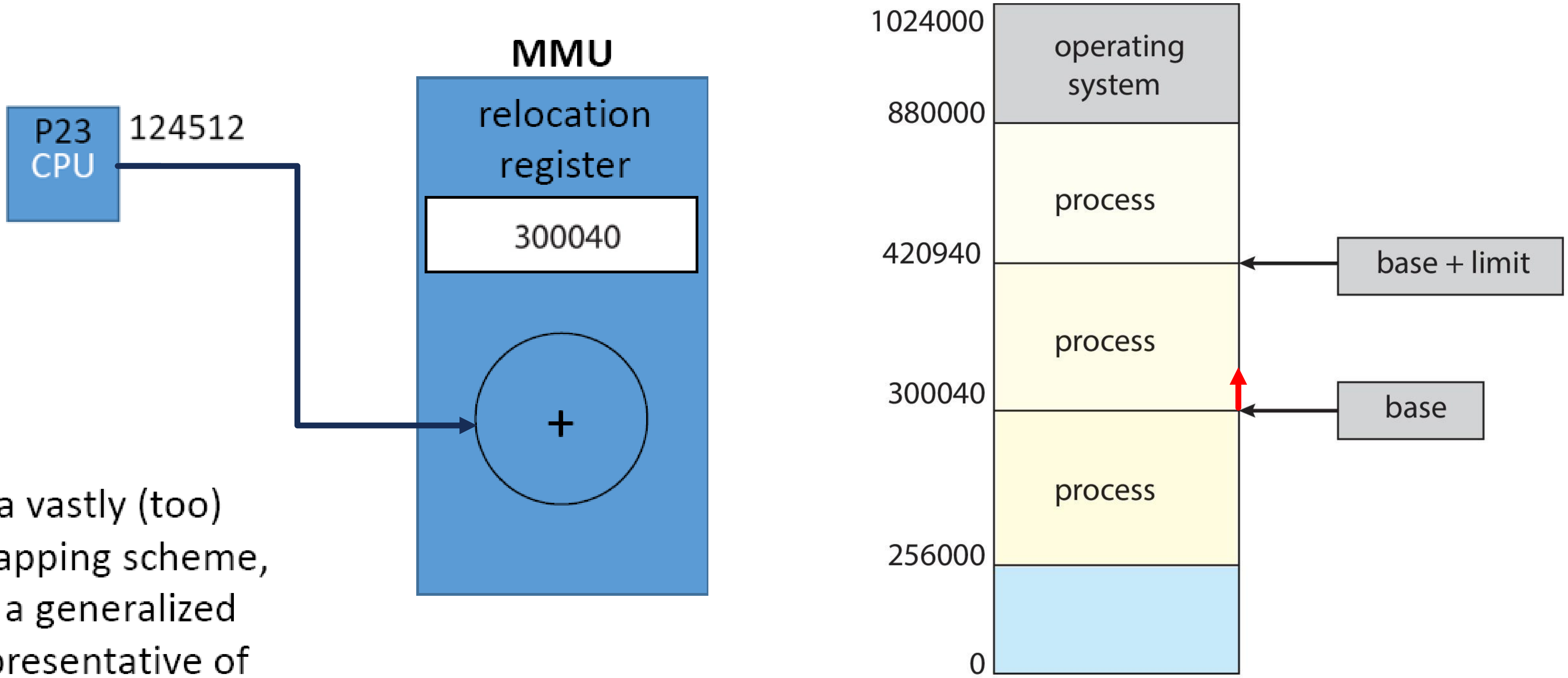
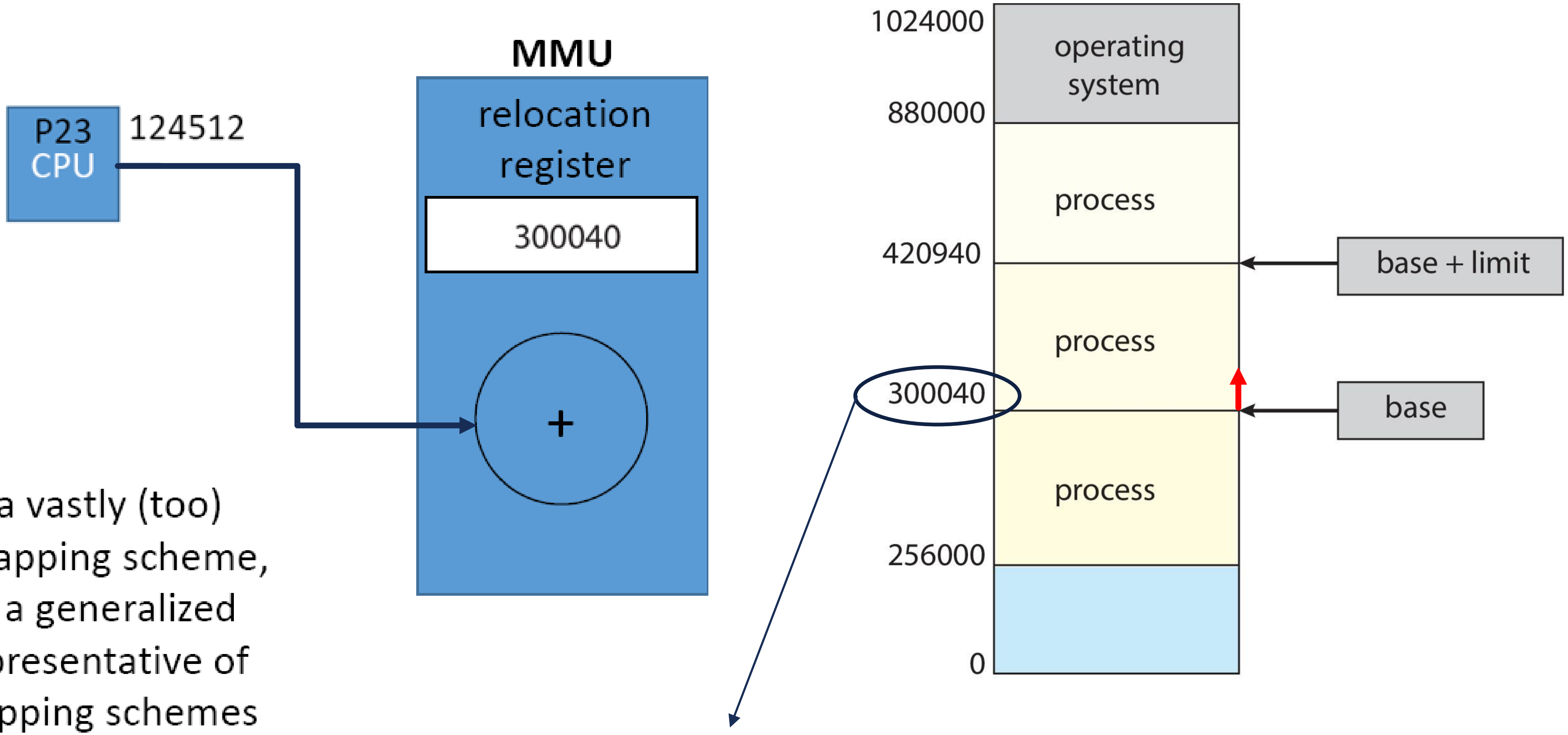


This is a vastly (too) simple mapping scheme, but it is a generalized form representative of most mapping schemes

MEMORY MANAGEMENT UNIT



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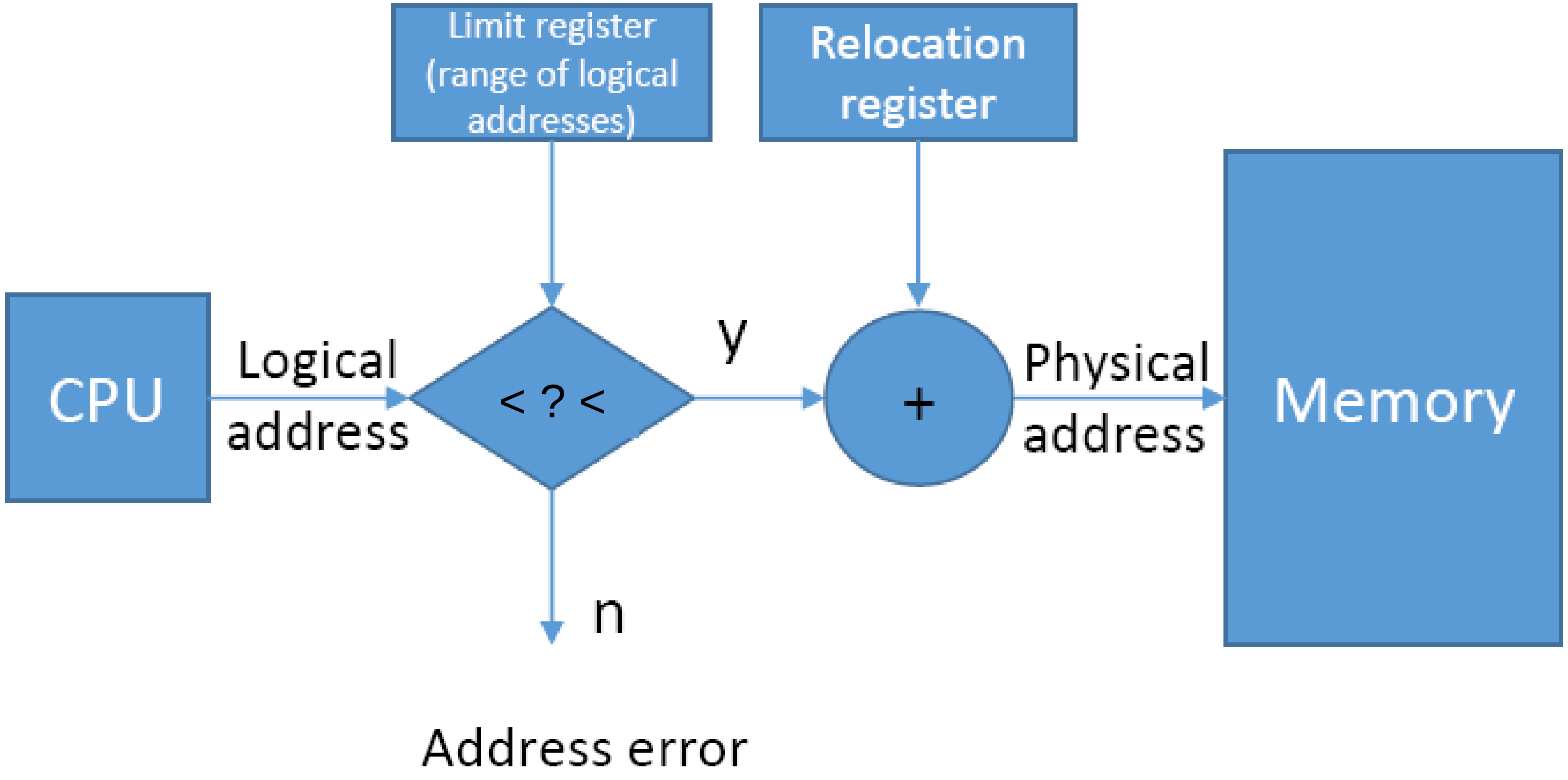
This could be logical address of '0'

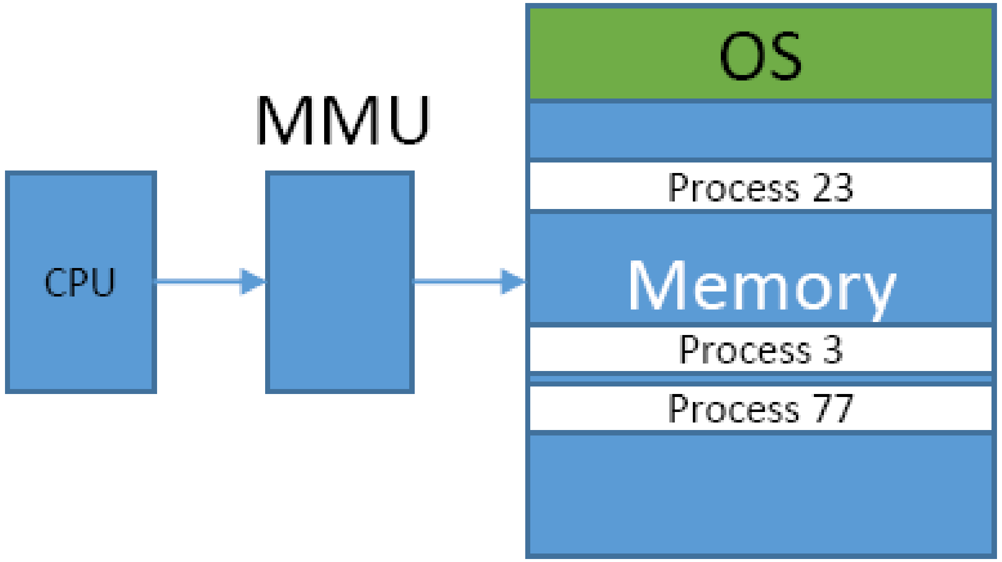
MEMORY PROTECTION AND TRANSLATION



MEMORY FORM

Regardless of how the MMU maps a logical/virtual address to a physical one …

Q: What is one assumption we've made about how processes fit into memory?



MEMORY ALLOCATION

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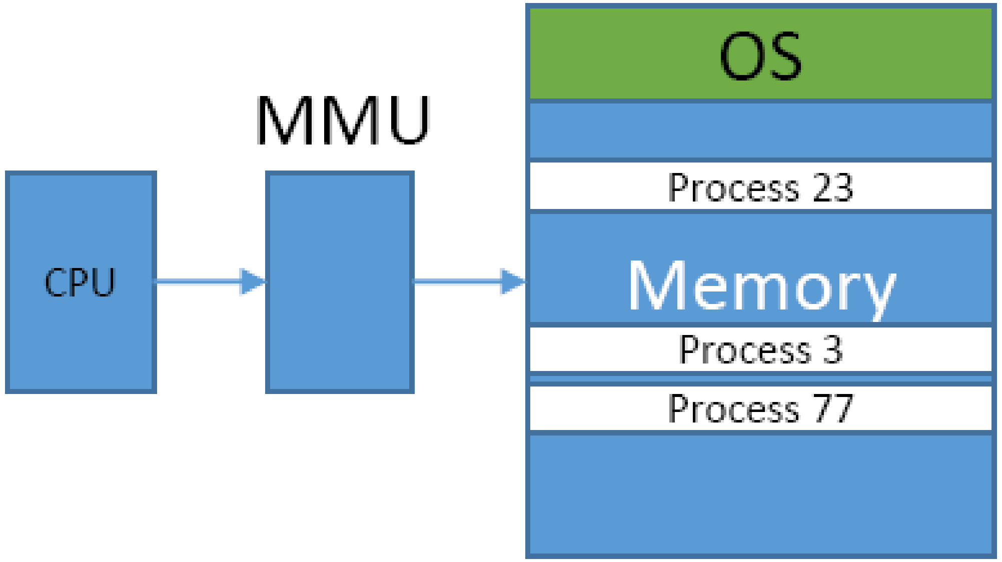
<u>Contiguous</u> memory allocation



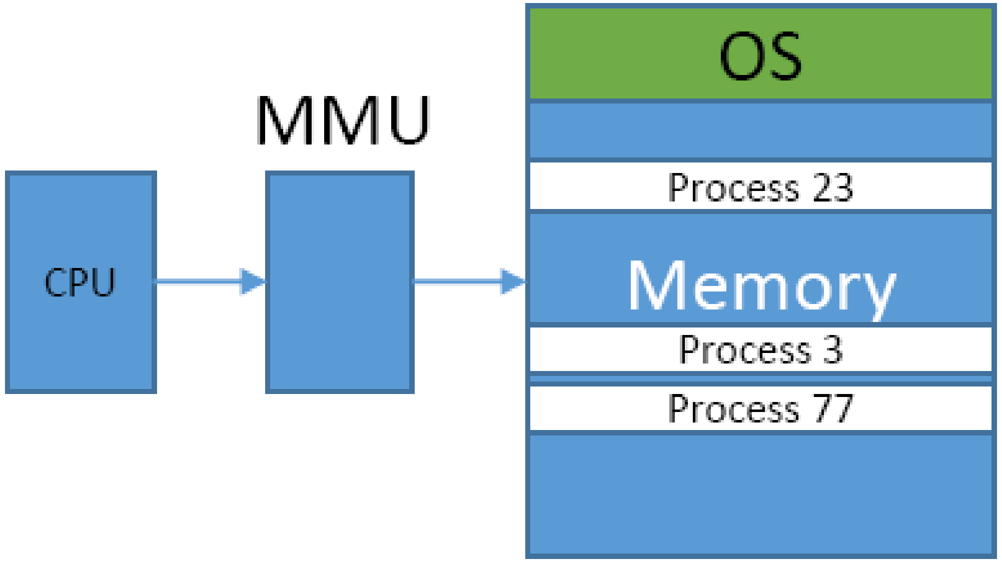
MEMORY ALLOCATION

Regardless of how the MMU maps a logical/virtual address to a physical one …

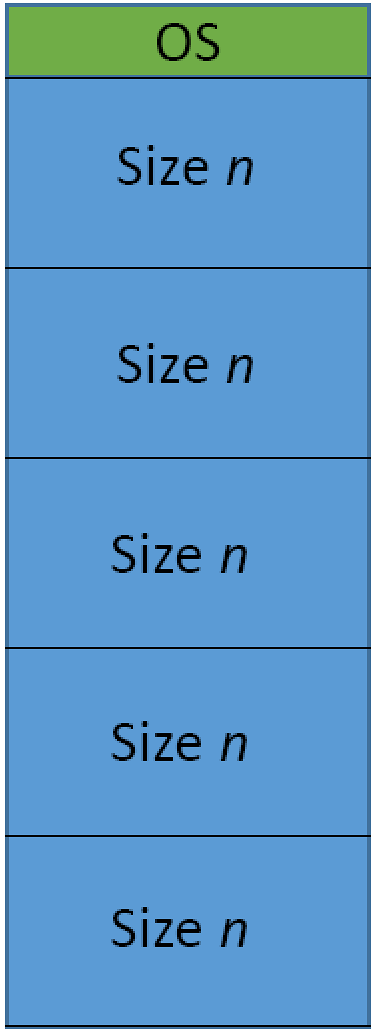
Q: What is one assumption we've made about how processes fit into memory?

<u>Contiguous</u> memory allocation

- Memory Allocation algorithms
- Memory fragmentation

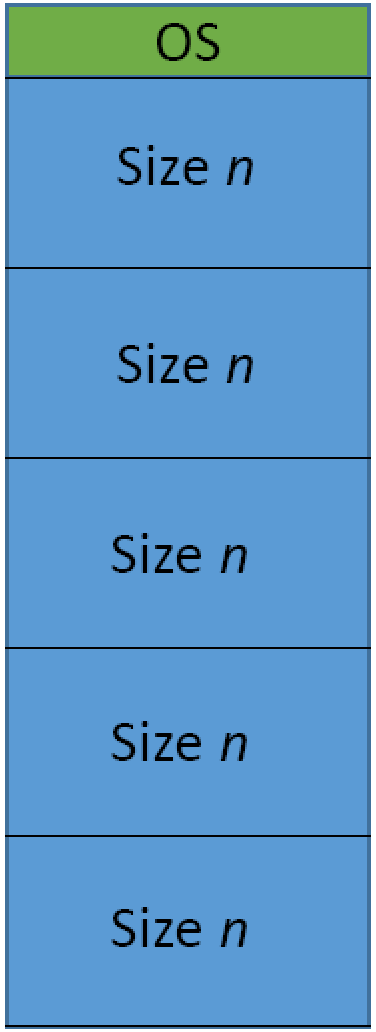


MEMORY ALLOCATION



The earliest partition methods relied on fixed-sized partitions of size *n*

MEMORY ALLOCATION



OS

Size *n*

Size *n*

Size *n*

Size *n*

Size *n*

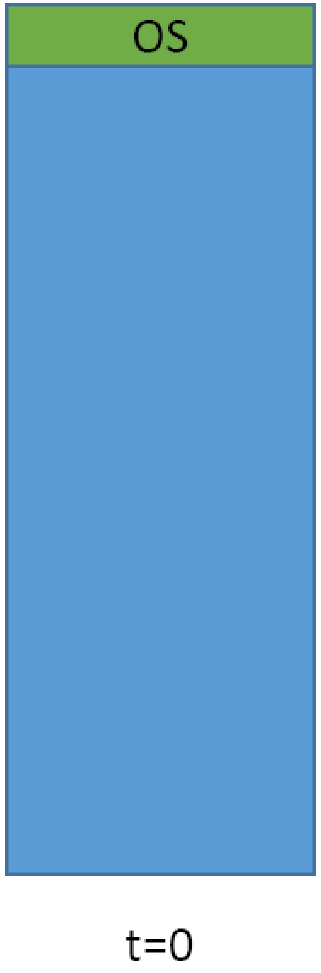
The earliest partition methods relied on fixed-sized partitions of size *n*

Assume a Process of size K

Q: What are the advantages of this approach?

Q: What are the disadvantages of this approach?

MEMORY ALLOCATION



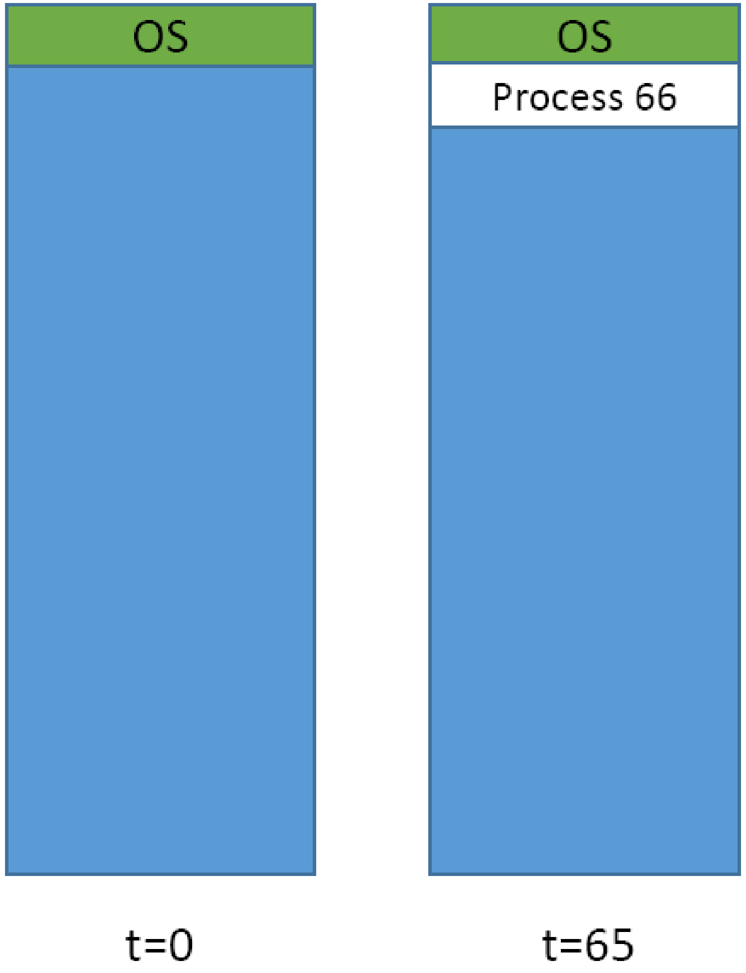
Assuming variable partition size
We just allocate enough memory for the process

At t=0, no process is in memory
... and process 66 is ready

Process 66
Size : 7

Q: Where should it be placed in memory?

MEMORY ALLOCATION

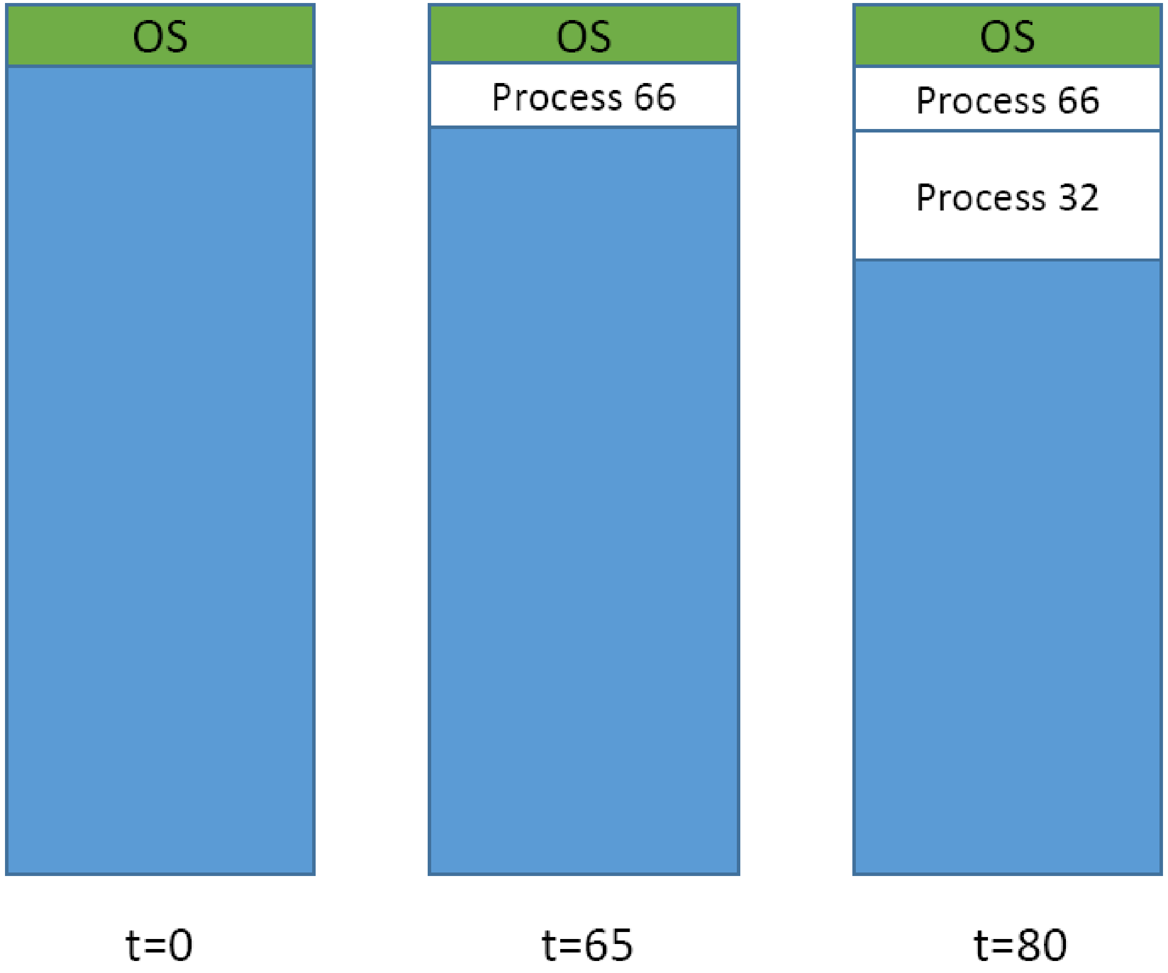


At t=65, process 66 is still running, and another process is ready …

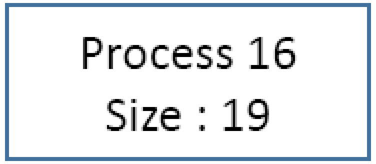
Process 32
Size : 12

Q: Where should it be placed?

