CSC 252: Computer Organization
Spring 2021: Lecture 18

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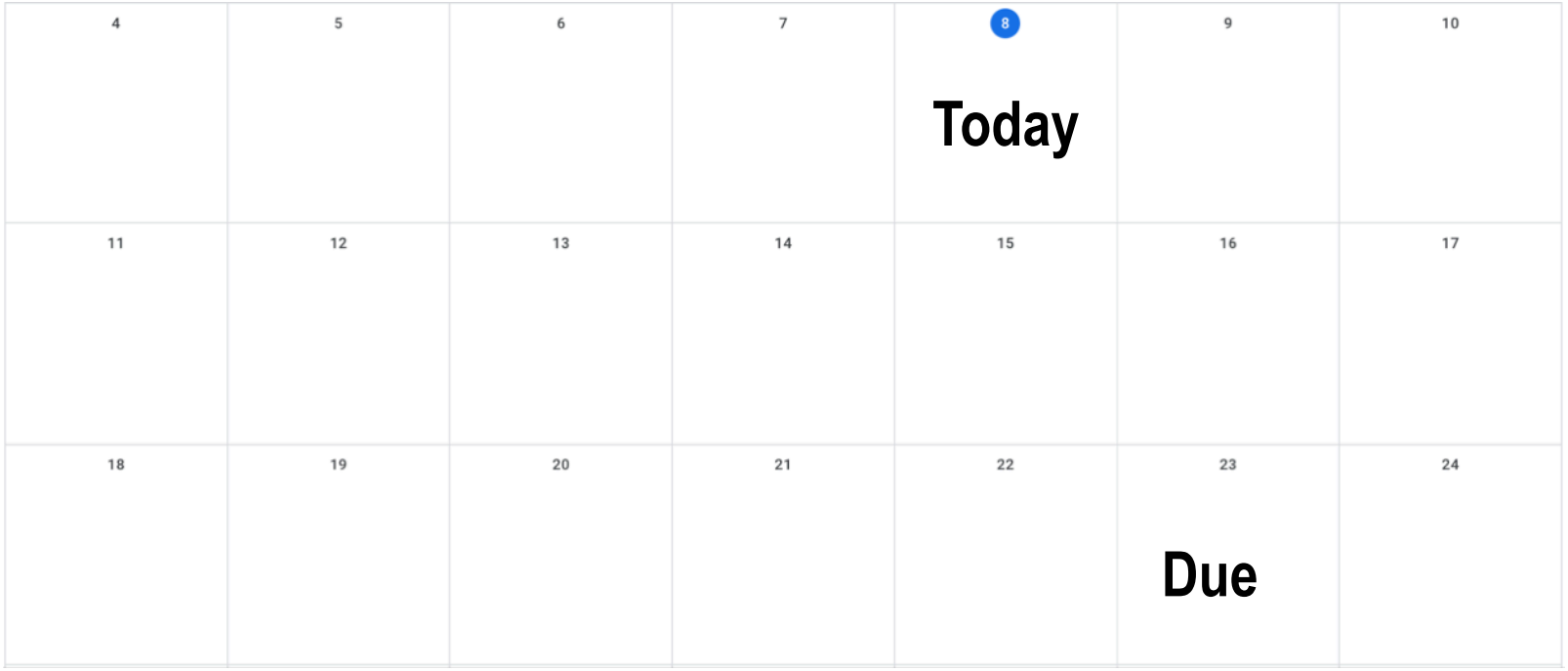
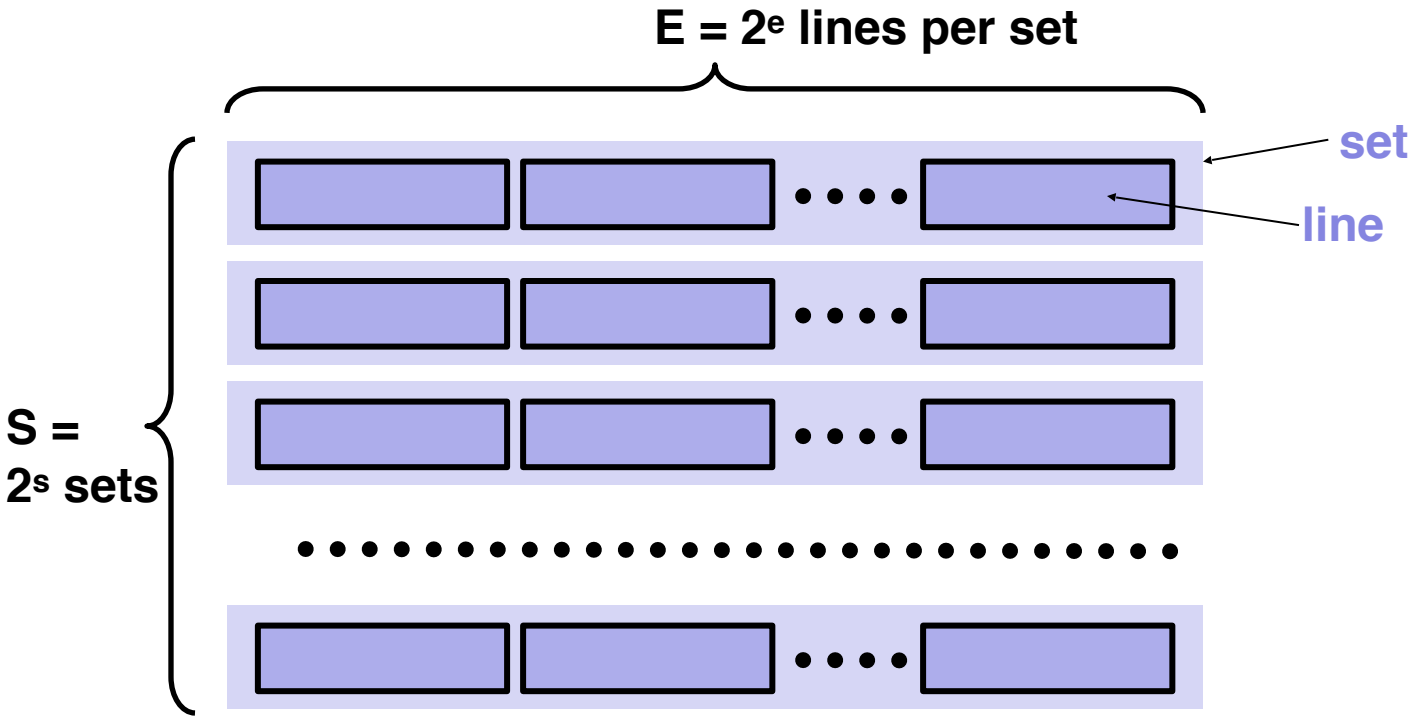
Announcements

- Cache problem set: https://www.cs.rochester.edu/courses/252/spring2021/handouts.html
- Not to be turned in. Won't be graded.
- Assignment 4 soon to be released later today.
- Final exam: Wednesday, May 12, 19:15 PM. 3 hours.



General Cache Organization (S, E, B)



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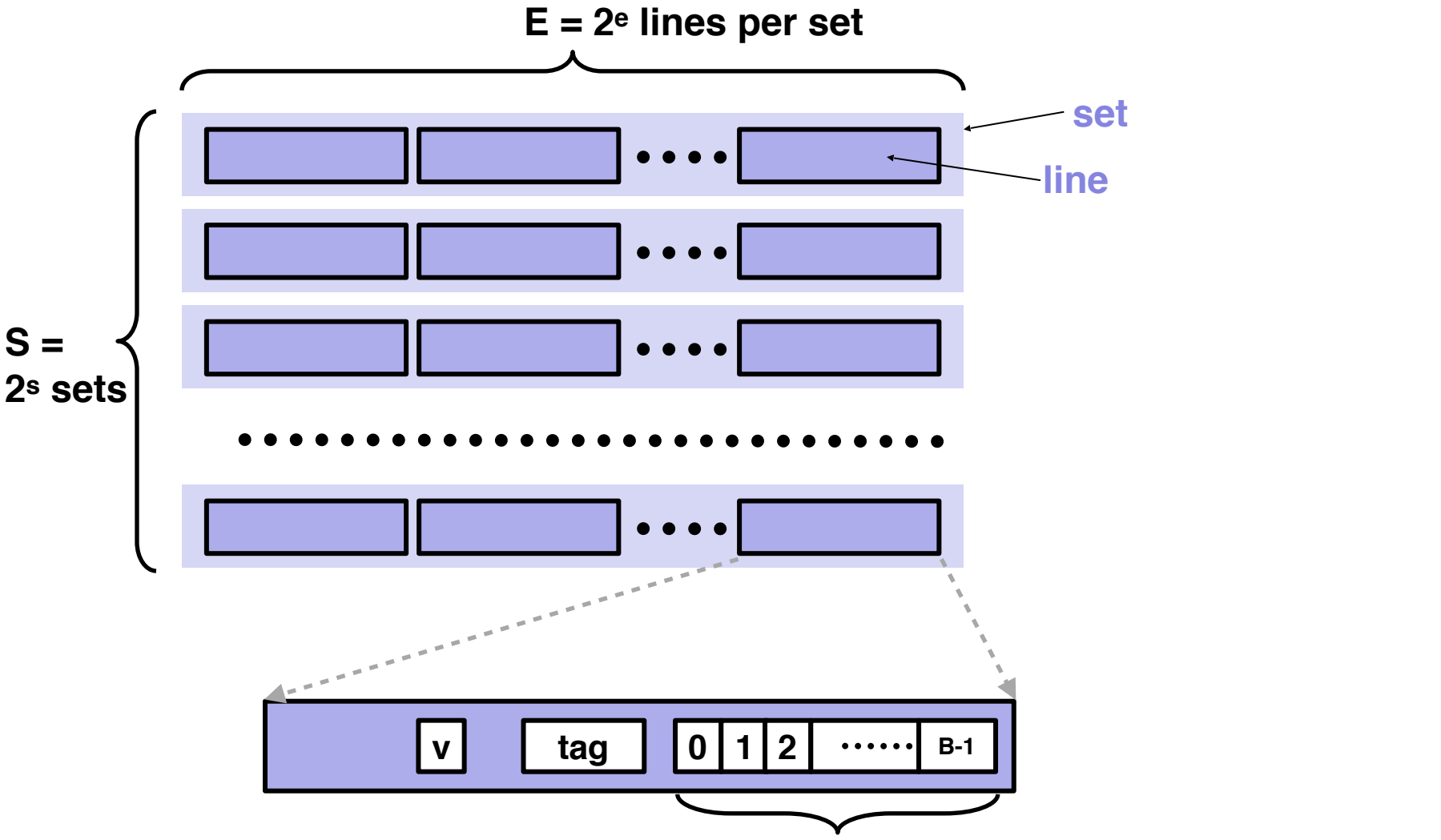

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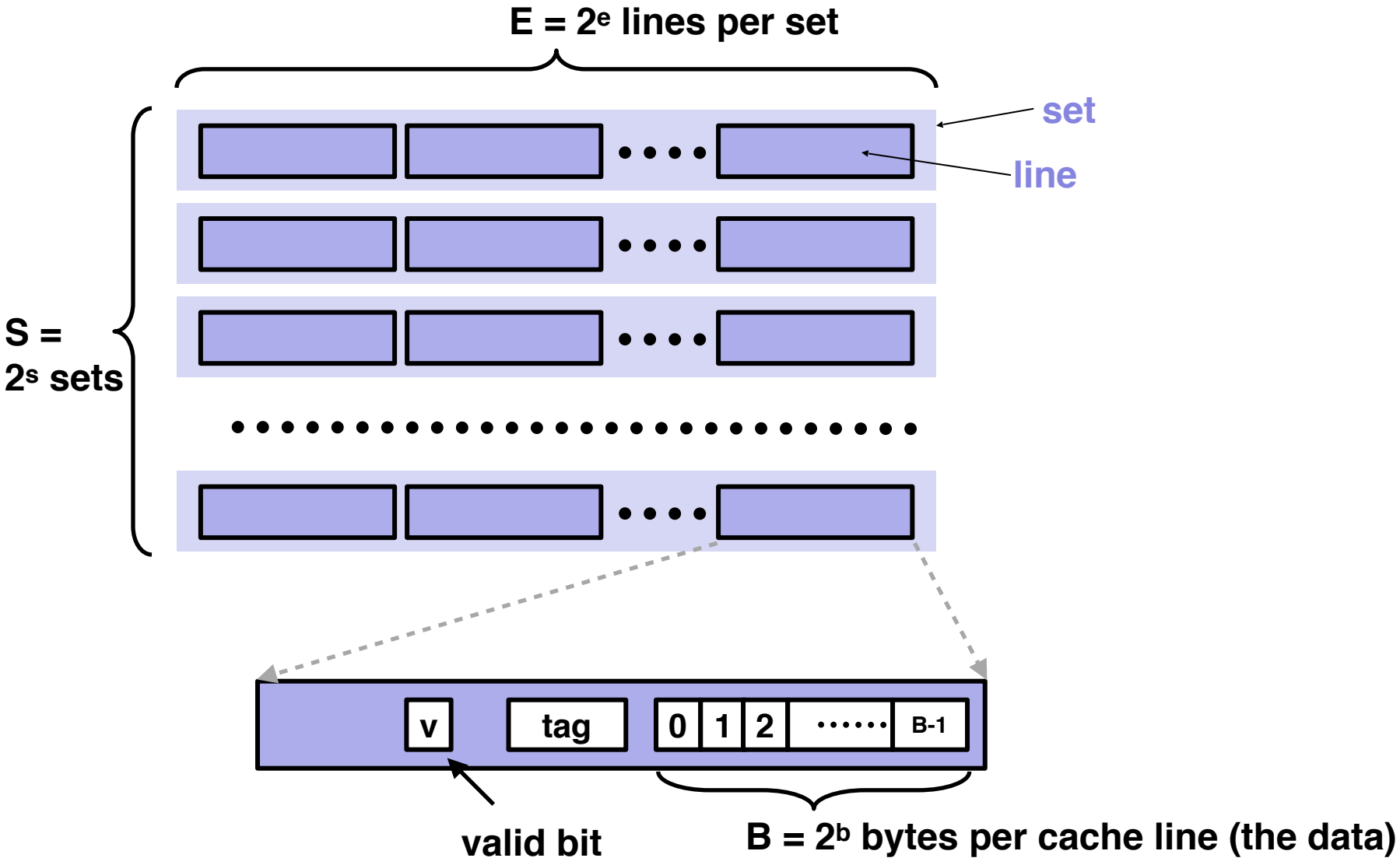

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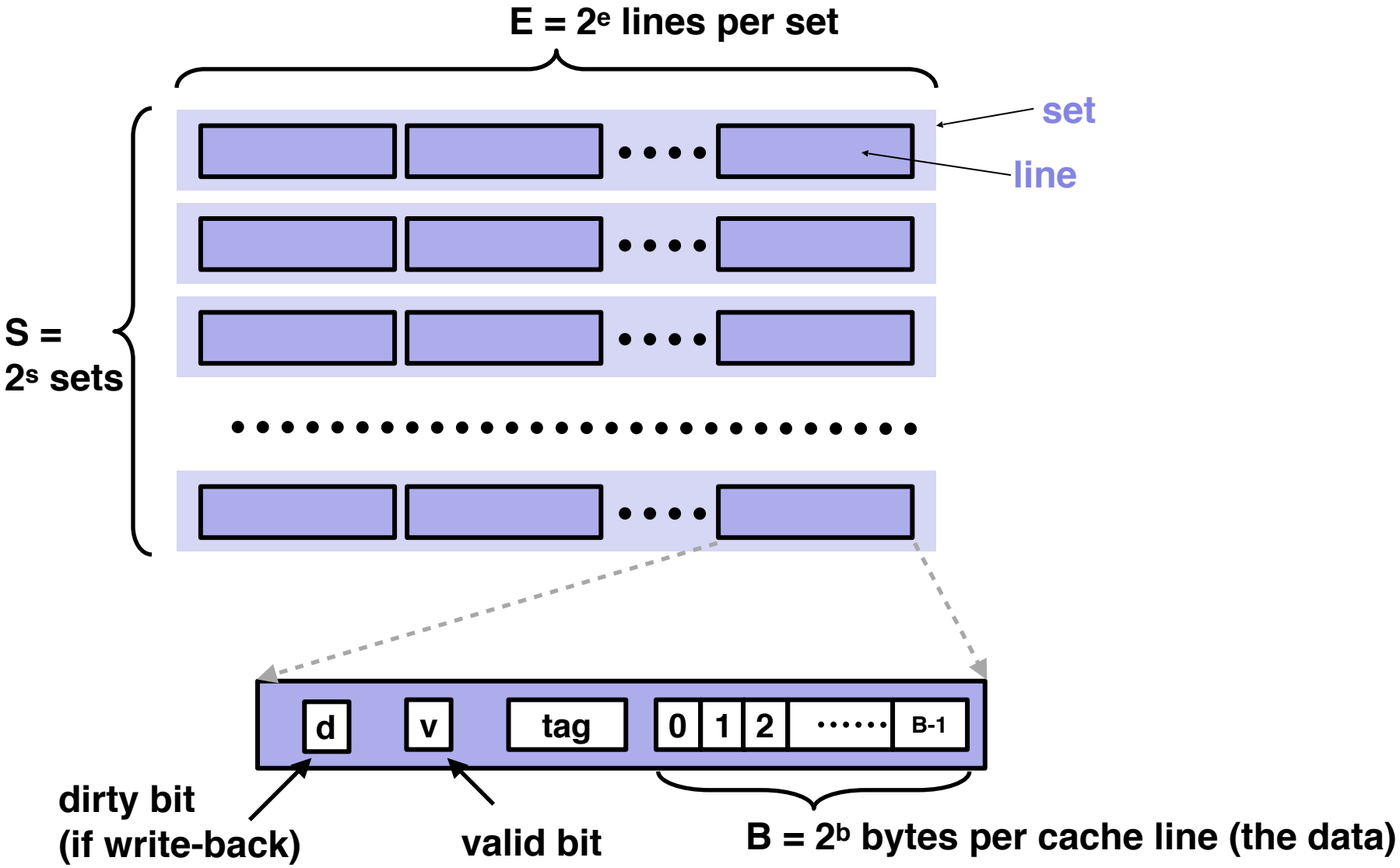