MEMORY ALLOCATION

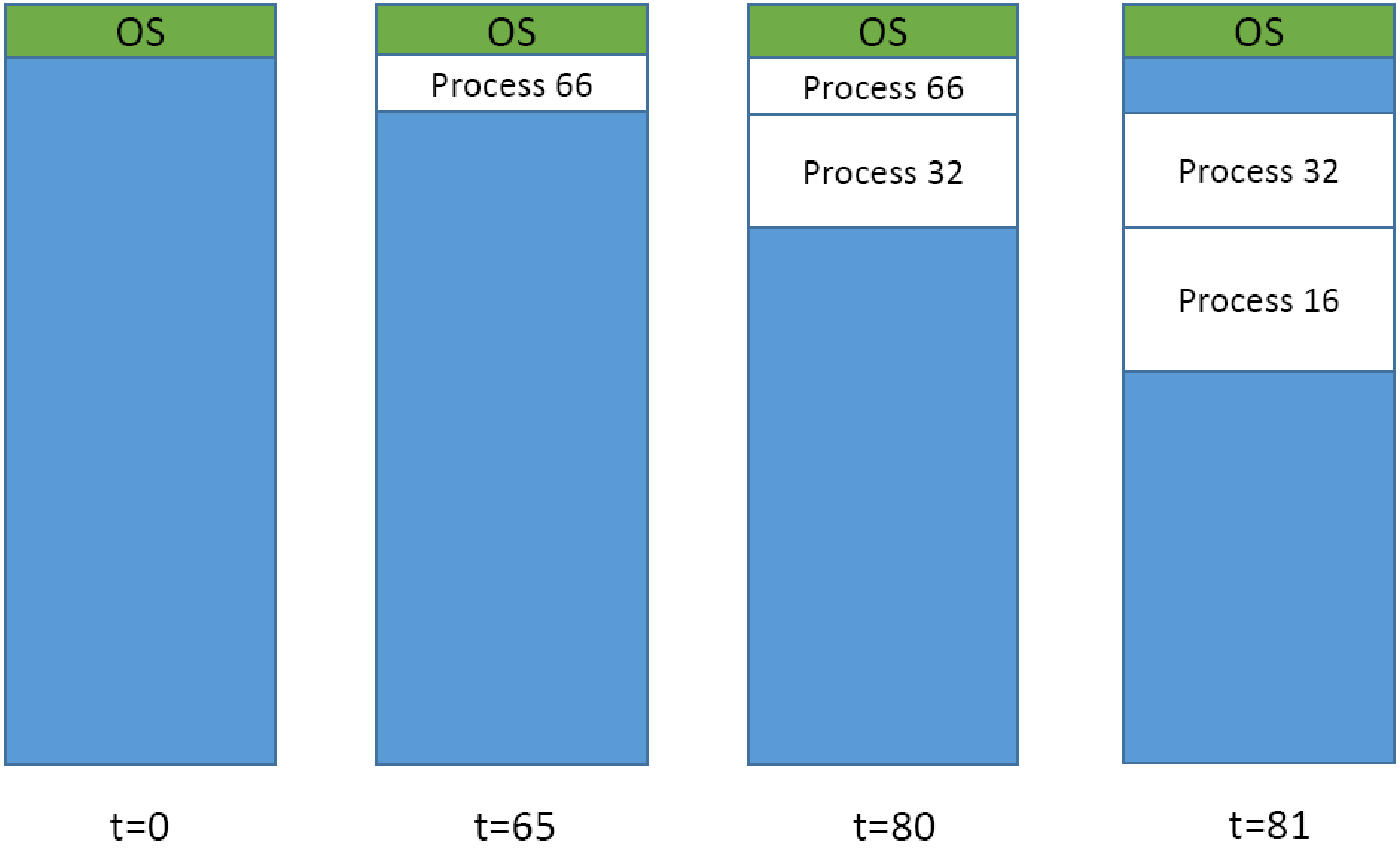


At t=80, process 66 completes, and at t=81, process 16 is ready

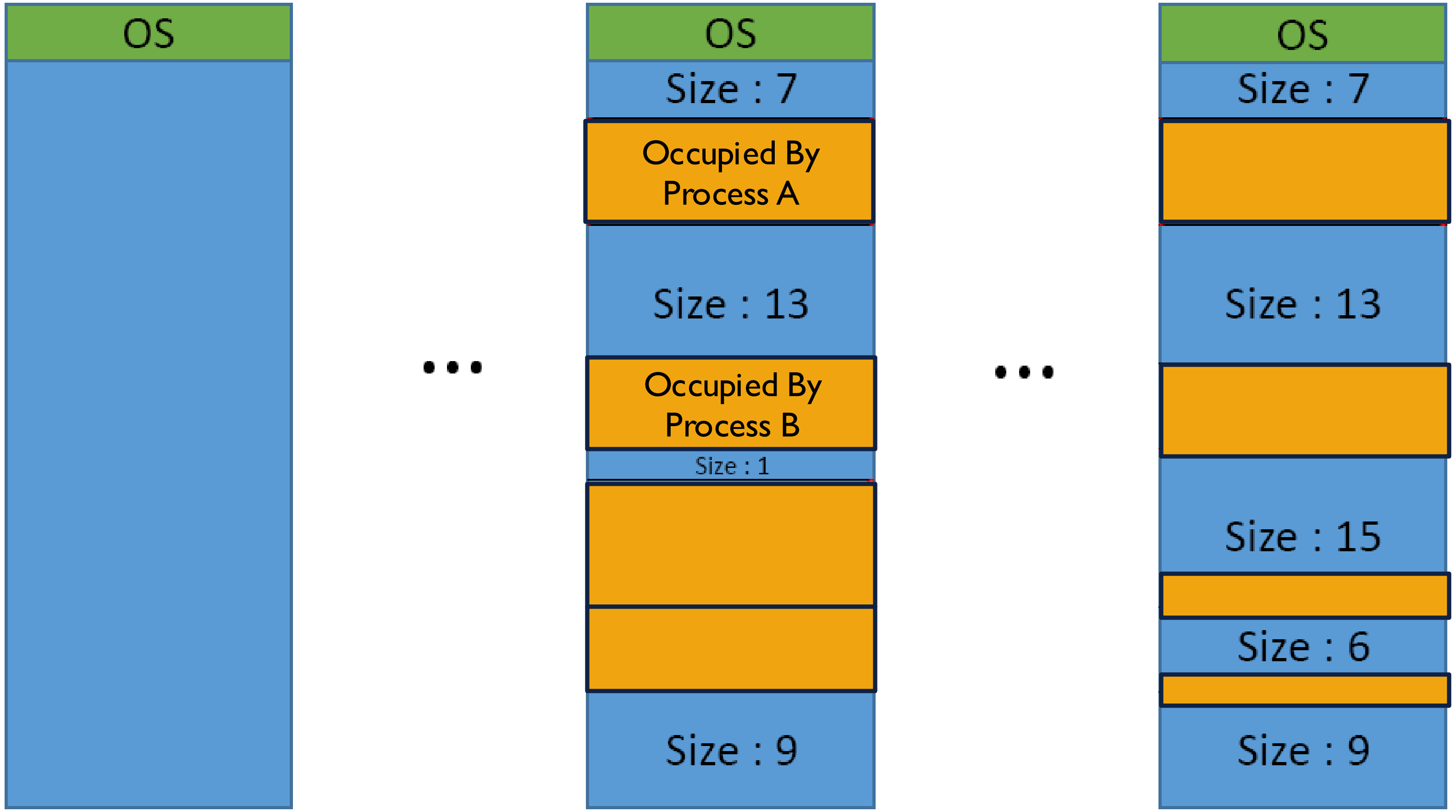


Q: Where should it be placed?

MEMORY ALLOCATION

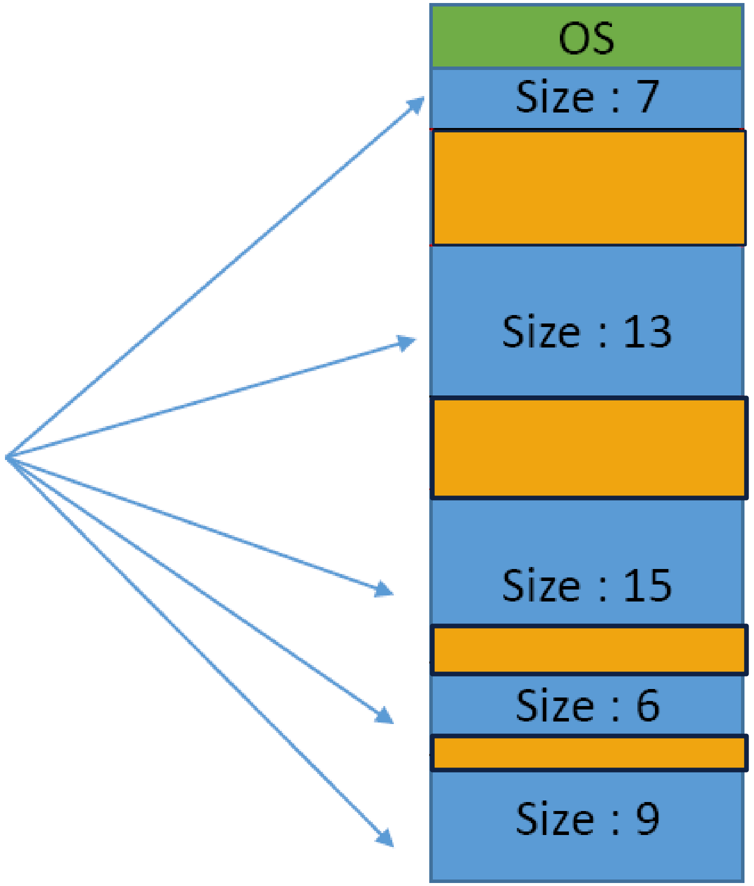


MEMORY ALLOCATION



MEMORY HOLES

Available slots are called memory holes

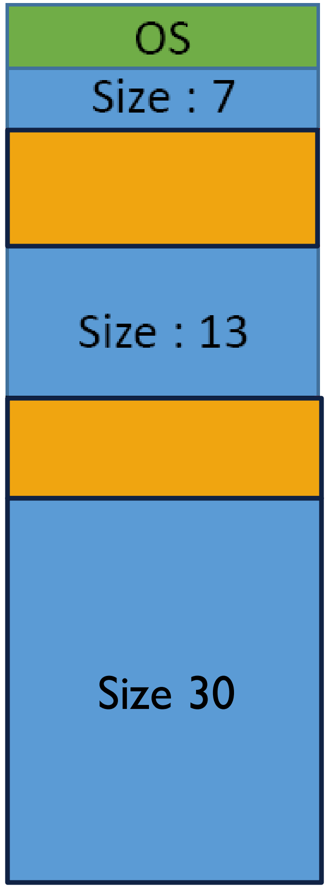


MEMORY ALLOCATION STRATEGY

Process 77
Size : 8

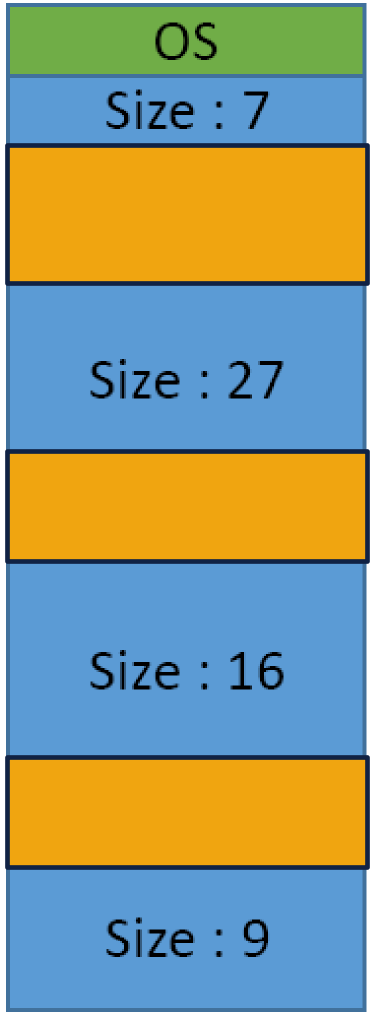
At time t, process 77 is ready, and the OS tries to place it into memory …

Task : enumerate three possible allocation strategies … where should Process 77 be placed?



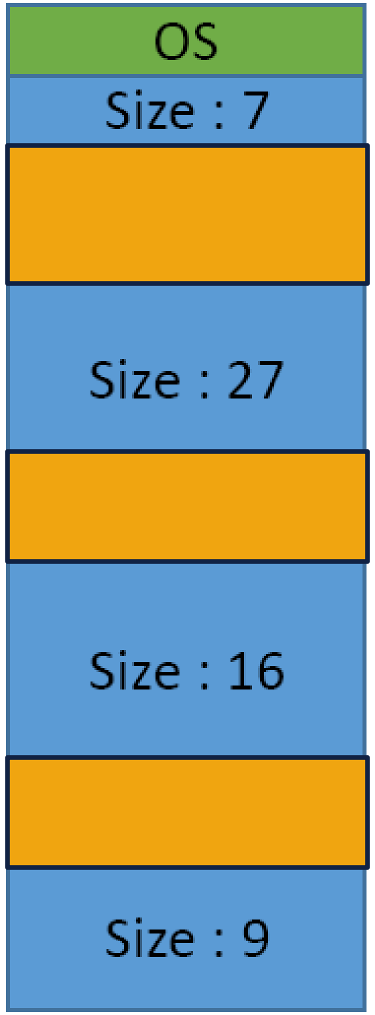
MEMORY ALLOCATION STRATEGY

- Best Fit: Place the process into the memory hole closest to the size required.



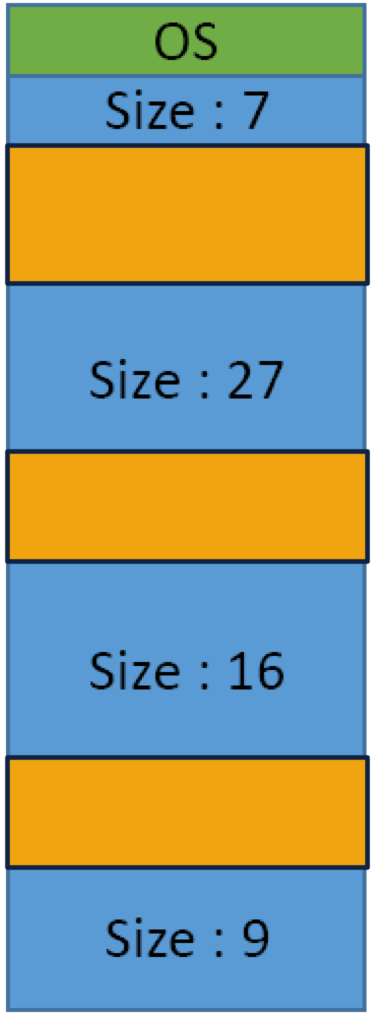
MEMORY ALLOCATION STRATEGY

- Best Fit: Place the process into the memory hole closest to the size required.
- Worst Fit: Place the process into the largest memory hole.

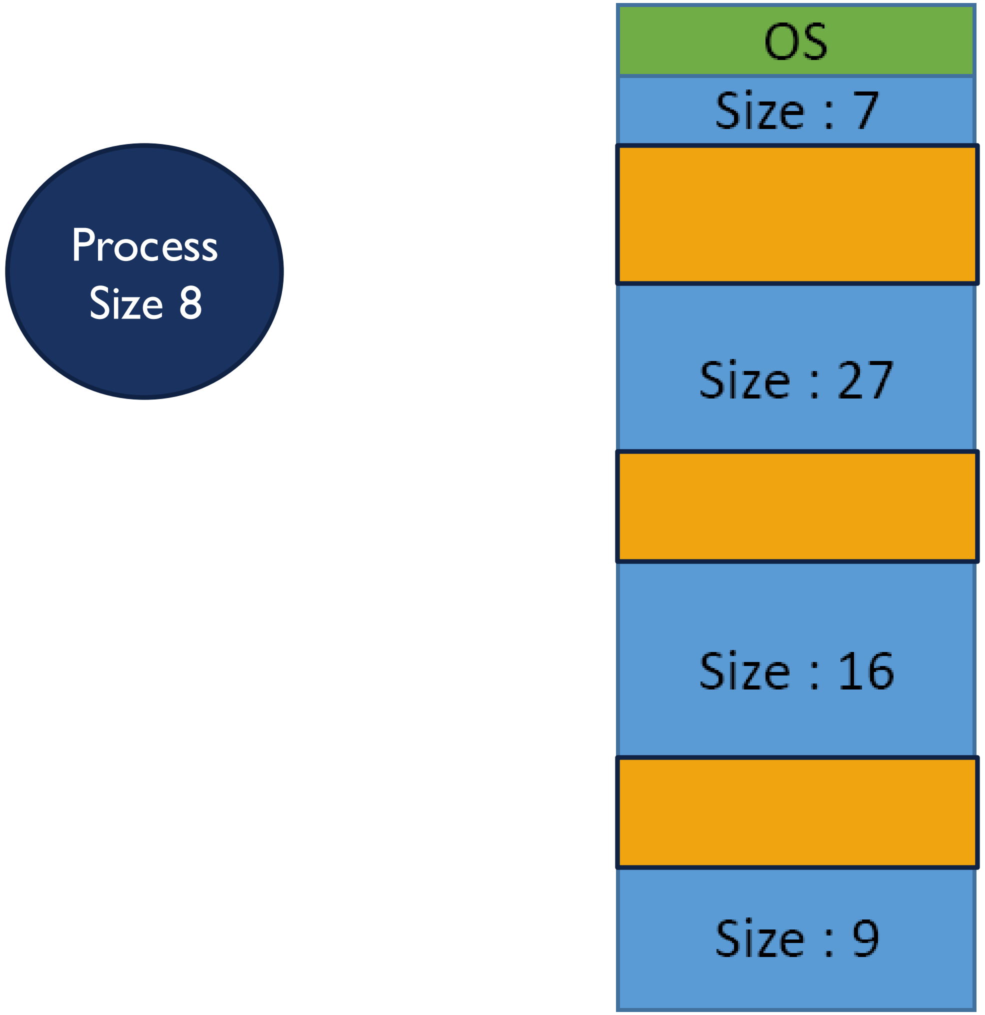


MEMORY ALLOCATION STRATEGY

- Best Fit: Place the process into the memory hole closest to the size required.
- Worst Fit: Place the process into the largest memory hole.
- First Fit: Place the process into the first memory space that can hold it.
- What are the advantages of each?

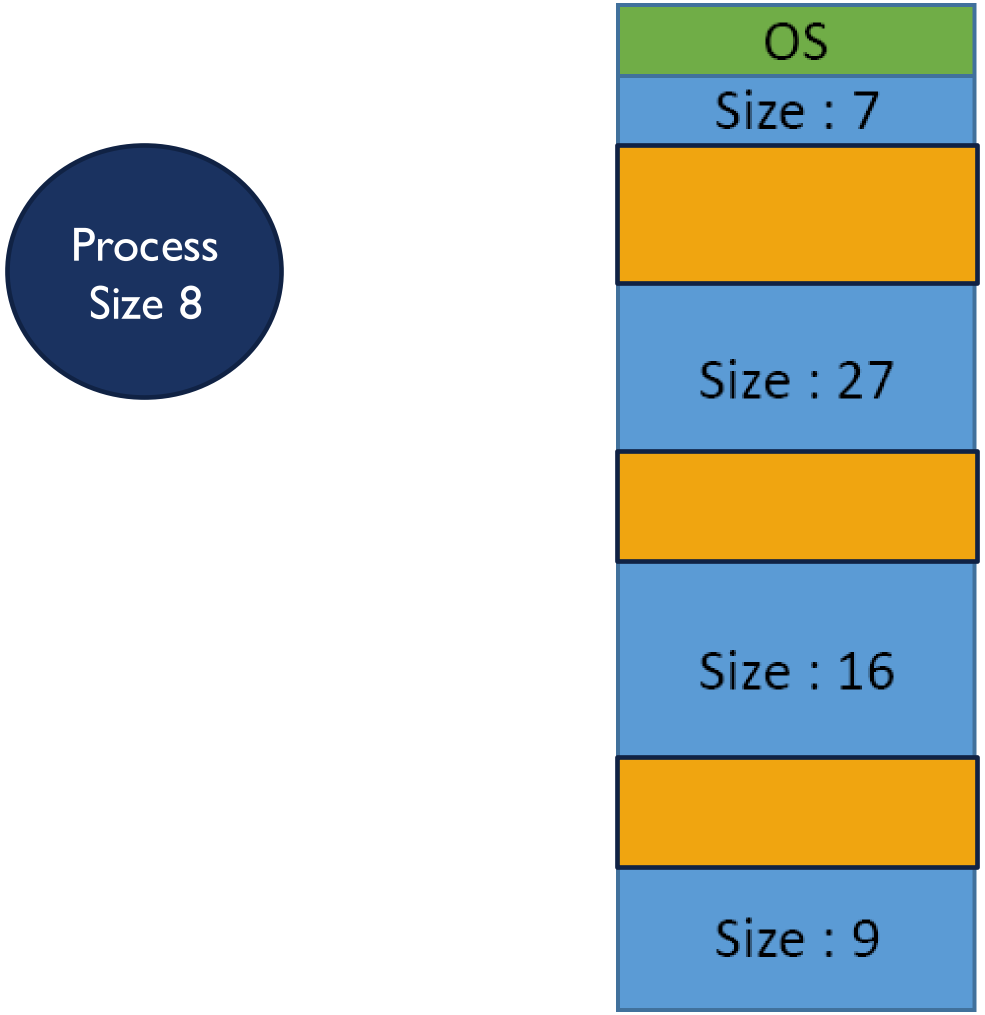


MEMORY ALLOCATION ALGORITHM



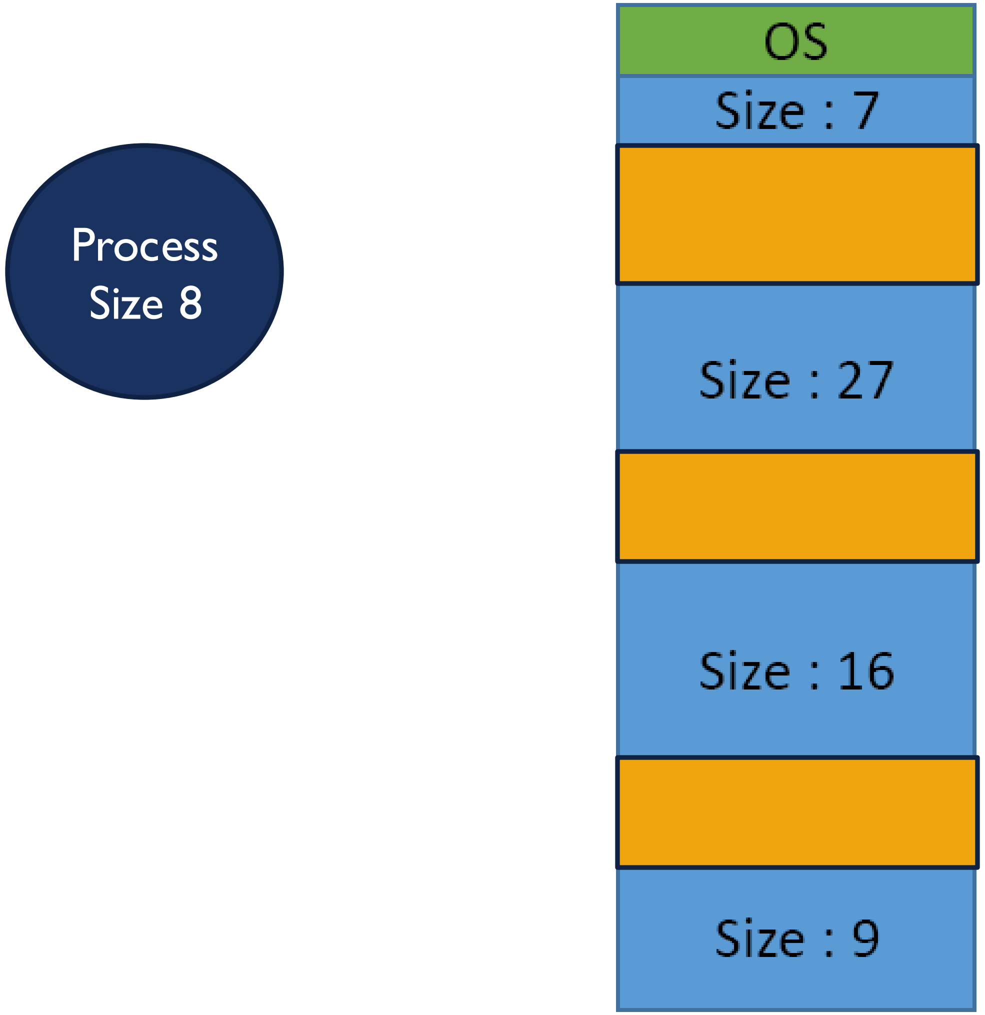
FIRST FIT

- First Fit: Place the process into the first memory space that can hold it.



FIRST FIT

- First Fit: Place the process into the first memory space that can hold it.
- Fastest: No need to search through all memory.



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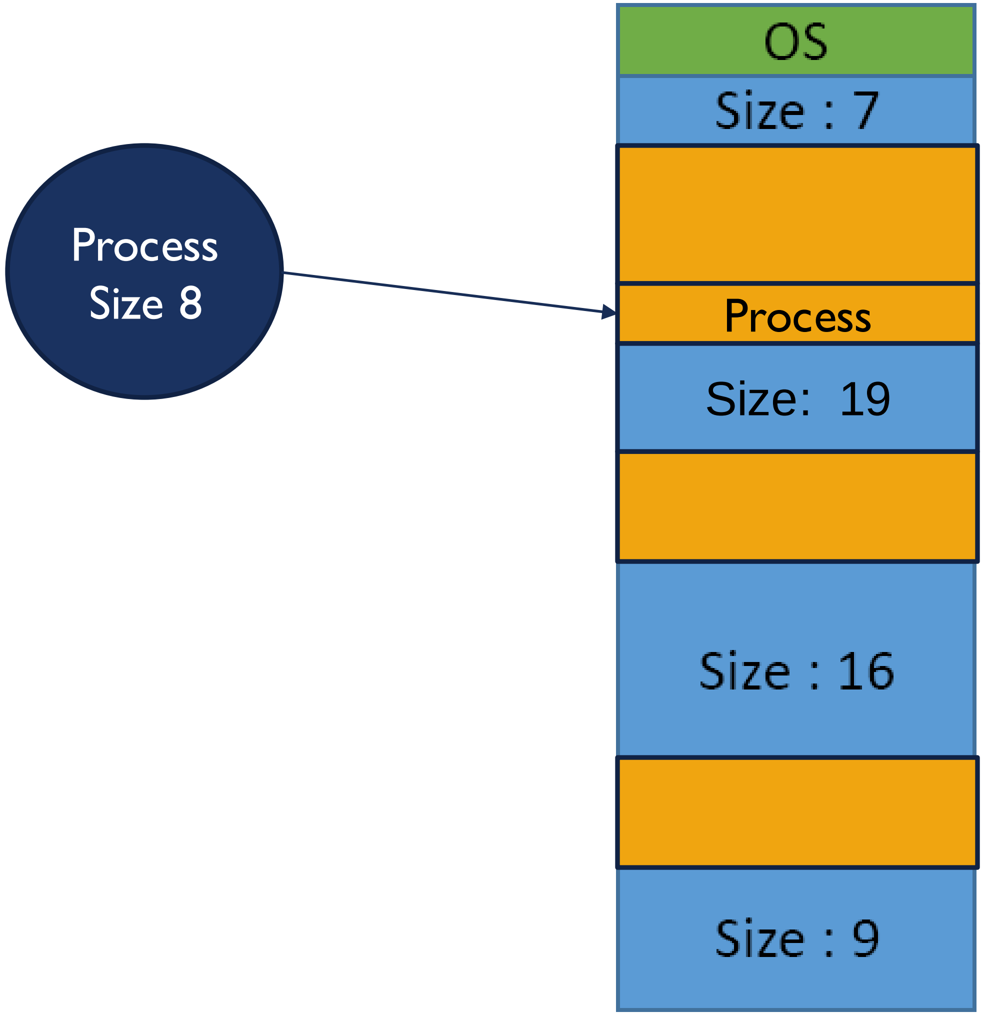
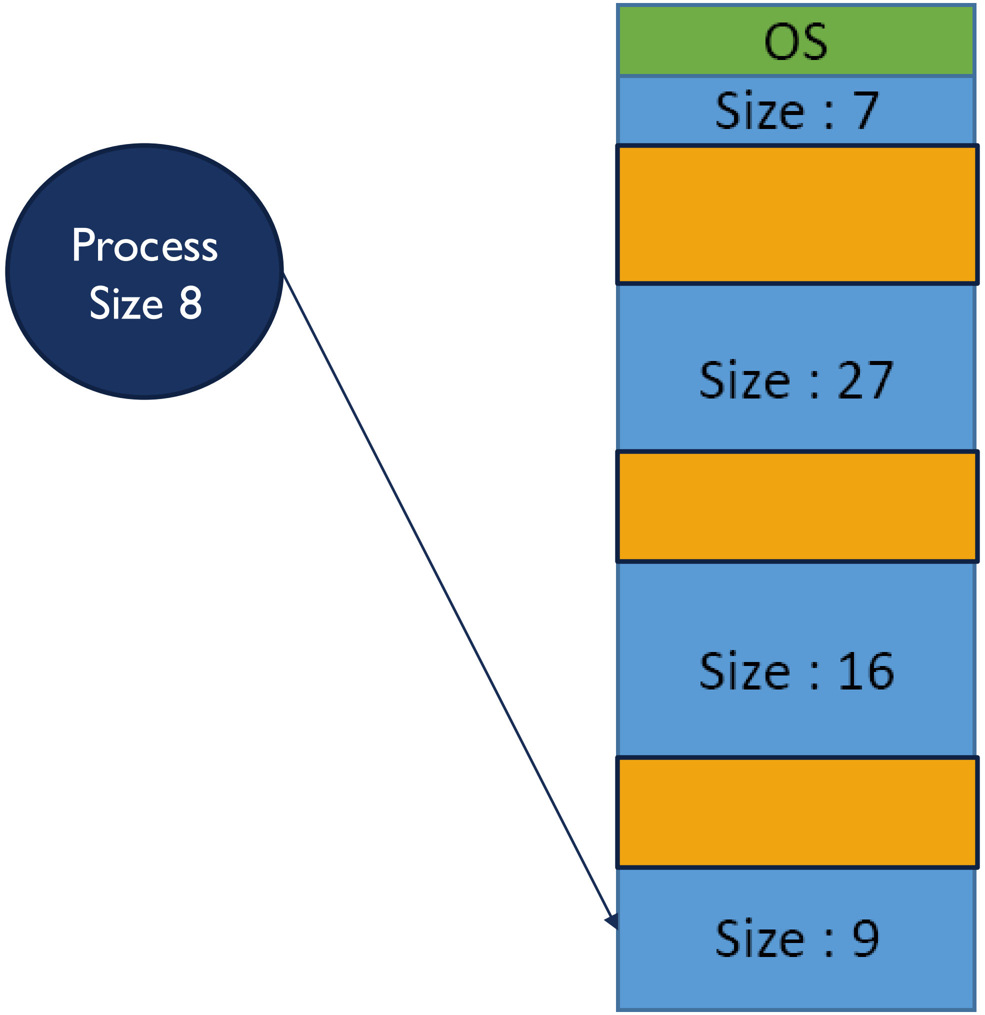
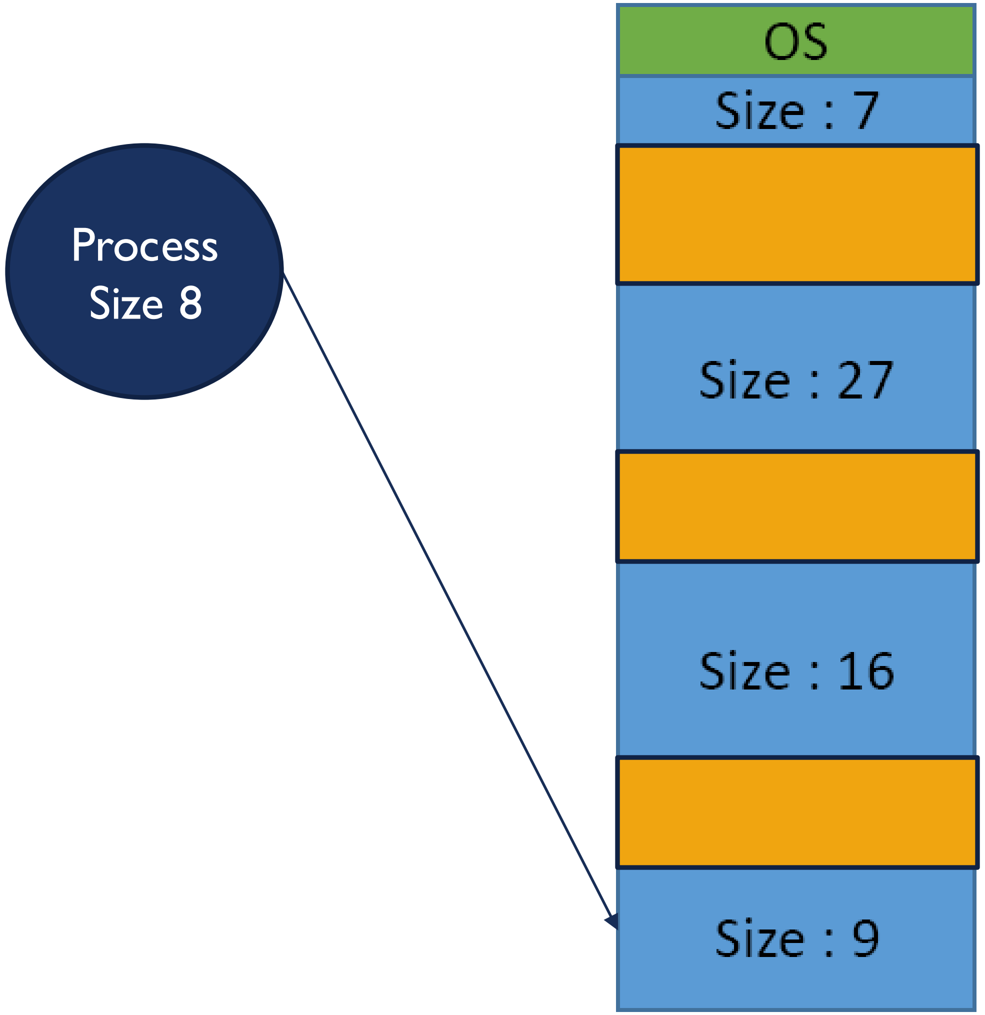