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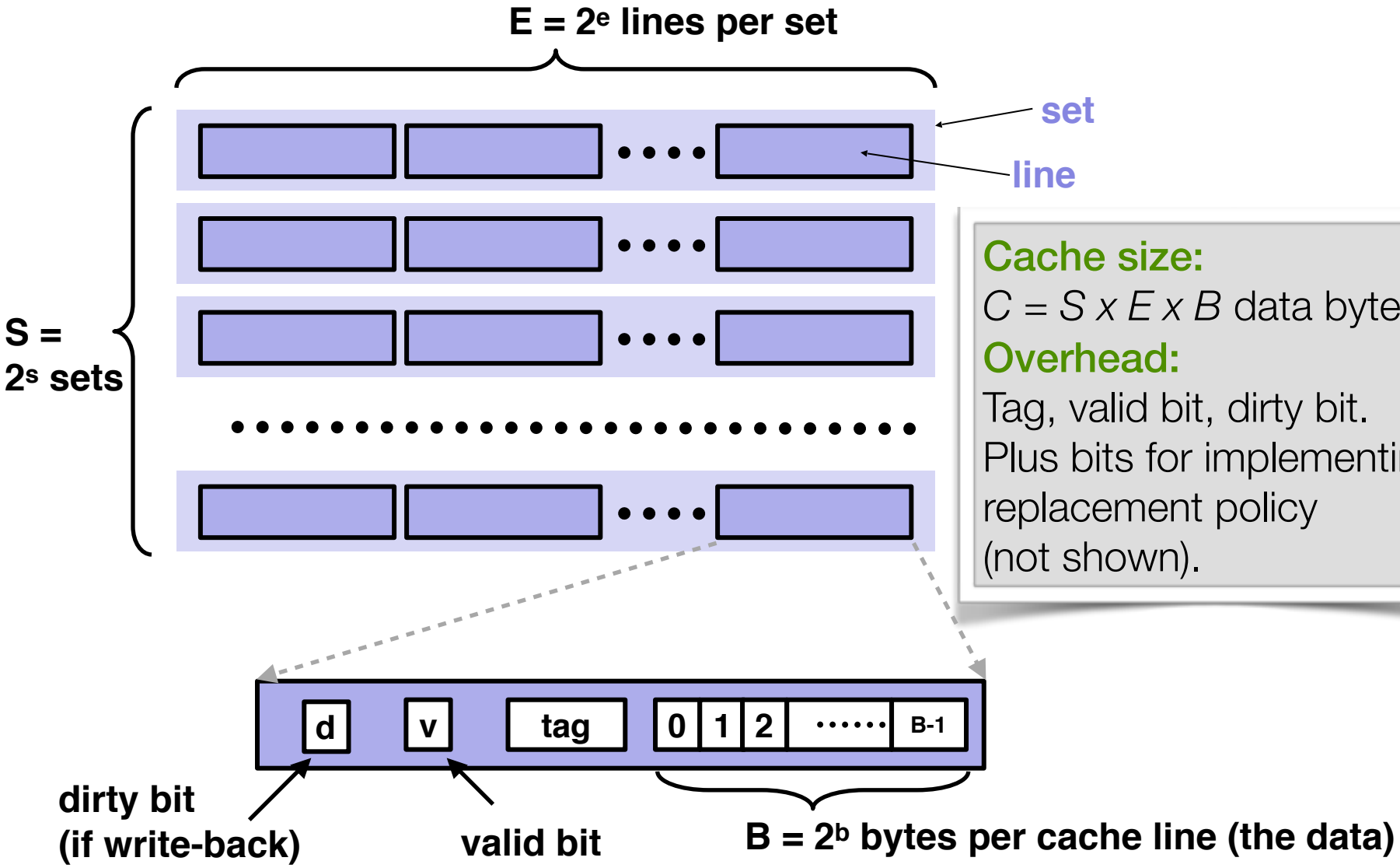
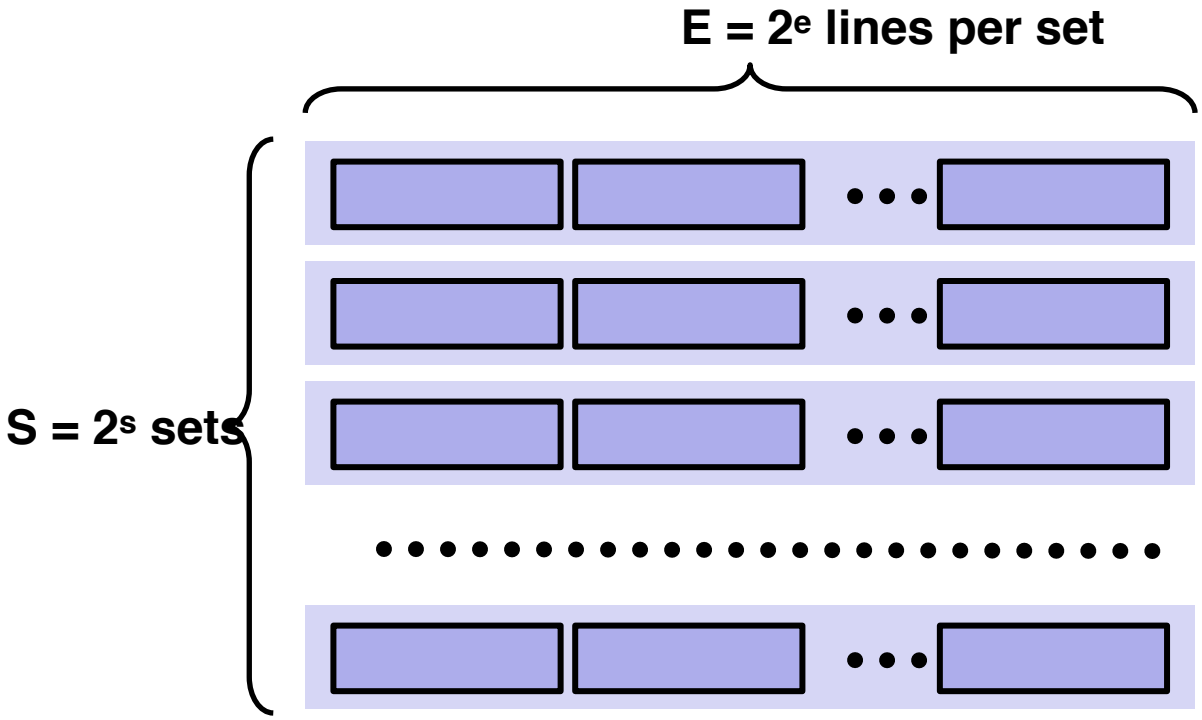
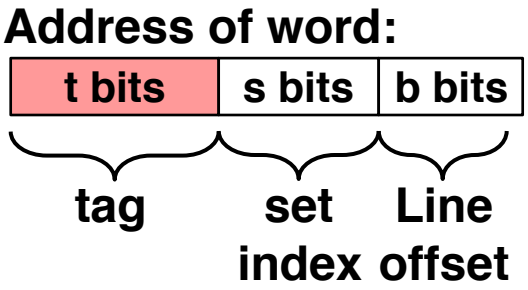


Cache size:
C = S x E x B data bytes

Overhead:
Tag, valid bit, dirty bit.
Plus bits for implementing replacement policy (not shown).

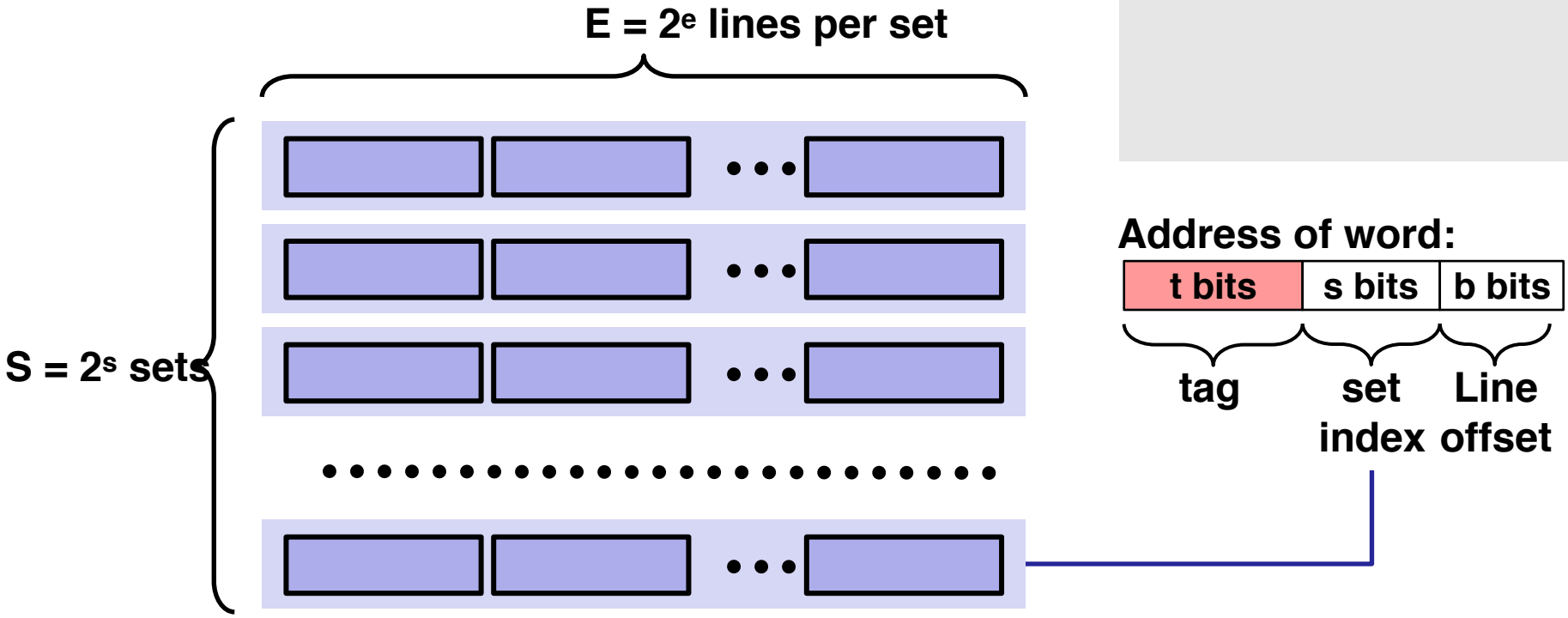
Cache Access





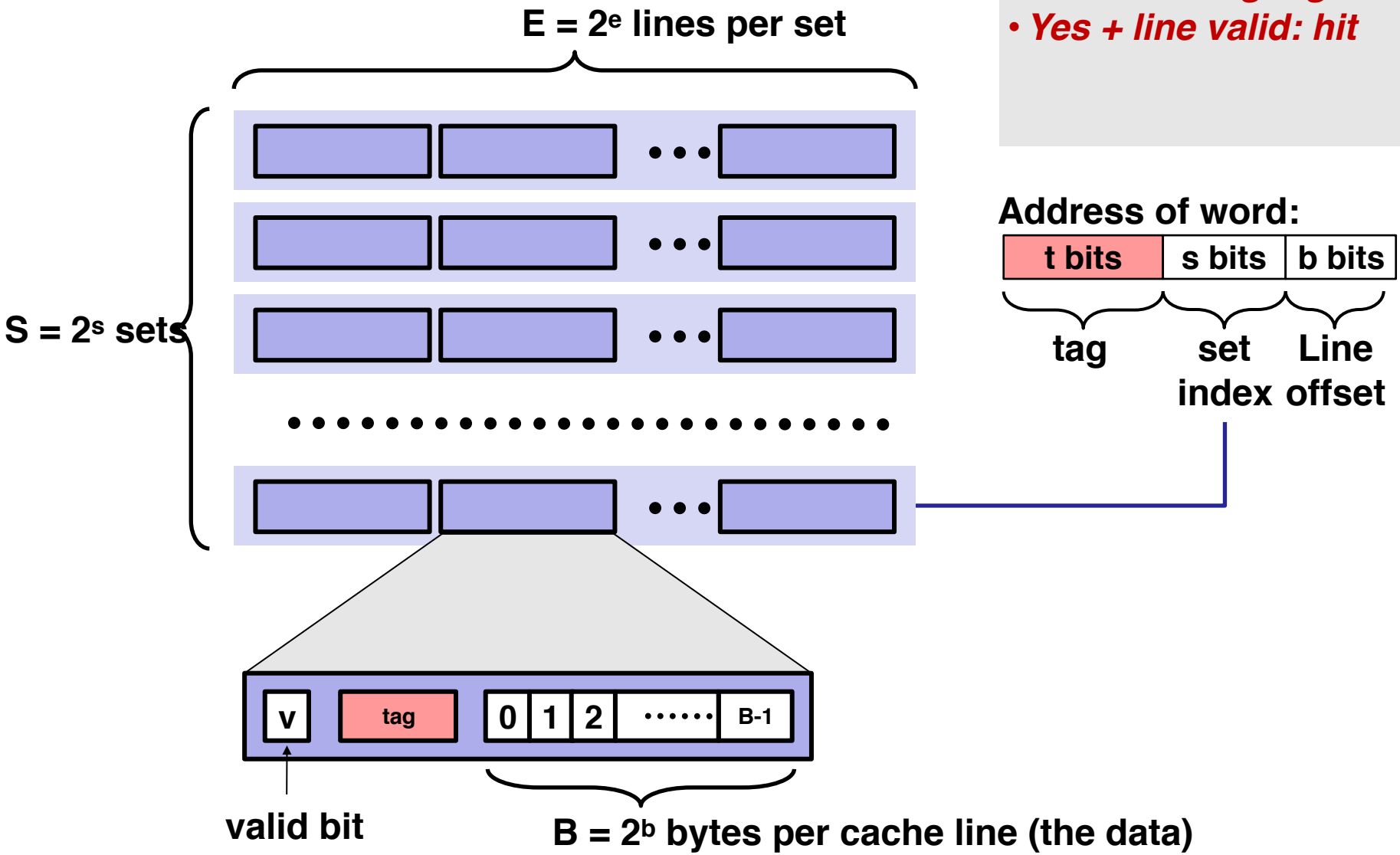
Cache Access

- *Locate set*



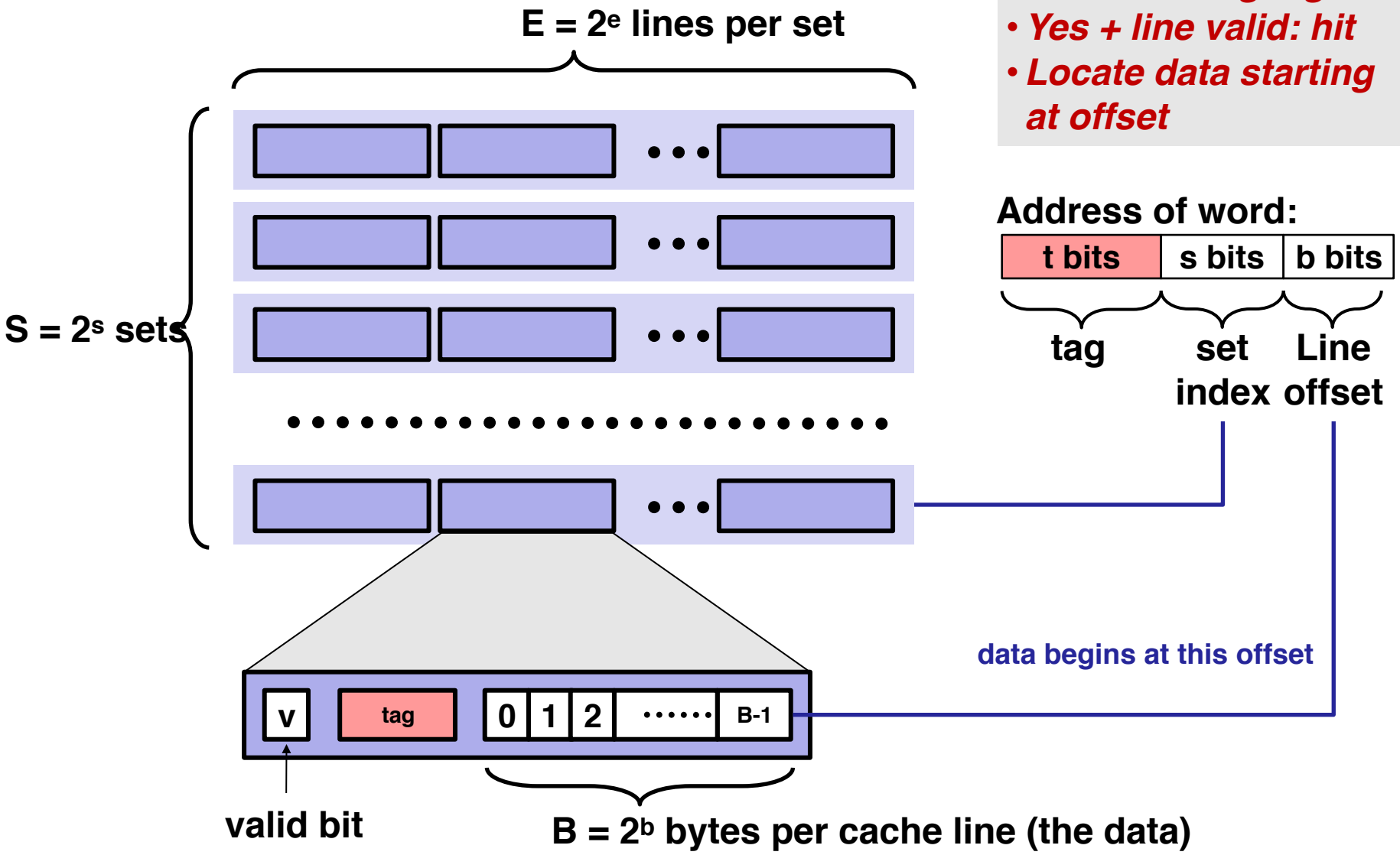
Cache Access

- *Locate set*
- *Check if any line in set has matching tag*
- *Yes + line valid: hit*



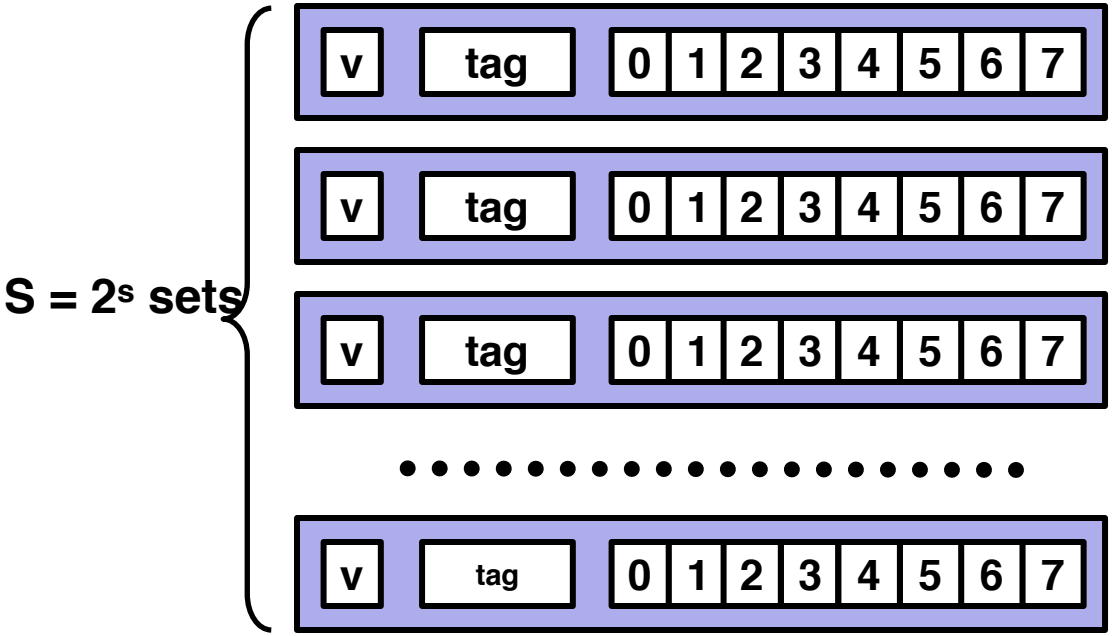
Cache Access

- *Locate set*
- *Check if any line in set has matching tag*
- *Yes + line valid: hit*
- *Locate data starting at offset*

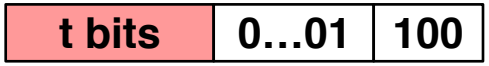


Example: Direct Mapped Cache

Direct mapped: One line per set
Assume: cache line size 8 bytes



Address of `char`:



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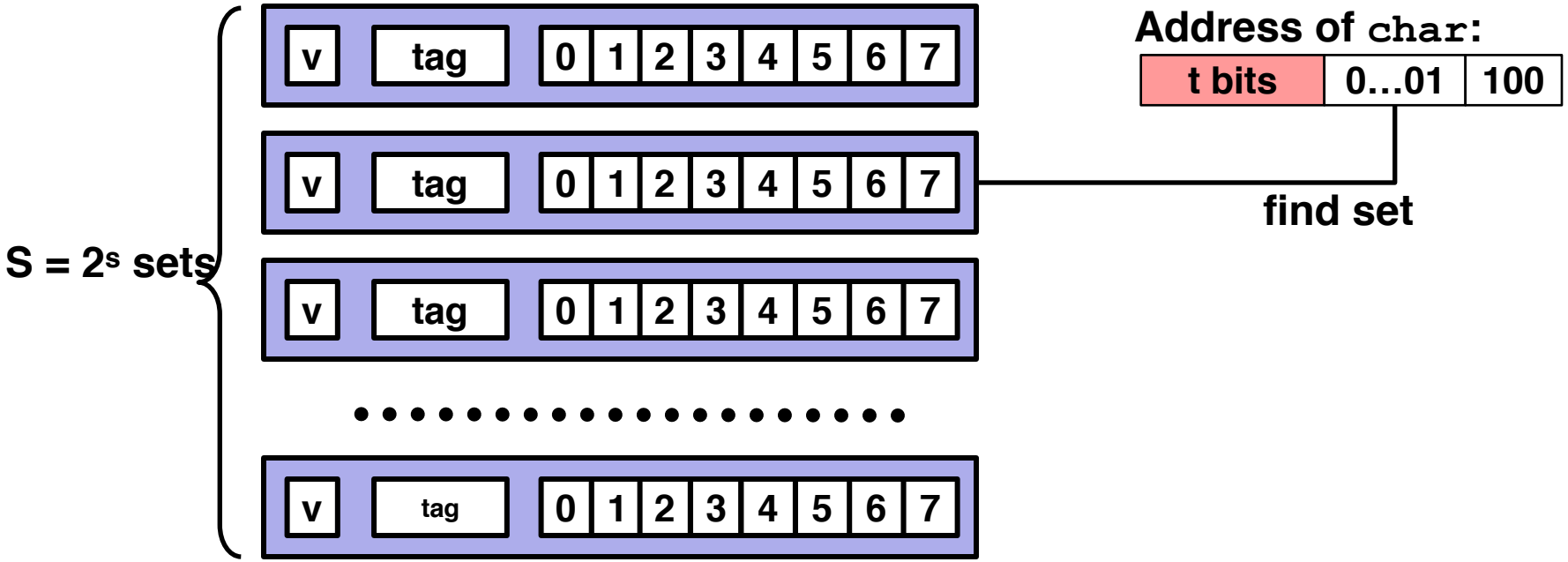

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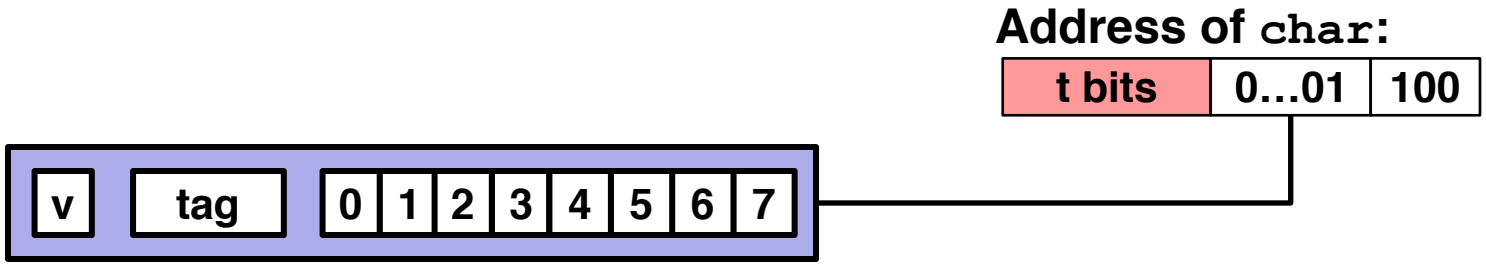

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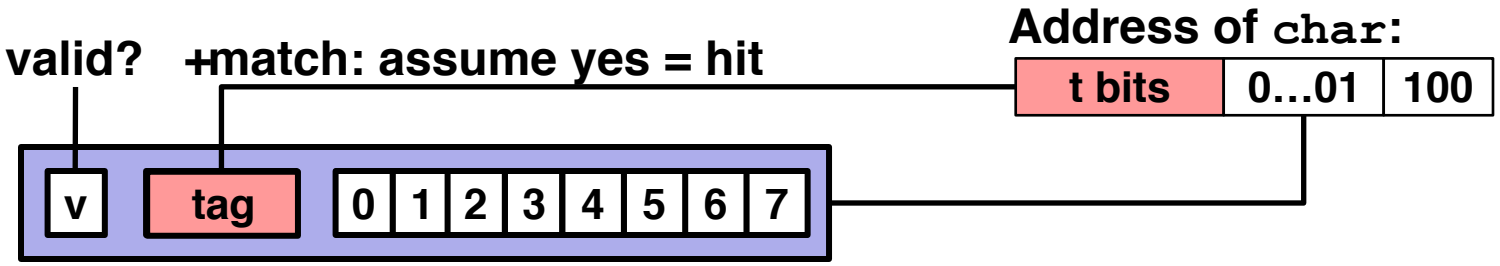

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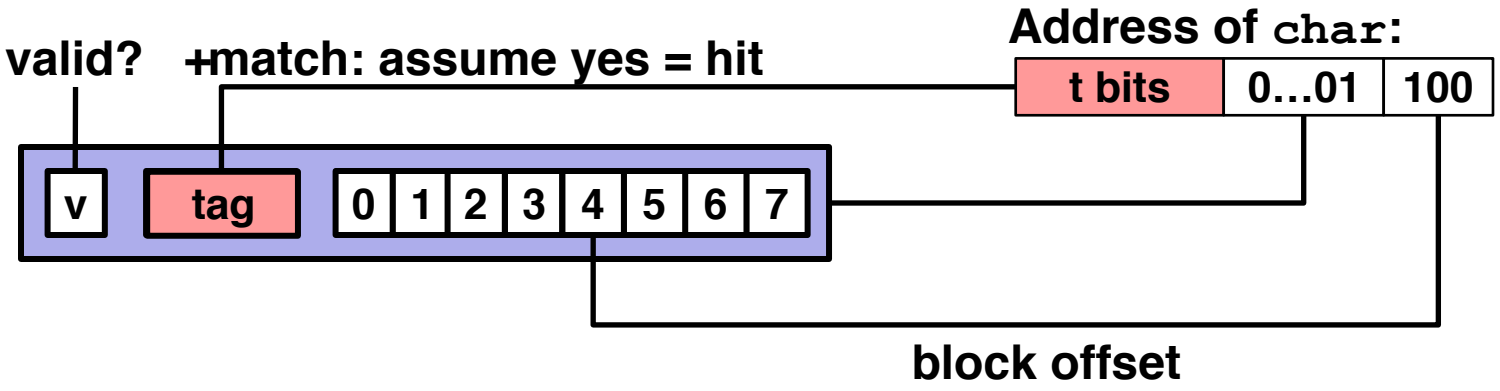

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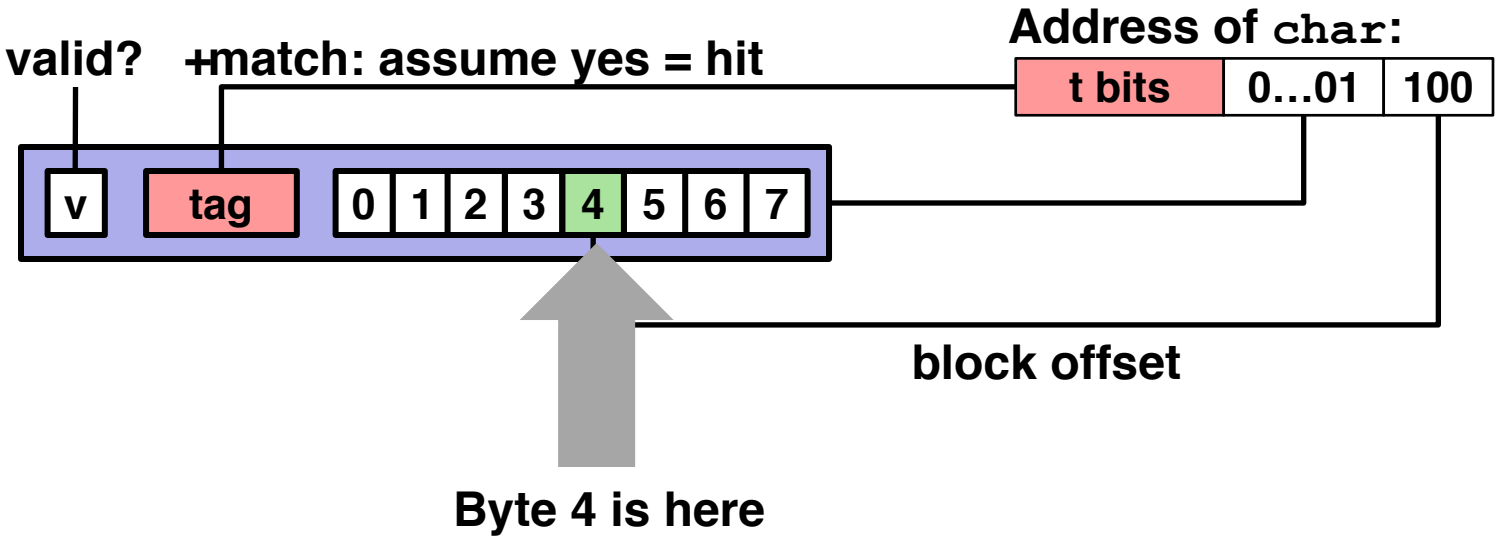

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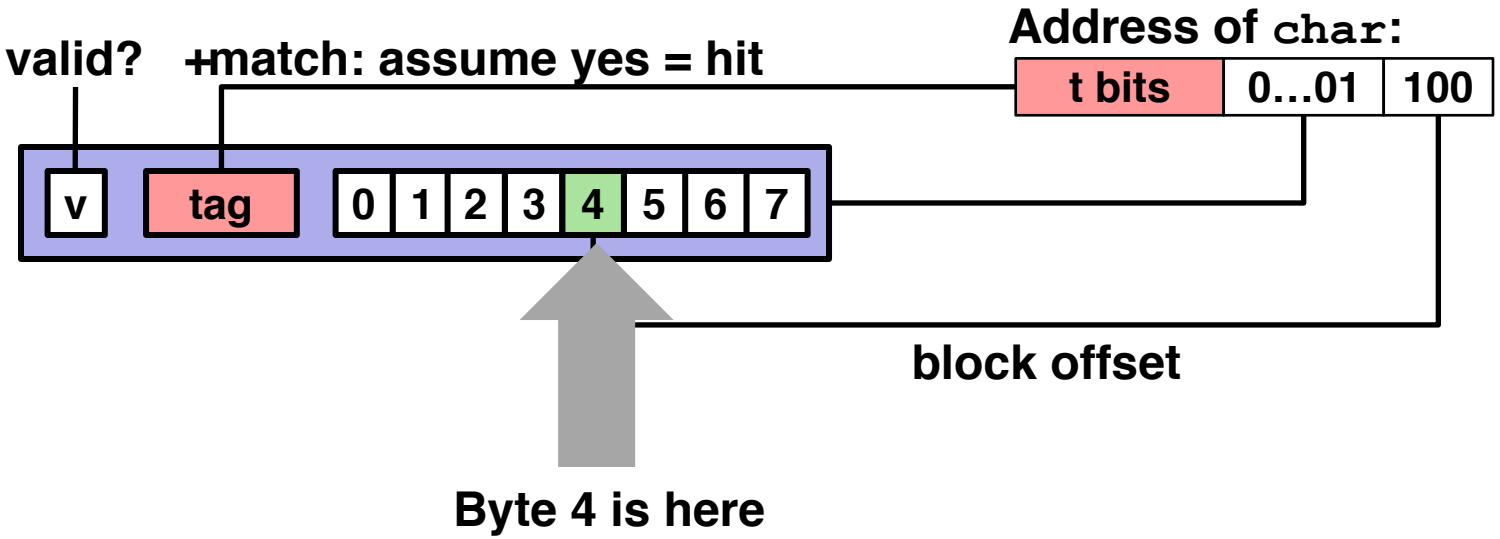

If tag doesn't match: old line is evicted and replaced

Direct-Mapped Cache Simulation

t=1	s=2	b=1
x	xx	x

4-bit address space, i.e., Memory = 16 bytes
B=2 bytes/line, S=4 sets, E=1 line/set

Address trace (reads, one byte per read):

0 **[0$\underline{00}$0$_2$],**
1 **[0$\underline{00}$1$_2$],**
7 **[0$\underline{11}$1$_2$],**
8 **[1$\underline{00}$0$_2$],**
0 **[0$\underline{00}$0$_2$]**

	v	Tag	Line
Set 0	0	?	?
Set 1			
Set 2			
Set 3			

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Address trace (reads, one byte per read):

0	**[0$\underline{00}$0$_2$],**	miss
1	**[0$\underline{00}$1$_2$],**	
7	**[0$\underline{11}$1$_2$],**	
8	**[1$\underline{00}$0$_2$],**	
0	**[0$\underline{00}$0$_2$]**	

	v	Tag	Line
Set 0	0	?	?
Set 1			
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8	**[1$\underline{00}$0$_2$],**	
0	**[0$\underline{00}$0$_2$]**	

	v	Tag	Line
Set 0	1	0	M[0-1]
Set 1			
Set 2			
Set 3			

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	v	Tag	Line
Set 0	1	0	M[0-1]
Set 1			
Set 2			
Set 3			

← The two bytes at memory address 0 and 1

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t=1	s=2	b=1
x	xx	x

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Address trace (reads, one byte per read):

0	**[0$\underline{00}$0$_2$],**	miss
1	**[0$\underline{00}$1$_2$],**	hit
7	**[0$\underline{11}$1$_2$],**	
8	**[1$\underline{00}$0$_2$],**	
0	**[0$\underline{00}$0$_2$]**	

	v	Tag	Line	
Set 0	1	0	M[0-1]	← The two bytes at memory address 0 and 1
Set 1				
Set 2				
Set 3				

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8	**[1$\underline{00}$0$_2$],**	
0	**[0$\underline{00}$0$_2$]**	

	v	Tag	Line	
Set 0	1	0	M[0-1]	← The two bytes at memory address 0 and 1
Set 1				
Set 2				
Set 3	1	0	M[6-7]	

Direct-Mapped Cache Simulation

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0	**[0$\underline{00}$0$_2$]**	

	v	Tag	Line	
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Set 1				
Set 2				
Set 3	1	0	M[6-7]	← The two bytes at memory address 6 and 7

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Address trace (reads, one byte per read):

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1	**[0$\underline{000}$1$_2$],**	hit
7	**[0$\underline{111}$1$_2$],**	miss
8	**[1$\underline{000}$0$_2$],**	miss
0	**[0$\underline{000}$0$_2$]**	

	v	Tag	Line	
Set 0	1	1	M[8-9]	← The two bytes at memory address 8 and 9
Set 1				
Set 2				
Set 3	1	0	M[6-7]	← The two bytes at memory address 6 and 7

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1	**[0$\underline{00}$1$_2$],**	hit
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8	**[1$\underline{00}$0$_2$],**	miss
0	**[0$\underline{00}$0$_2$]**	miss

	v	Tag	Line	
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Set 1				
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1	**[0$\underline{00}$1$_2$],**	hit
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8	**[1$\underline{00}$0$_2$],**	miss
0	**[0$\underline{00}$0$_2$]**	miss

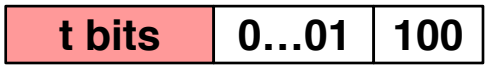
	v	Tag	Line	
Set 0	1	0	M[0-1]	← The two bytes at memory address 0 and 1
Set 1				
Set 2				
Set 3	1	0	M[6-7]	← The two bytes at memory address 6 and 7

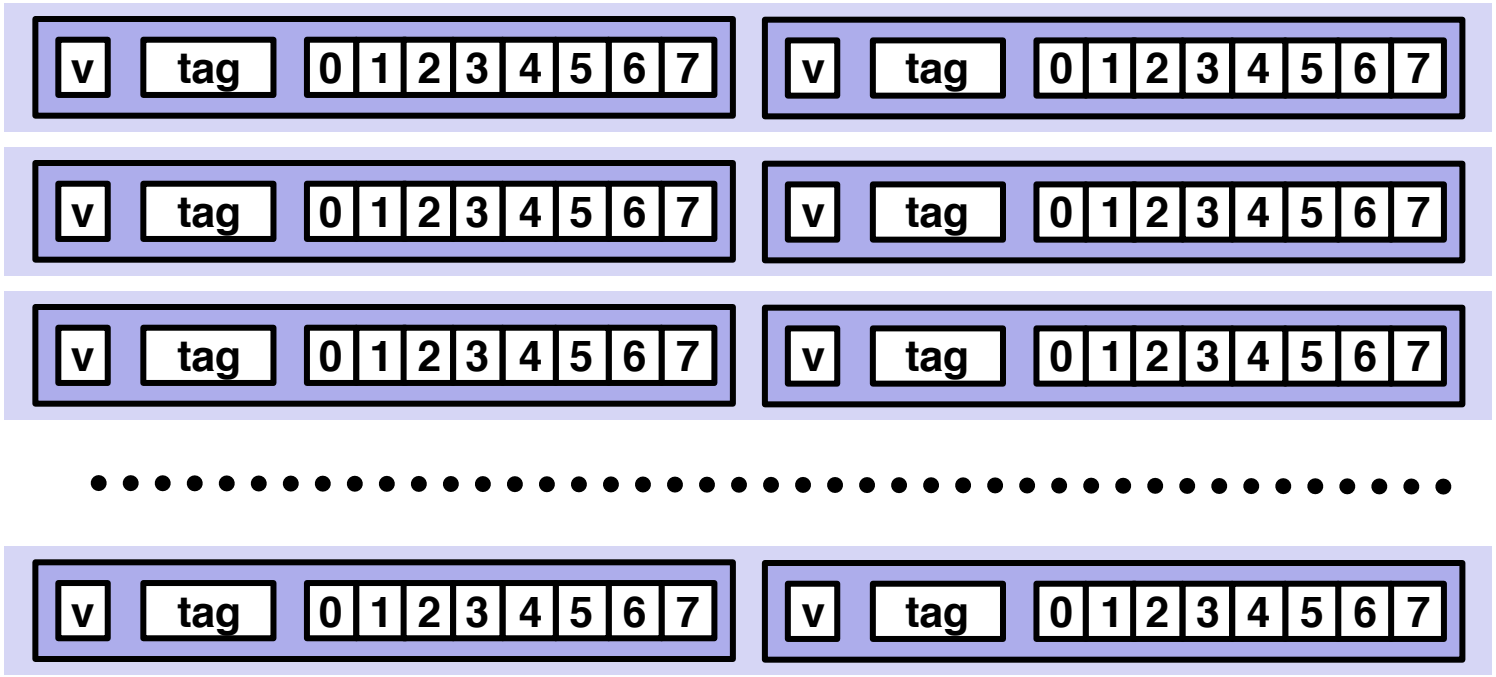
E-way Set Associative Cache (Here: E = 2)

E = 2: Two lines per set

Assume: cache line size 8 bytes

Address of `short int`:





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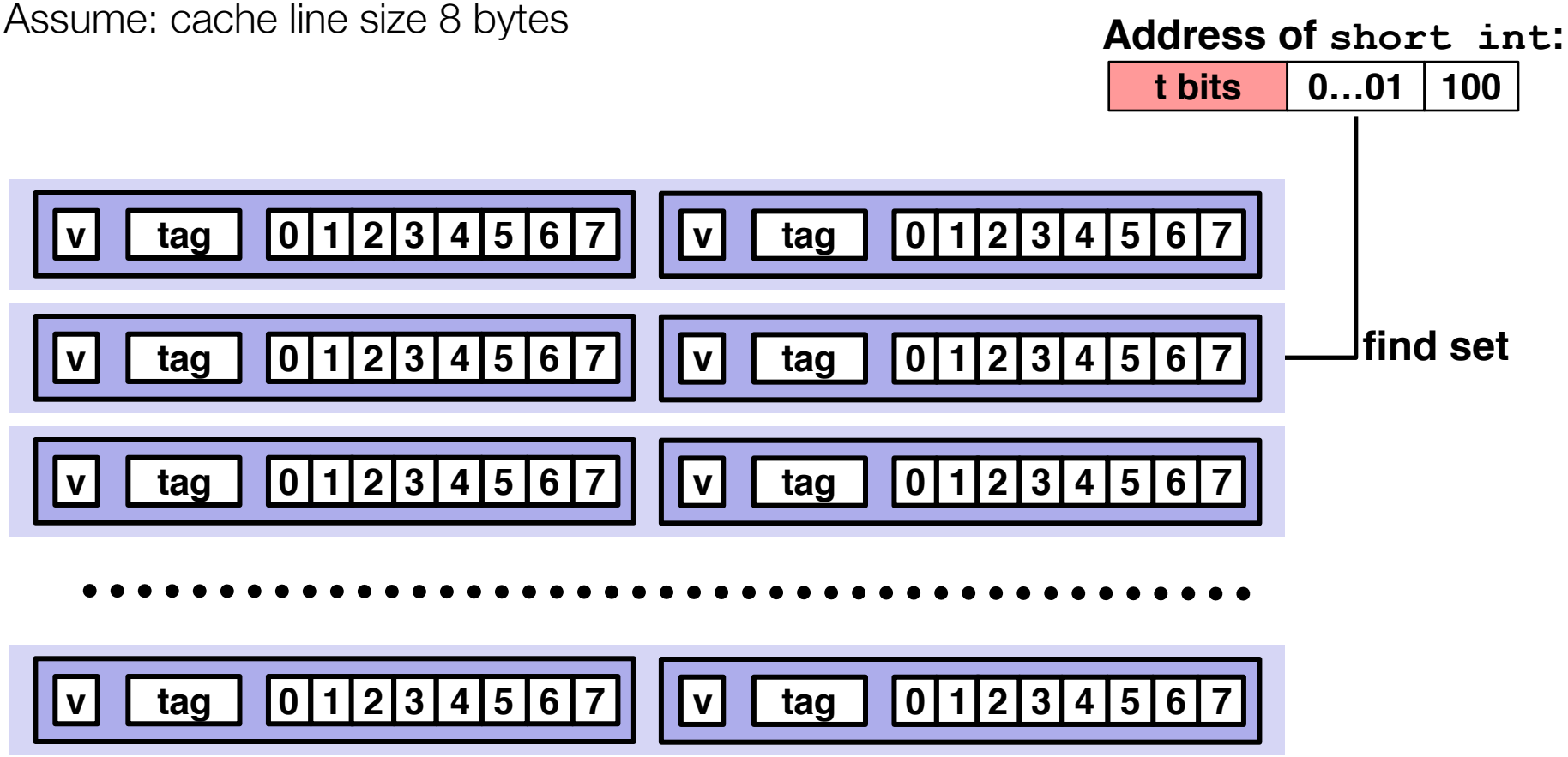