BEST FIT



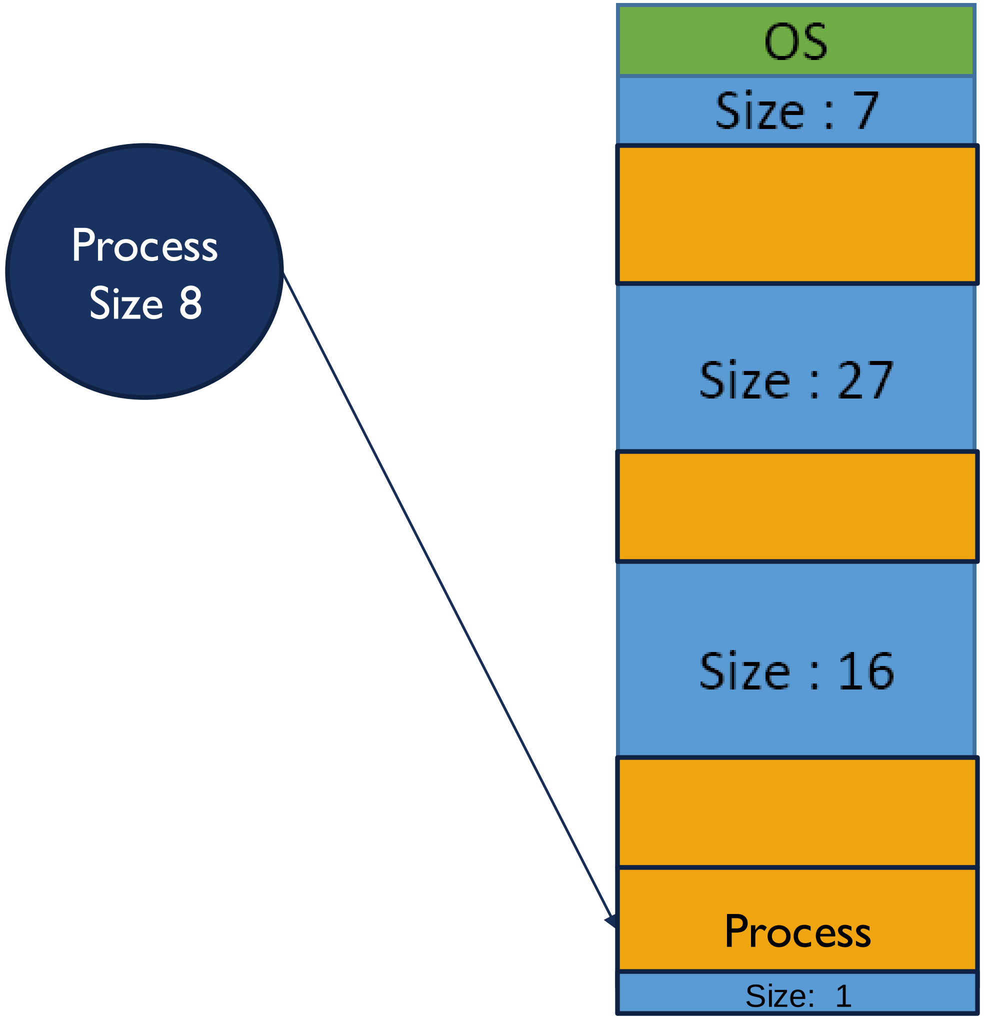
BEST FIT

- Best Fit: Smallest hole left behind

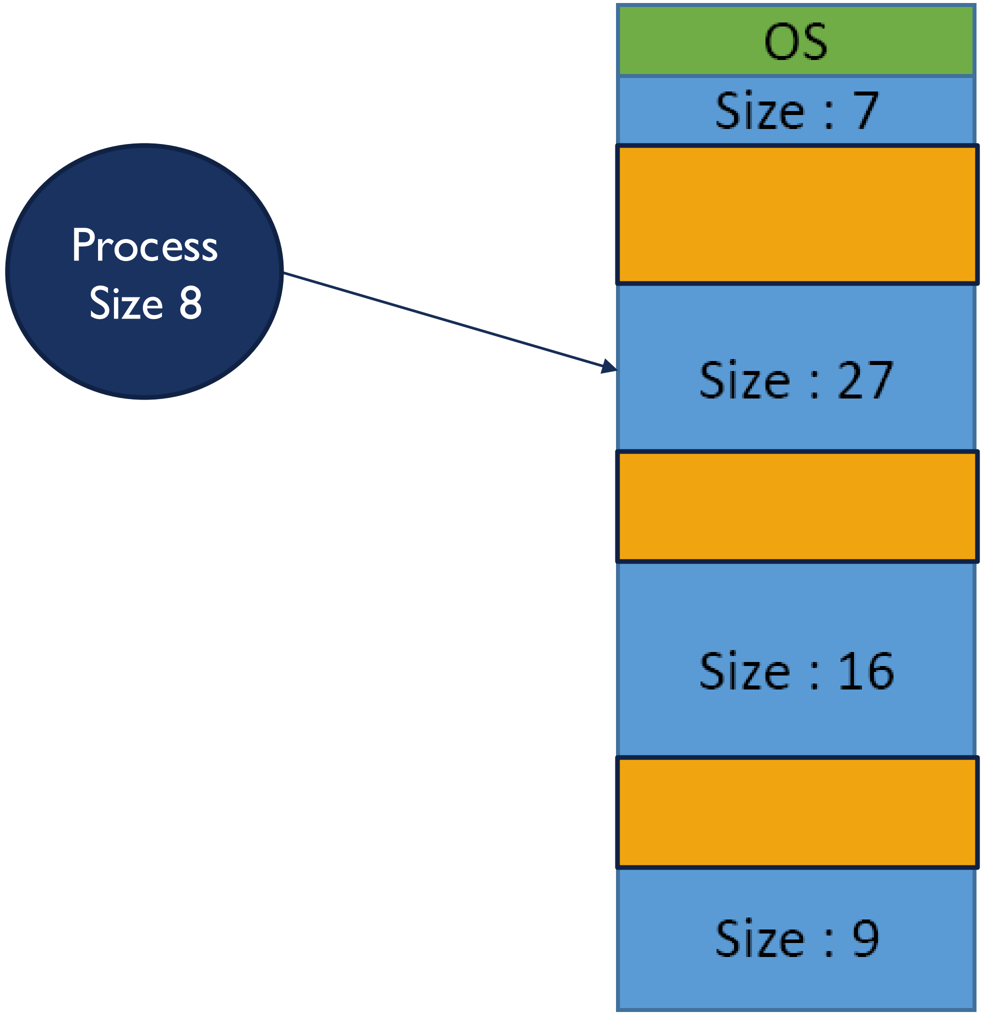


BEST FIT

- Best Fit: Smallest hole left behind
- Smallest hole = less wasted memory space.



WORST FIT



- Worst Fit: Largest hole left behind.
- Why would that be good?

WORST FIT

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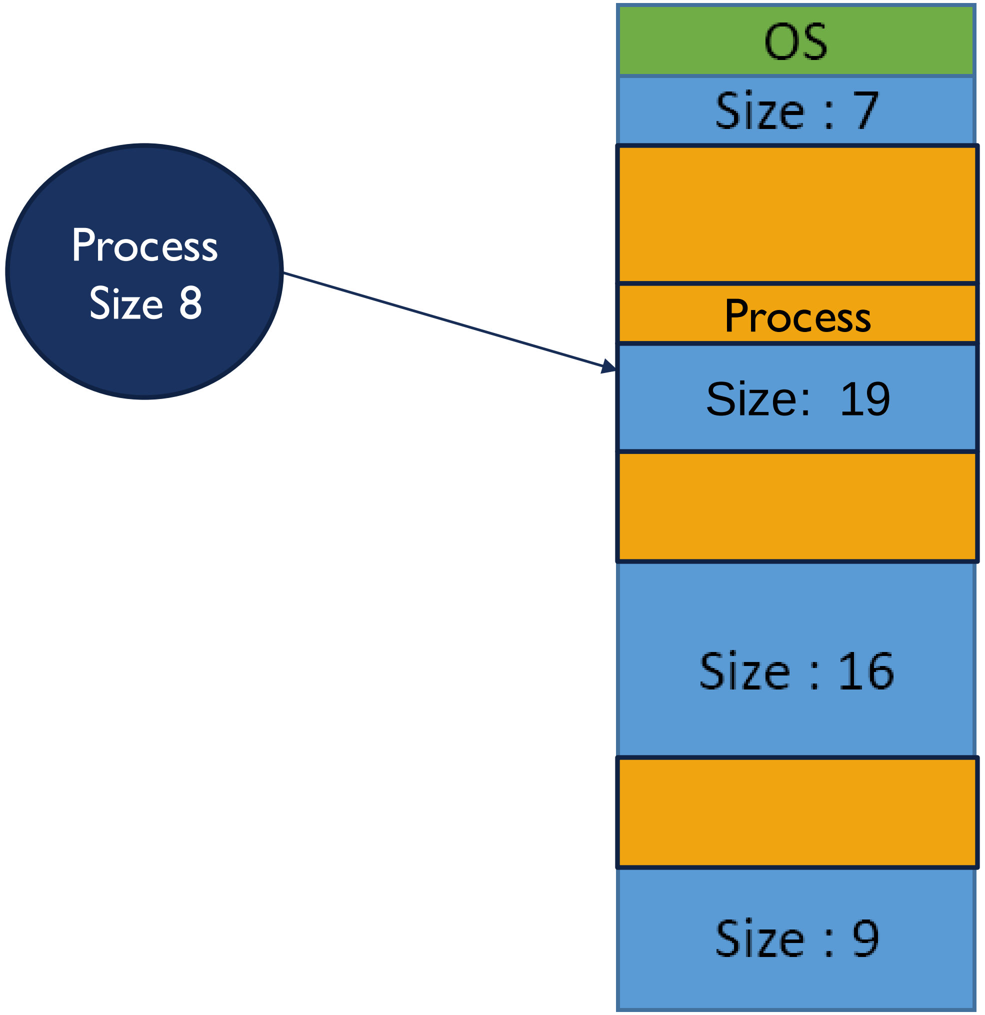
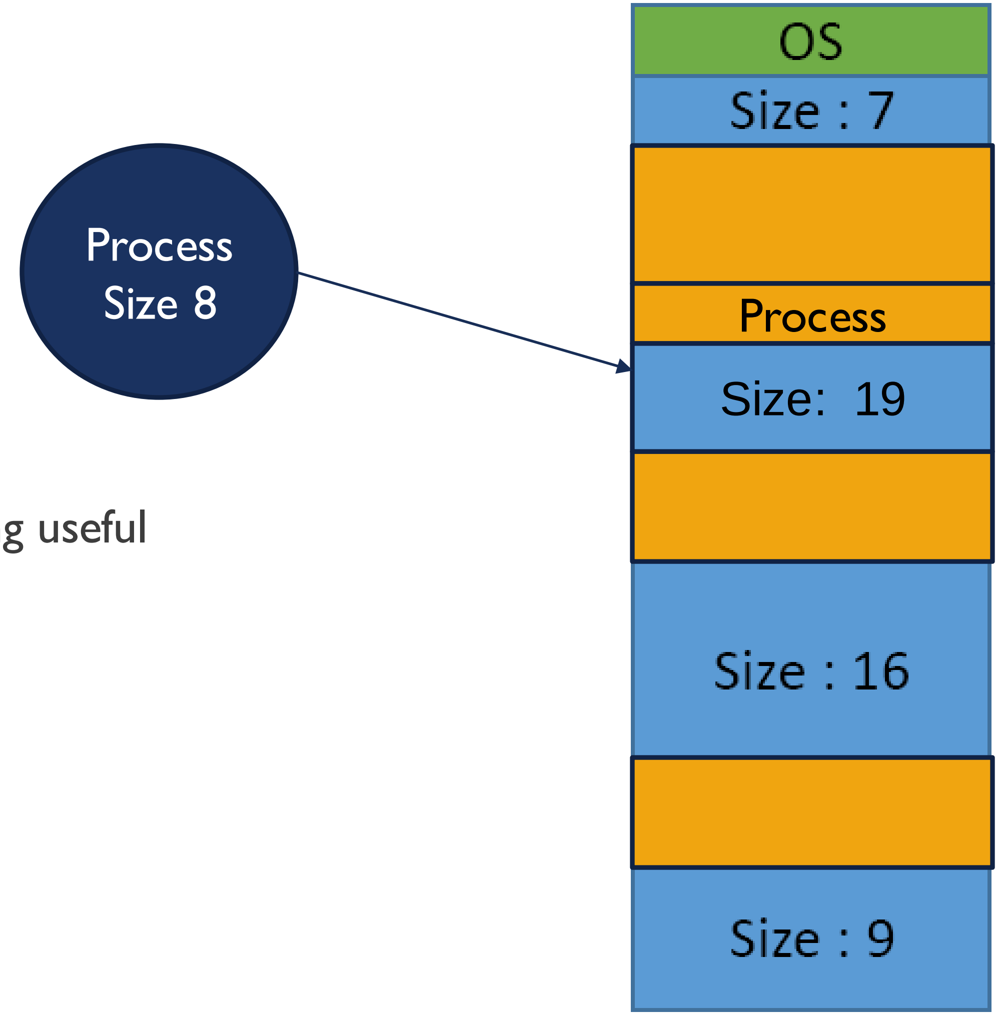


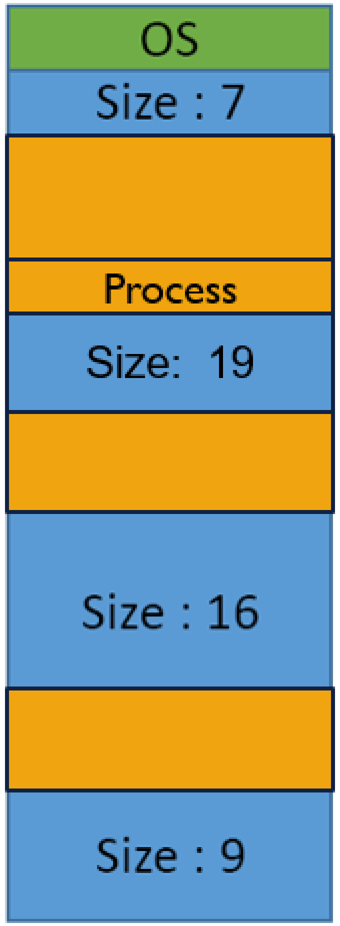
WORST FIT

- Worst Fit: Largest hole left behind.
- Why would that be good?
- Large holes have a higher change of being useful again.



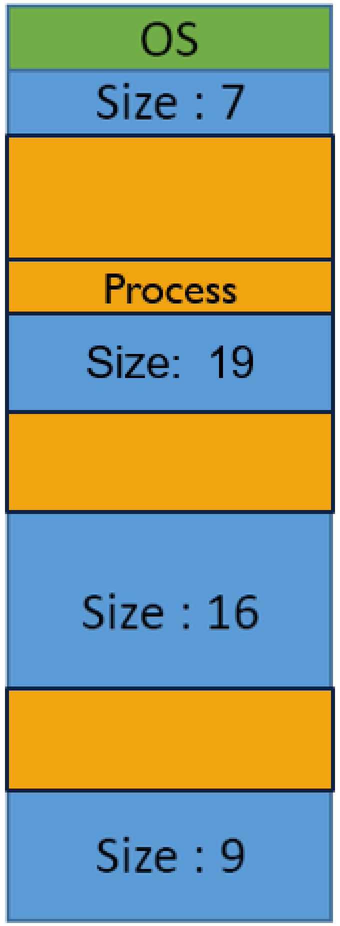
EXTERNAL FRAGMENTATION

- Statics showed that the best algorithms are Best Fit and First Fit.
- No matter what algorithm we use, we goanna end up with holes that are too small to use …



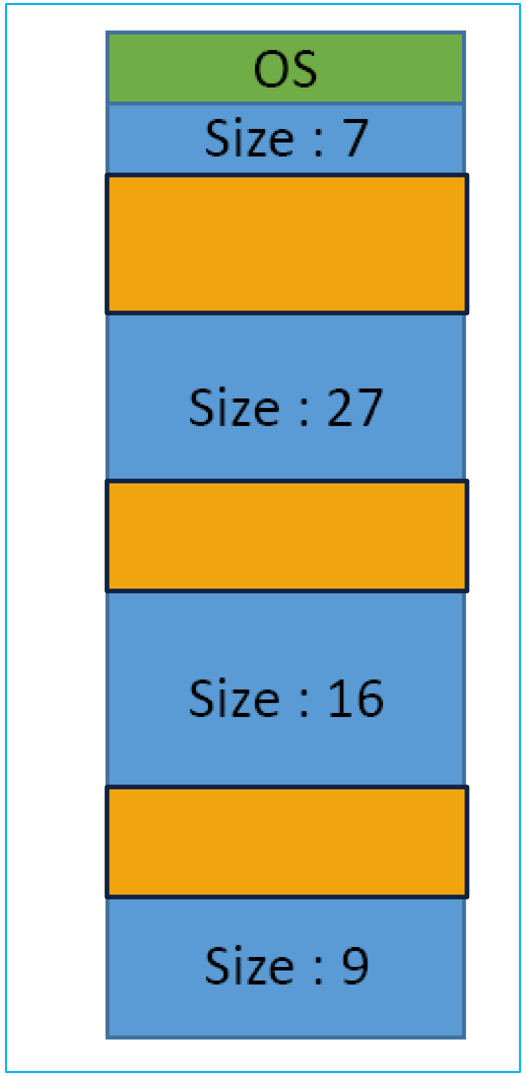
EXTERNAL FRAGMENTATION

- Statics showed that the best algorithms are Best Fit and First Fit.
- No matter what algorithm we use, we goanna end up with holes that are too small to use …
- Roughly 1/3 of the memory is unusable because holes being too small.
- This is what we External Fragmentation



INTERNAL FRAGMENTATION

To simplify hardware, Memory is assigned in blocks.



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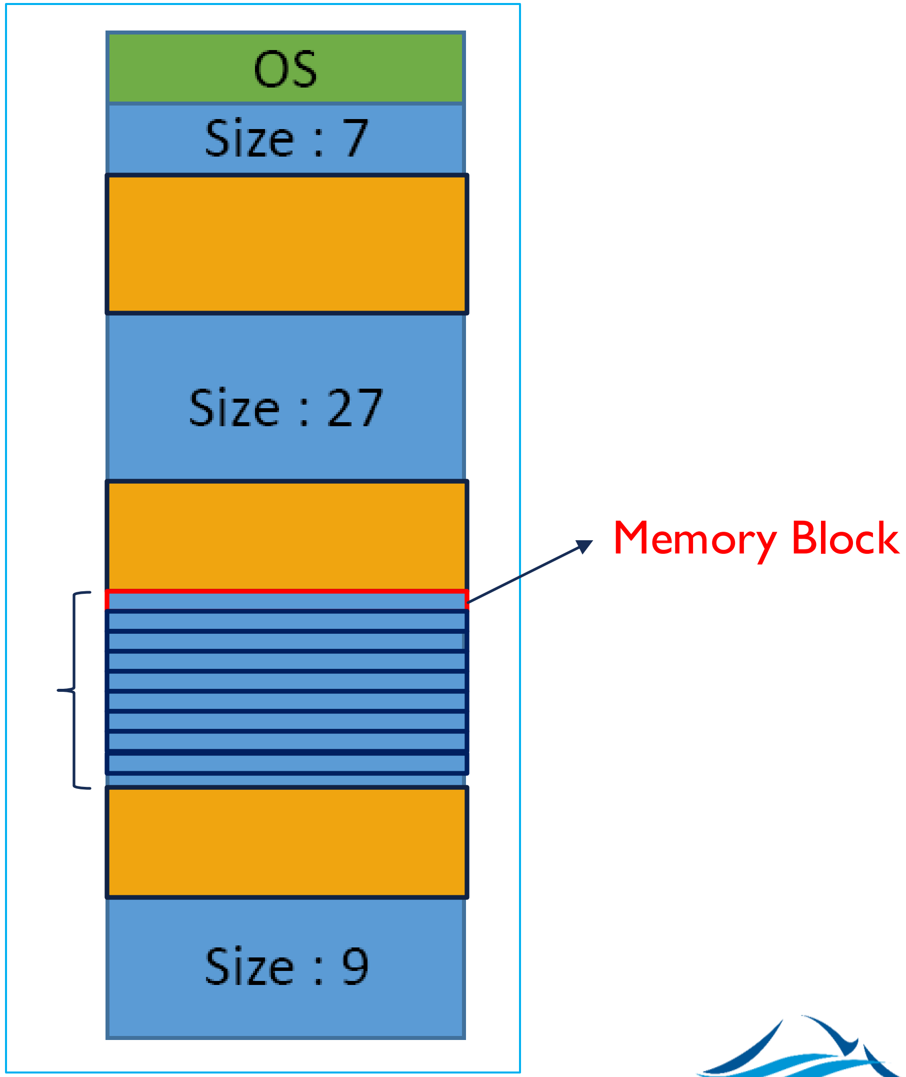

INTERNAL FRAGMENTATION

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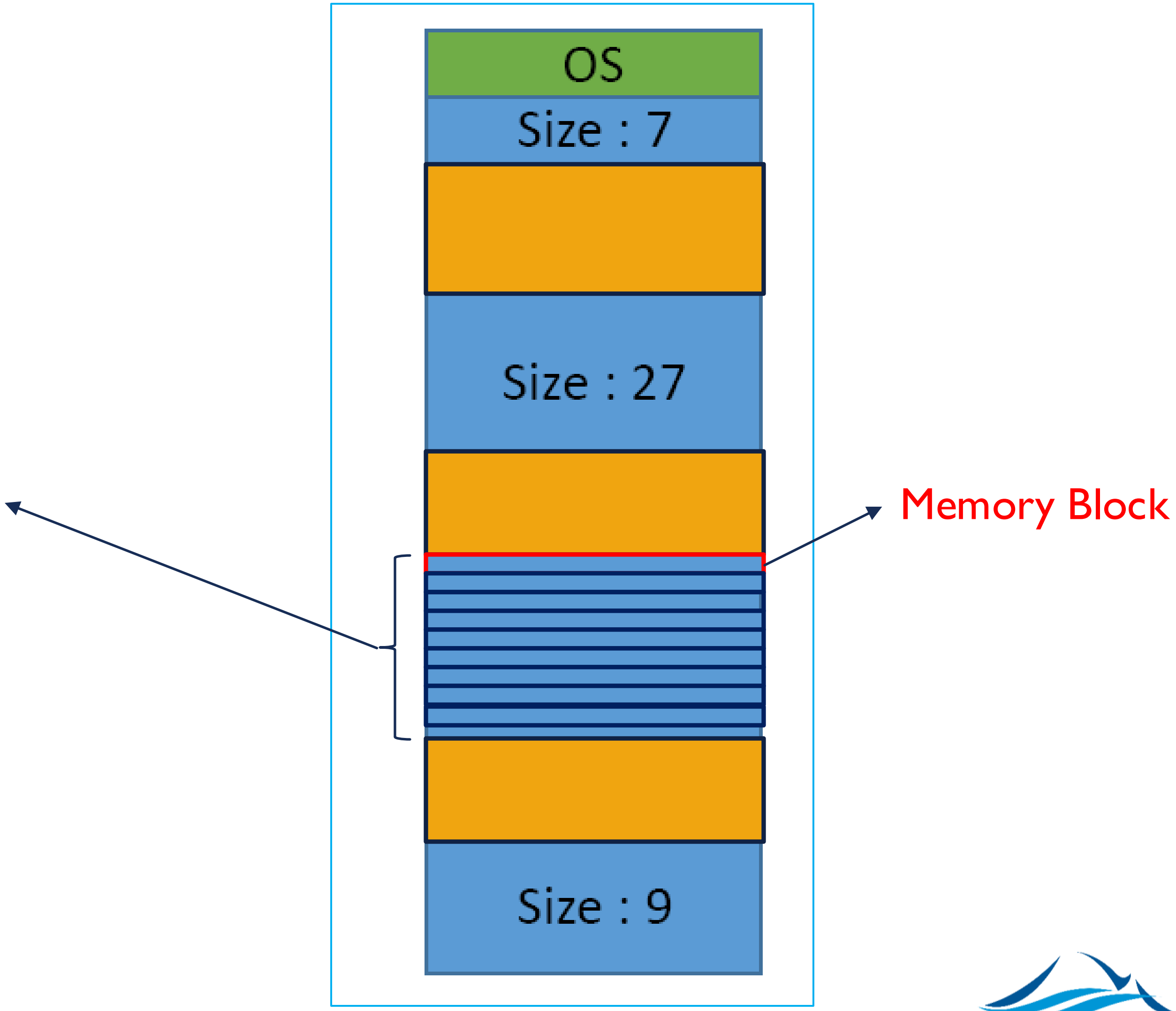
Assume a block size of 64 KB, If a process needs 96 KB of memory. How many blocks the OS will allocate to it?



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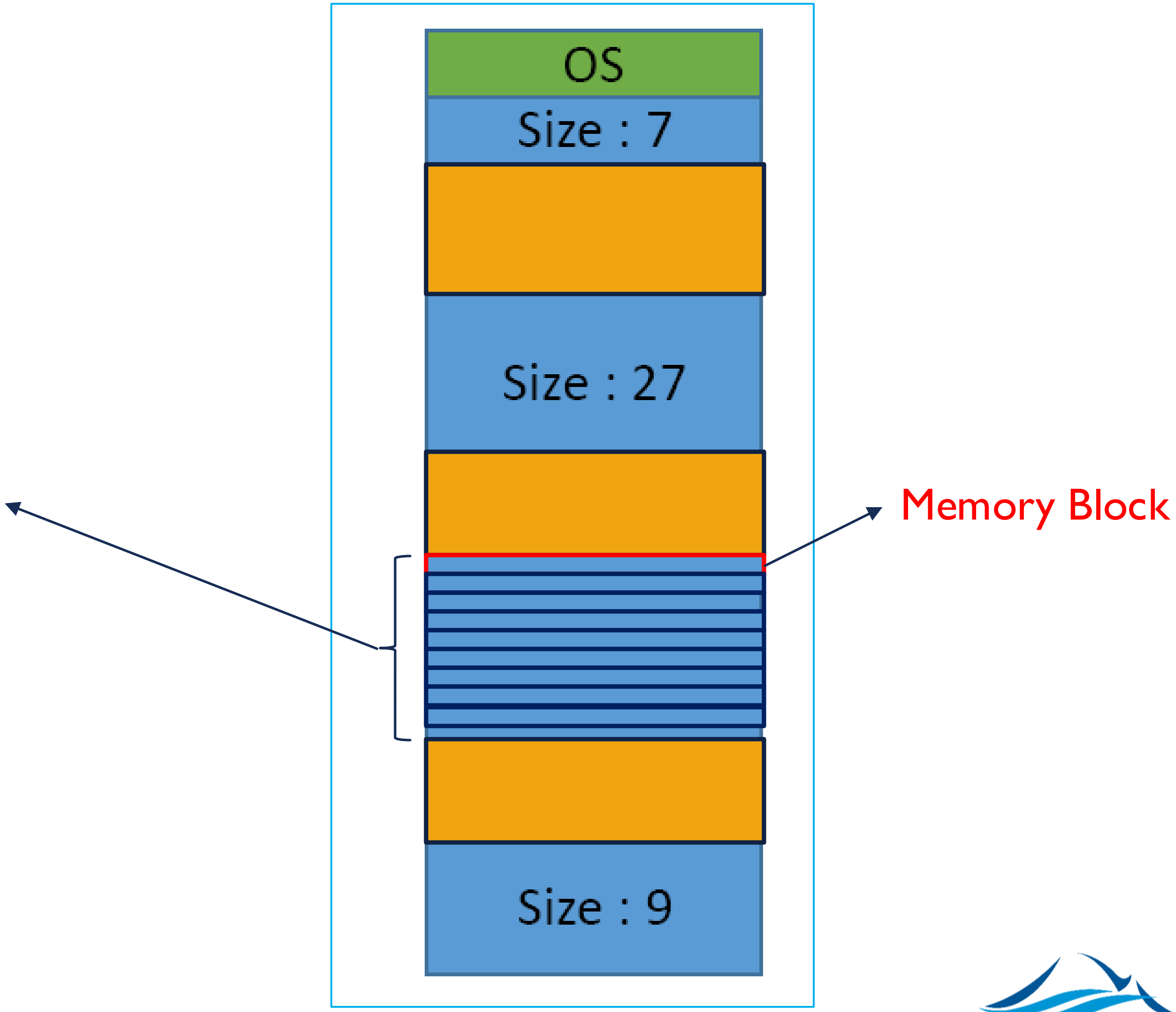
Two blocks but half of block 2 is never used and is essentially wasted ...



INTERNAL FRAGMENTATION

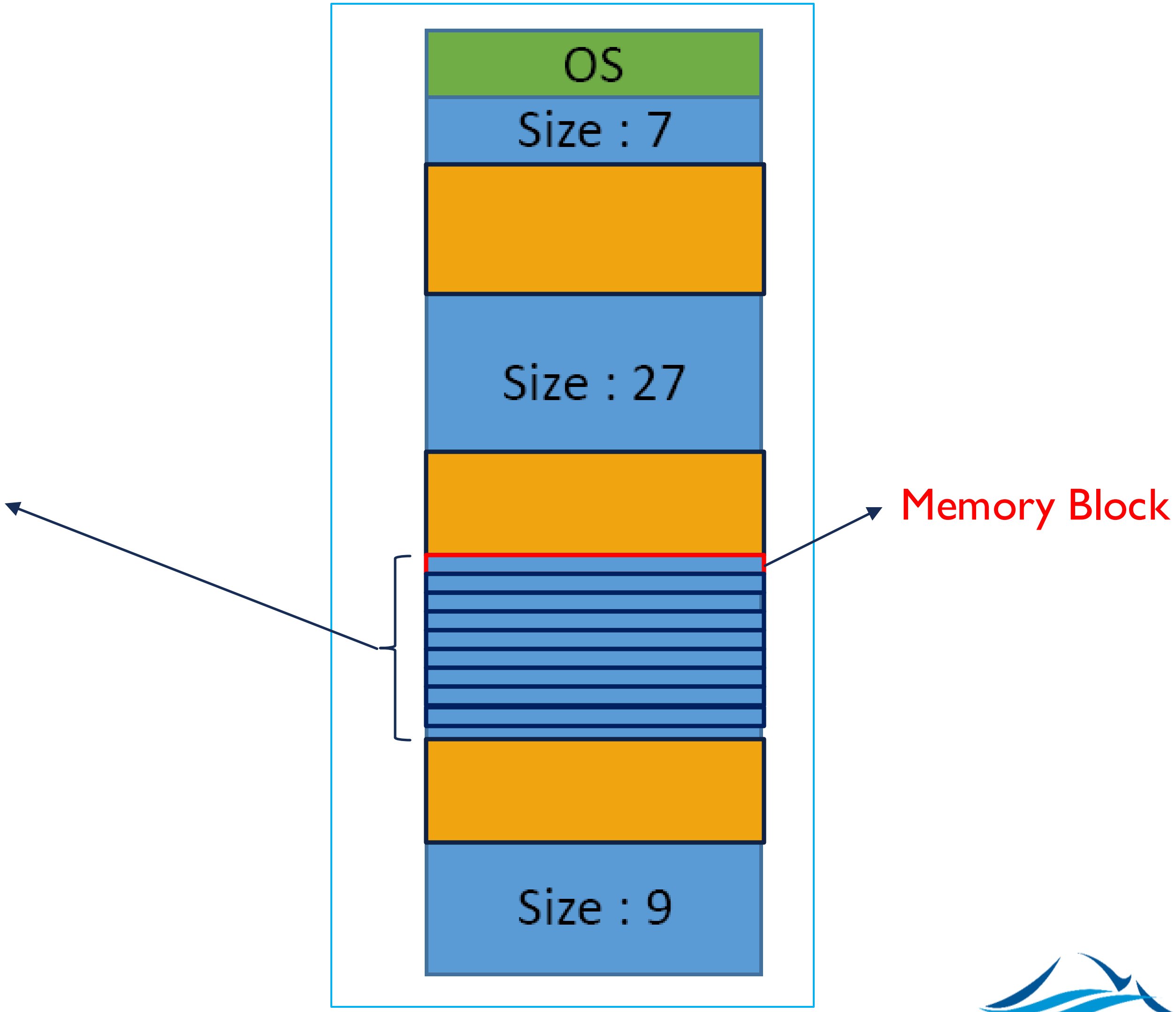
To simplify hardware, Memory is assigned in blocks.

Assume a block size of 64 KB, If a process needs 96 KB of memory. How many blocks the OS will allocate to it?

Two blocks but half of block 2 is never used and is essentially wasted ...

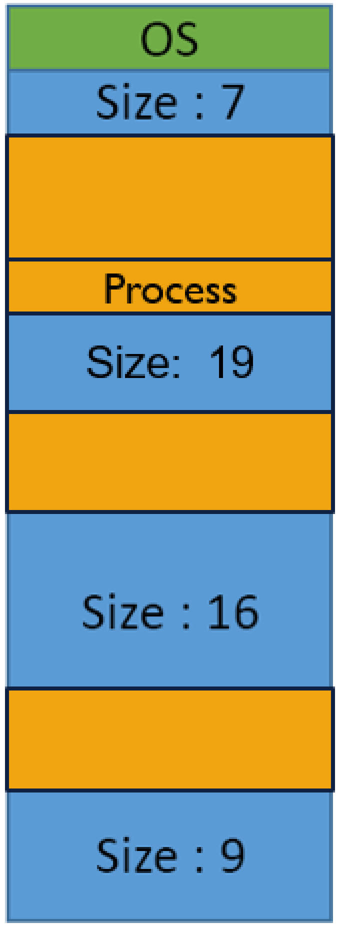
This is known as internal fragmentation.

There is not much to do about internal fragmentation except for using smaller block sizes.



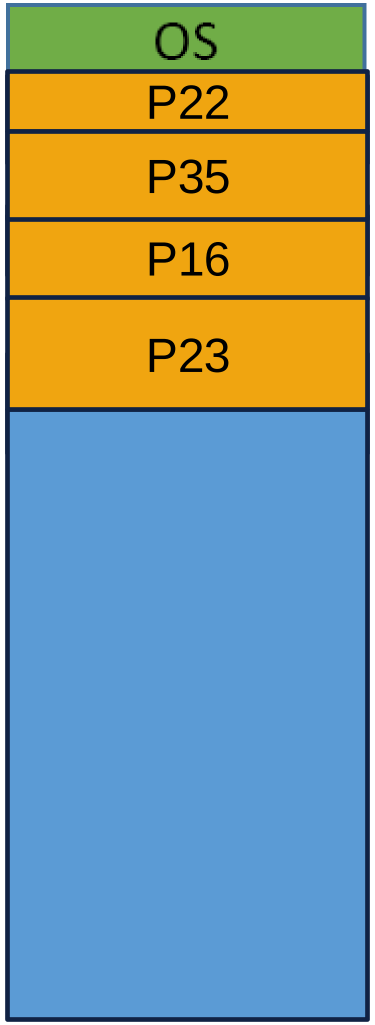
EXTERNAL FRAGMENTATION

- How to solve the problem of holes too small for new processes?



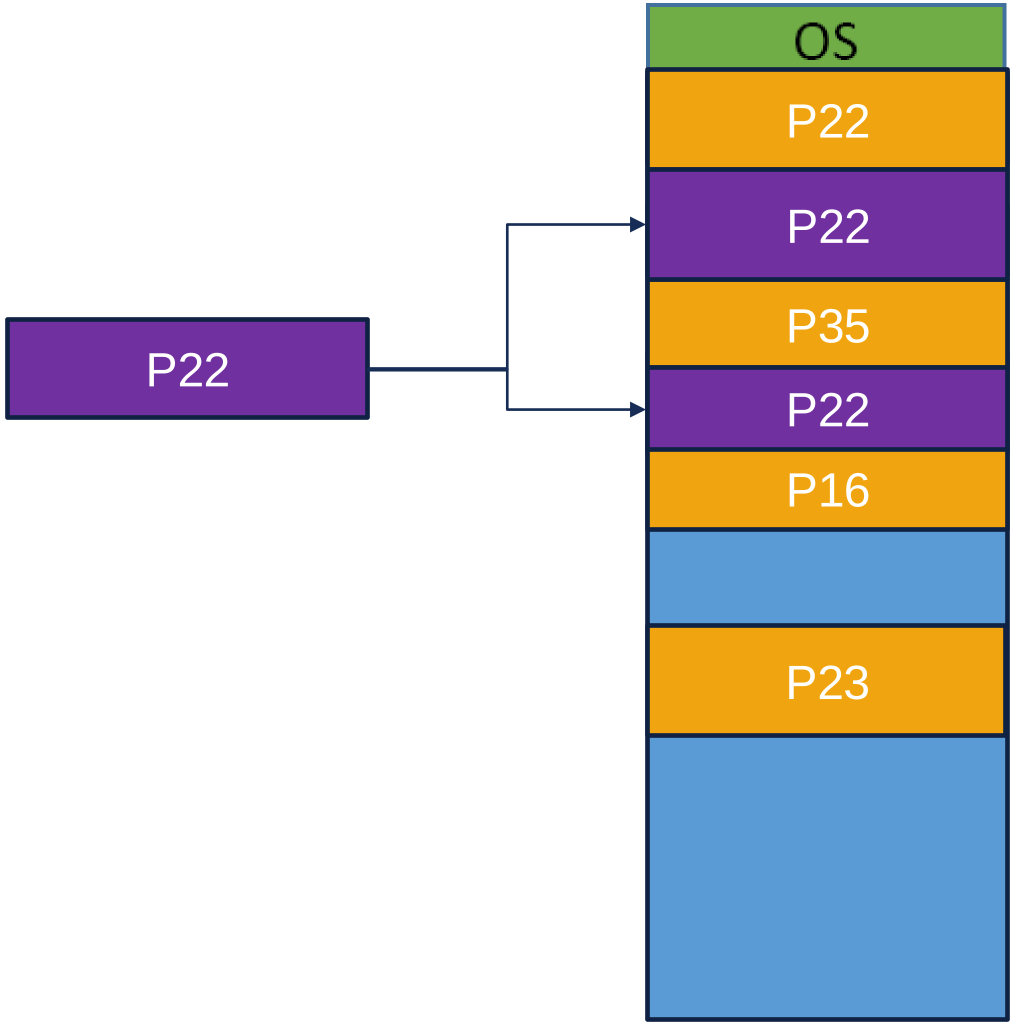
MEMORY COMPACTION

- How to solve the problem of holes too small for new processes?
- Rearranging processes and "compacting" them.

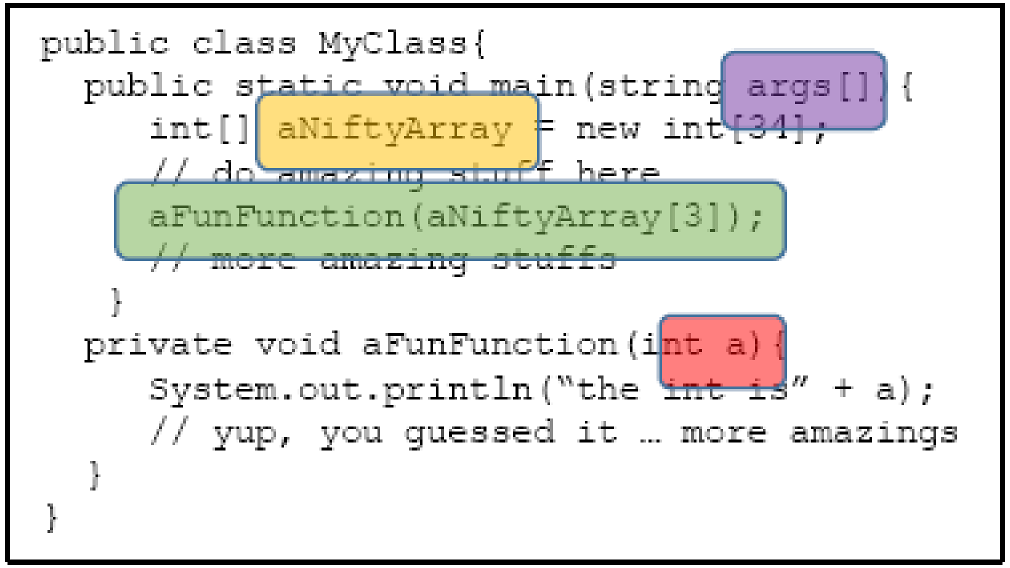


MEMORY SEGMENTATION

- How to solve the problem of holes too small for new processes?
- Rearranging processes and "compacting" them.
- Or using non contiguous memory for the process!



MEMORY SEGMENTATION



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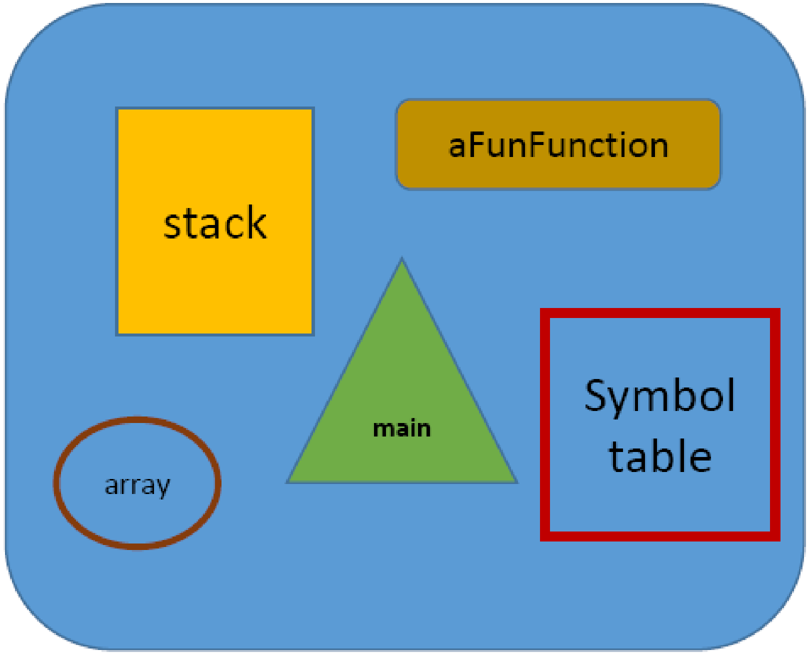
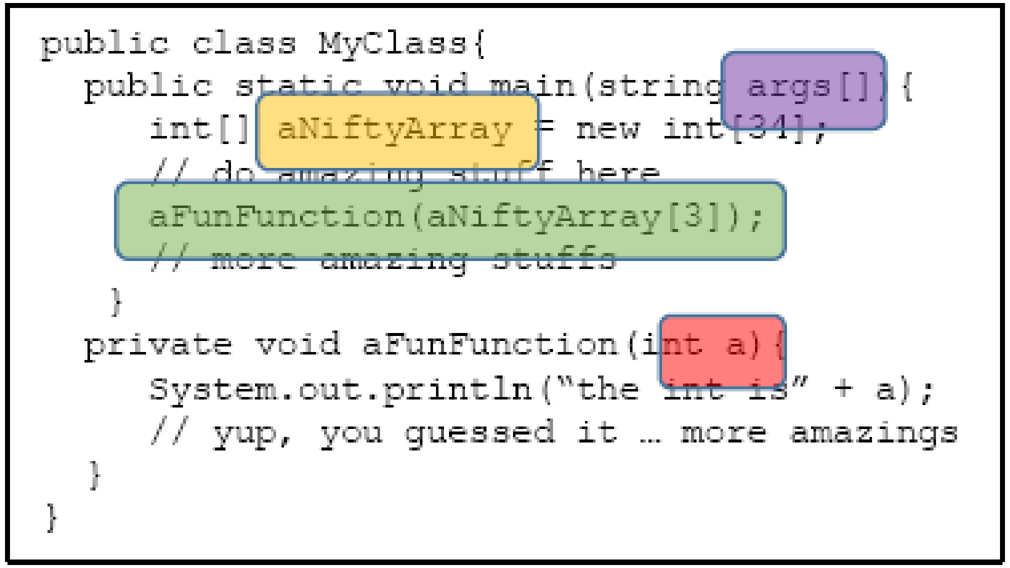
As programmers, we don't treat memory as contiguous.



Logical address space (Programmer's perspective)

MEMORY SEGMENTATION



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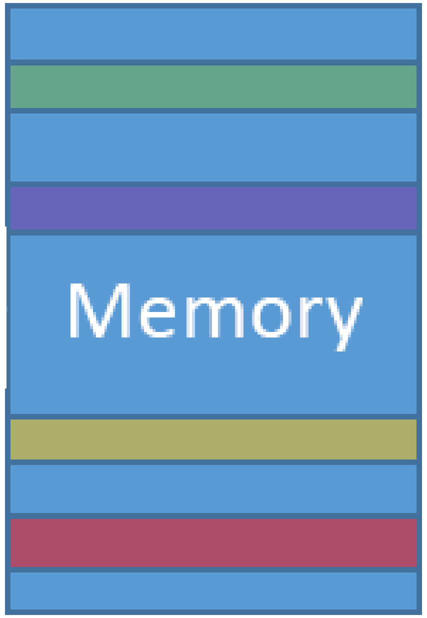
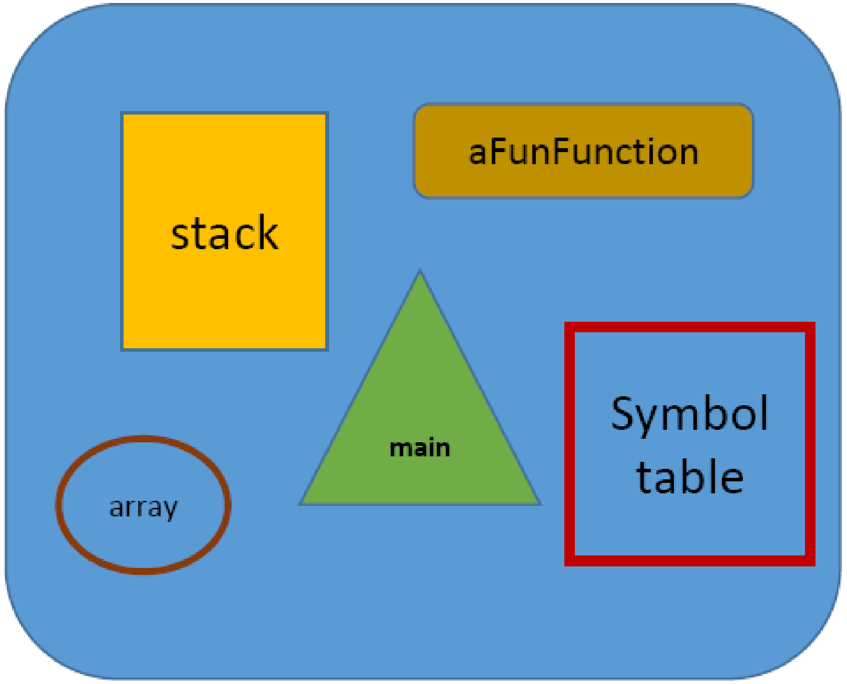


As programmers, we don't treat memory as contiguous.

Memory segmentation: allocate memory in segments representing logical entities.

SEGMENT ADDRESS

Two tuple : <*segment num, offset*>



Logical address space
(Programmer's perspective)

SEGMENT ADDRESS

If each piece of code/statement can be uniquely identified via a 2D address (segment num, offset) …

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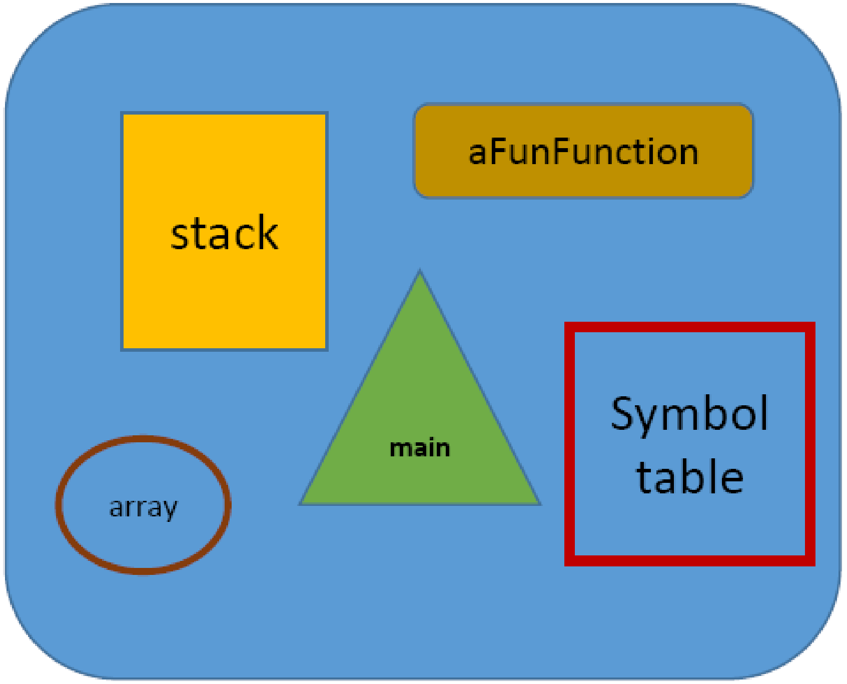


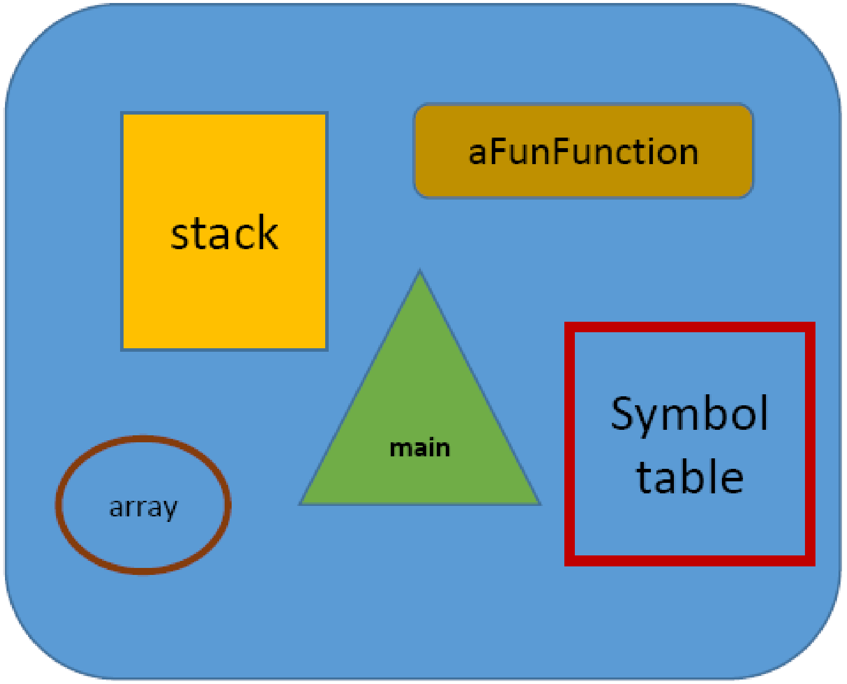
Logical address space
(Programmer's perspective)

SEGMENT ADDRESS

Two tuple : *<segment num, offset>*

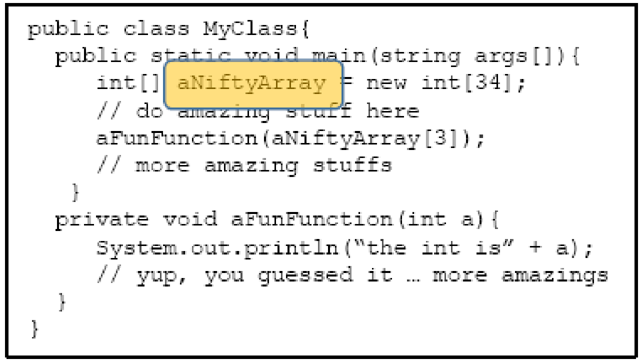
If each piece of code/statement can be uniquely identified via a 2D address (segment num, offset) …

Q: How does the OS map from the 2D address space (programmer's perspective) to the 1D physical address space?