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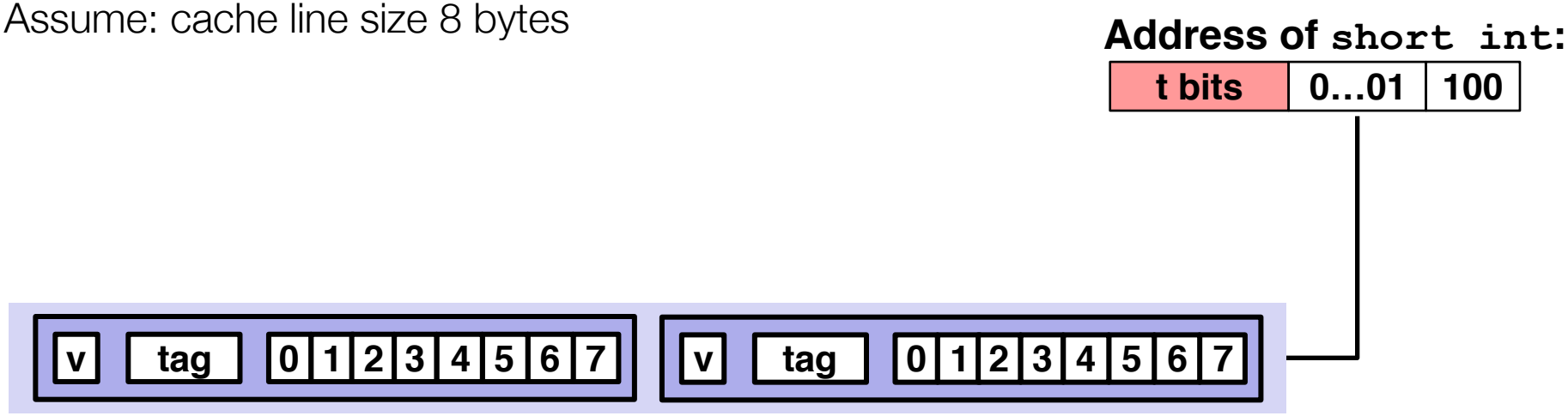

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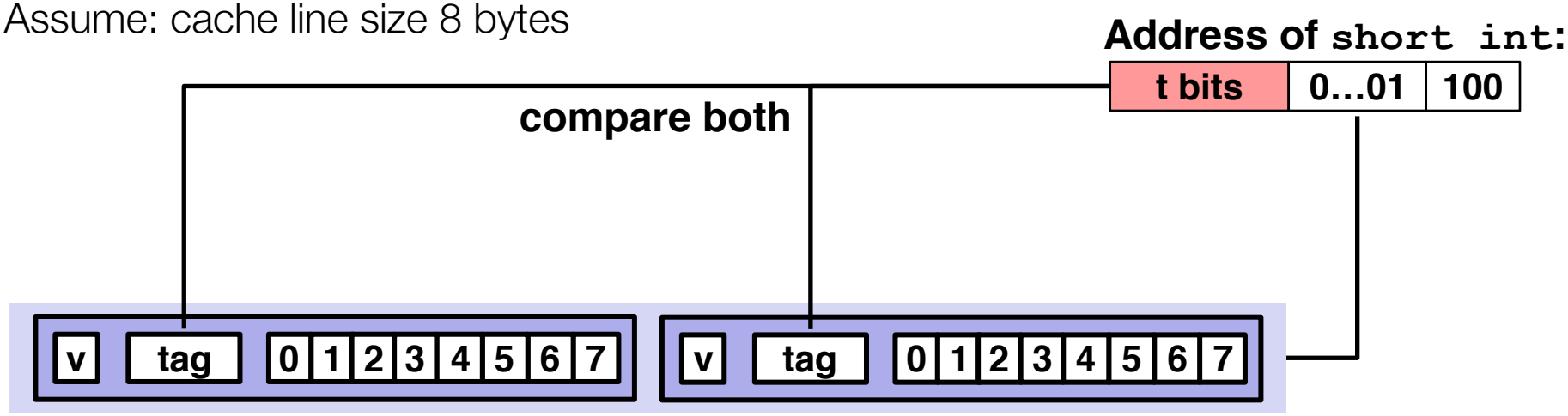

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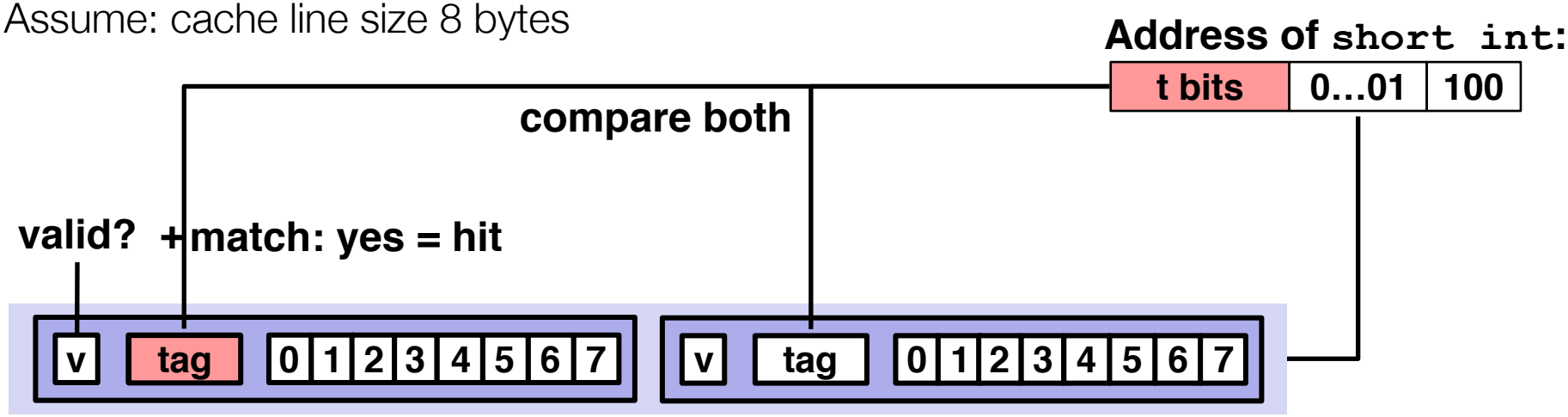

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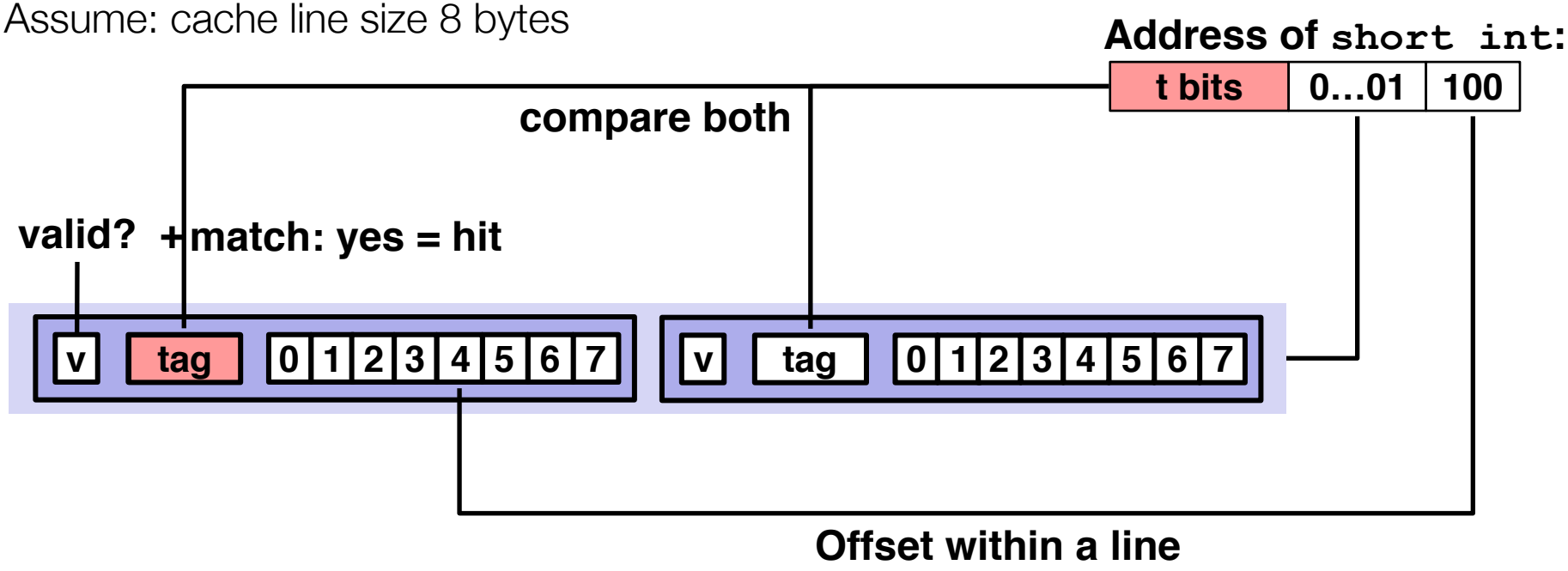

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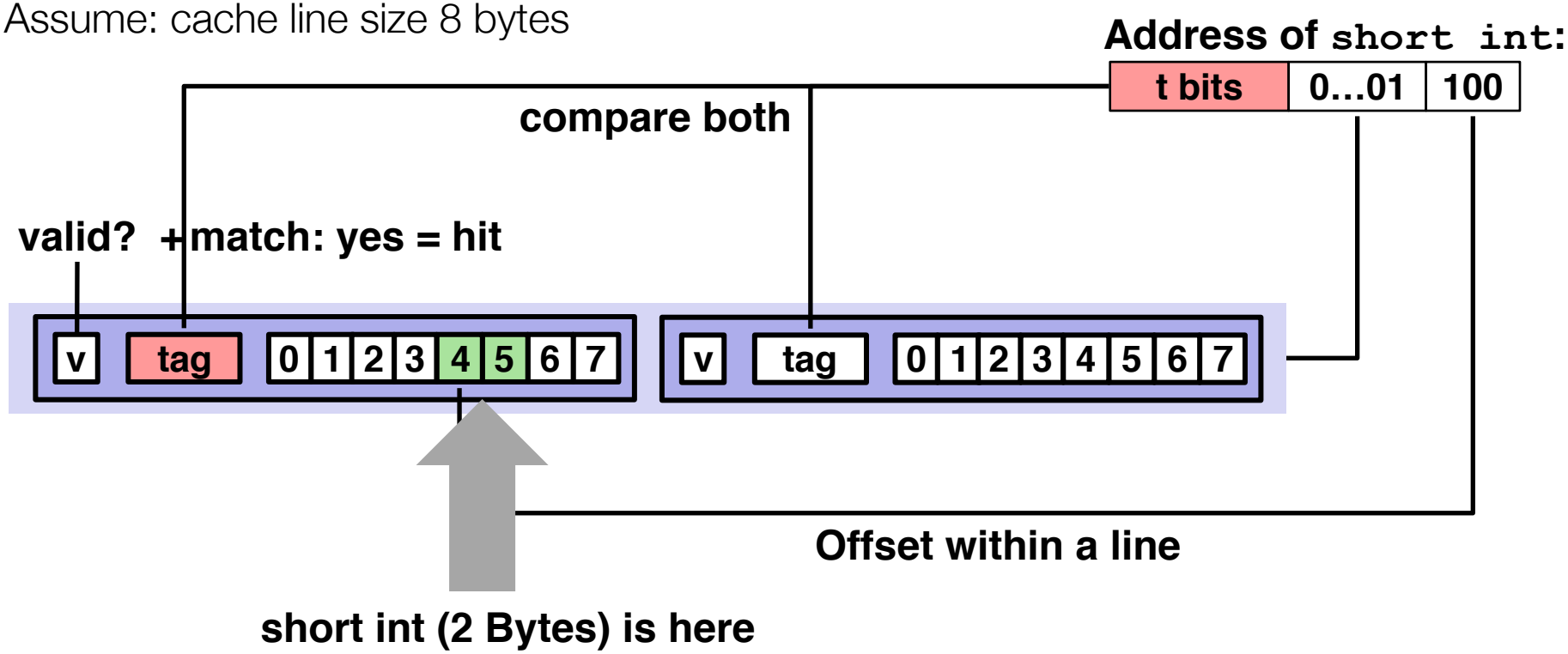

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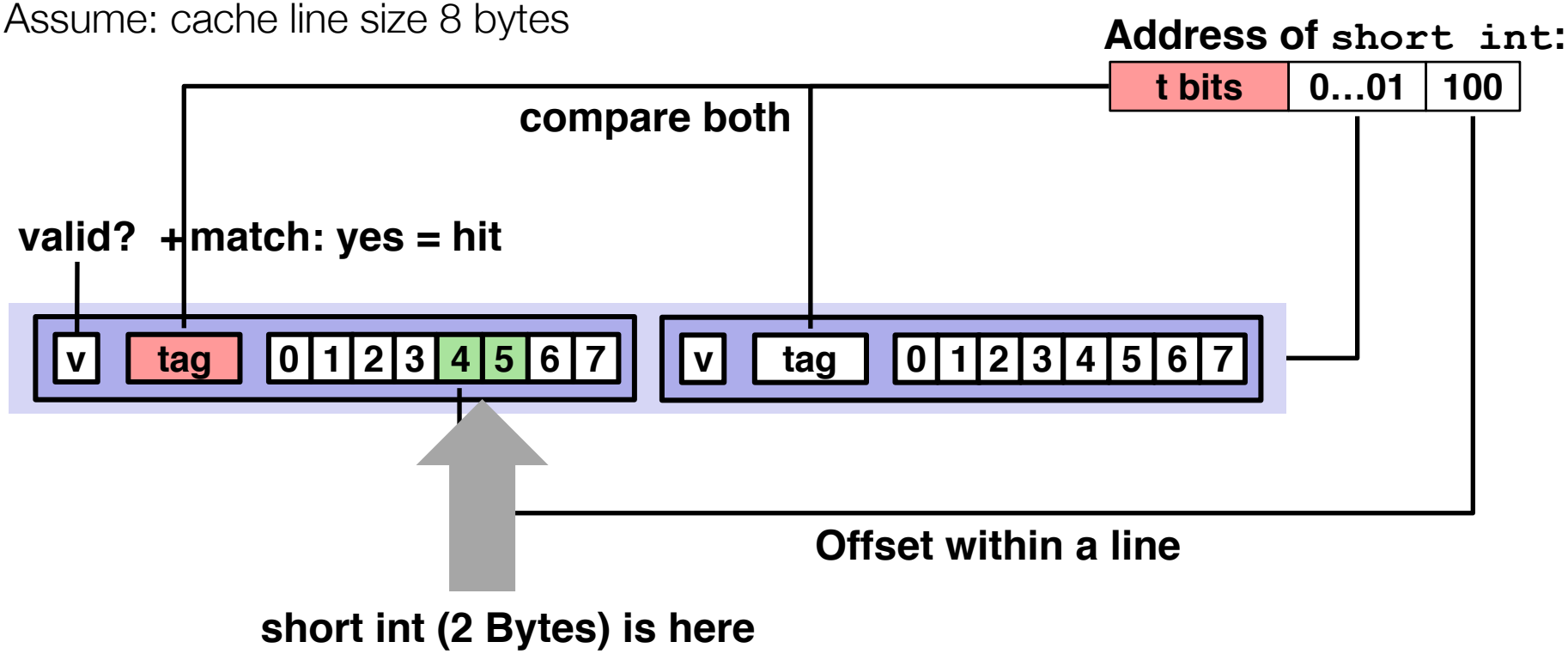

No match:

- **One line in set is selected for eviction and replacement**
- **Replacement policies: random, least recently used (LRU),**

2-Way Set Associative Cache Simulation

t=2	s=1	b=1
xx	x	x

4-bit address space, i.e., Memory = 16 bytes
S=2 sets, E=2 cache lines/set

Address trace (reads, one byte per read):

0 **[00$\underline{0}$0$_2$],**
1 **[00$\underline{0}$1$_2$],**
7 **[01$\underline{1}$1$_2$],**
8 **[10$\underline{0}$0$_2$],**
0 **[00$\underline{0}$0$_2$]**

	v	Tag	Line			
Set 0	0	?	?	0		
Set 1	0			0		

2-Way Set Associative Cache Simulation

t=2	s=1	b=1
xx	x	x

4-bit address space, i.e., Memory = 16 bytes
S=2 sets, E=2 cache lines/set

Address trace (reads, one byte per read):

0 **[00$\underline{0}$0$_2$],** miss
1 **[000$\underline{1}_2$],**
7 **[01$\underline{1}$1$_2$],**
8 **[10$\underline{0}$0$_2$],**
0 **[00$\underline{0}$0$_2$]**

	v	Tag	Line			
Set 0	0	?	?	0		
Set 1	0			0		

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8 **[10$\underline{0}$0$_2$],**
0 **[00$\underline{0}$0$_2$]**

	v	Tag	Line			
Set 0	1	00	M[0-1]	0		
Set 1	0			0		

2-Way Set Associative Cache Simulation

t=2	s=1	b=1
xx	x	x

4-bit address space, i.e., Memory = 16 bytes
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Address trace (reads, one byte per read):

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7	**[01$\underline{1}$1$_2$],**	
8	**[10$\underline{0}$0$_2$],**	
0	**[00$\underline{0}$0$_2$]**	

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Set 0	1	00	M[0-1]	0		
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7	**[01$\underline{1}$1$_2$],**	miss
8	**[10$\underline{0}$0$_2$],**	
0	**[00$\underline{0}$0$_2$]**	

	v	Tag	Line			
Set 0	1	00	M[0-1]	0		
Set 1	0			0		

2-Way Set Associative Cache Simulation

t=2	s=1	b=1
xx	x	x

4-bit address space, i.e., Memory = 16 bytes
S=2 sets, E=2 cache lines/set

Address trace (reads, one byte per read):

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Today

- Processes and Signals: running multiple programs concurrently
  - Processes
  - Process Control
  - Signals

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  - One of the most profound ideas in computer science
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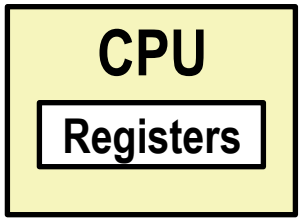

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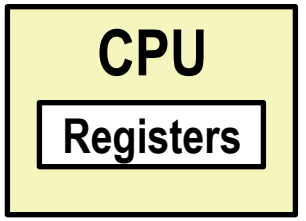

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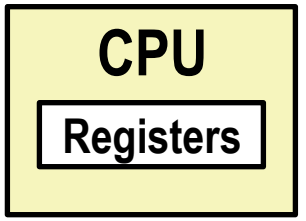

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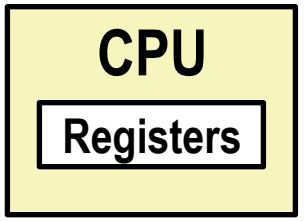

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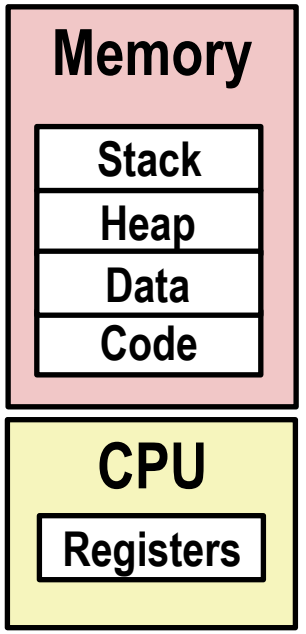

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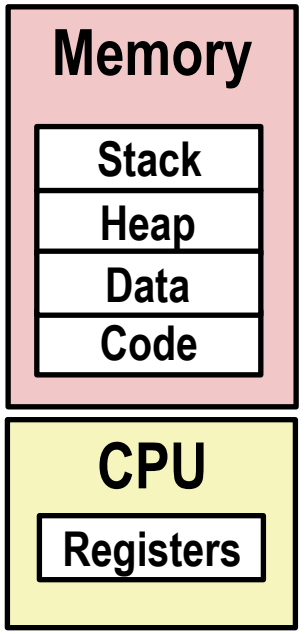

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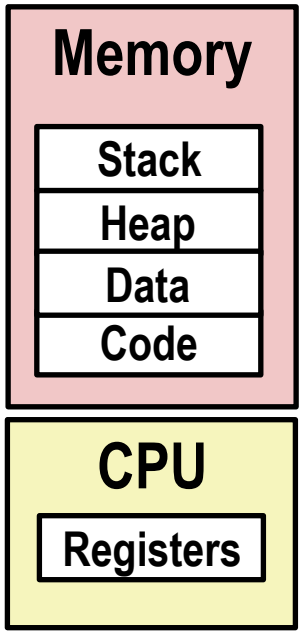
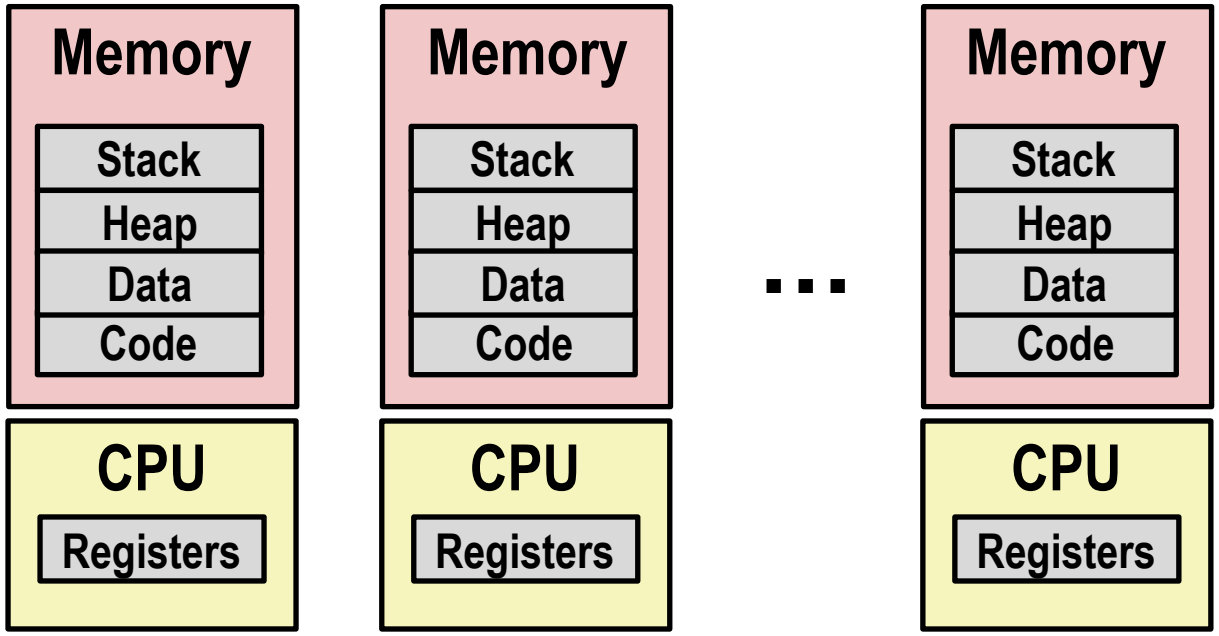
  - *Private address space*
    - Each program seems to have exclusive use of main memory.
    - Provided by OS through “virtual memory”

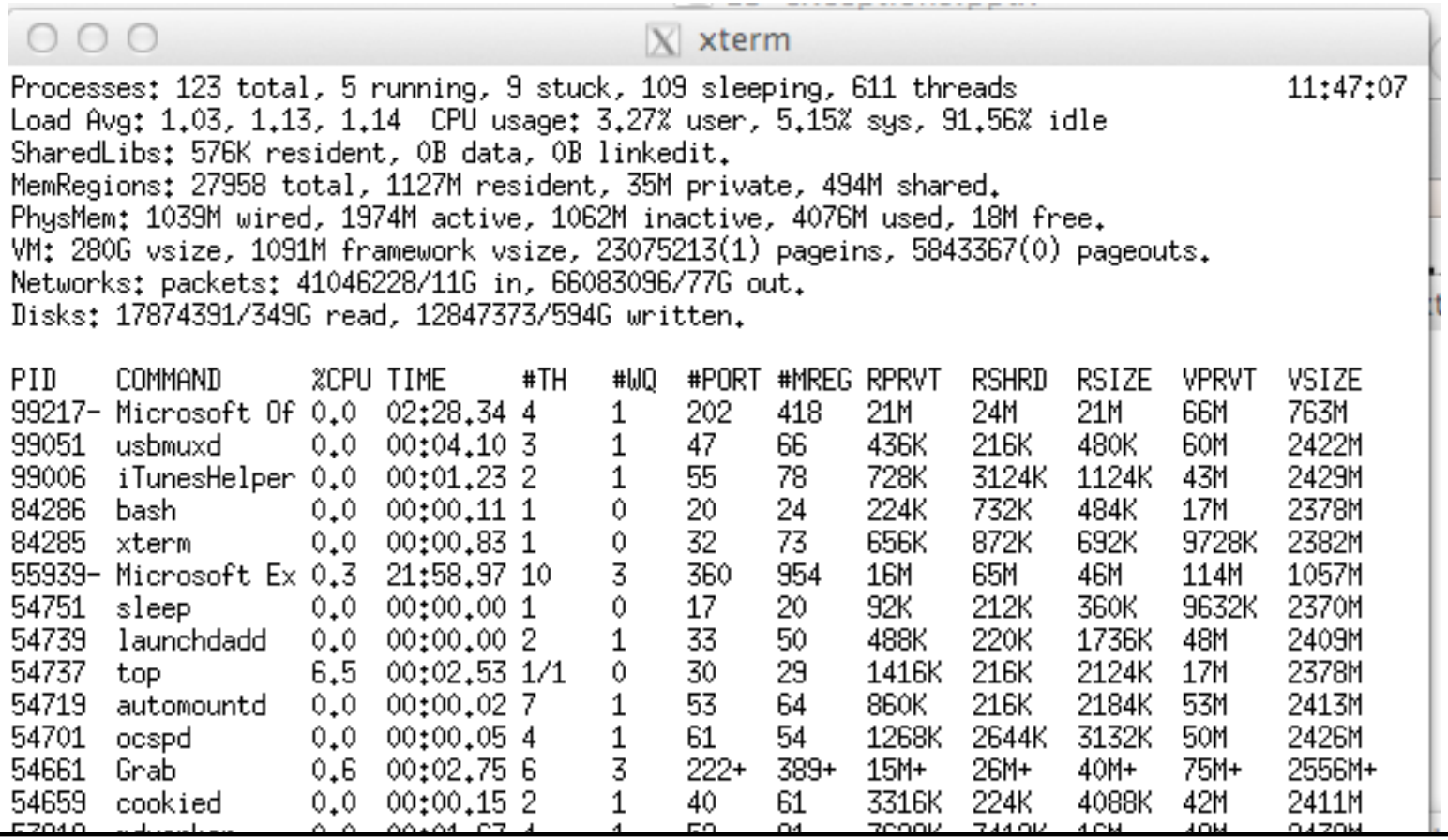


Multiprocessing: The Illusion



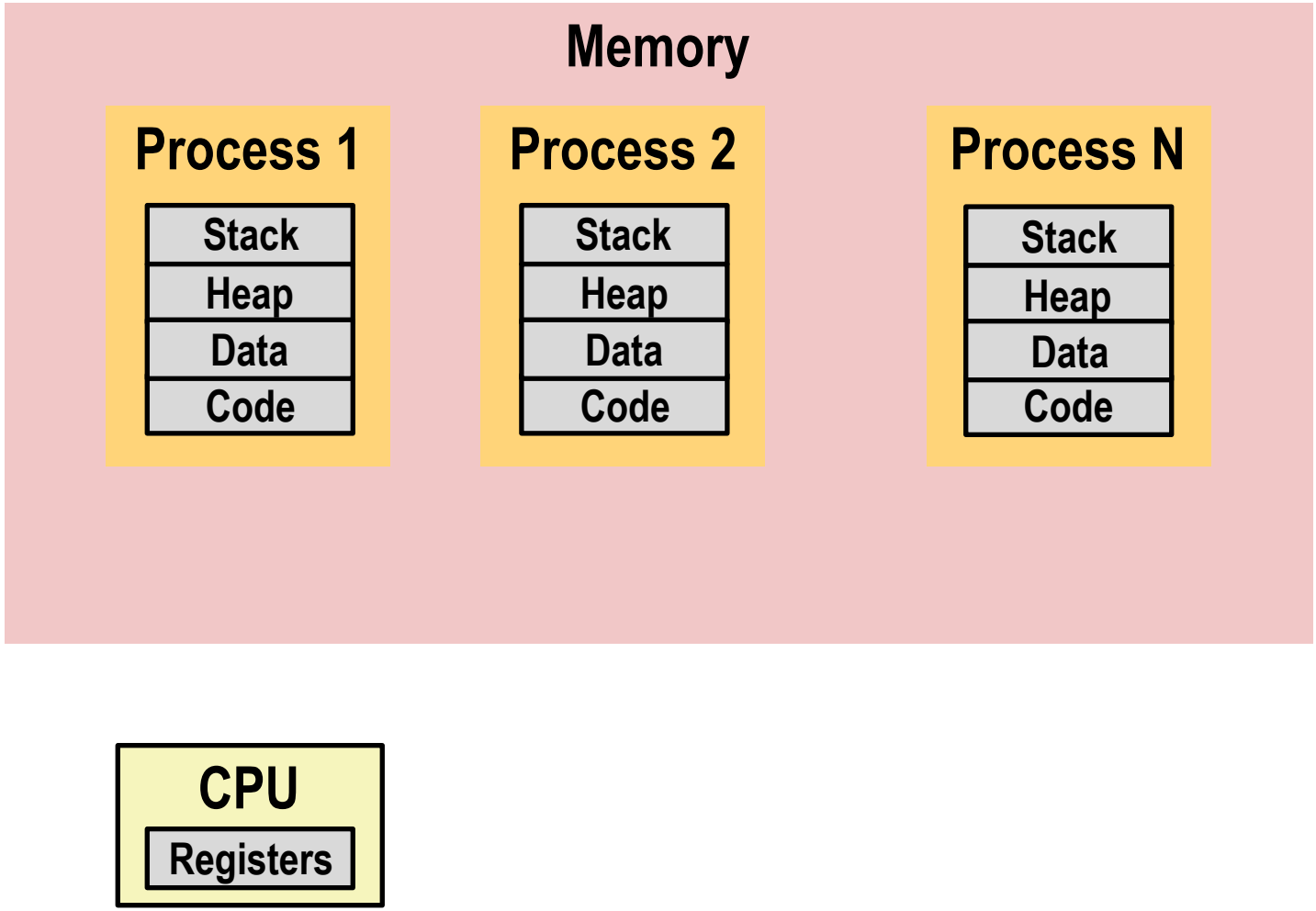
- Computer runs many processes simultaneously
  - Applications for one or more users
    - Web browsers, email clients, editors, …
  - Background tasks
    - Monitoring network & I/O devices

Multiprocessing Example



- Running program “top” on Unit/Linux
  - System has 123 processes, 5 of which are active
  - Identified by Process ID (PID)

Multiprocessing Illustration



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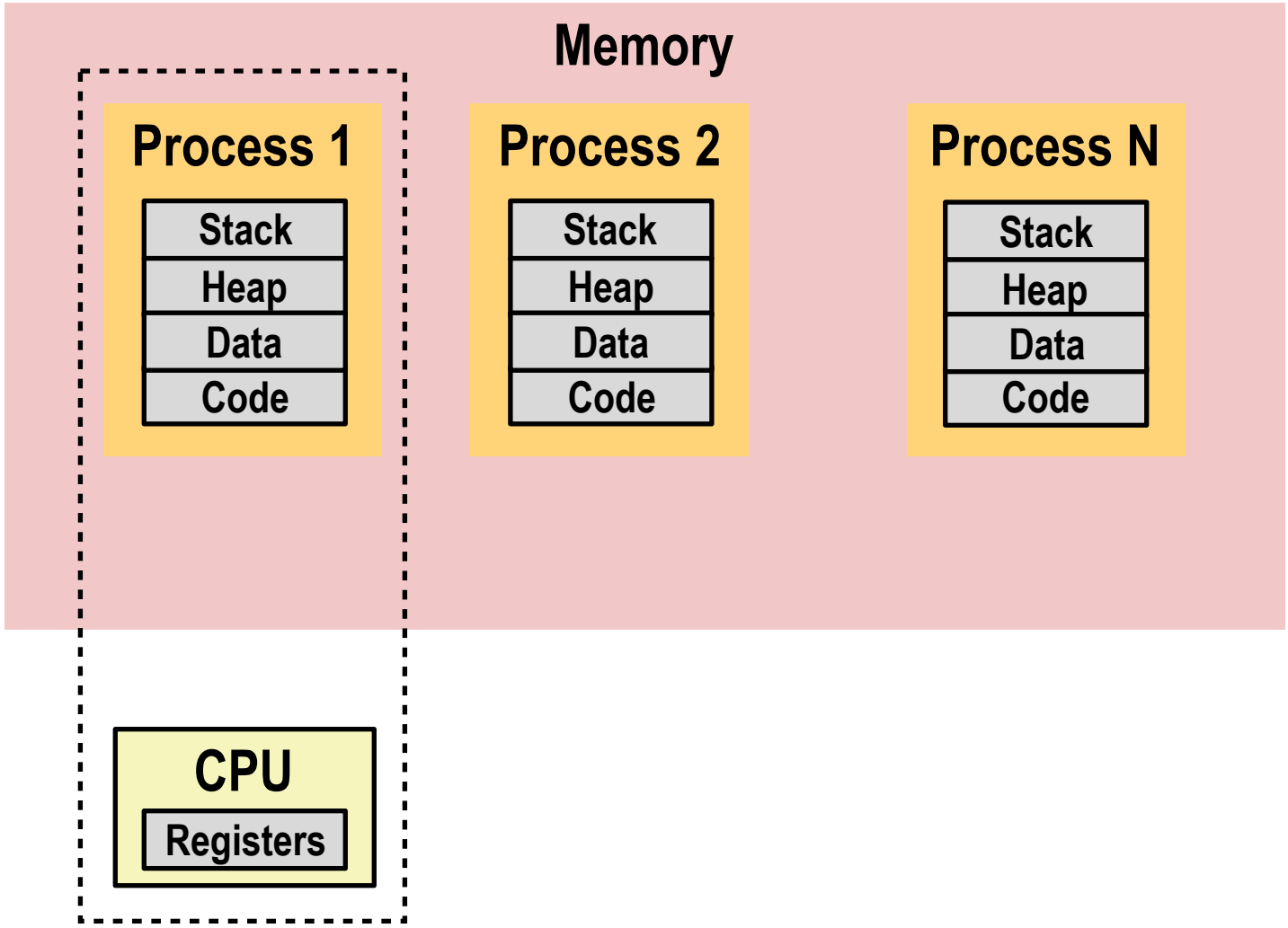

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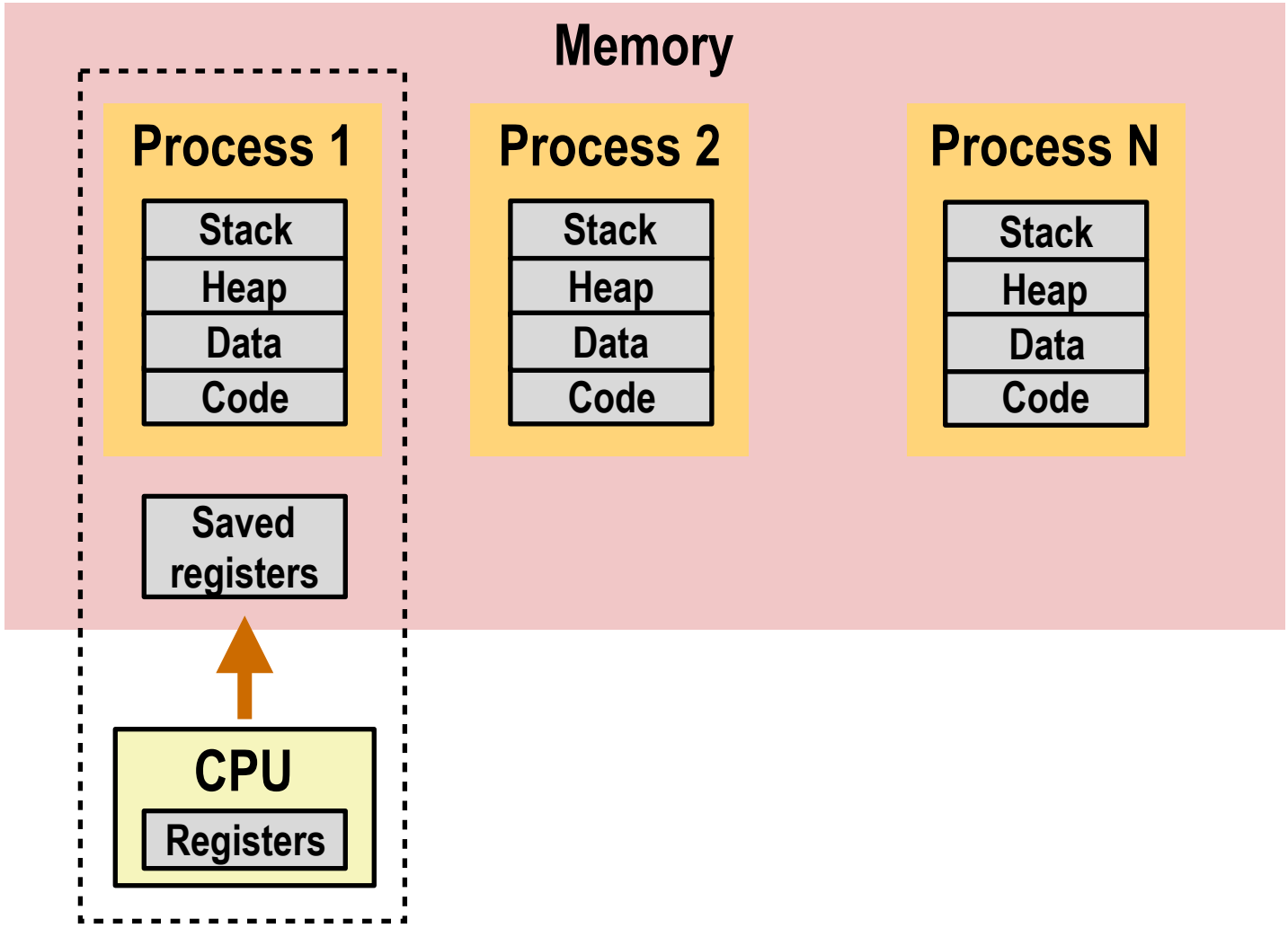

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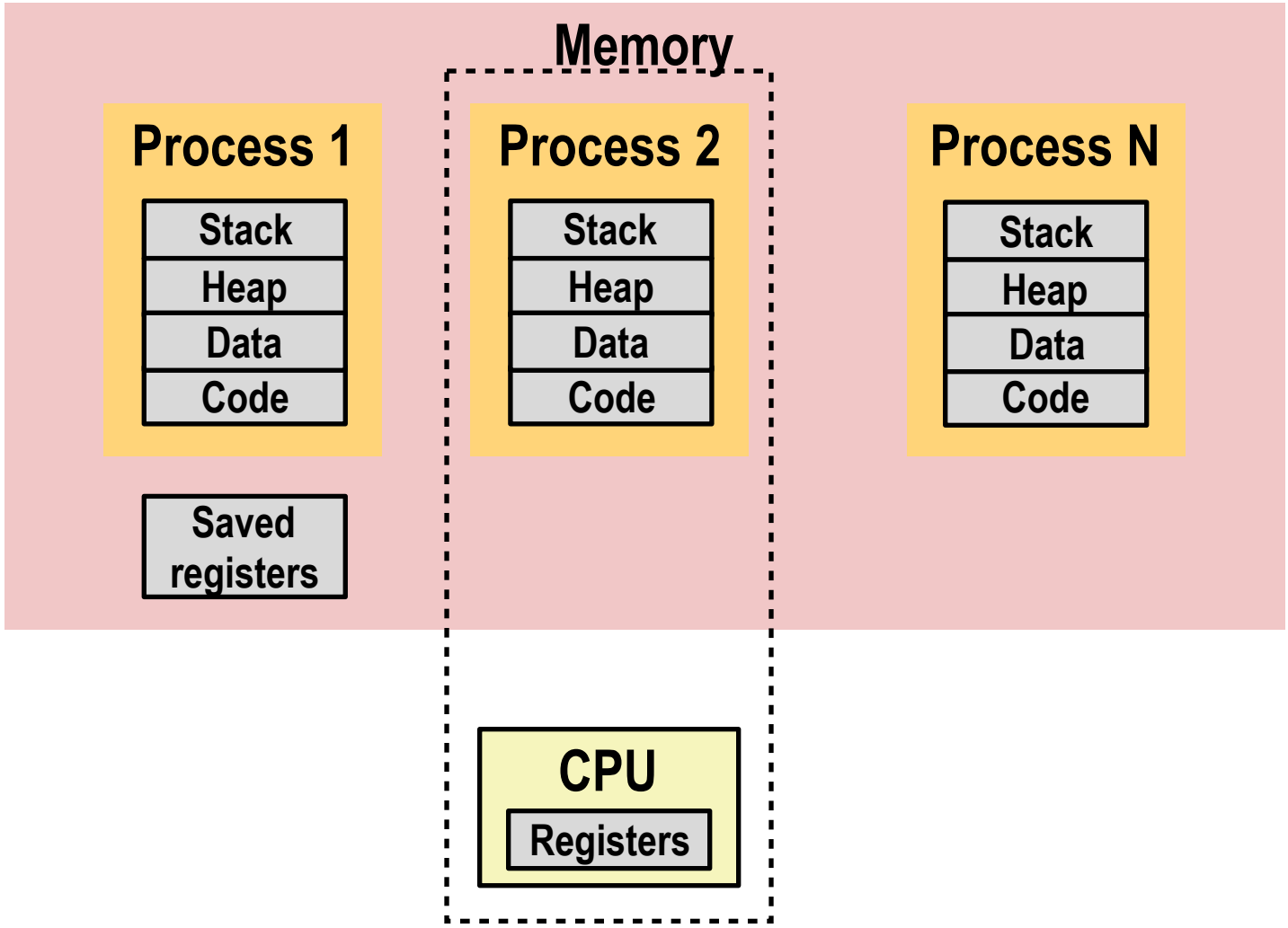