Logical address space (Programmer's perspective)

SEGMENT TABLE



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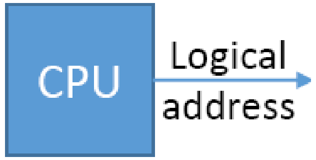
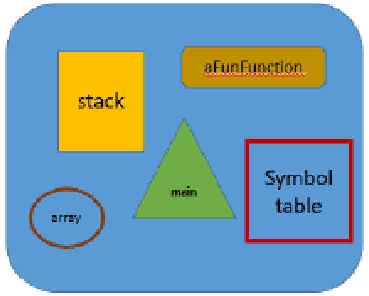
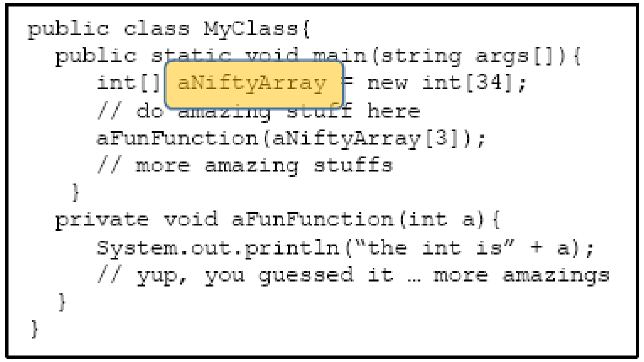




The process executing on a CPU generates an address … for example, the process needs the address of the variable `aNiftyArray`

SEGMENT TABLE



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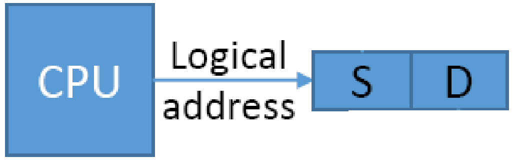
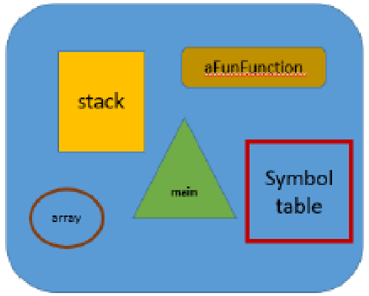
```

The logical address is made up of 2 parts

<segment num, offset>

<S, D>





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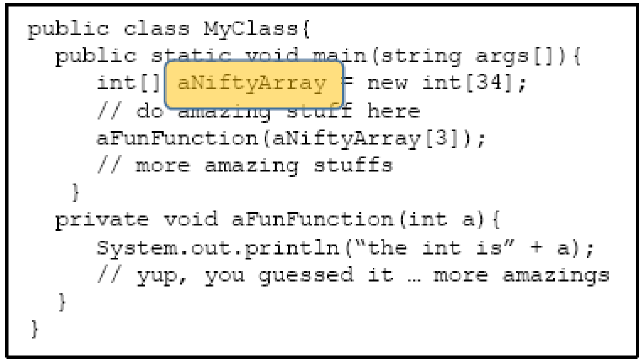

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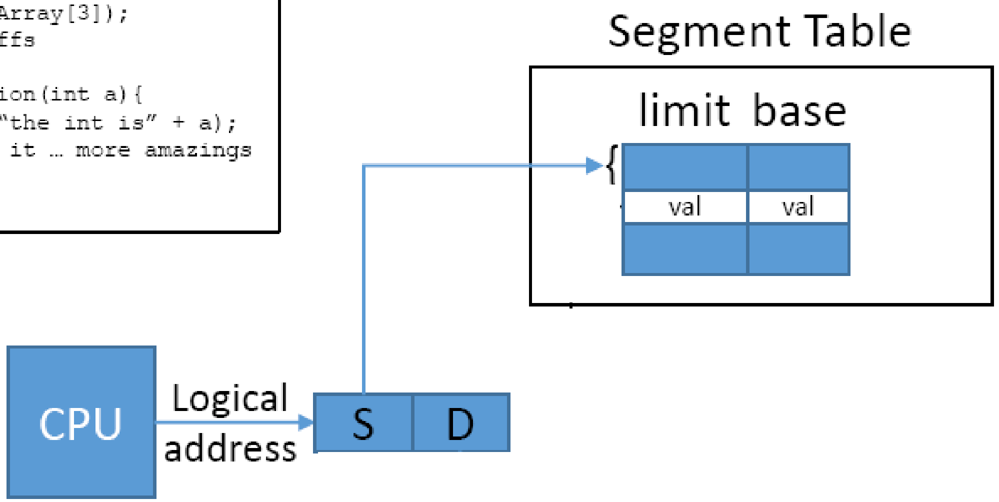
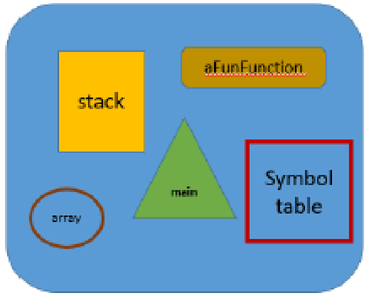
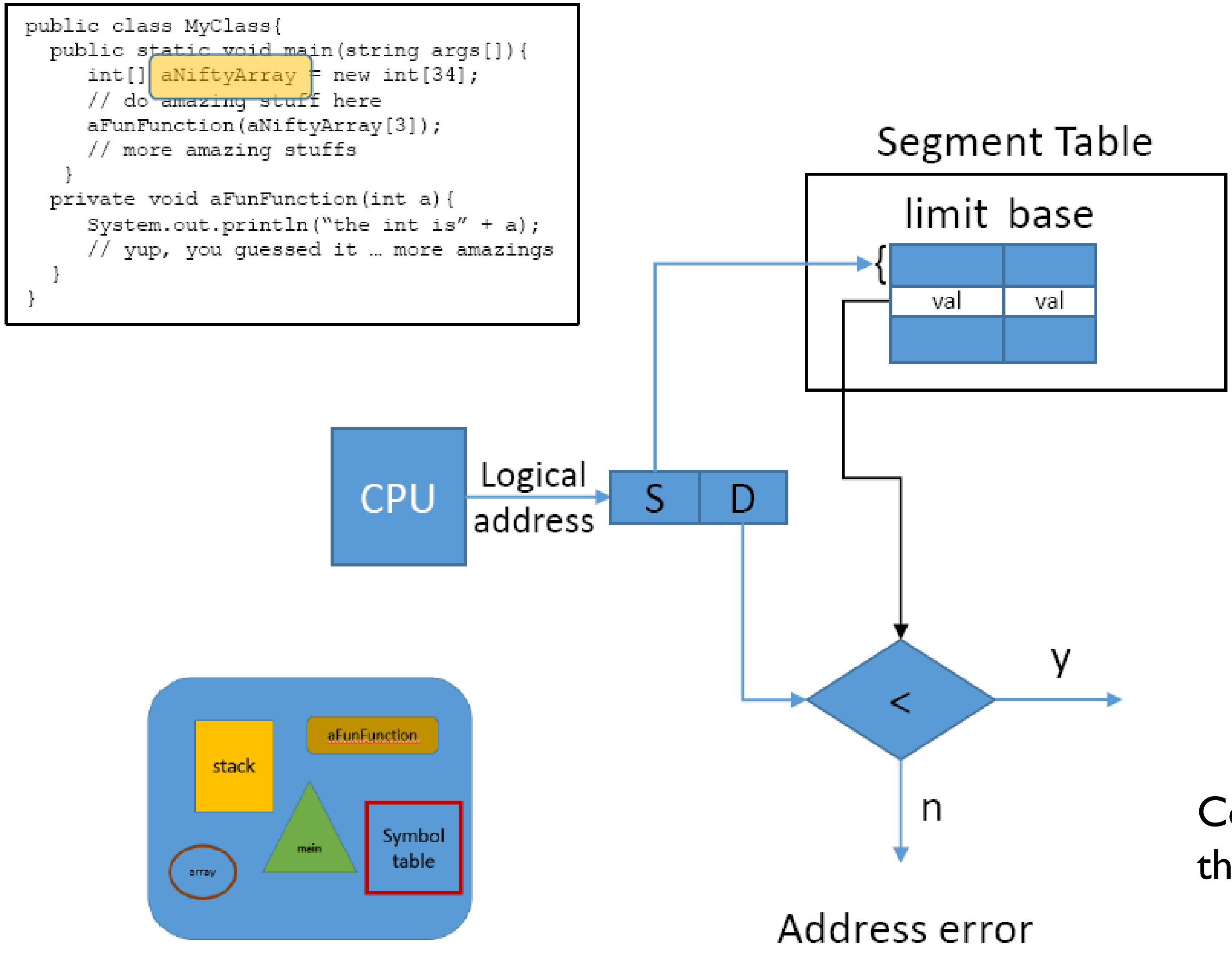




- Base: value of physical starting address
- Limit: size of segment

SEGMENT TABLE



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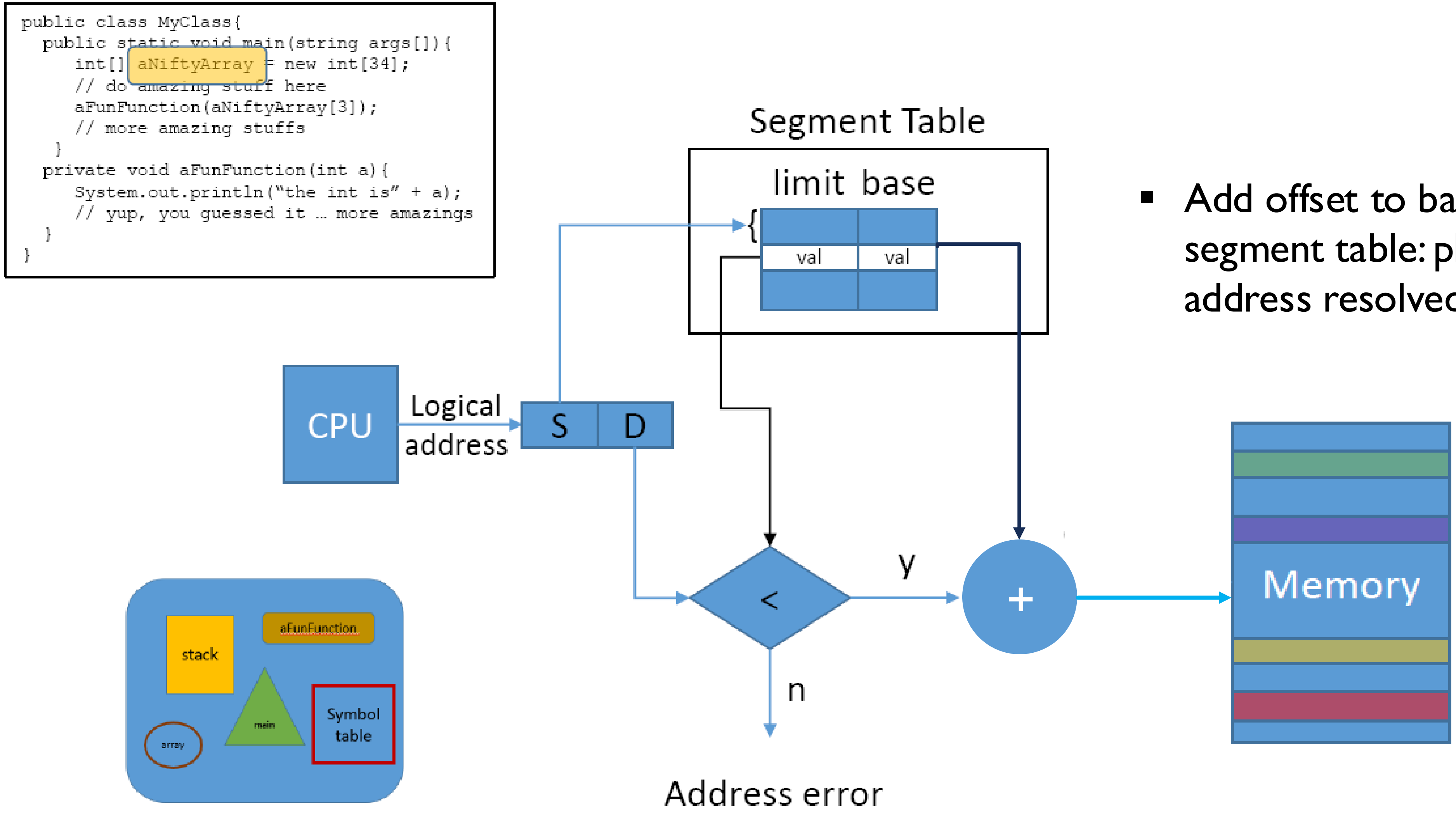
Comparing ‘D’, the offset, with the limit.

SEGMENT TABLE



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```

- Add offset to base value from segment table: physical address resolved.

SEGMENT TABLE

Segment table

base	limit
4000	2000
760	120
56500	300
43000	700

Q: Is the Segment table valid?

A	B
C	D

A : Yes

B : No

SEGMENT TABLE

Segment table

	base	limit
0	1400	250
1	2600	3500
2	200	300
3	60000	5
4	17000	1800

I. <3,200>
II. <0,50>
III. <3,60000>
IV. <1,200>
V. <4,4>

Q: For the segment table shown right, which of the choices I-V of logical addresses would result in an address error?

A B
C D

A : I only
B : II and III only
C : I and III only
D : IV and V only

SEGMENT TABLE

Segment table

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A : I only

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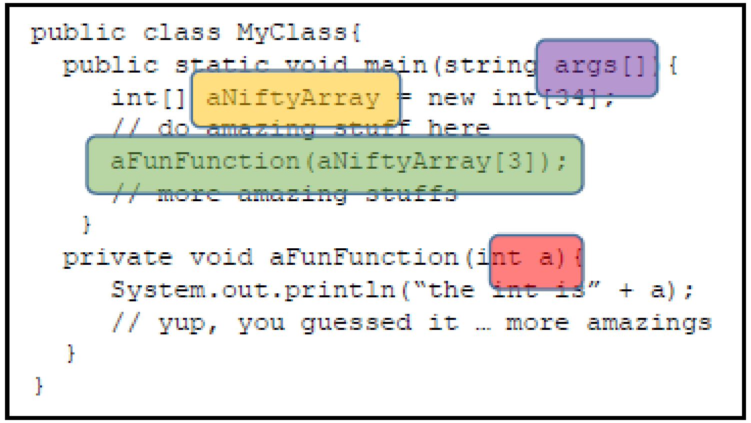
[✓ C : I and III only]

D : IV and V only

FRAGMENTATION



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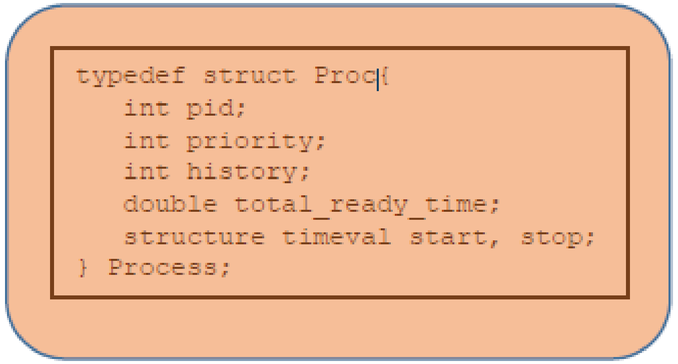
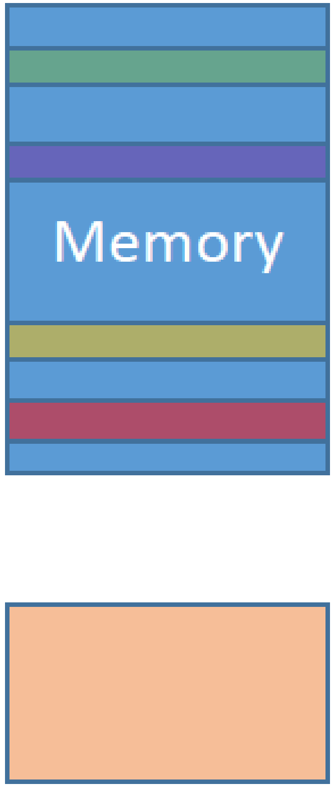