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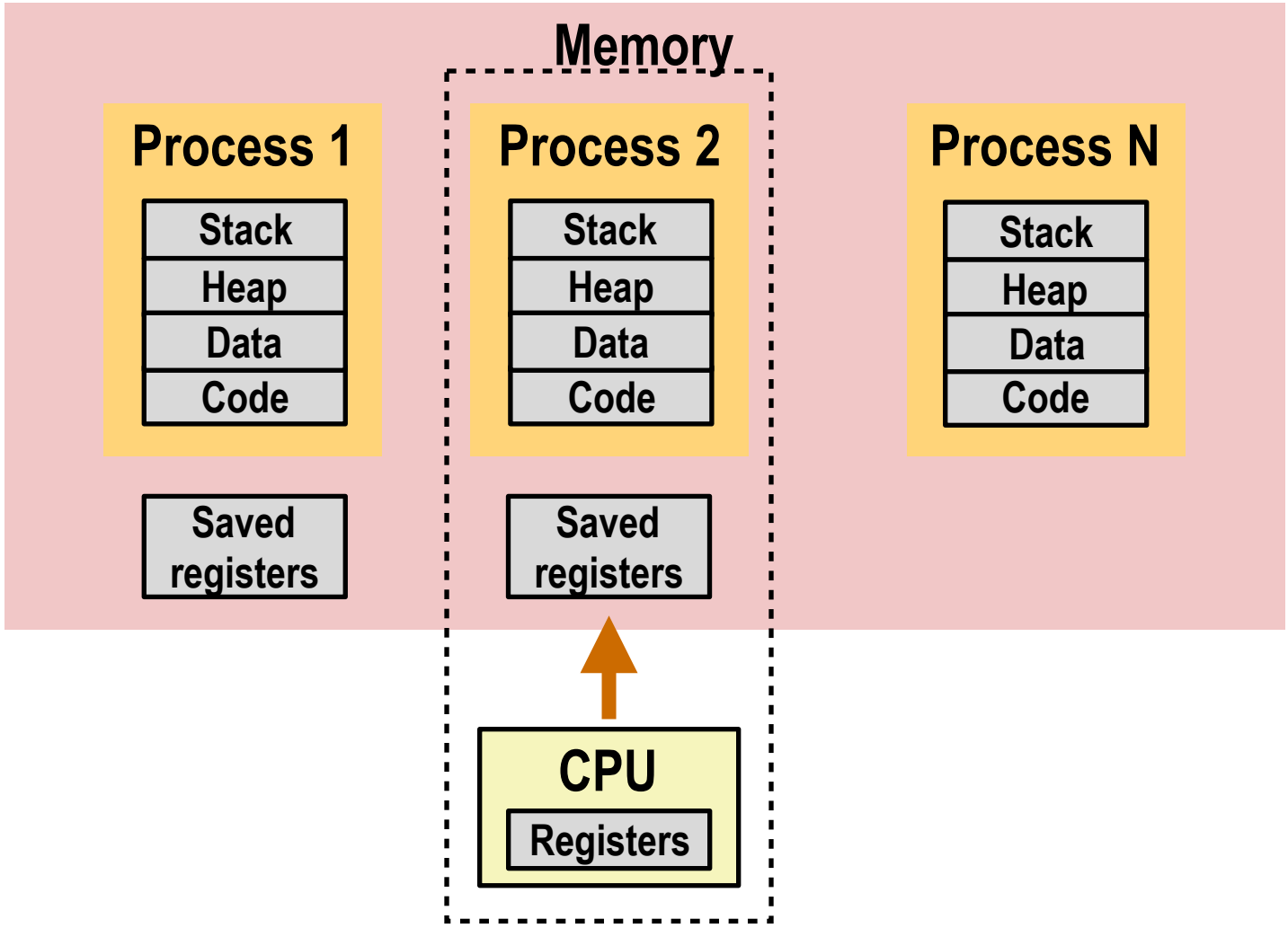

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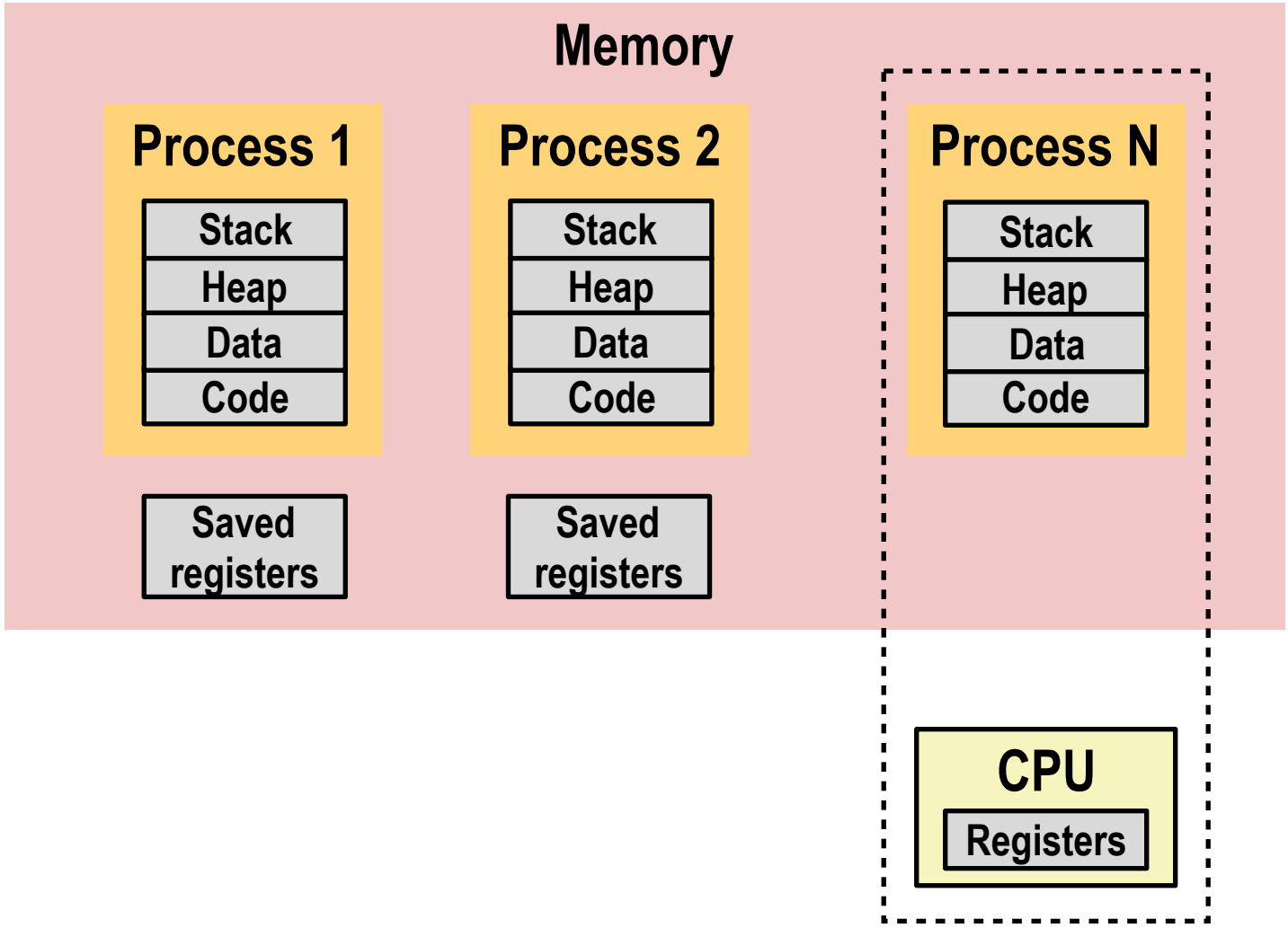

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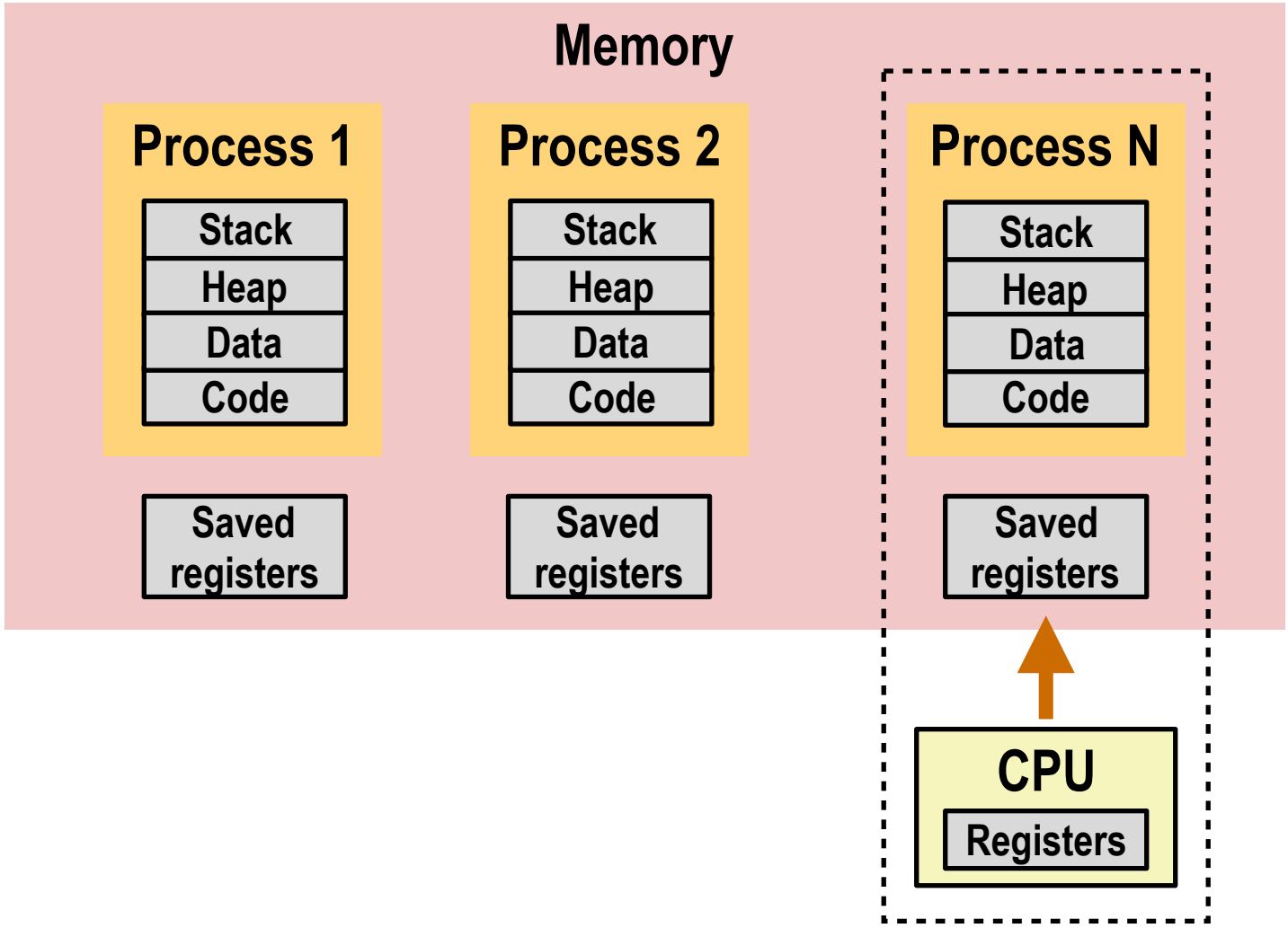

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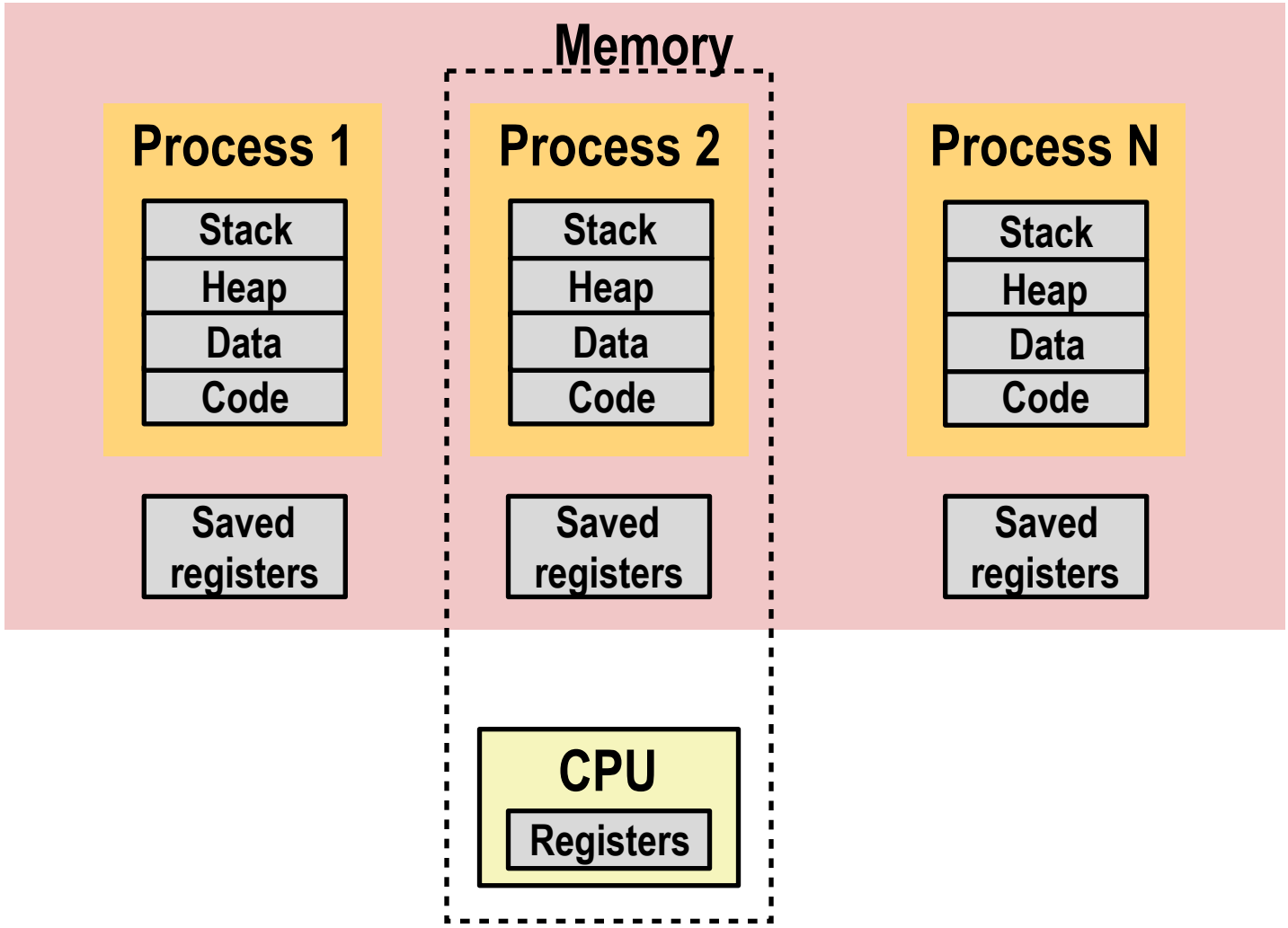

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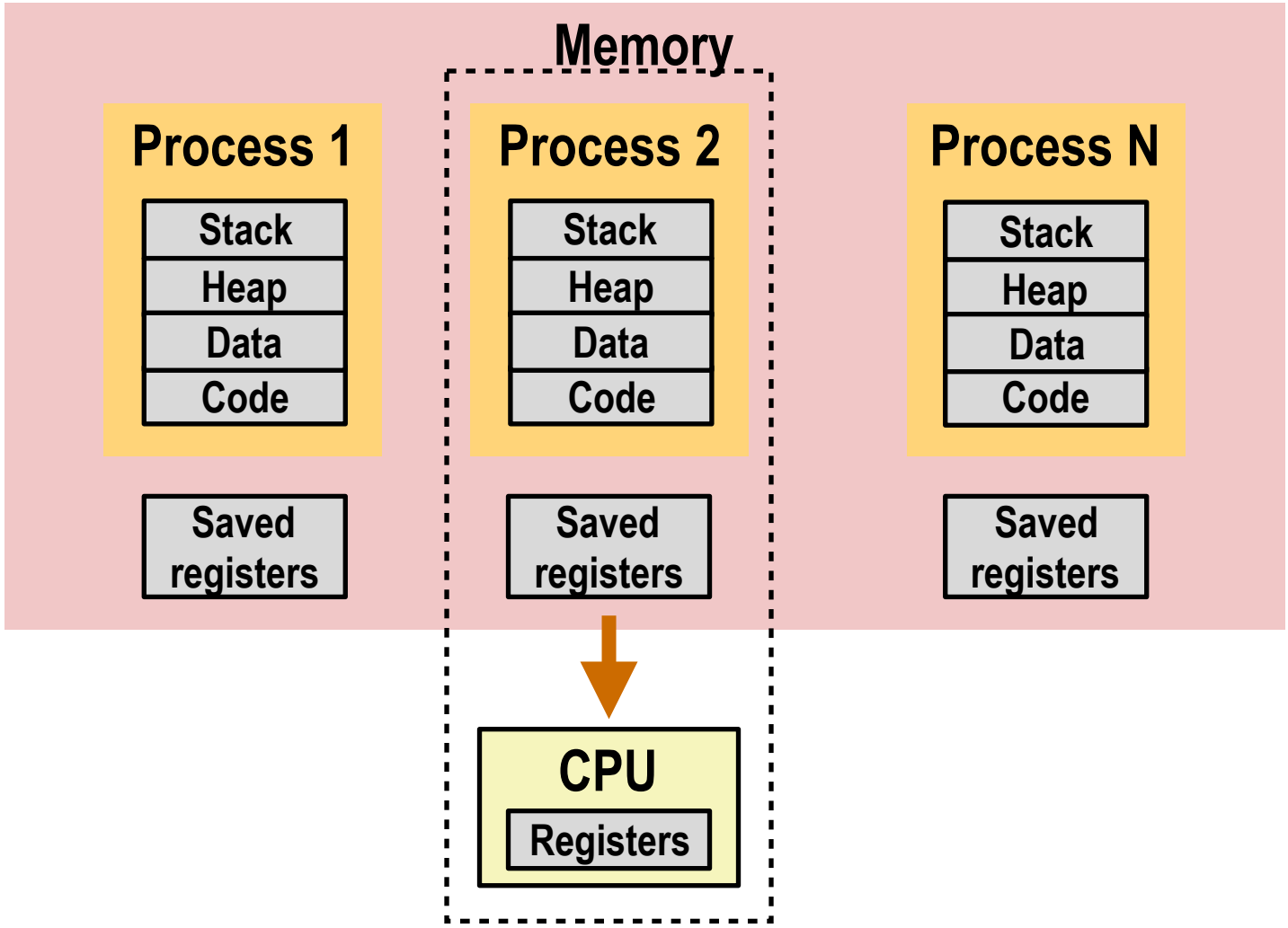

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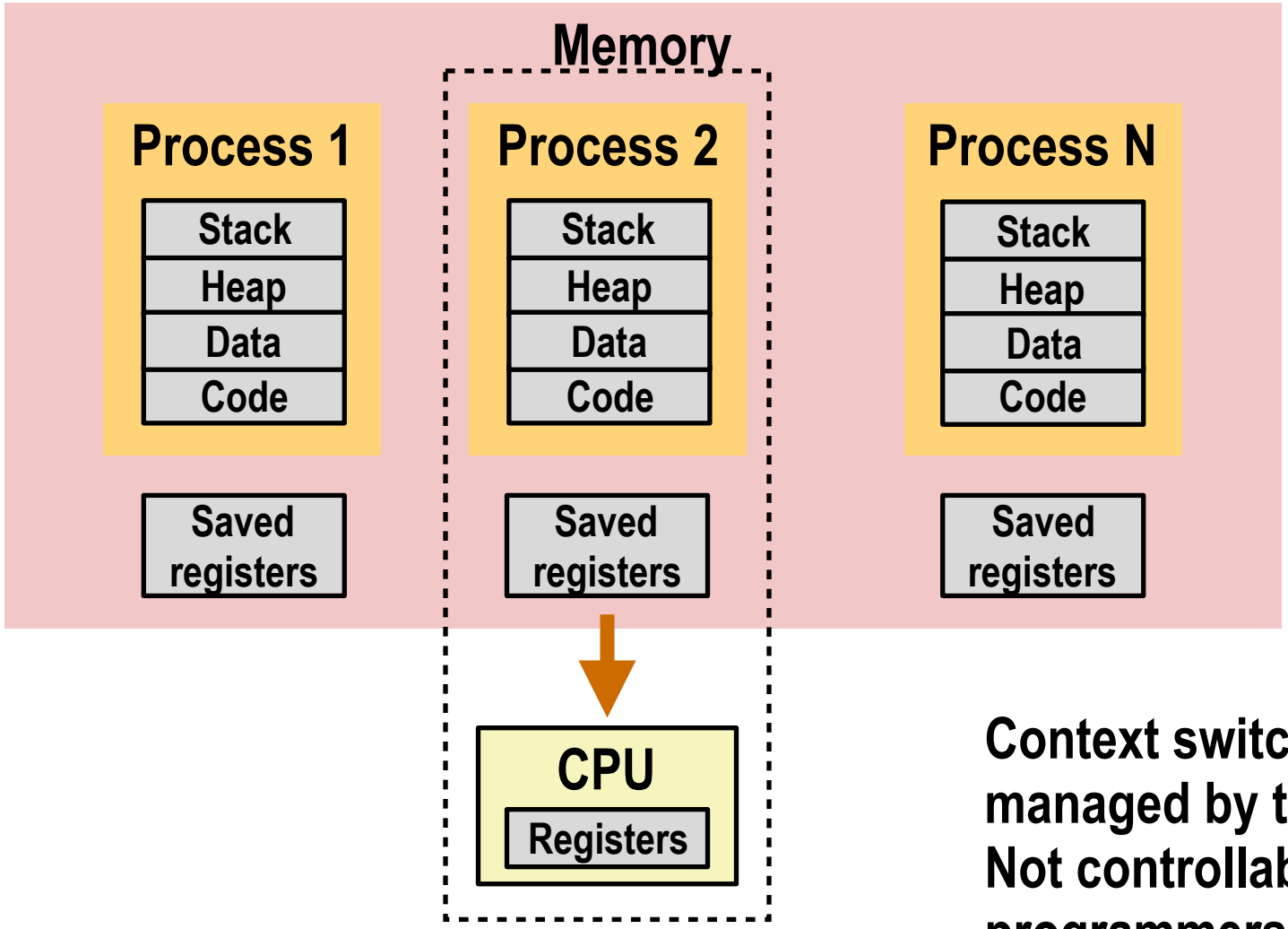
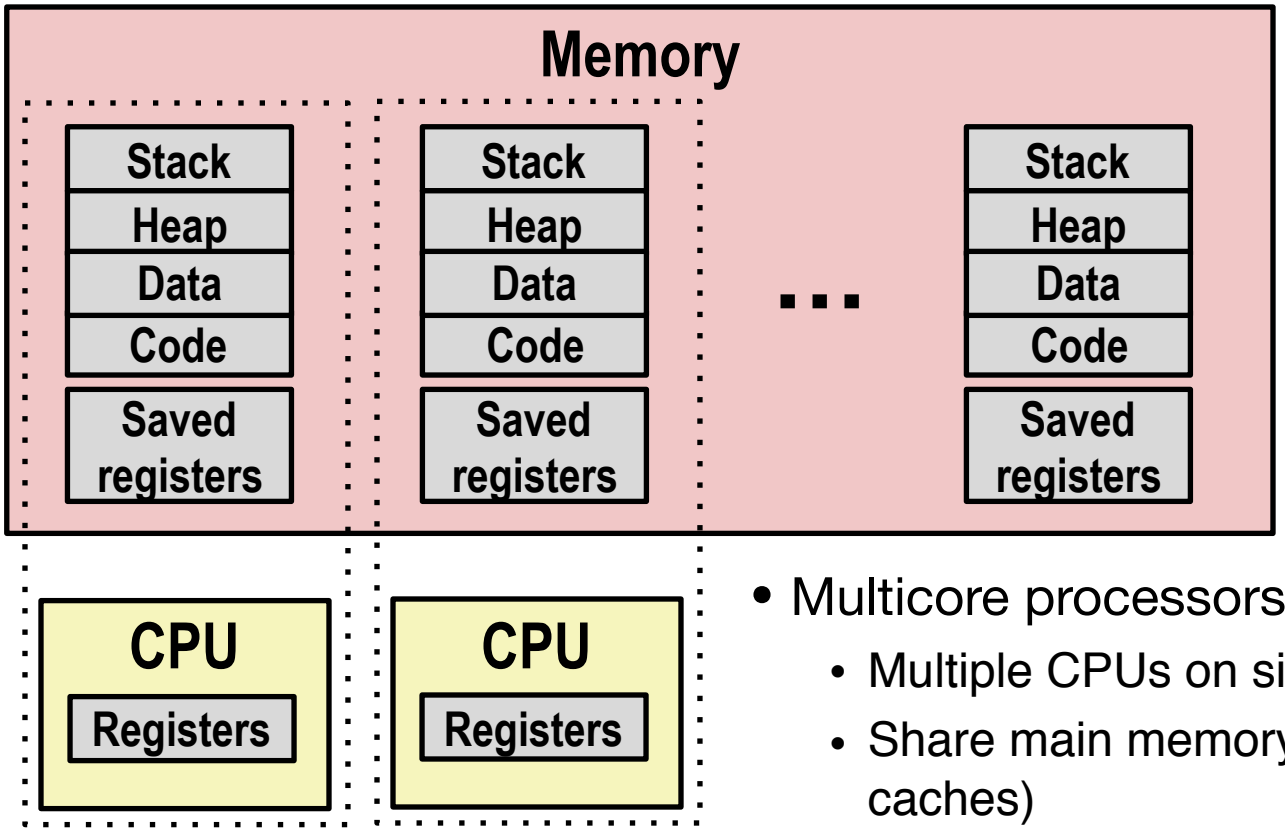


Context switch managed by the OS. Not controllable by programmers.

Multiprocessing: The Multi-Core Case



- Multicore processors
  - Multiple CPUs on single chip
  - Share main memory (and some of the caches)
  - Each can execute a separate process
    - Scheduling of processors onto cores done by kernel

Concurrent Processes

- Each process is a logical control flow.
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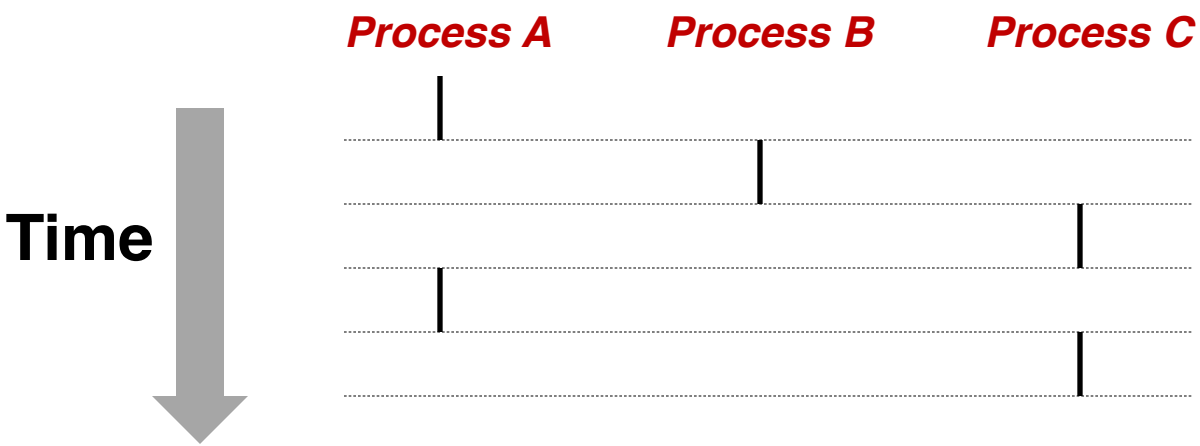

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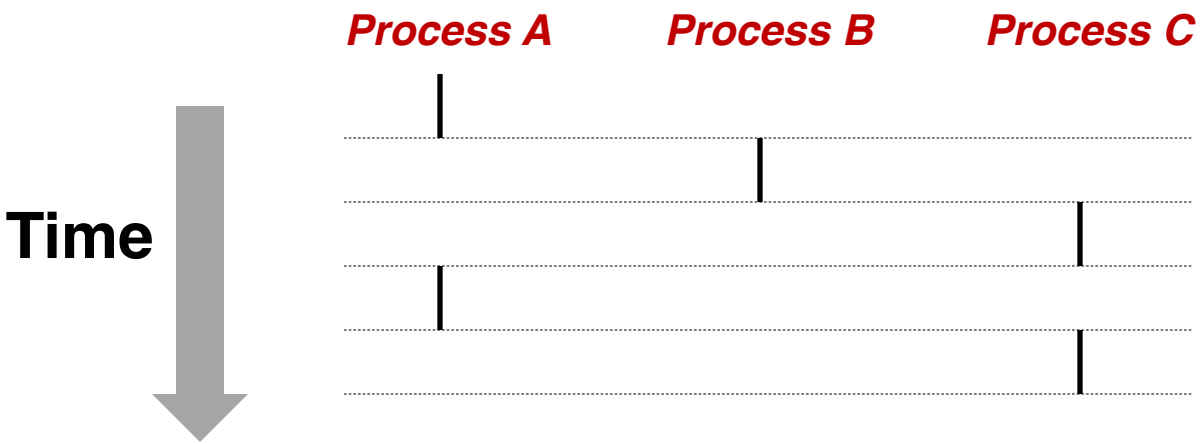

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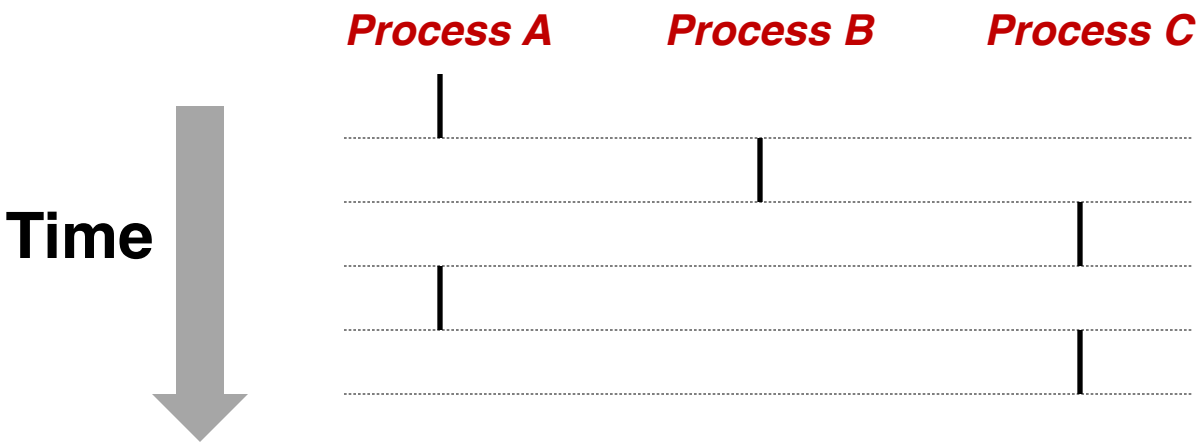
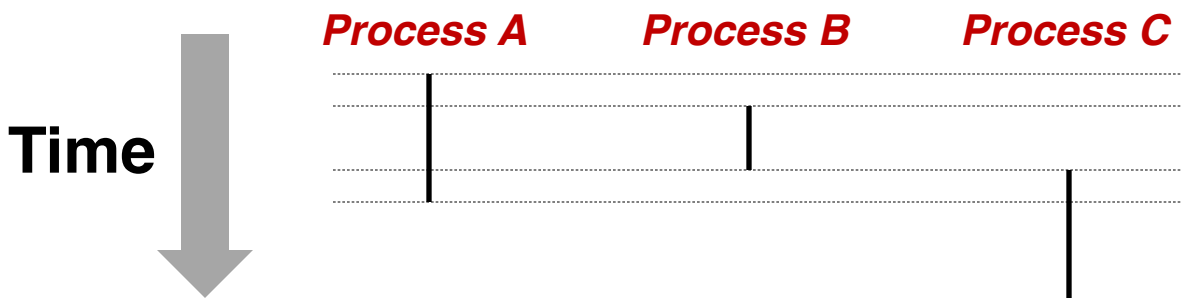


User View of Concurrent Processes

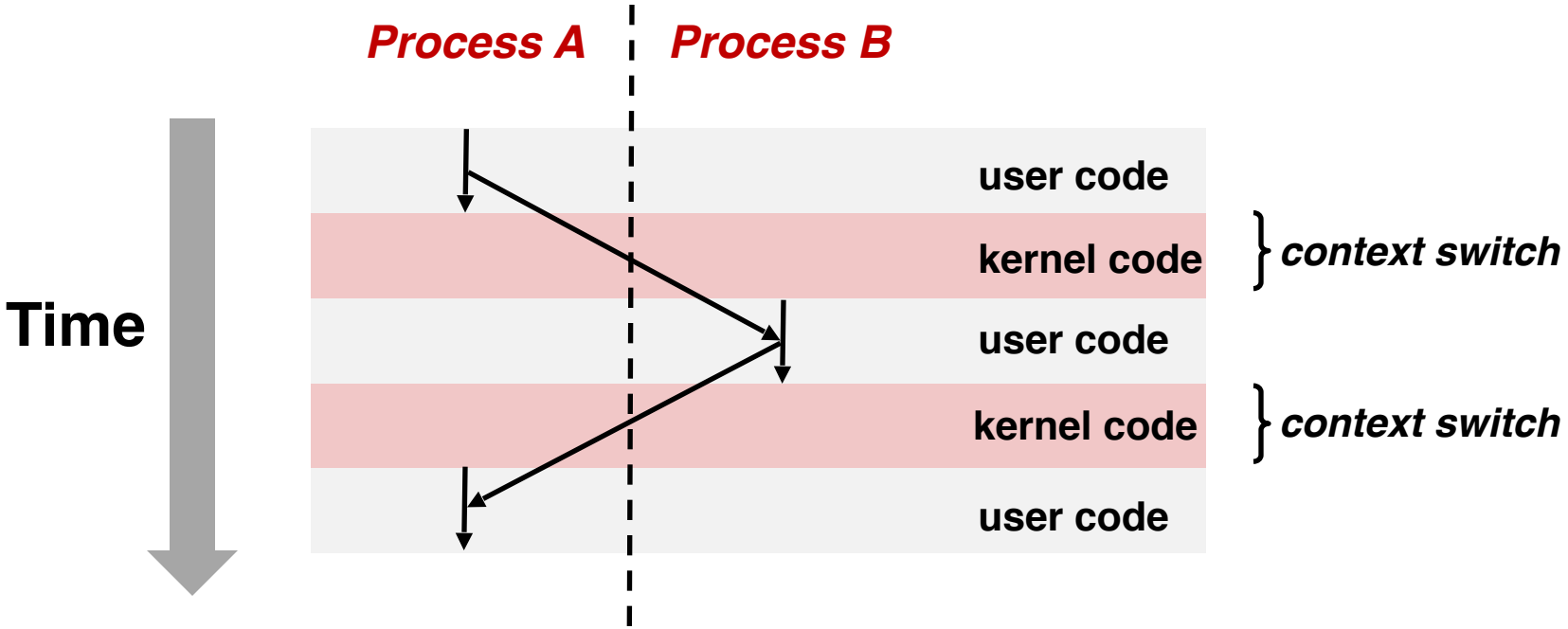
- Control flows for concurrent processes are physically disjoint in time

- However, we can think of concurrent processes as running in parallel with each other



Context Switching

- Processes are managed by a shared chunk of memory-resident OS code called the *kernel*
  - Important: the kernel is not a separate process, but rather runs as part of some existing process.
- Control flow passes from one process to another via a *context switch*



Today

- Exceptions/Interrupts
- Processes and Signals: Special kinds of exception
  - Processes
  - Process Control
  - Signals

Obtaining Process IDs

- `pid_t getpid(void)`
  - Returns PID of current process

- `pid_t getppid(void)`
  - Returns PID of parent process

Creating and Terminating Processes

From a programmer's perspective, we can think of a process as being in one of three states

- Running
  - Process is either executing, or waiting to be executed and will eventually be *scheduled* (i.e., chosen to execute) by the kernel
- Stopped
  - Process execution is suspended and will not be scheduled until further notice (through something call **signals**)
- Terminated
  - Process is stopped permanently

Terminating Processes

- Process becomes terminated for one of three reasons:
  - Receiving a signal whose default action is to terminate
  - Returning from the `main` routine
  - Calling the `exit` function

- `void exit(int status)`
  - Terminates with an *exit status* of `status`
  - Convention: normal return status is 0, nonzero on error
  - Another way to explicitly set the exit status is to return an integer value from the main routine

- `exit` is called once but never returns.

Creating Processes

- Parent process creates a new running child process by calling `fork`

- `int fork(void)`
  - Returns 0 to the child process, child's PID to parent process
  - Child is almost identical to parent:
    - Child get an identical (but separate) copy of the parent's (virtual) address space (i.e., same stack copies, code, etc.)
    - Child gets identical copies of the parent's open file descriptors
    - Child has a different PID than the parent

- `fork` is interesting (and often confusing) because it is called once but returns twice

`fork` Example

```c
int main()
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
        exit(0);
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
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fork.c

```
linux> ./fork
parent: x=0
child : x=2
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- Duplicate but separate address space
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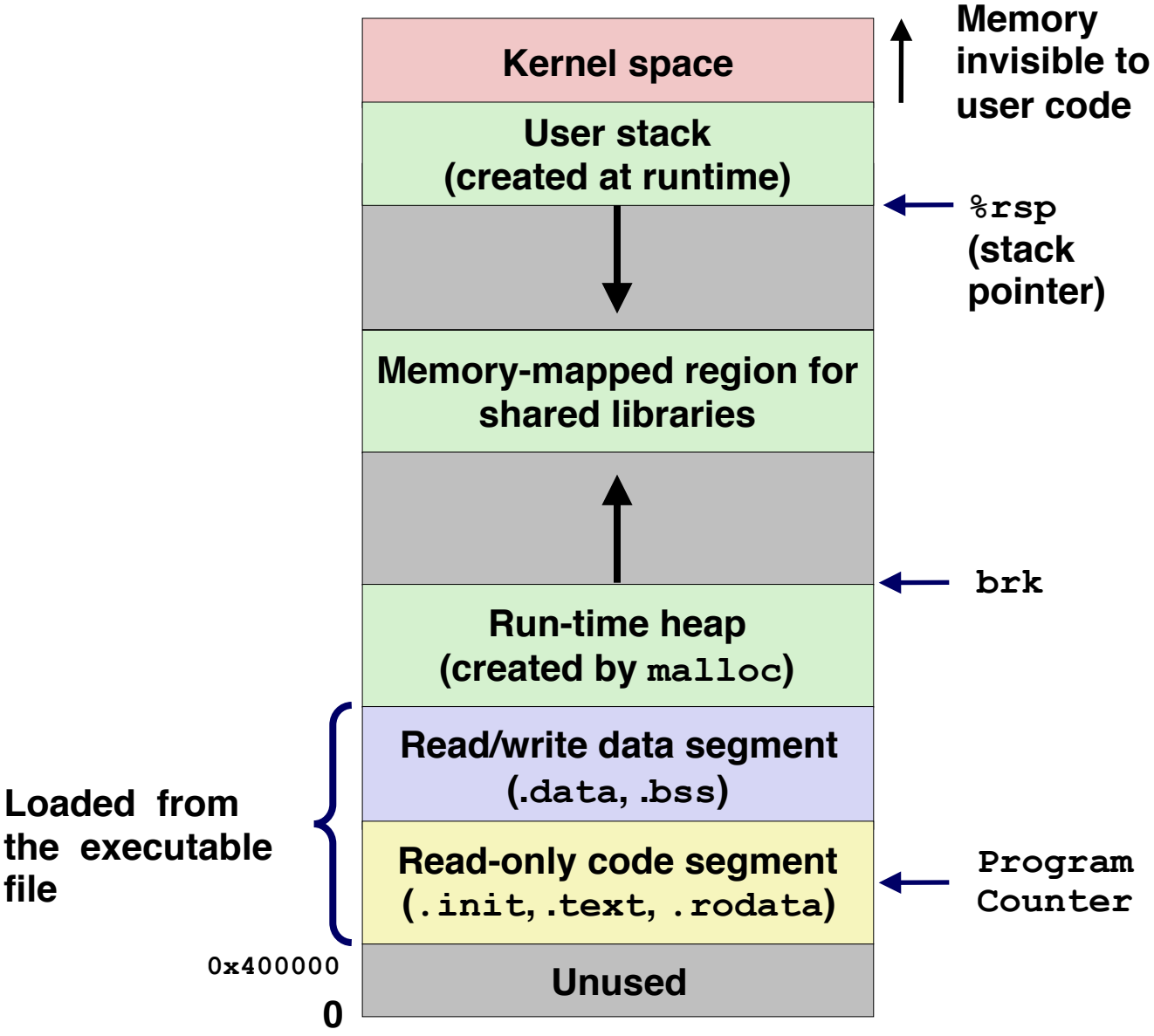
  - Subsequent changes to x are independent
- Shared open files
  - stdout is the same in both parent and child