```
typedef struct Proc{
   int pid;
   int priority;
   int history;
   double total_ready_time;
   structure timeval start, stop;
} Process;
```

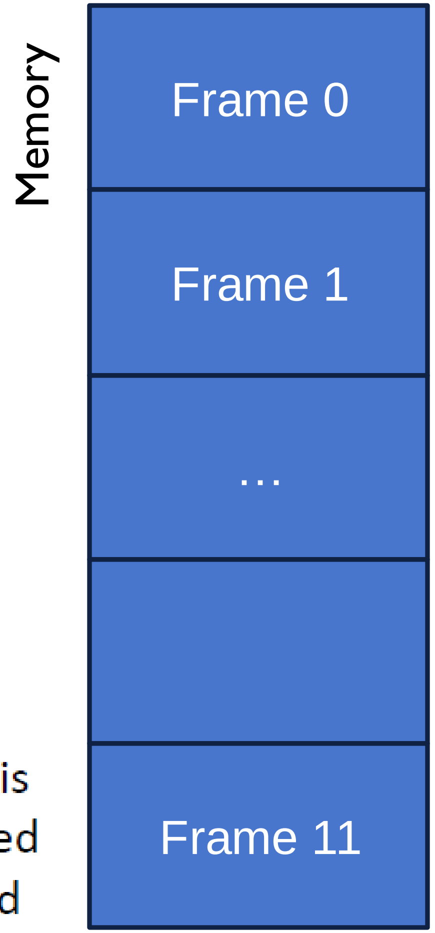


Q: Where might the HUGE orange data structure be placed into memory?

Segmentation can’t completely eliminate fragmentation.

Solution: Paging

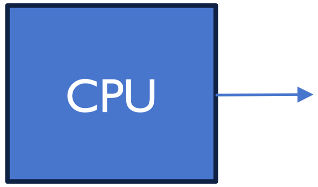
PAGING

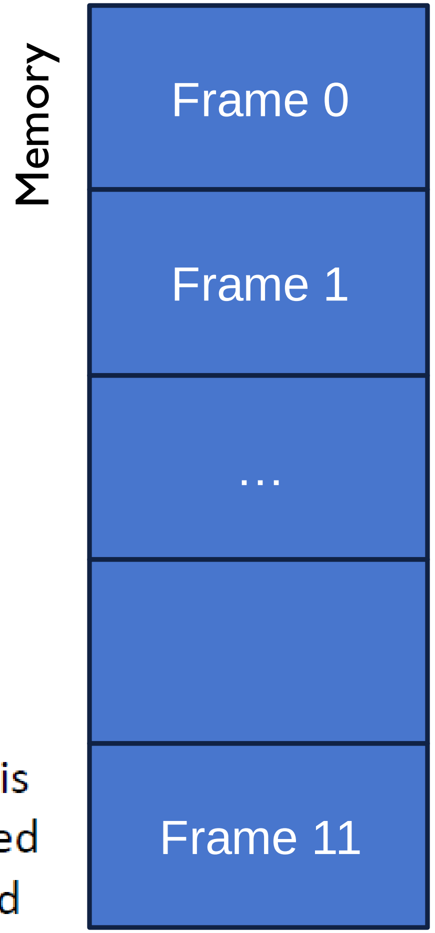


Physical memory is broken up into fixed sized blocks called **frames**

PAGING

The logical memory space is broken up into blocks of the same size, named **pages**





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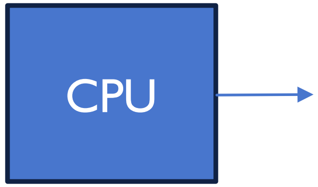
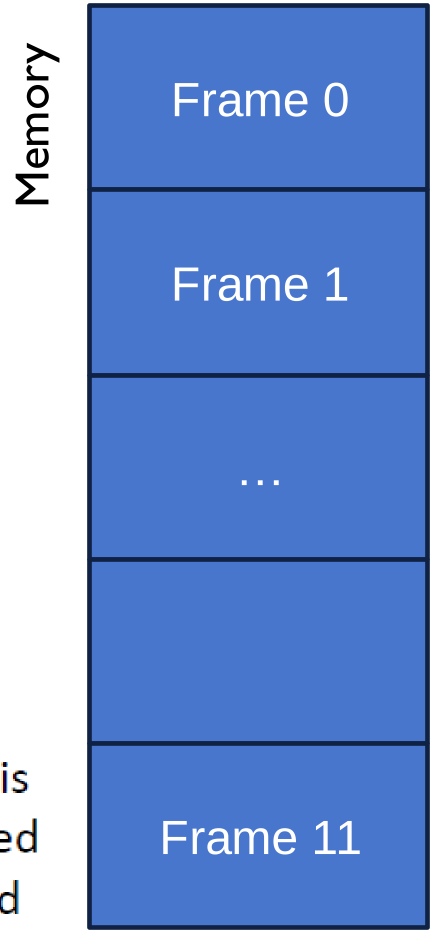


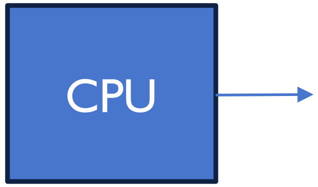
- The logical address space is totally separate from the physical address space … the “data” page can residue in any frame.



Physical memory is broken up into fixed sized blocks called **frames**

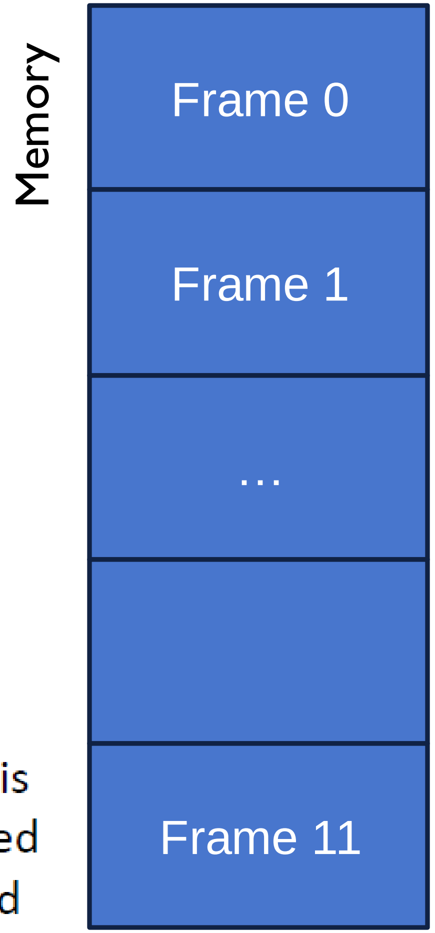
PAGING

The logical memory space is broken up into blocks of the same size, named **pages**

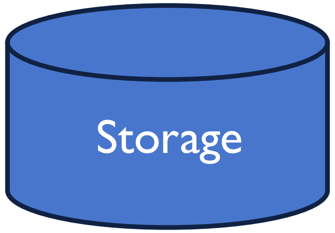


- The logical address space is totally separate from the physical address space … the "data" page can residue in any frame.
- Not all pages need to reside in memory, some can reside on disk/secondary storage!

Physical memory is broken up into fixed sized blocks called **frames**

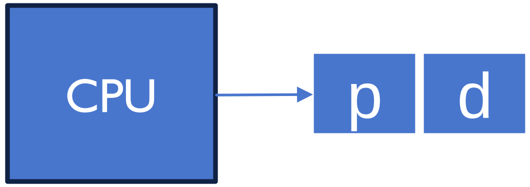


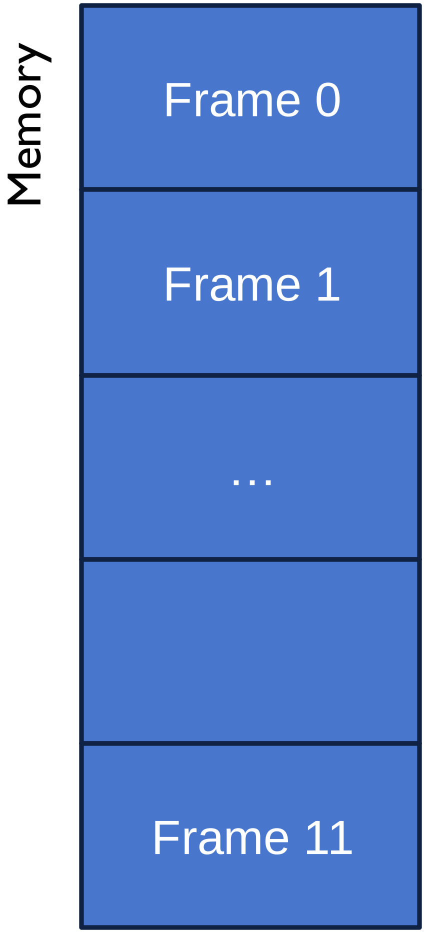
A very large capacity backing store (aka disk) is available for storing data.

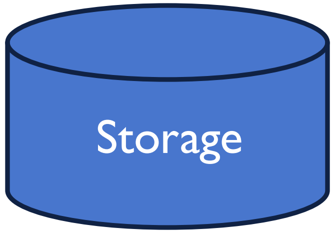


Huge Capacity

PAGING





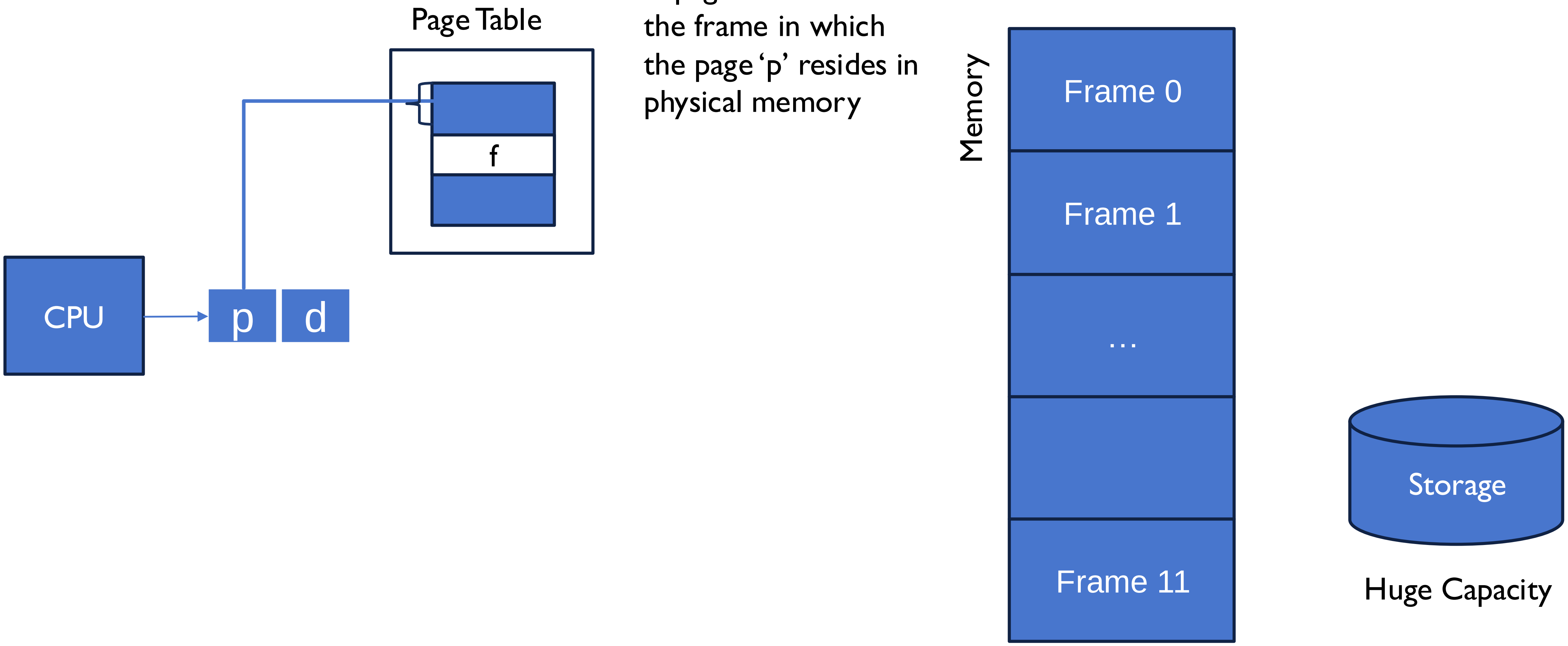


Each address generated by the CPU has a page number (p) and a page offset (d) value

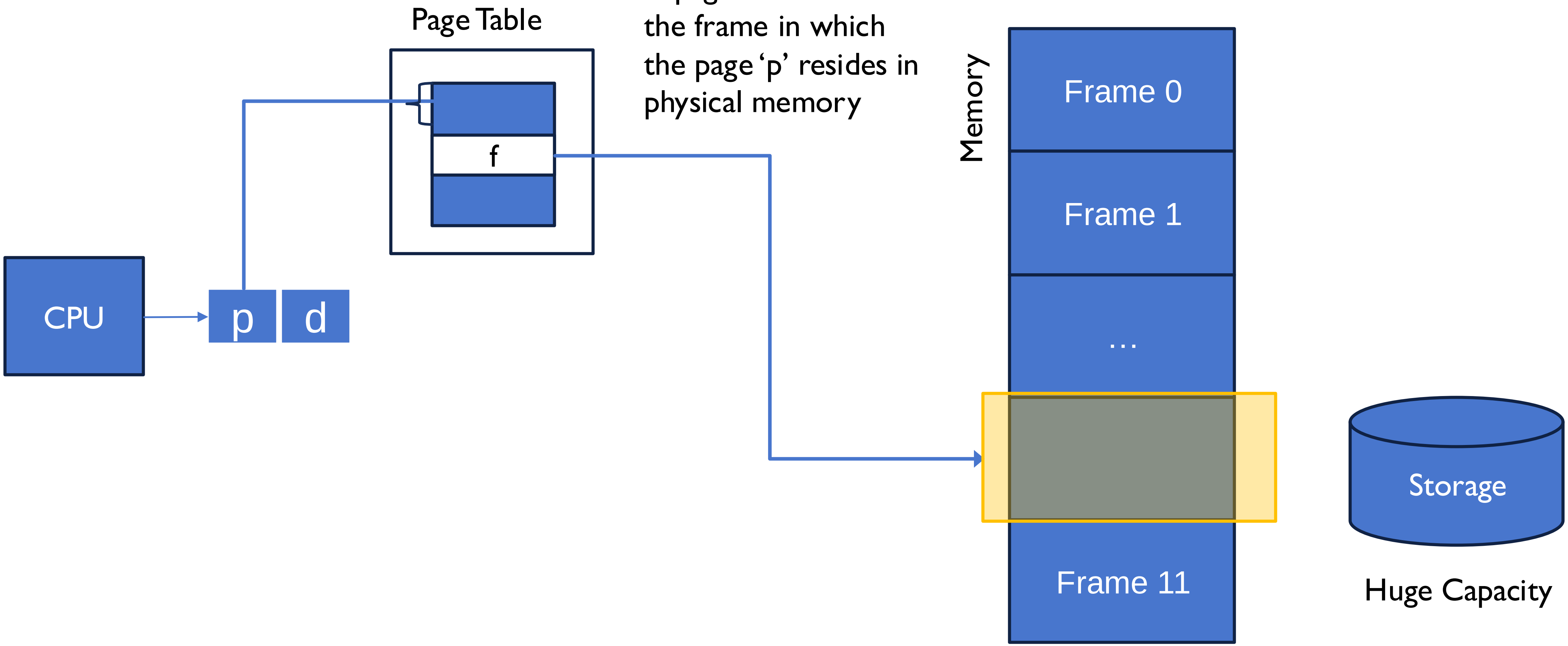
Huge Capacity

PAGING

A page table indicates the frame in which the page 'p' resides in physical memory

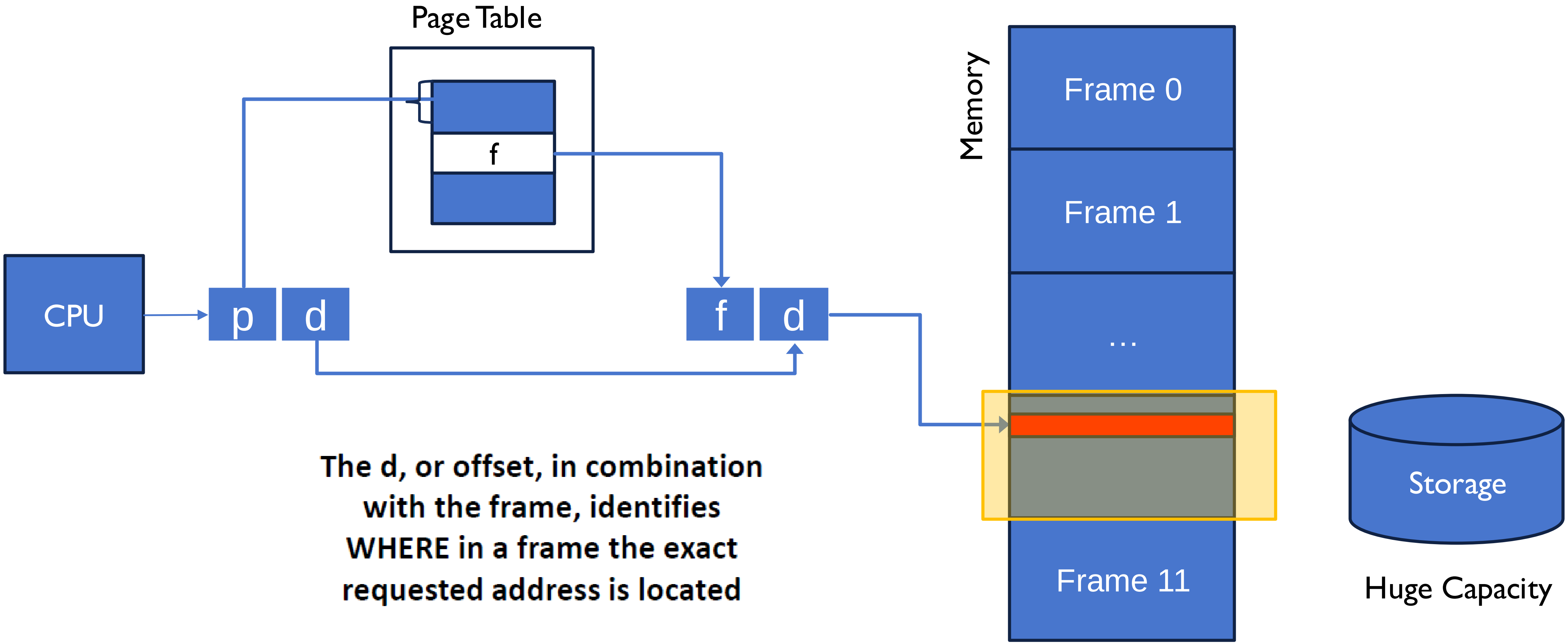


PAGING



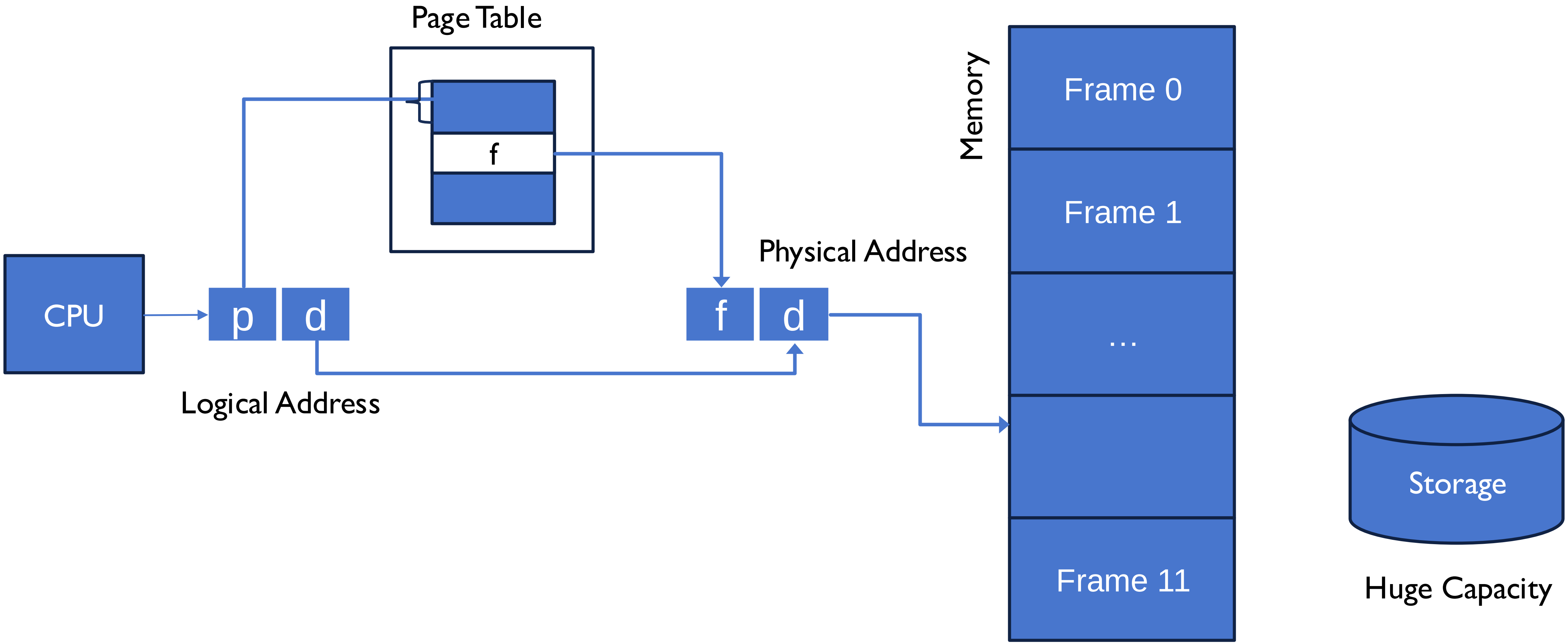
A page table indicates the frame in which the page ‘p’ resides in physical memory

PAGING

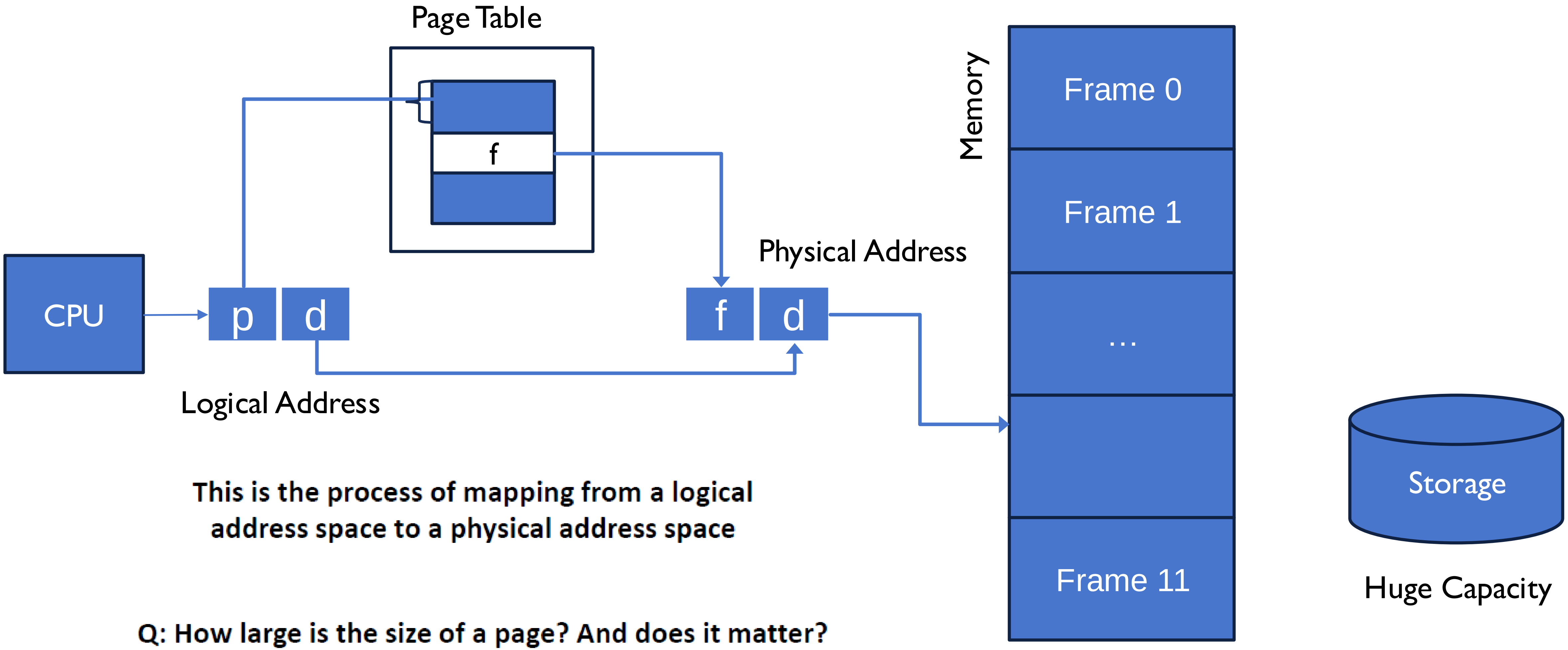


The d, or offset, in combination with the frame, identifies WHERE in a frame the exact requested address is located

PAGING


Page Table
f
CPU
p
d
Logical Address
f
d
Physical Address
Memory
Frame 0
Frame 1
…
Frame 11
Storage
Huge Capacity

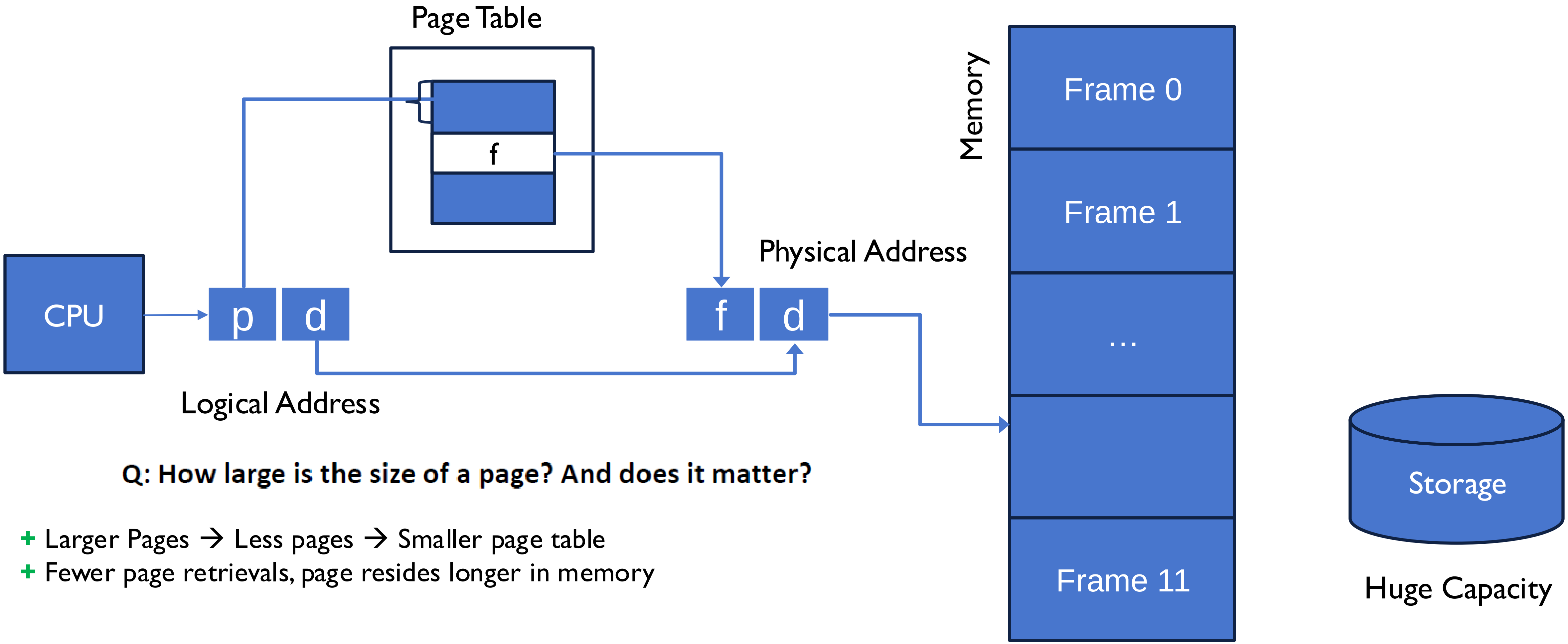
PAGING



This is the process of mapping from a logical address space to a physical address space

Q: How large is the size of a page? And does it matter?

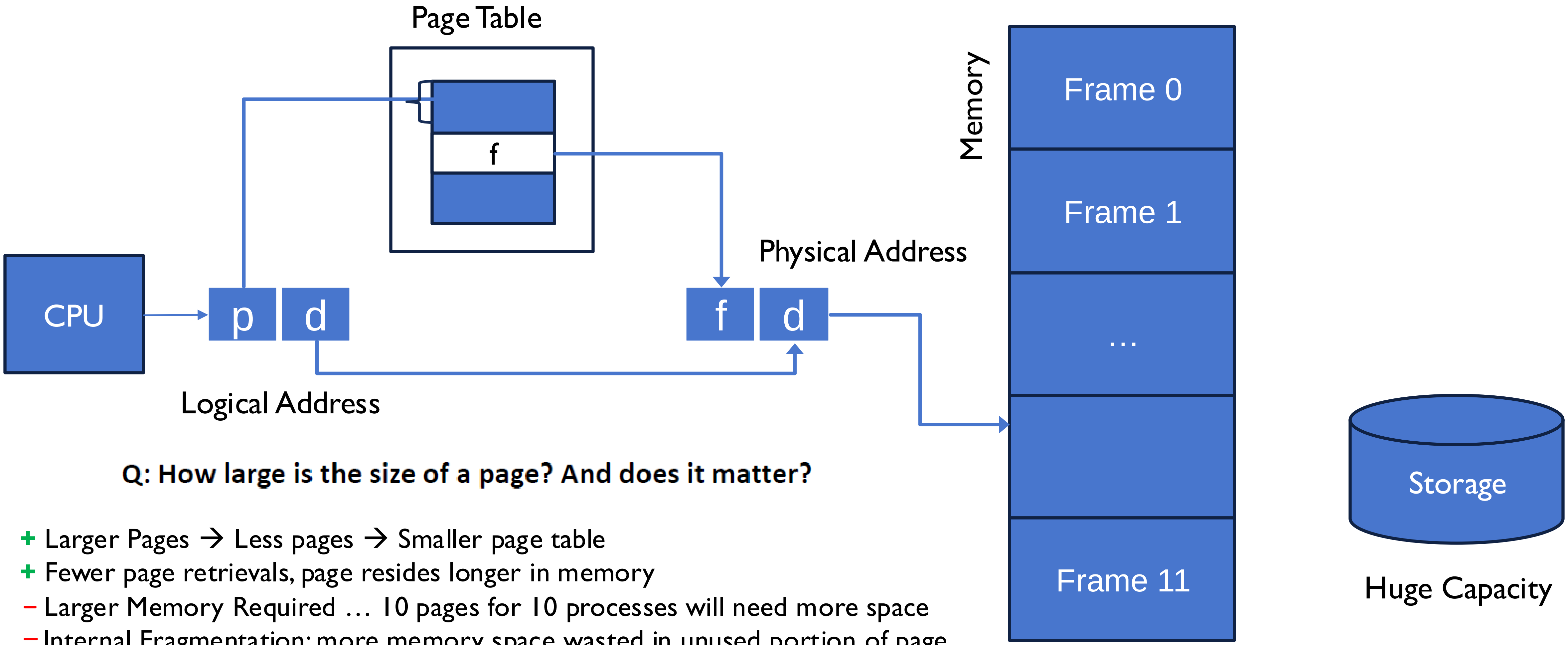
PAGING



Q: How large is the size of a page? And does it matter?

+ Larger Pages → Less pages → Smaller page table
+ Fewer page retrievals, page resides longer in memory

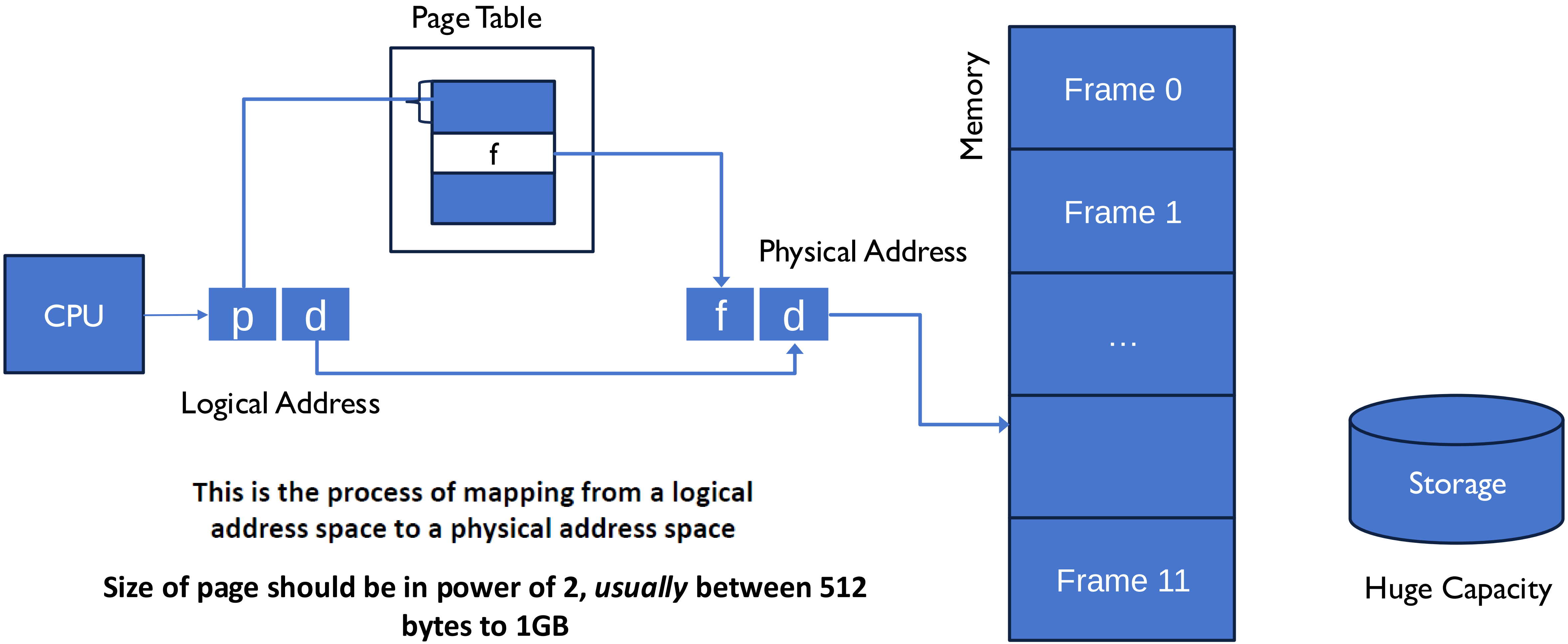
PAGING



Q: How large is the size of a page? And does it matter?

+ Larger Pages → Less pages → Smaller page table
+ Fewer page retrievals, page resides longer in memory
− Larger Memory Required … 10 pages for 10 processes will need more space
− Internal Fragmentation: more memory space wasted in unused portion of page

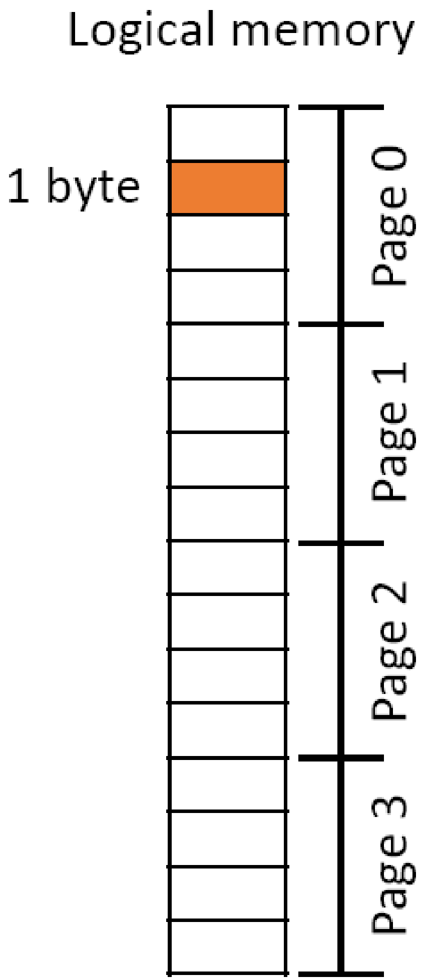
PAGING



This is the process of mapping from a logical address space to a physical address space

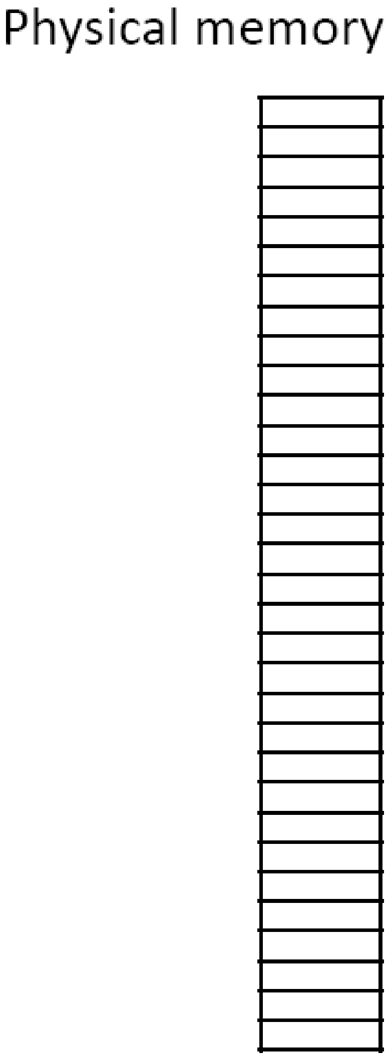
Size of page should be in power of 2, *usually* between 512 bytes to 1GB

PAGING

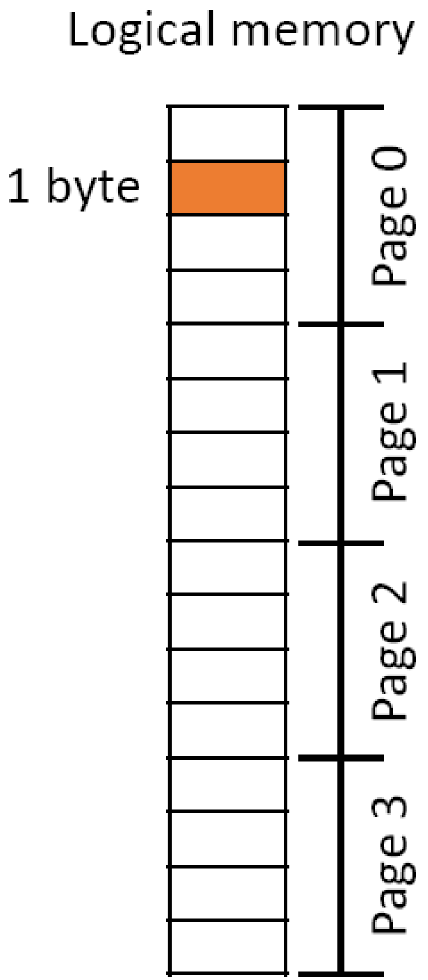


Size of logical address space : 16

Page size = 4 bytes



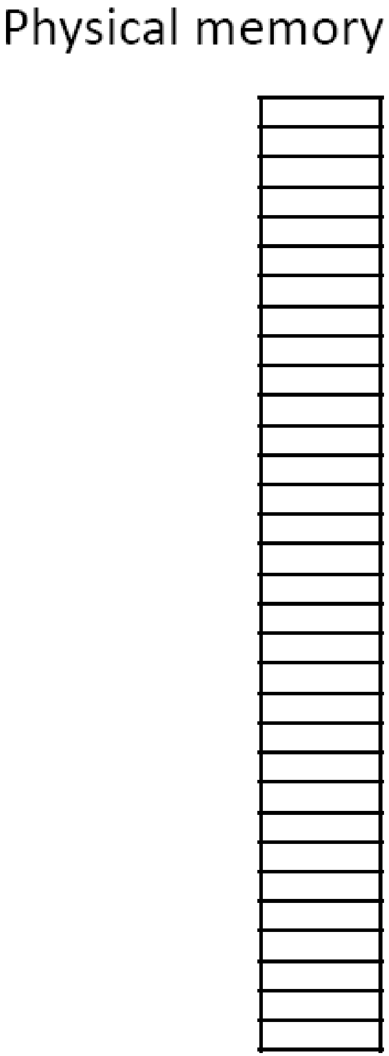
PAGING



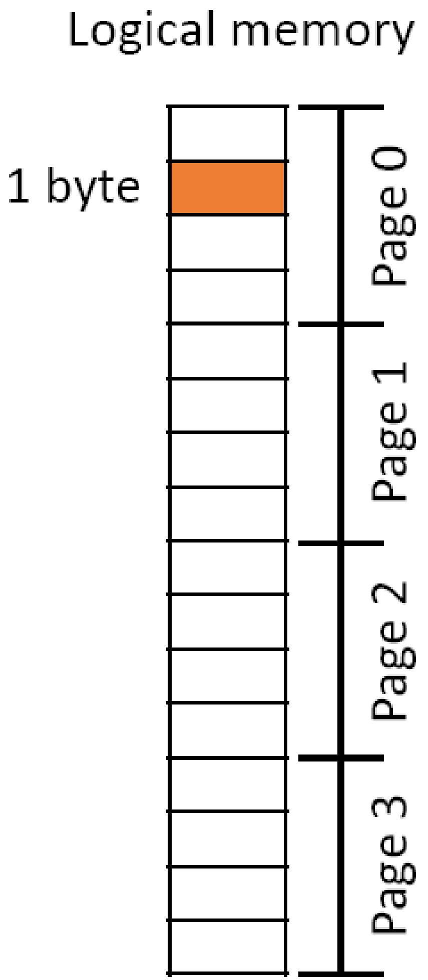
Size of logical address space : 16

Page size = 4 bytes

Q: How many bytes should each frame be?

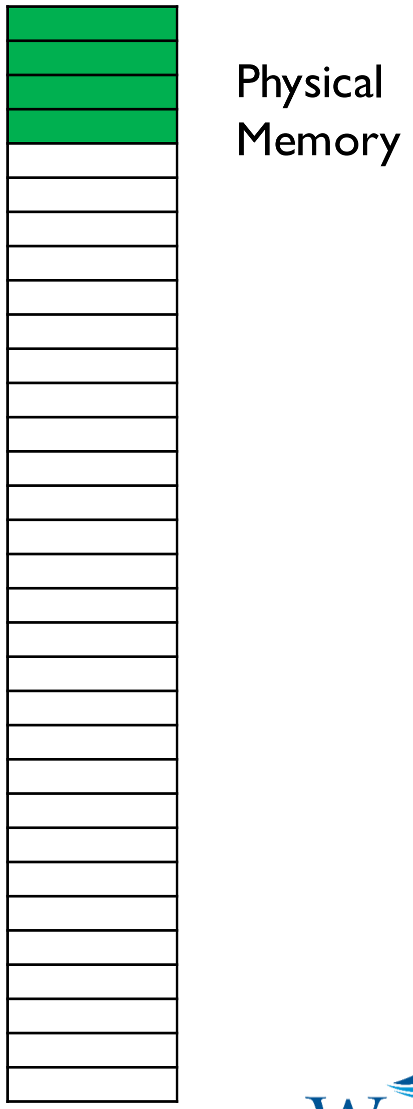


PAGING

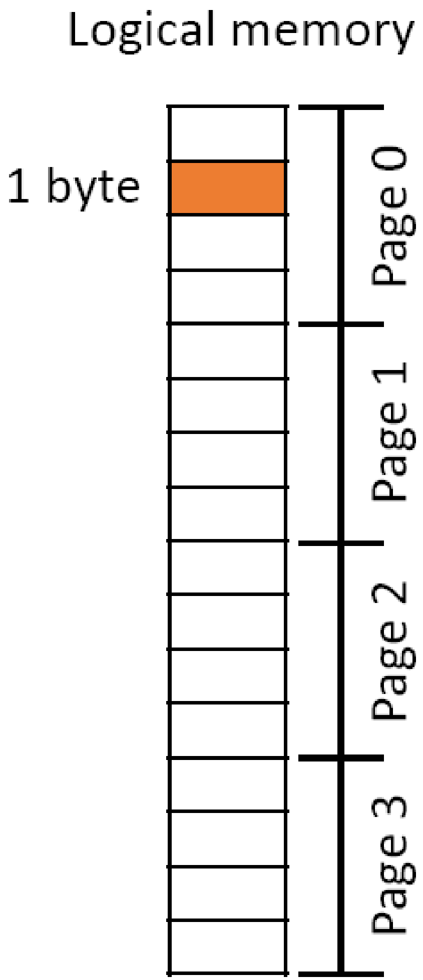


Size of logical address space : 16
Page size = 4 bytes

Q: How many bytes should each frame be?



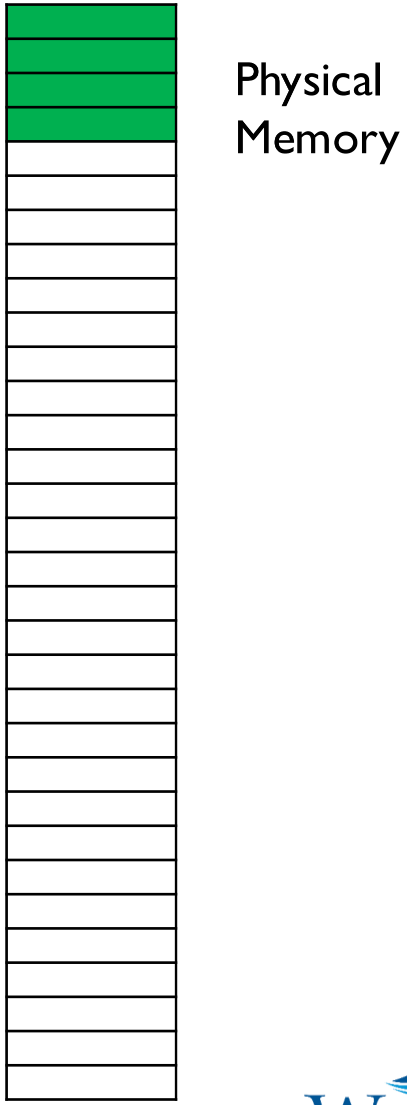
PAGING



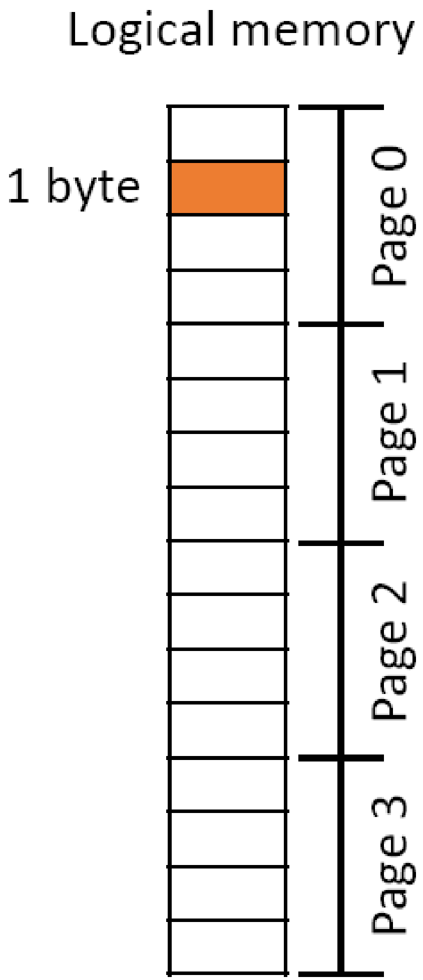
Size of logical address space : 16
Page size = 4 bytes

Q: How many bytes should each frame be?

Worksheet Q2: How many bits do we need for the logical address?



PAGING



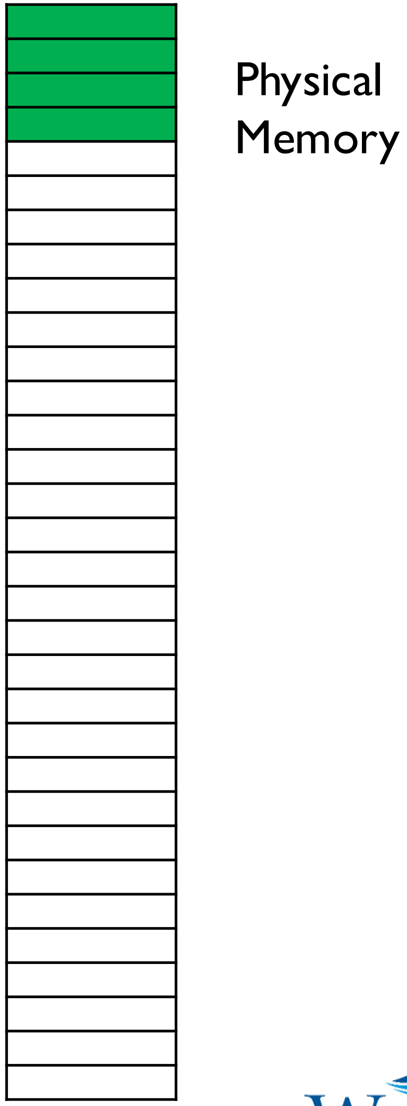
Size of logical address space : 16

Page size = 4 bytes

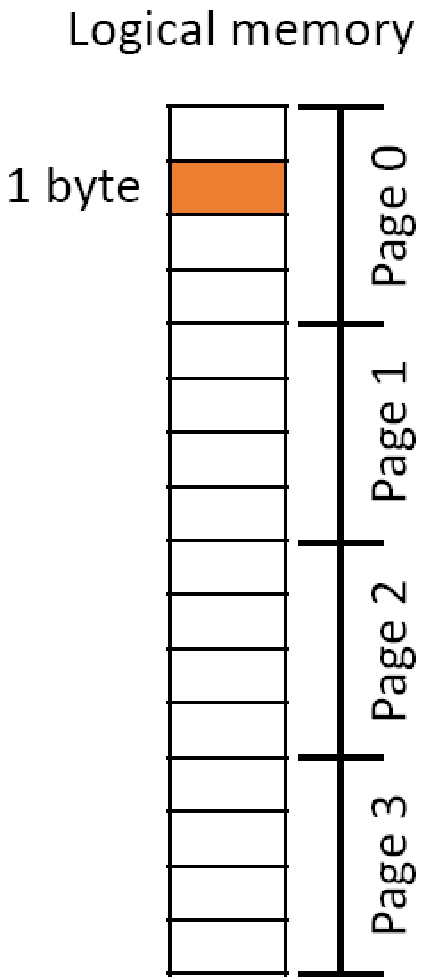
Worksheet Q2: How many bits do we need for the logical address?

m: total number of bits needed

n: number of bits needed for offset bits

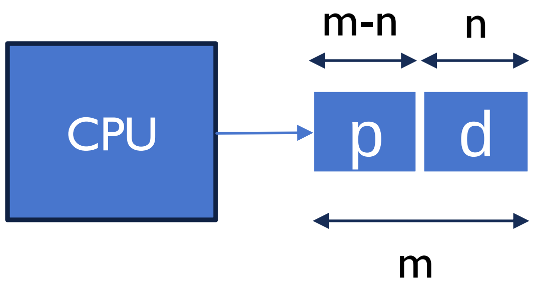


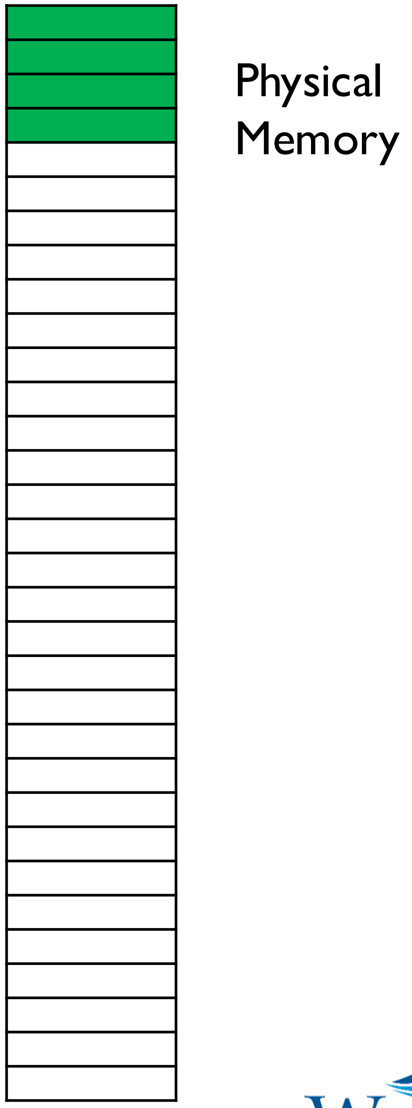
PAGING



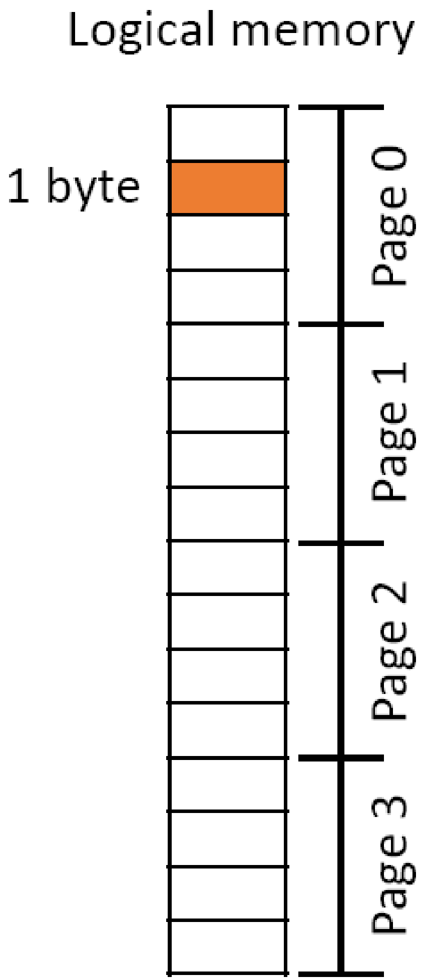
Size of logical address space : 16

Page size = 4 bytes





PAGING

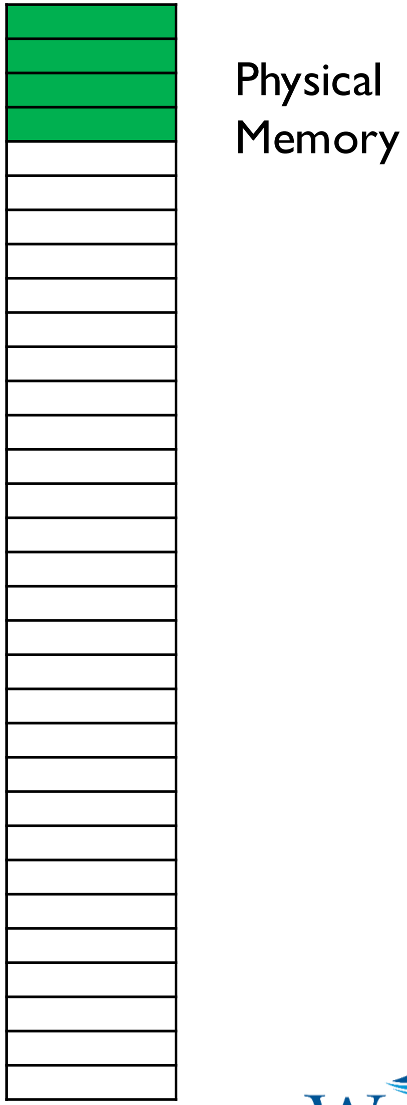


Size of logical address space : 16
Page size = 4 bytes

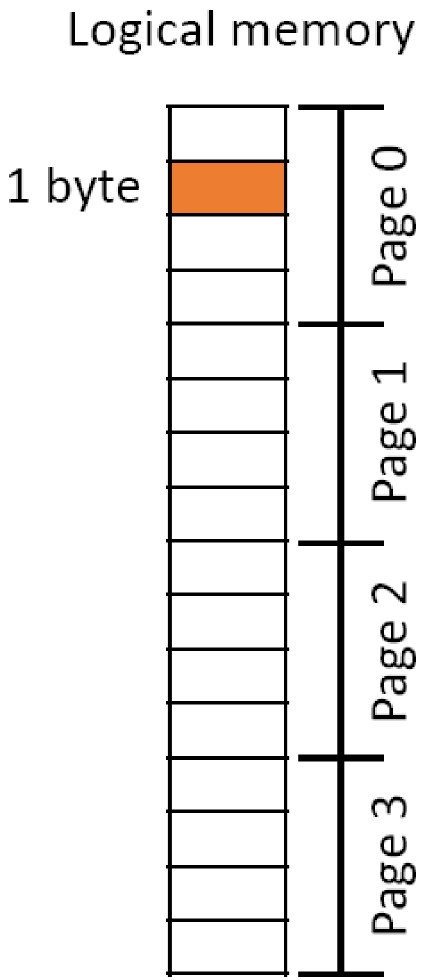
Worksheet Q2: How many bits do we need for the logical address?

m: total number of bits needed
n: number of bits needed for offset bits

Q: 16 is what power of 2? → $m = \log_2(16) = 4$



PAGING



Size of logical address space : 16

Page size = 4 bytes

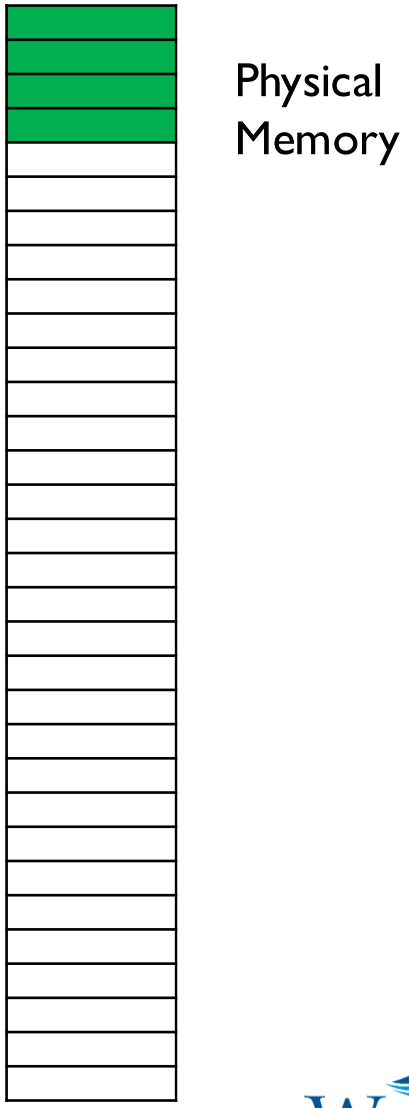
Worksheet Q2: How many bits do we need for the logical address?

m: total number of bits needed

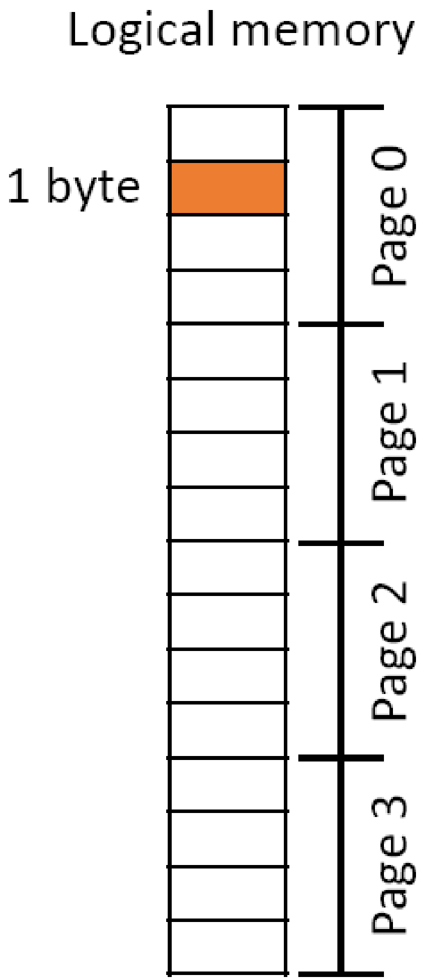
n: number of bits needed for offset bits

Q: 16 is what power of 2? → $m = \log_2(16) = 4$

Q: 4 is what power of 2? → $n = \log_2(4) = 2$



PAGING



Size of logical address space : 16

Page size = 4 bytes

Worksheet Q2: How many bits do we need for the logical address?

m: total number of bits needed

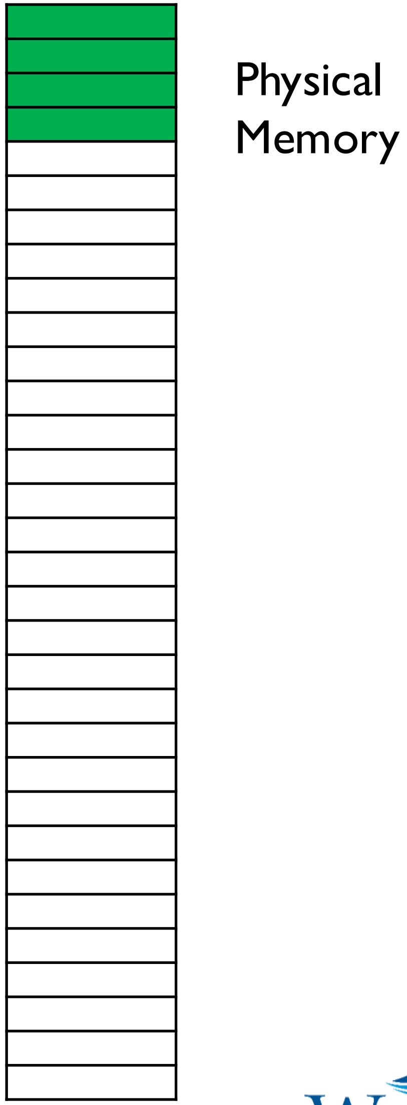
n: number of bits needed for offset bits

Q: 16 is what power of 2? → $m = \log_2(16) = 4$

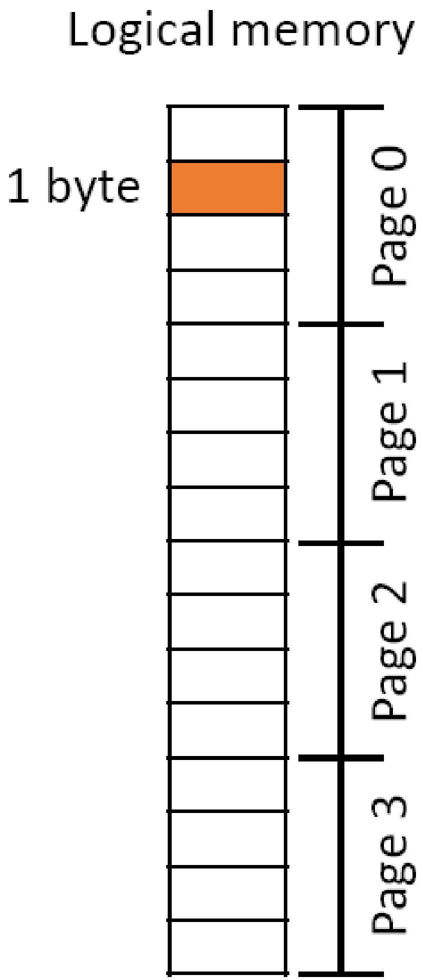
Q: 4 is what power of 2? → $n = \log_2(4) = 2$

Size of logical address space : 2^m

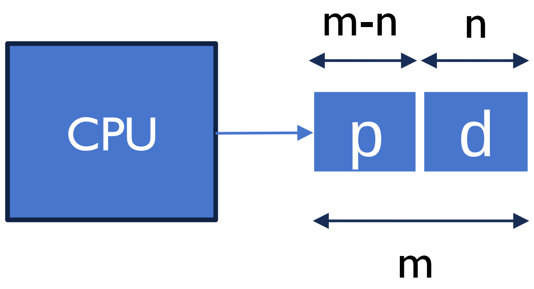
Page size : 2^n bytes



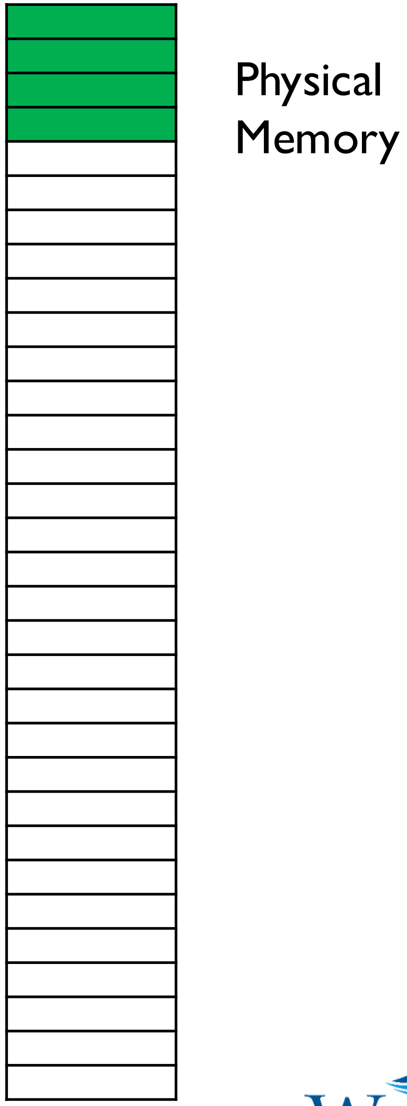
PAGING



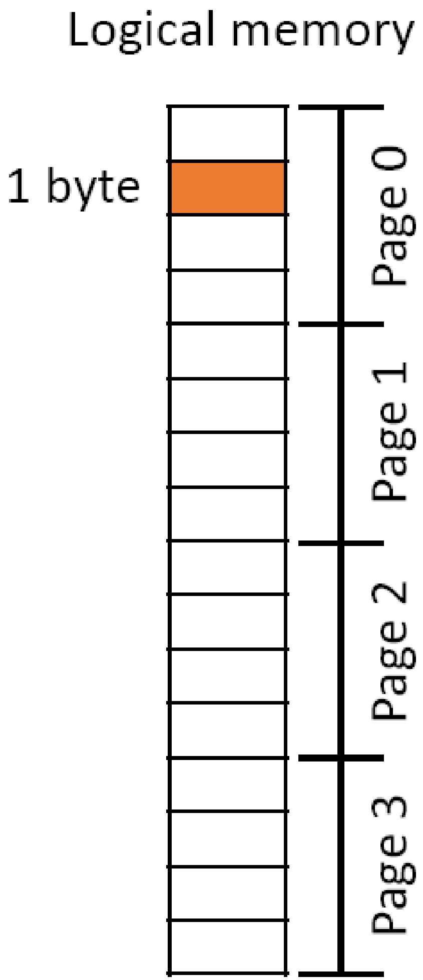
Size of logical address space : 16
Page size = 4 bytes



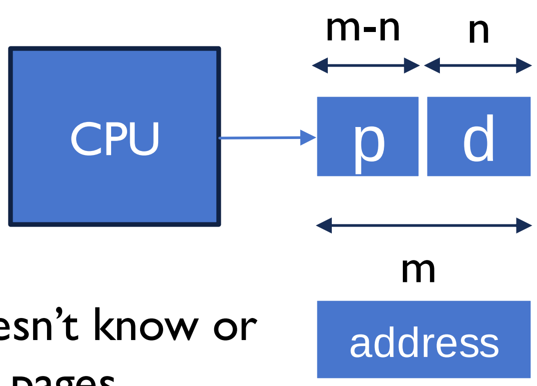
When page # and page size are both a power of 2 … logical address becomes contiguous!



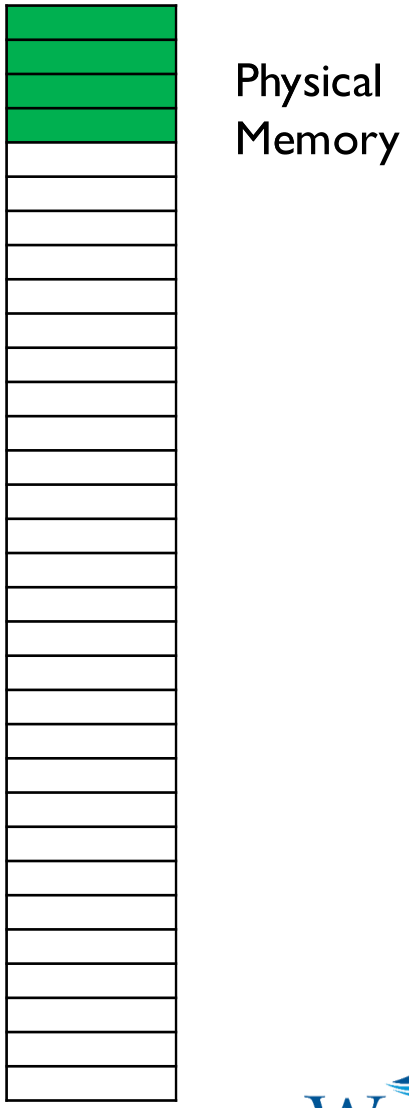
PAGING



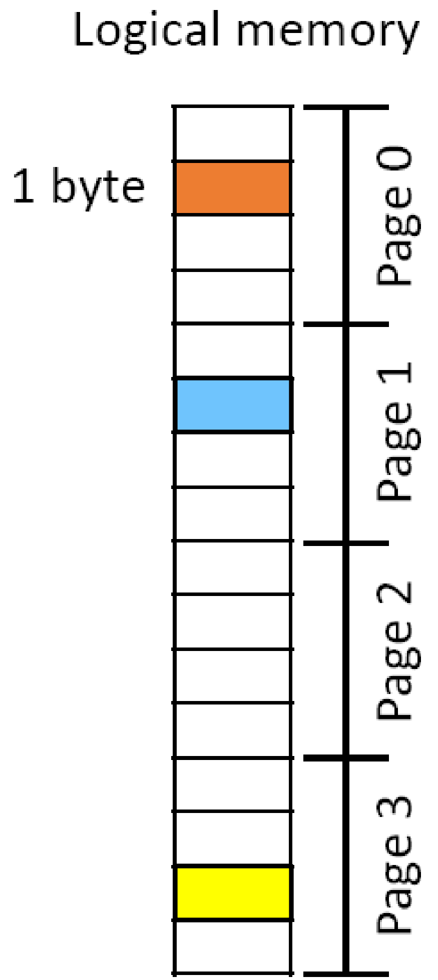
Size of logical address space : 16
Page size = 4 bytes



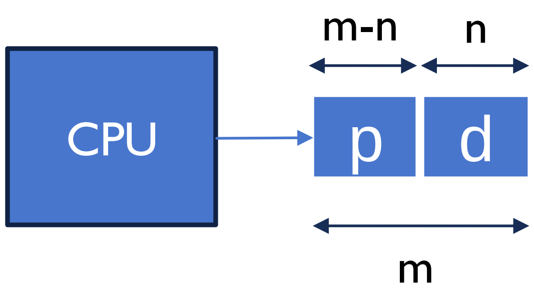
Software doesn't know or worry about pages …

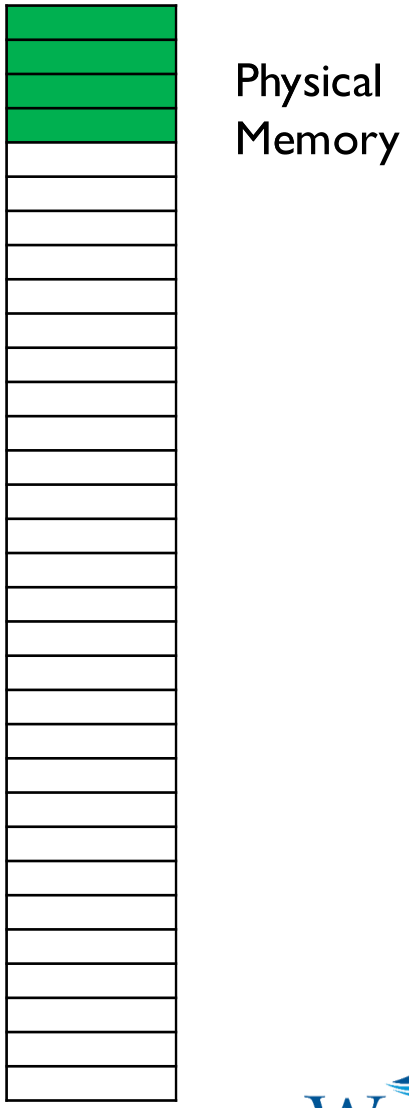


PAGING

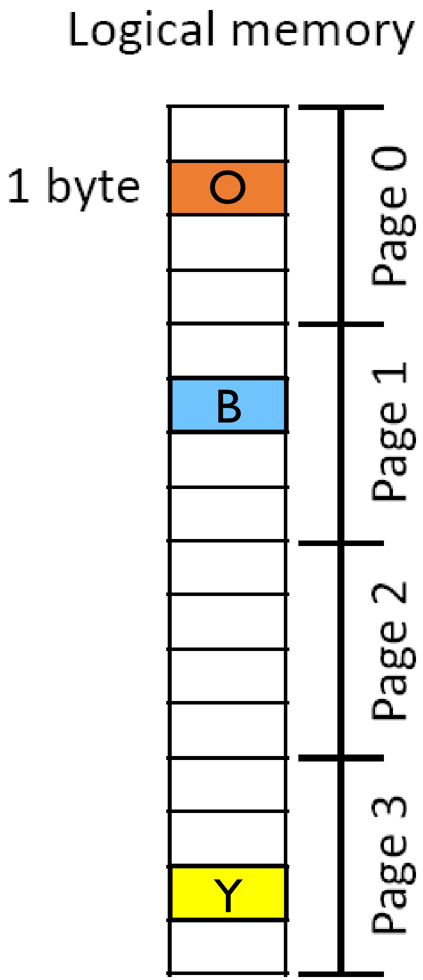


- What does this mean?
- Program doesn’t see pages, it sees contiguous memory …





PAGING

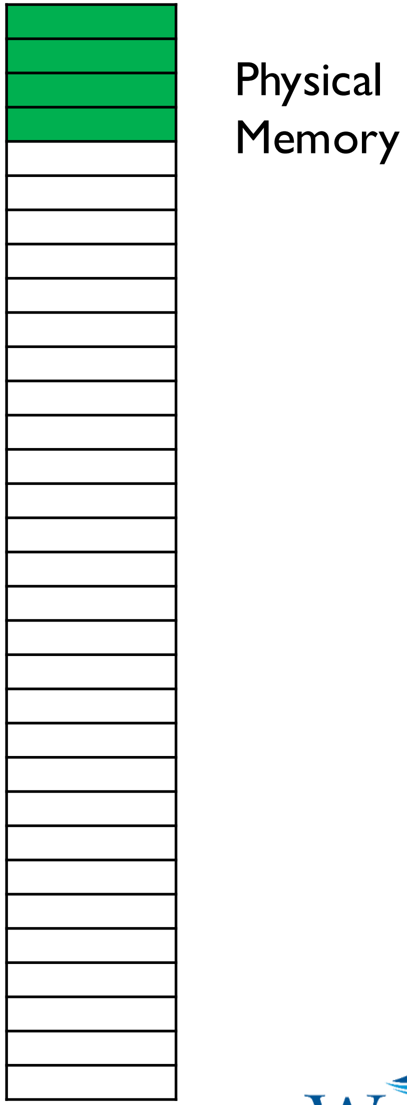


m = 4 = total size of logical address space

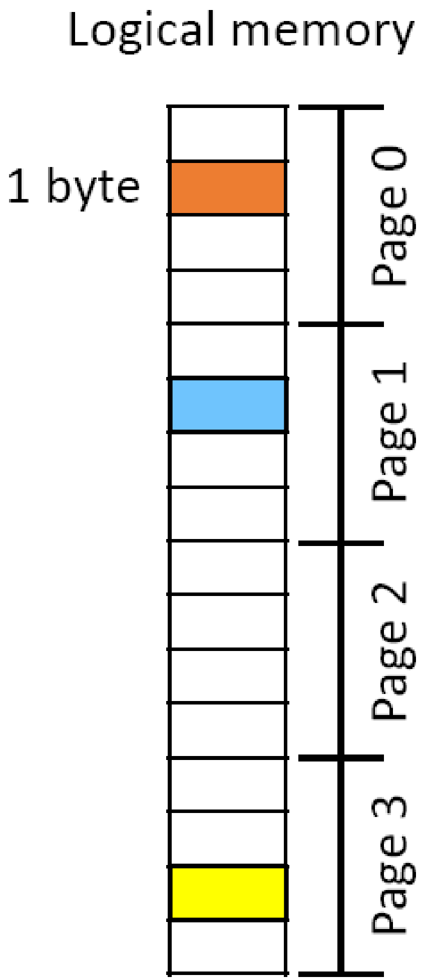
n = 2 = size of page

Worksheet Q3

Q: What is the address of the orange byte?
Q: What is the address of the blue byte?
Q: What is the address of the yellow byte?



PAGING



m = 4 = total size of logical address space

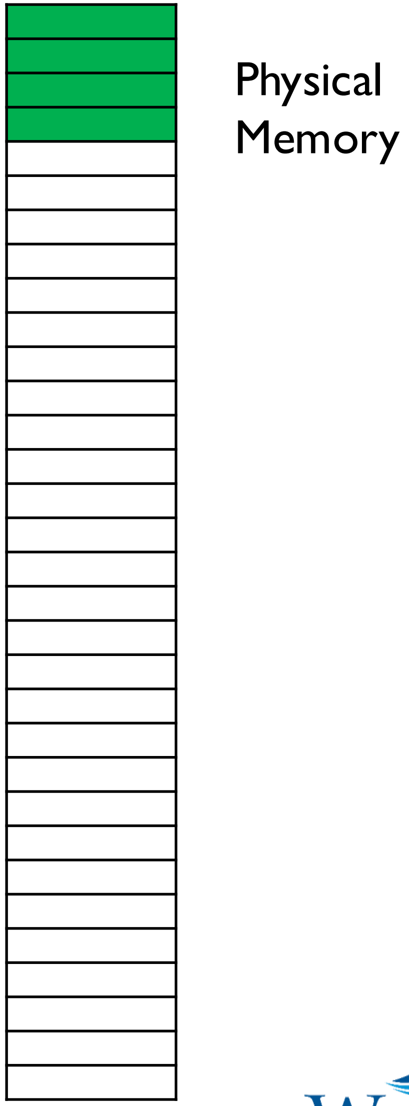
n = 2 = size of page

Q: What is the address of the orange byte?
Q: What is the address of the blue byte?
Q: What is the address of the yellow byte?

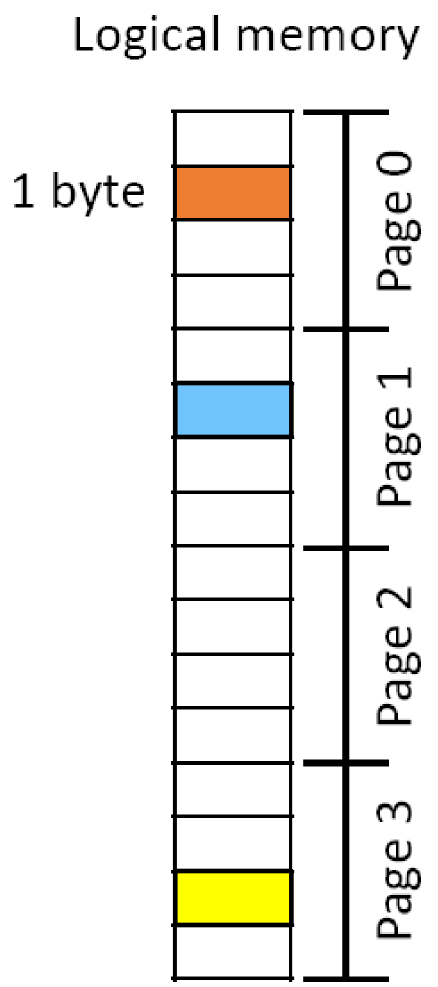
🟧 0001

🟦 0101

🟨 1110



PAGING

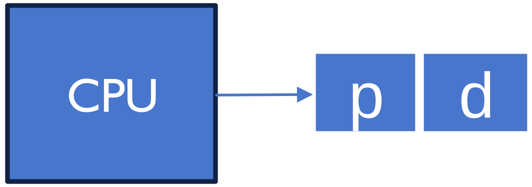


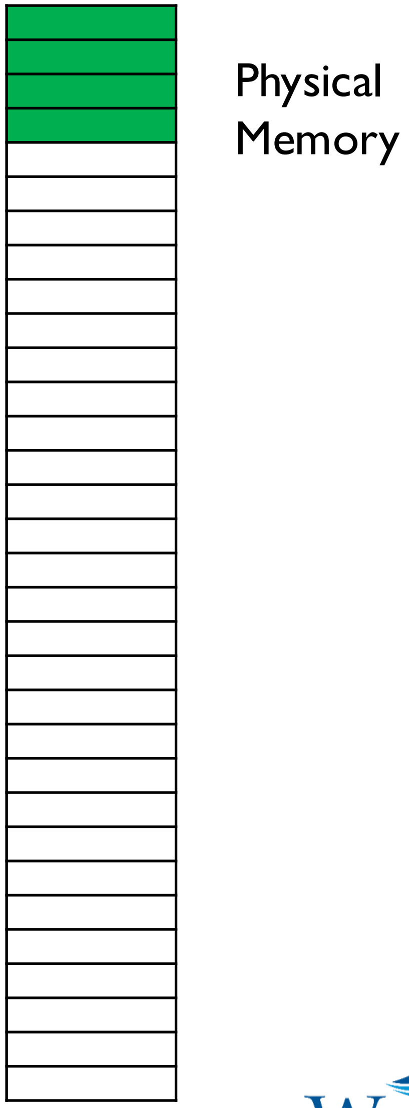
m = 4 = total size of logical address space

n = 2 = size of page

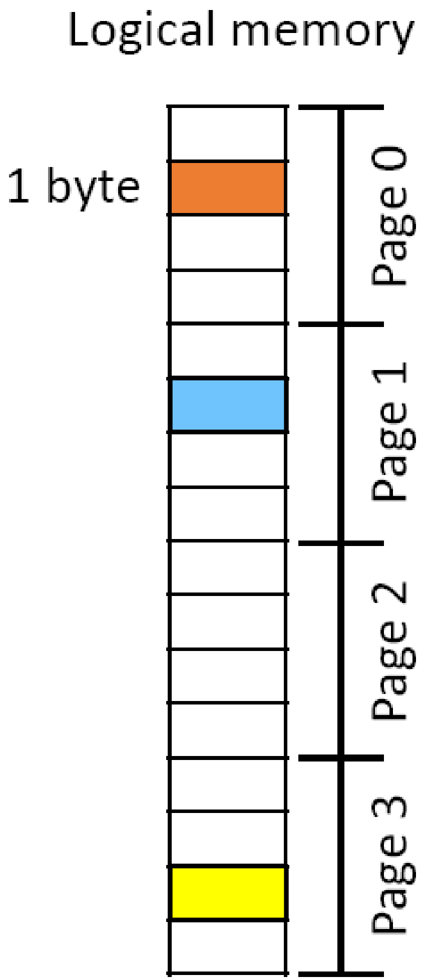
Q: What is the address of the orange byte?
Q: What is the address of the blue byte?
Q: What is the address of the yellow byte?

🟧	0001
🟦	0101
🟨	1110





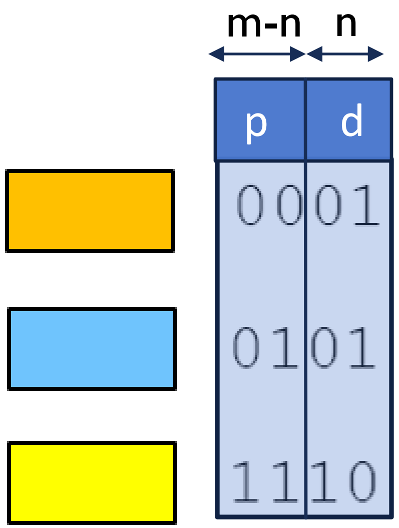
PAGING



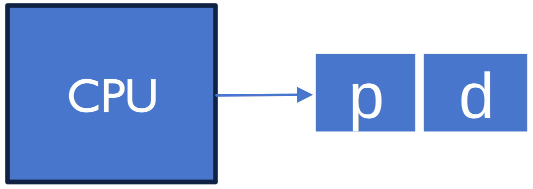
m = 4 = total size of logical address space

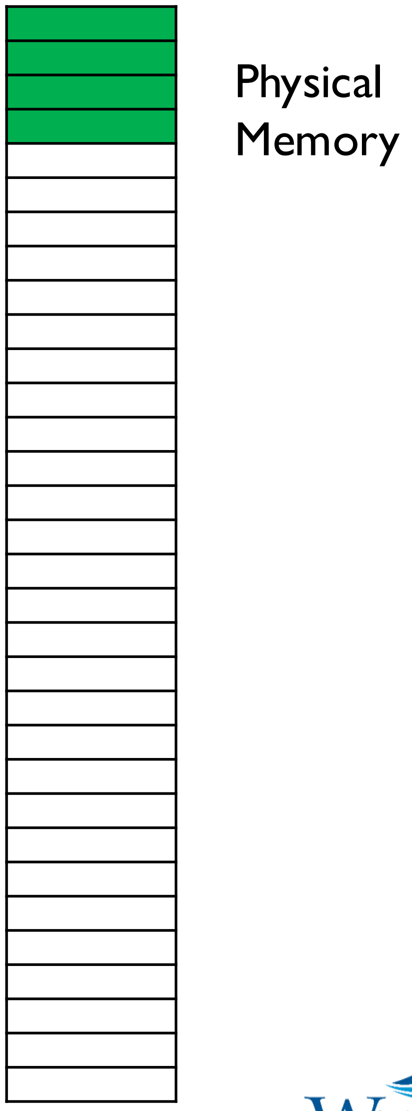
n = 2 = size of page

Q: What is the address of the orange byte?
Q: What is the address of the blue byte?
Q: What is the address of the yellow byte?



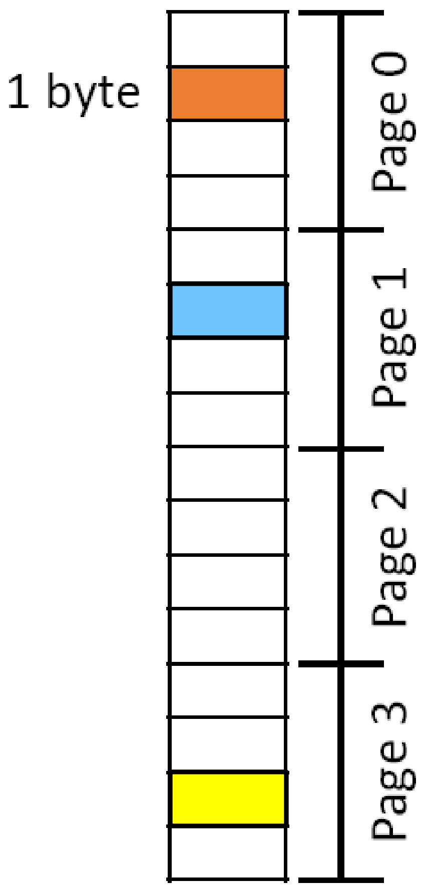
	m-n	n
	p	d
🟧	00	01
🟦	01	01
🟨	11	10





PAGING

Logical memory

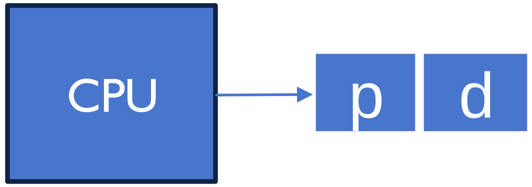


m = 4 = total size of logical address space

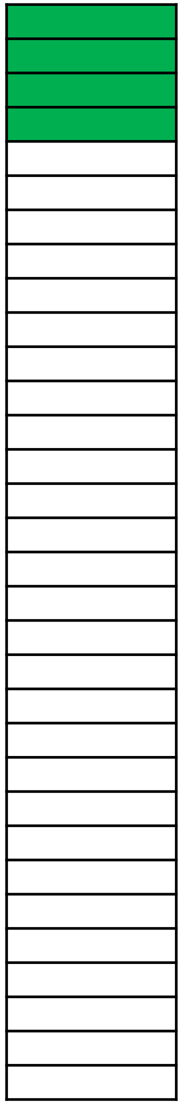
n = 2 = size of page

Q: What is the address of the orange byte?
Q: What is the address of the blue byte?
Q: What is the address of the yellow byte?

	m-n	n
	p	d
🟧	00	01
🟦	01	01
🟨	11	10



Contiguous logical memory can naturally be treated as page, offset <p,d>

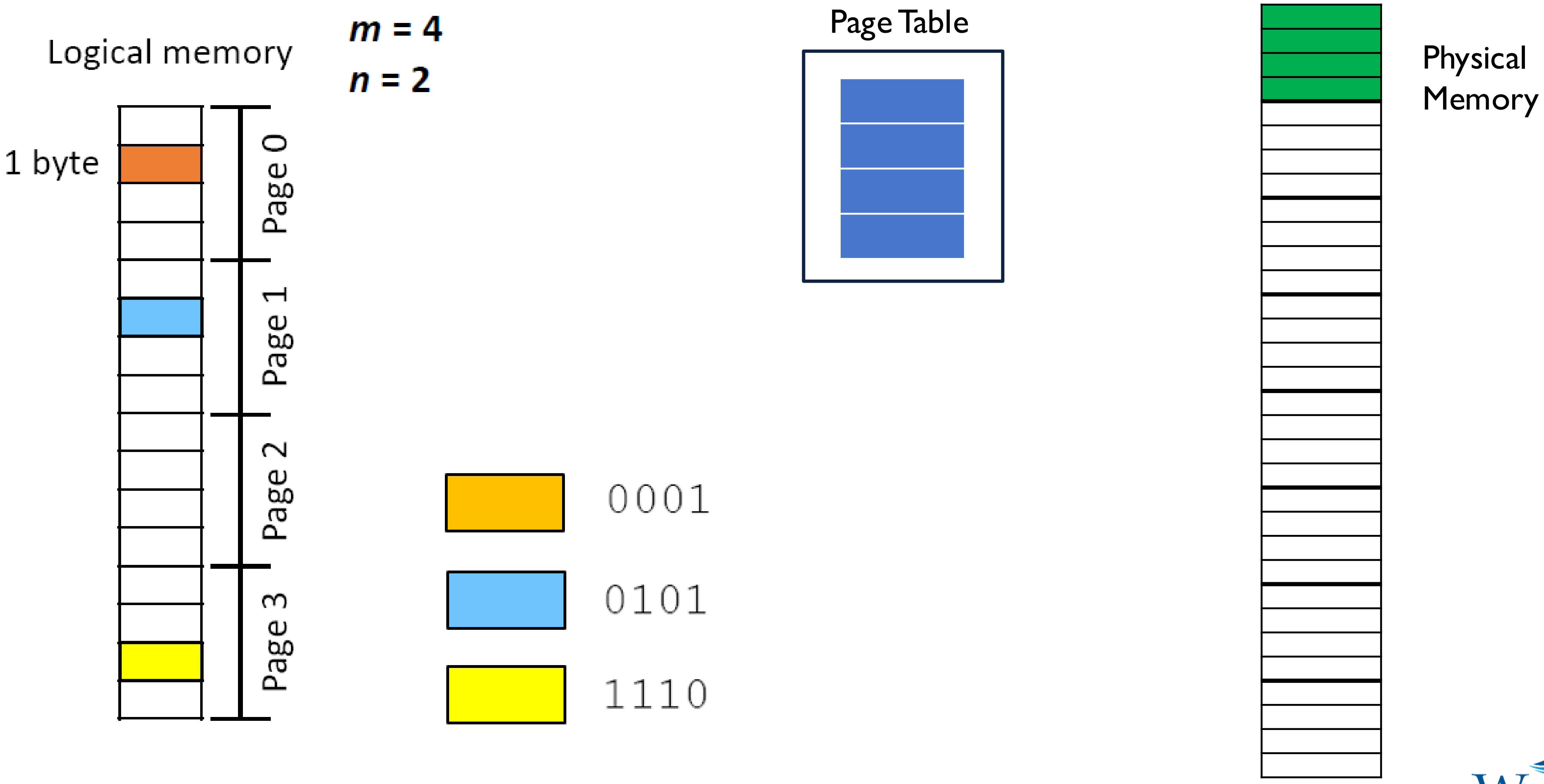


Physical Memory

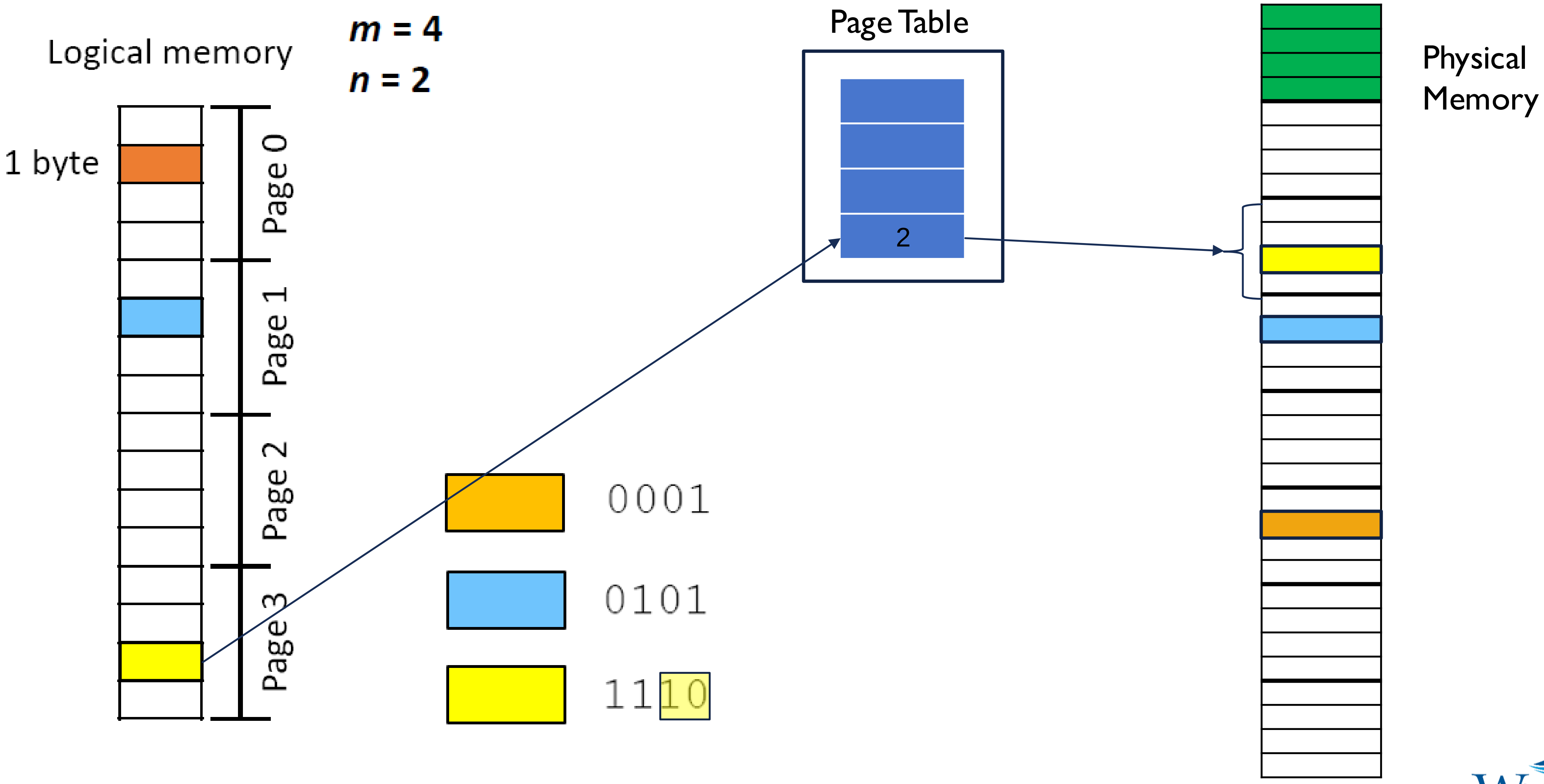
PAGING

$m = 4$

$n = 2$


Logical memory
1 byte
Page 0
Page 1
Page 2
Page 3
Page Table
Physical Memory
0001
0101
1110

PAGING



$m = 4$

$n = 2$

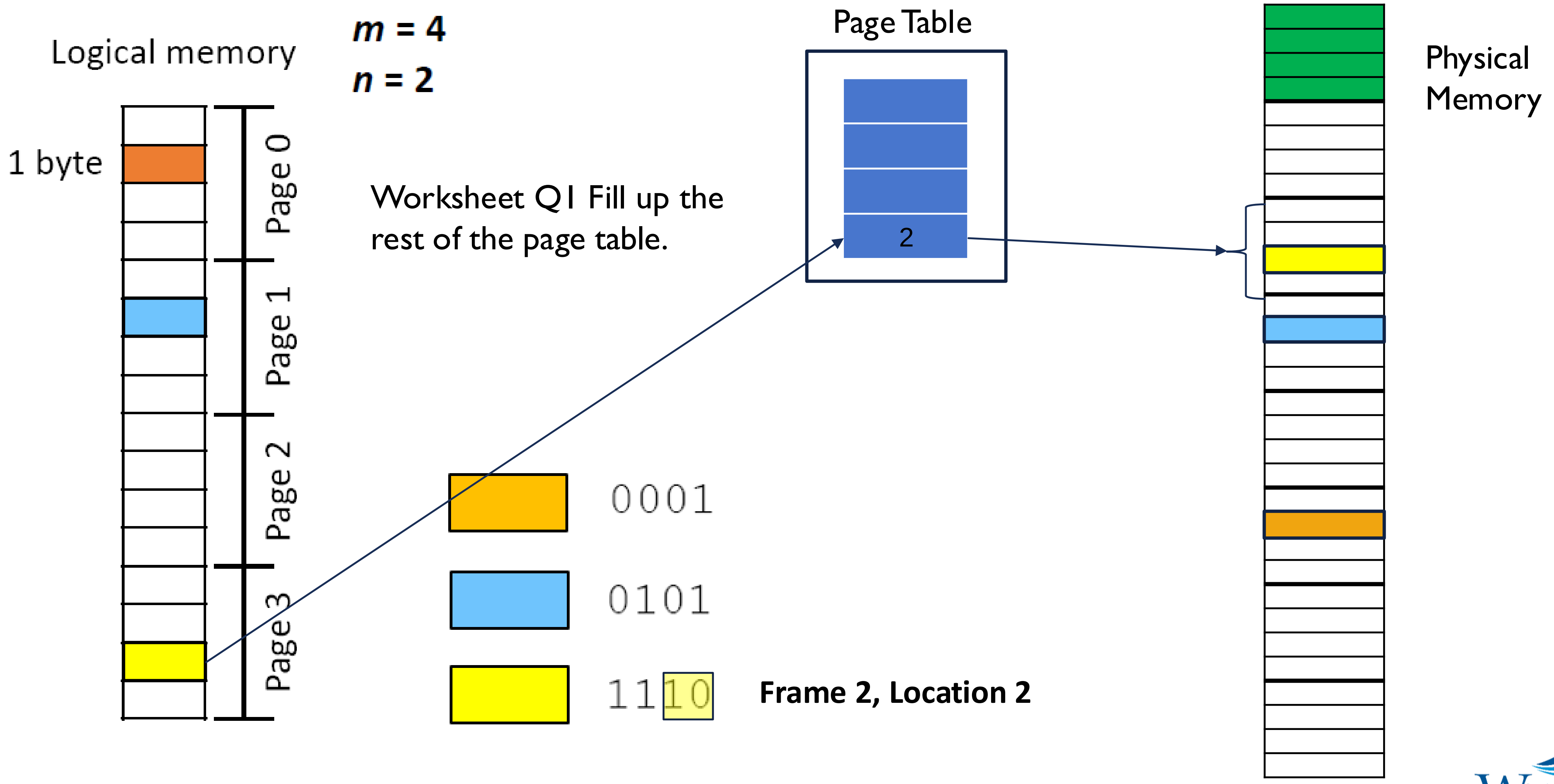
Logical memory
1 byte
Page 0
Page 1
Page 2
Page 3
Page Table
2
Physical Memory
0001
0101
1110

PAGING

***m* = 4**

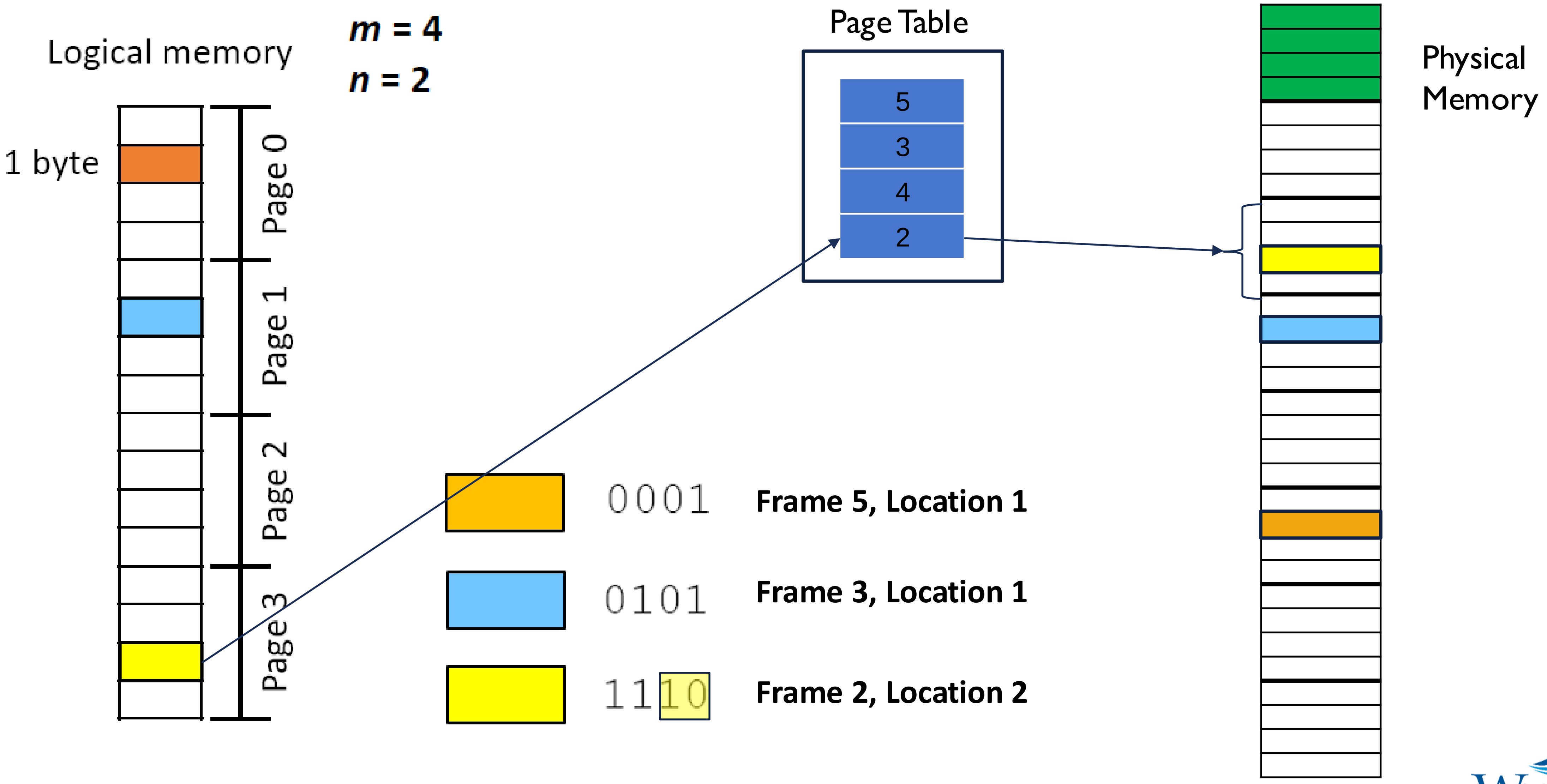
***n* = 2**

Worksheet Q1 Fill up the rest of the page table.



Frame 2, Location 2

PAGING



Logical memory

m = 4

n = 2

1 byte

Page 0

Page 1

Page 2

Page 3

Page Table

5

3

4

2

Physical Memory

🟧 0001 **Frame 5, Location 1**

🟦 0101 **Frame 3, Location 1**

🟨 1110 **Frame 2, Location 2**