Process Address Space



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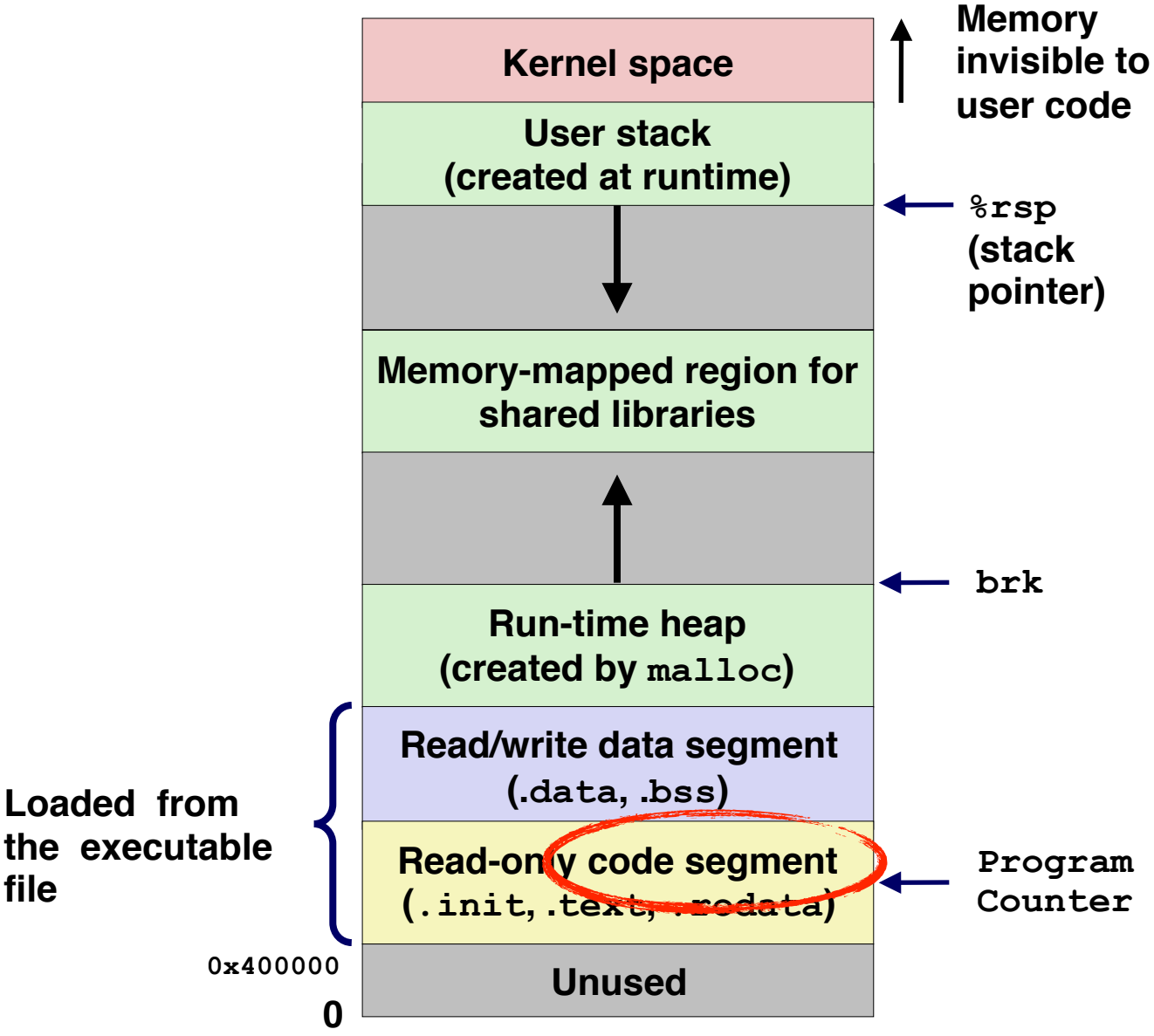


What Happens at `fork()`?

Code Segment

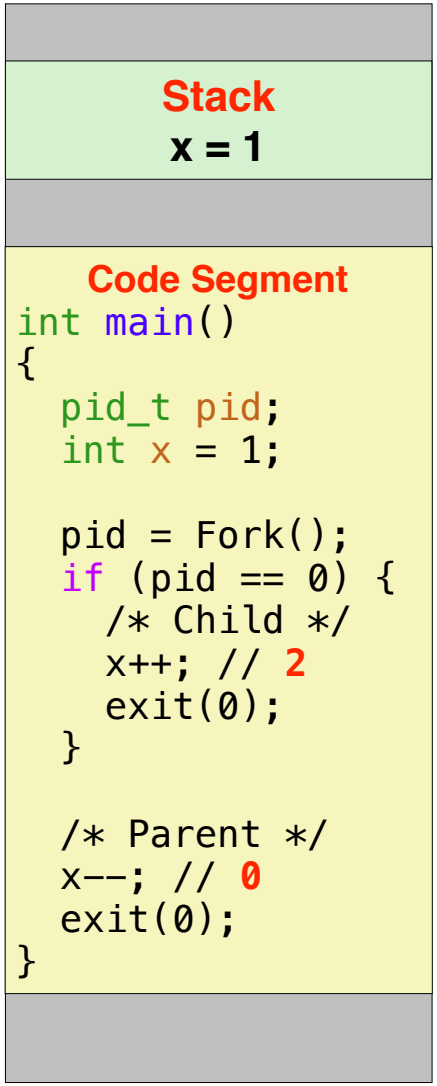
```
int main()
{
  pid_t pid;
  int x = 1;

  pid = Fork();
  if (pid == 0) {
    /* Child */
    x++; // 2
    exit(0);
  }

  /* Parent */
  x--; // 0
  exit(0);
}
```

What Happens at `fork()`?

Parent Address Space



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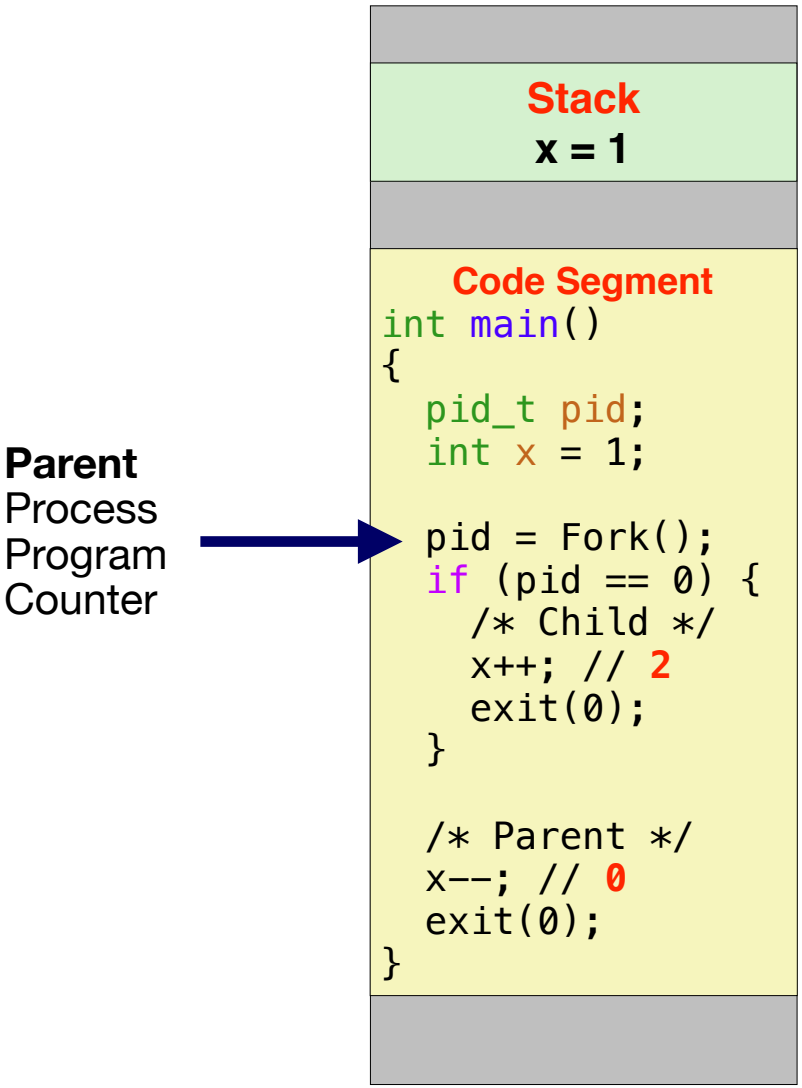

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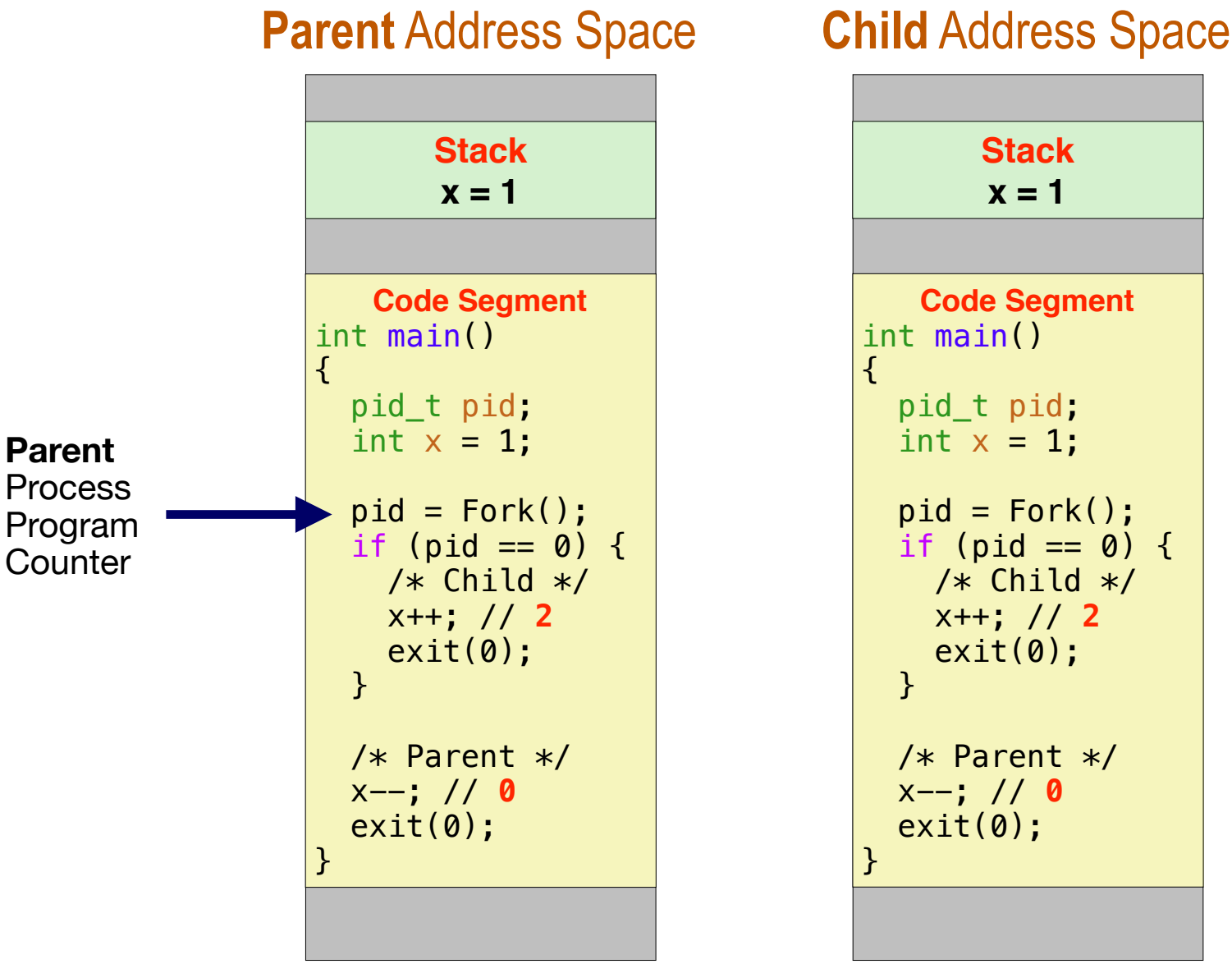

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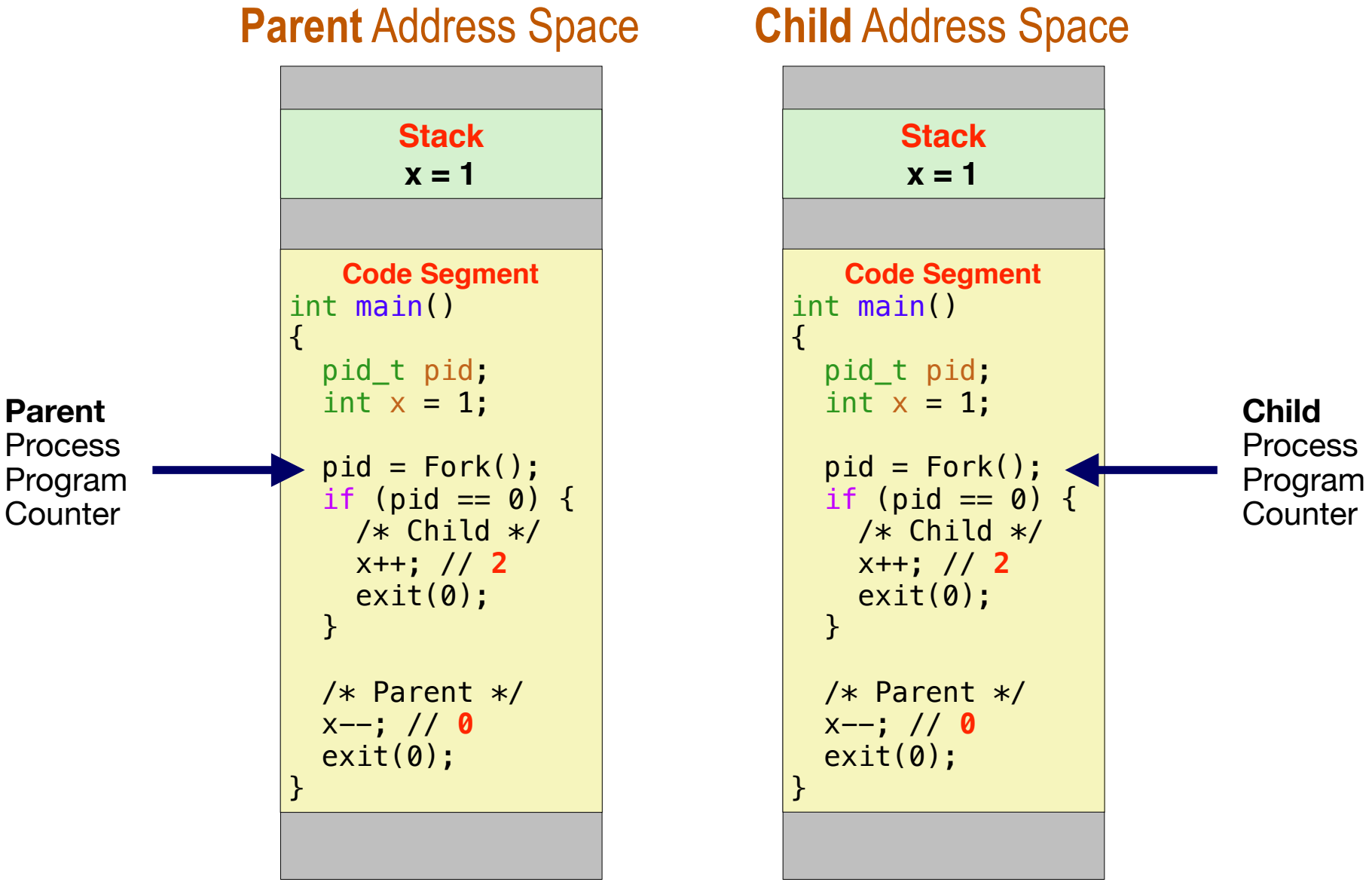

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- `int fork(void)`
  - Returns **0** to the child process
  - Returns **child's PID** to the parent process

Process Graph Example

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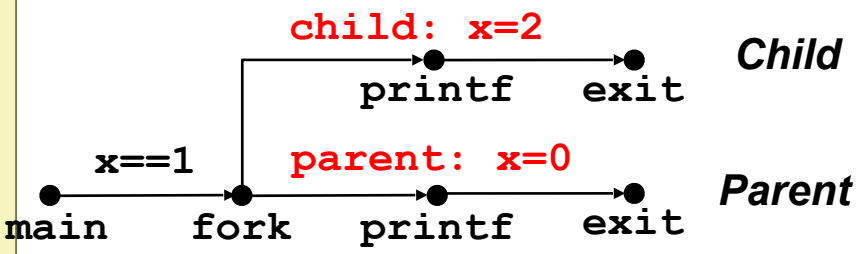
        printf("child : x=%d\n", ++x);
        exit(0);
    }

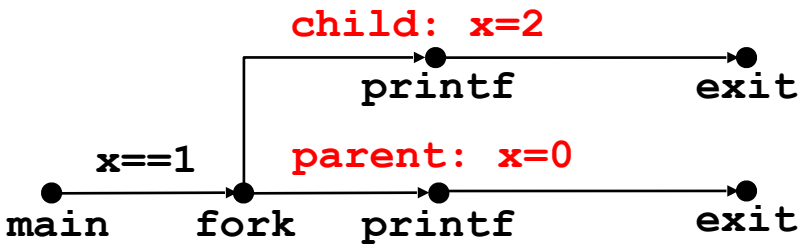
    /* Parent */
    printf("parent: x=%d\n", --x);
    exit(0);
}
```

fork.c

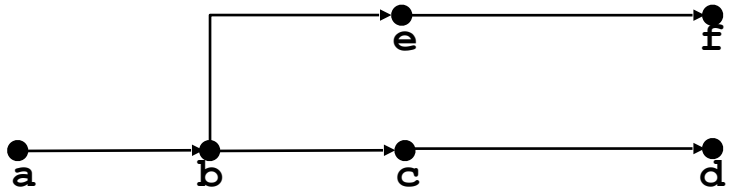


Interpreting Process Graphs

- Original graph:

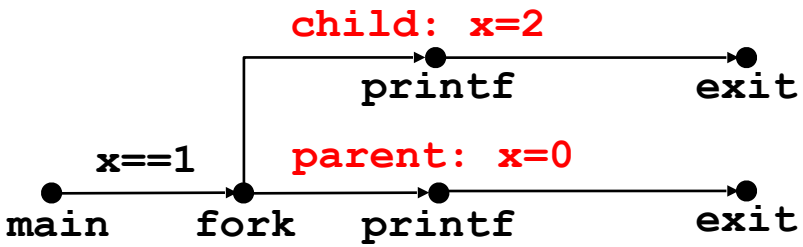


- Abstracted graph:

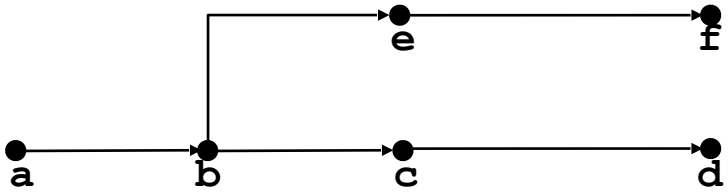


Interpreting Process Graphs

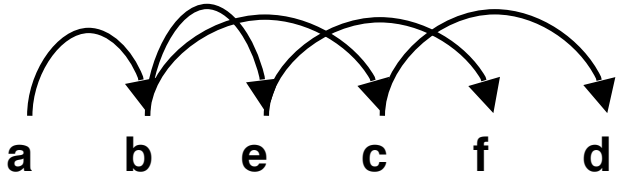
- Original graph:



- Abstracted graph:

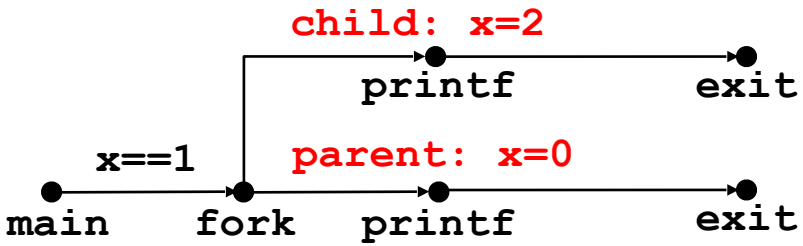


Feasible execution ordering:

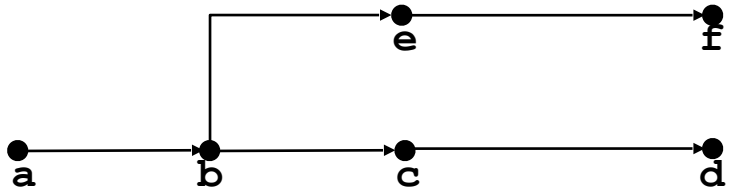


Interpreting Process Graphs

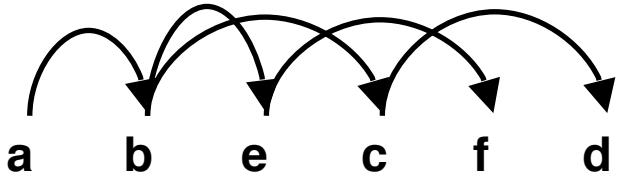
- Original graph:



- Abstracted graph:



Feasible execution ordering:



Infeasible execution ordering: