

Lecture 5

Synchronization

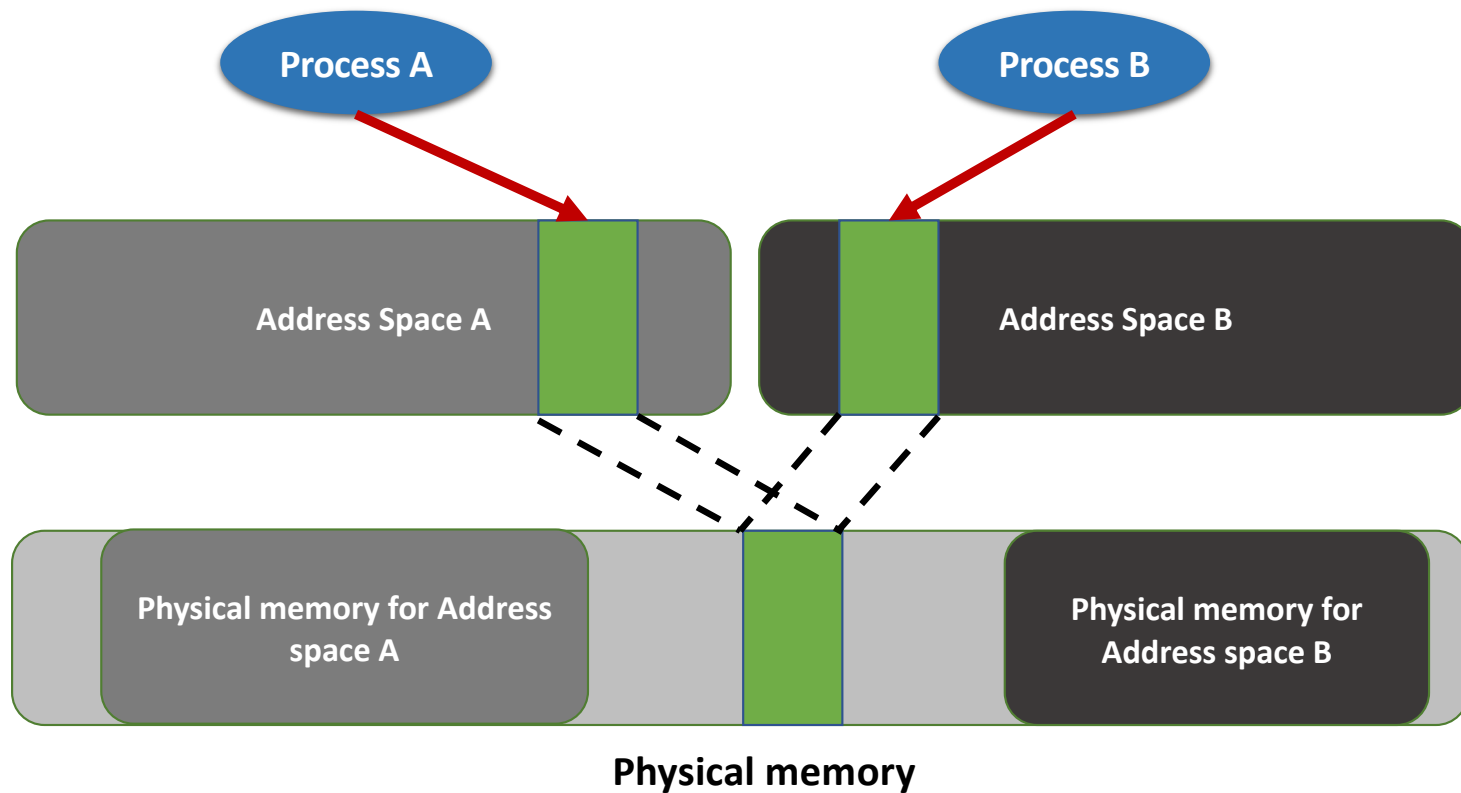
Prof. Yinqian Zhang

Spring 2023

Process Communication

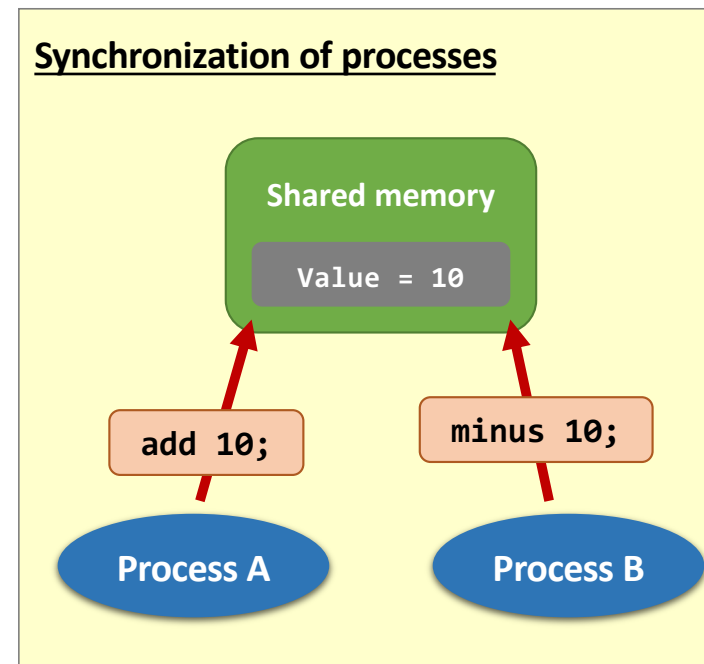
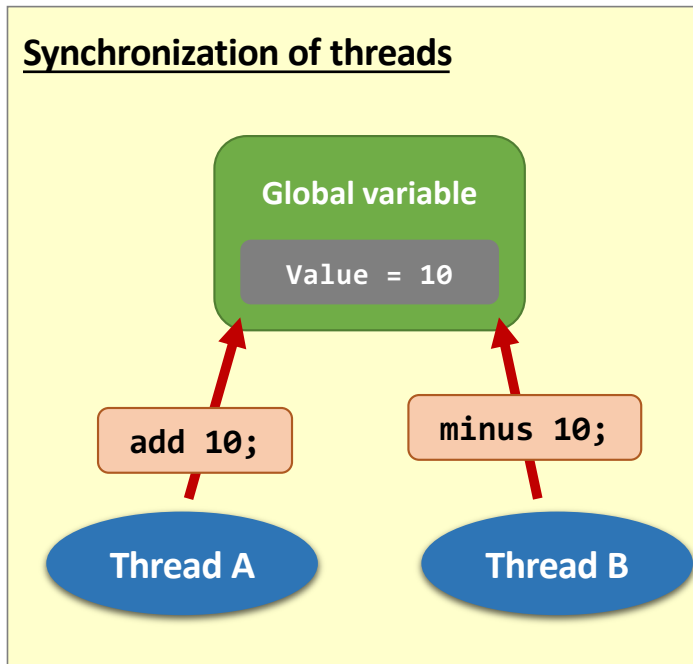
- Threads of the same process share the same address space
 - Global variables are shared by multiple threads
 - Communication between threads made easy
- Process may also need to communicate with each other
 - Information sharing:
 - e.g., sharing between Android apps
 - Computation speedup:
 - e.g., Message Passing Interface (MPI)
 - Modularity and isolation:
 - e.g., Chrome's multi-process architecture

Shared Memory between Processes



Synchronization of Threads/Processes

Process and thread synchronization can be considered in similar way



Synchronization of Threads/Processes

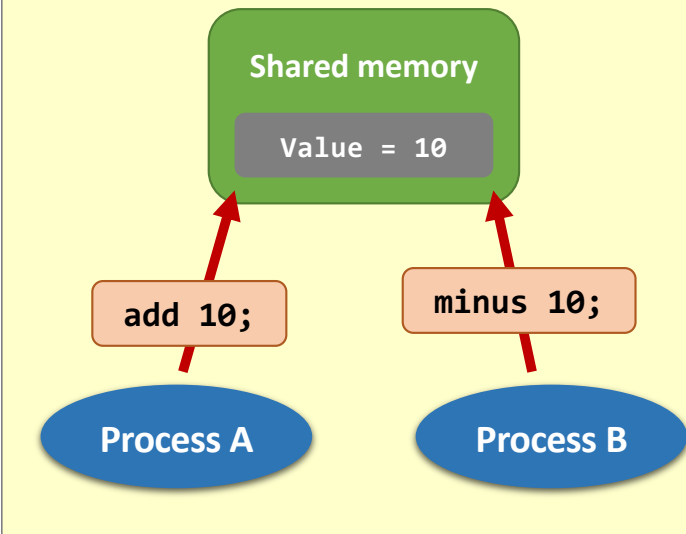
High-level language for Program A

```
1  attach to the shared memory X;  
2  add 10 to X;  
3  exit;
```

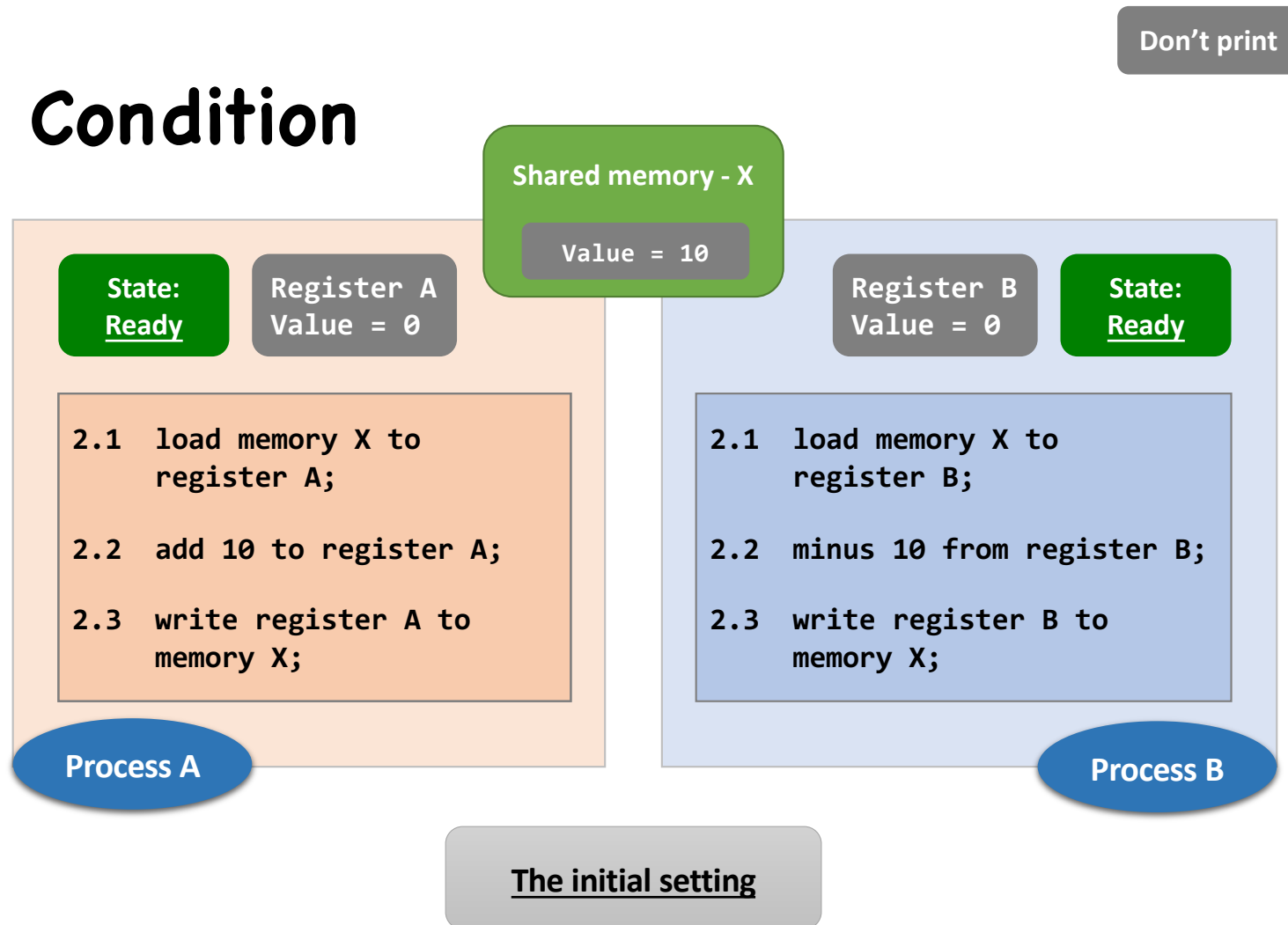
Partial low-level language for Program A

```
1    attach to the shared memory X;  
.....  
2.1  load memory X to register A;  
2.2  add 10 to register A;  
2.3  write register A to memory X;  
.....  
3    exit;
```

The Scenario



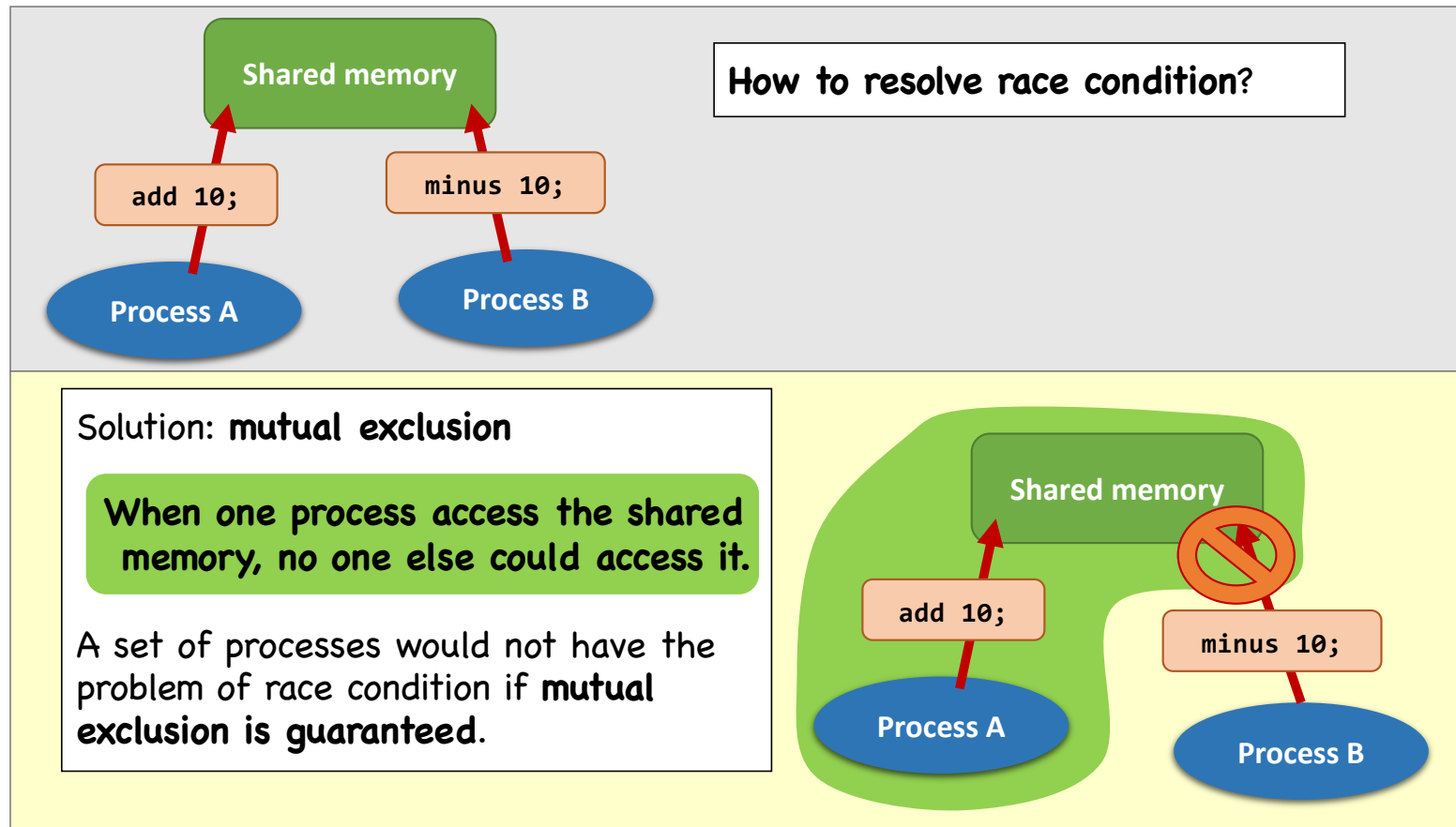
Race Condition



Race Condition

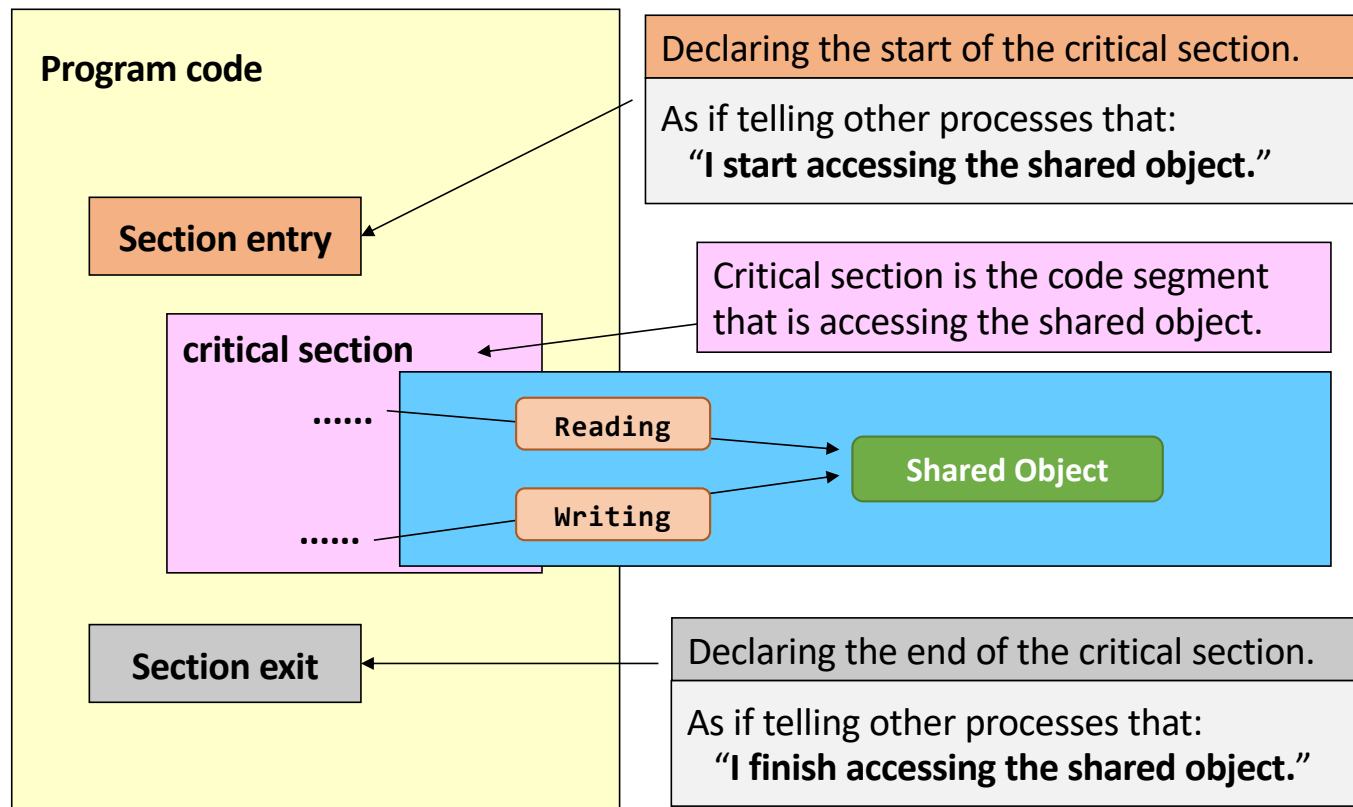
- The above scenario is called the **race condition**.
 - May happen whenever “**shared object**” + “**multiple processes/threads**” + “**concurrently**”
- A **race condition** means
 - The outcome of an execution depends on a particular order in which the shared resource is accessed.
- Remember: race condition is always a bad thing and debugging race condition is a **nightmare!**
 - It may end up ...
 - 99% of the executions are fine.
 - 1% of the executions are problematic.

Solution: Mutual Exclusion

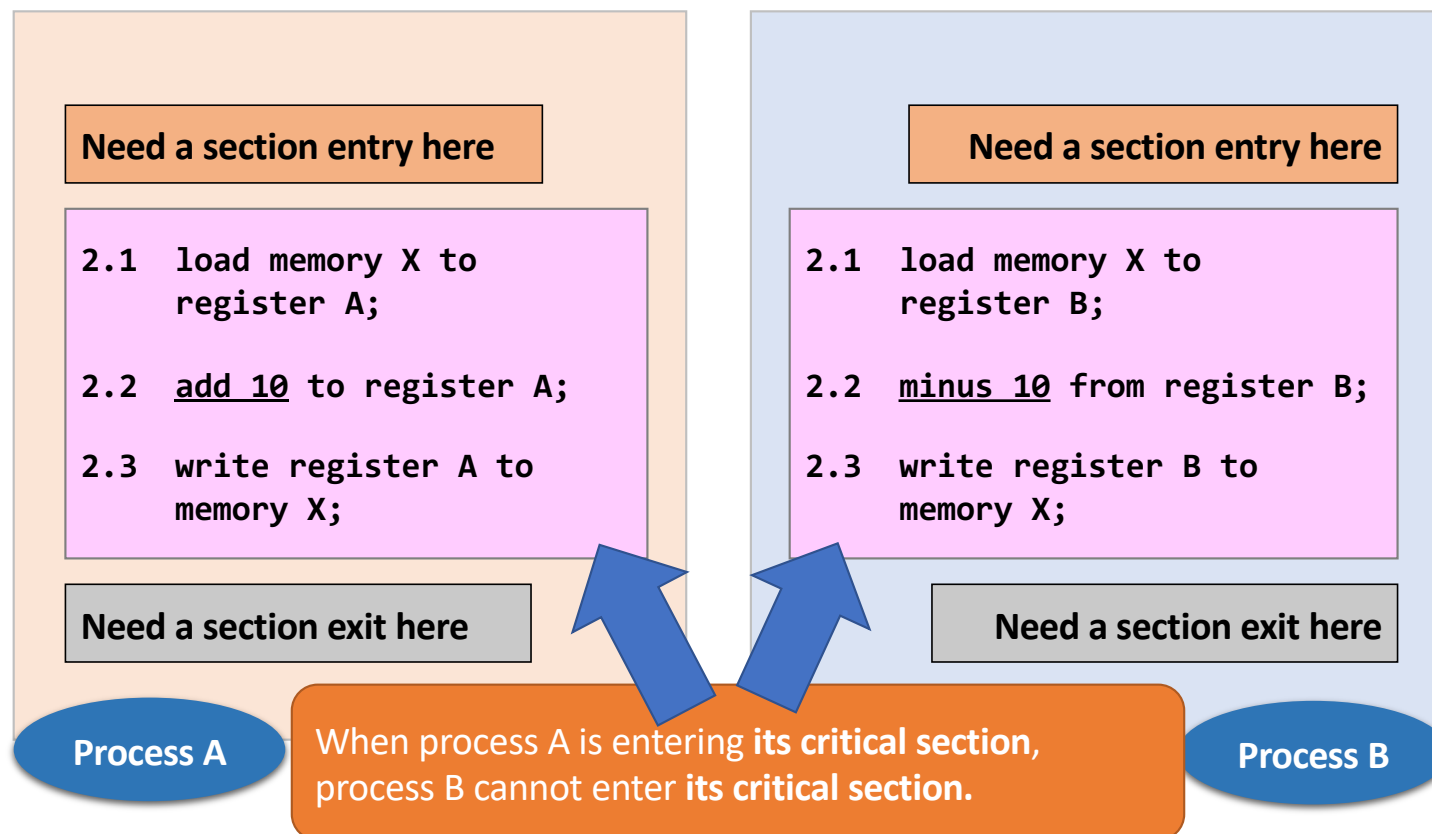


- Shared object is still sharable, but
- Do not access the "shared object" **at the same time**
- Access the "shared object" one by one

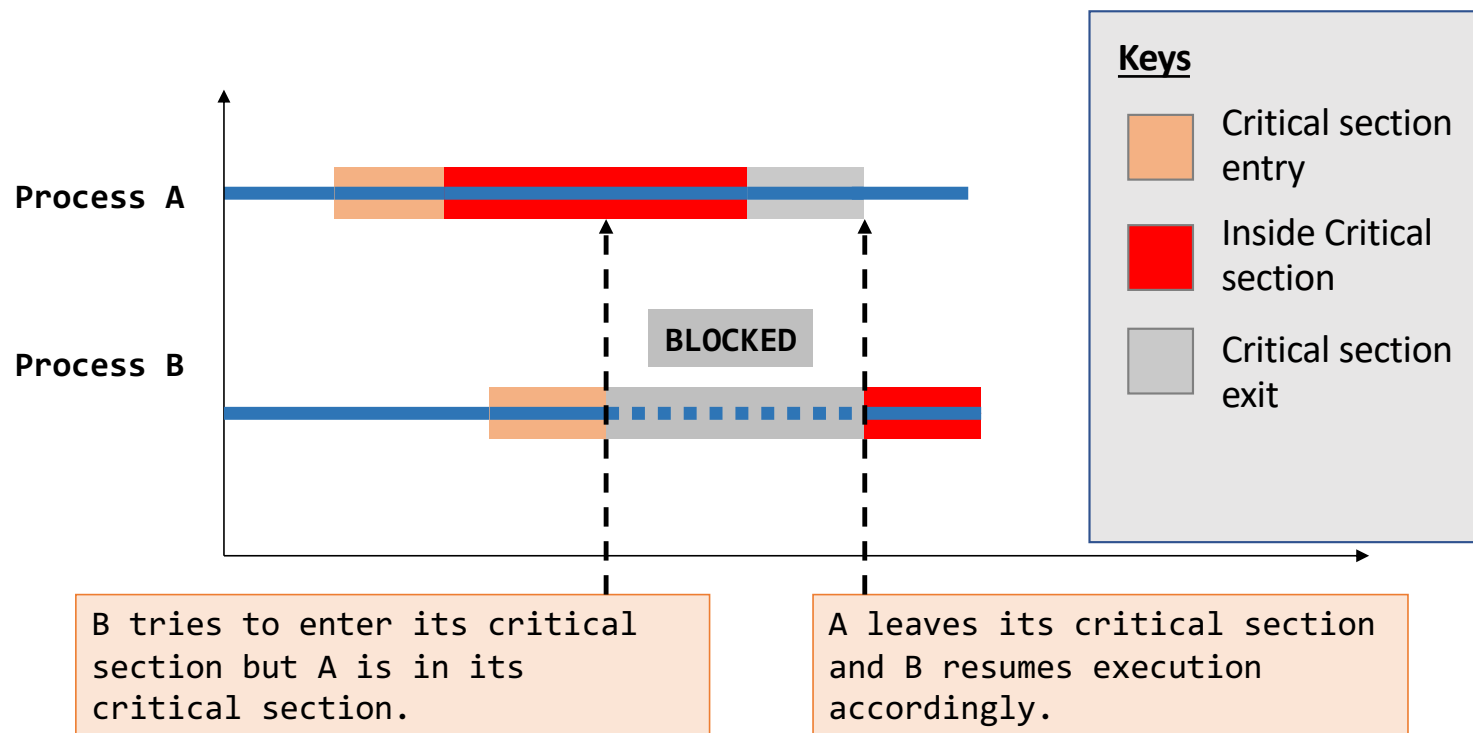
Critical Section: Realizing Mutual Exclusion



Critical Section: Realizing Mutual Exclusion



A Typical Mutual Exclusion Scenario



Summary

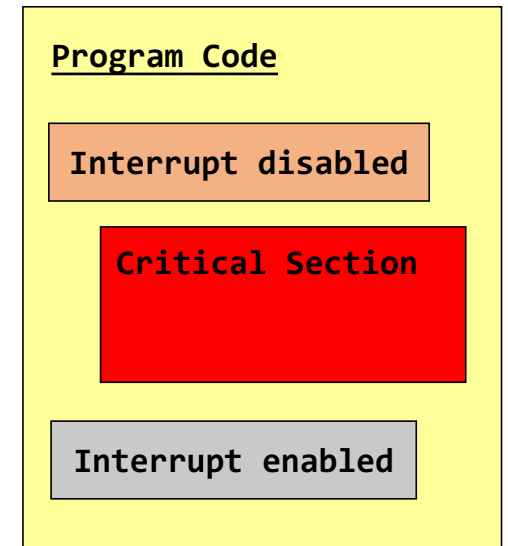
- Race condition
 - happens when programs accessing a shared object
 - The outcome of the computation totally depends on the execution sequences of the processes involved.
- Mutual exclusion is a requirement
 - If it could be achieved, then the problem of the race condition would be gone.
- A critical section is the code segment that access shared objects.
 - Critical section should be as tight as possible.
 - Well, you can set the entire code of a program to be a big critical section.
 - But, the program will have a very high chance to block other processes or to be blocked by other processes.
 - Note that one critical section can be designed for accessing more than one shared objects.

Critical Section Implementation

- Requirement #1. **Mutual Exclusion**
 - No two processes could be simultaneously go inside their own critical sections.
- Requirement #2. **Bounded Waiting**
 - Once a process starts trying to enter its critical section, there is a bound on the number of times other processes can enter theirs.
- Requirement #3. **Progress**
 - Say no process currently in critical section.
 - One of the processes trying to enter will eventually get in

Solution: Disabling Interrupts

- Disabling interrupts when the process is inside the critical section.
- When a process is in its critical section, no other processes could be able to run.
- Uni-core: Correct but not permissible
 - User level: what if one enters a critical section and loops infinitely?
 - OS cannot regain control if interrupt is disabled
 - Kernel level: yes, correct and permissible
- Multi-core: Incorrect
 - if there is another core modifying the shared object in the memory (unless you disable interrupts on all cores!!!!)

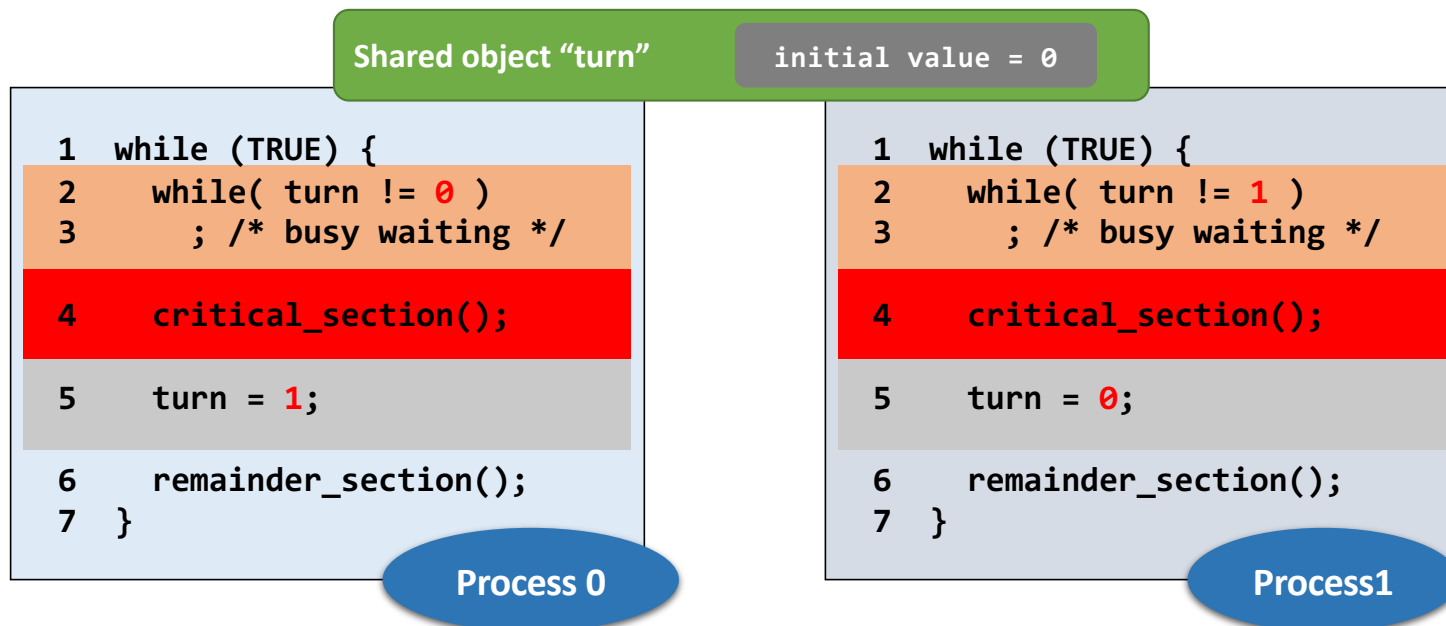


Solution: Locks

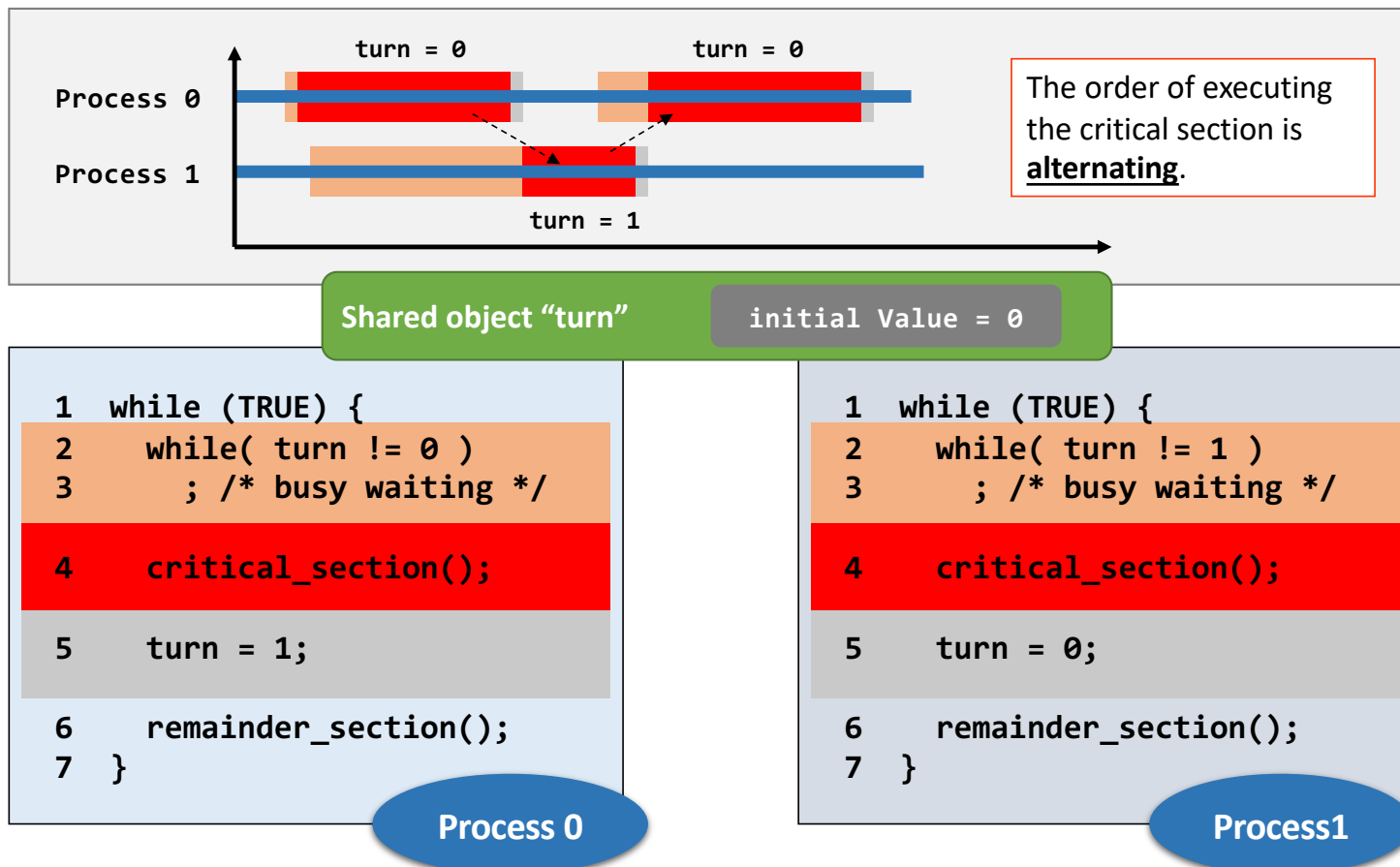
- Use yet another shared objects: **locks**
 - What about race condition on lock?
 - **Atomic instructions:** instructions that cannot be “interrupted”, not even by instructions running on another core
- Spin-based locks
 - Process synchronization
 - Basic spinning using 1 shared variable
 - Peterson’s solution: Spin using 2 shared variables
 - Thread synchronization: `pthread_spin_lock`
- Sleep-based locks
 - Process synchronization: POSIX semaphore
 - Thread synchronization: `pthread_mutex_lock`

Spin-based Locks

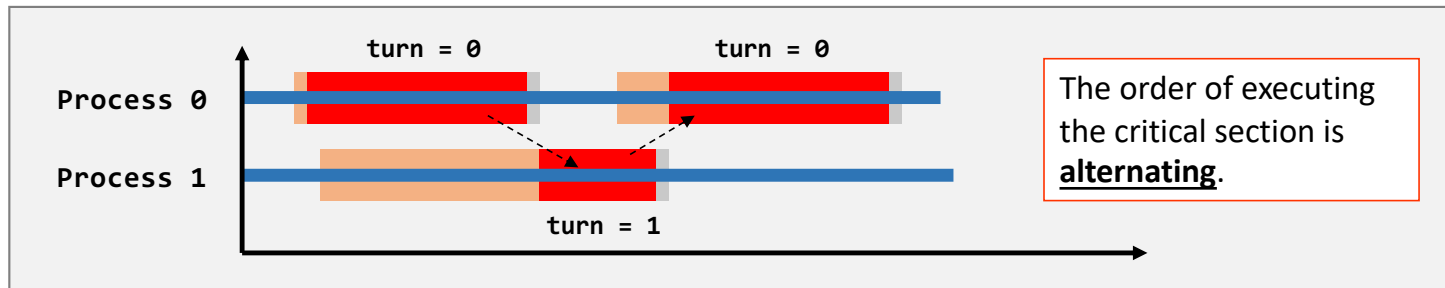
- Loop on a shared object, **turn**, to detect the status of other processes



Spin-based Locks (Cont'd)



Spin-based Locks (Cont'd)

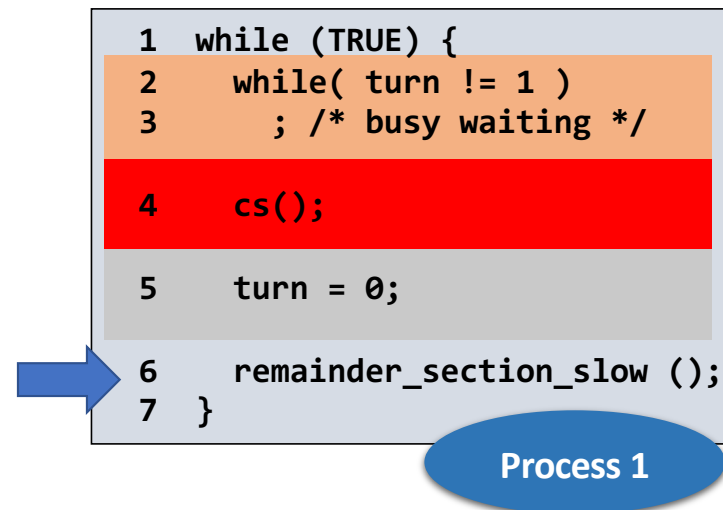
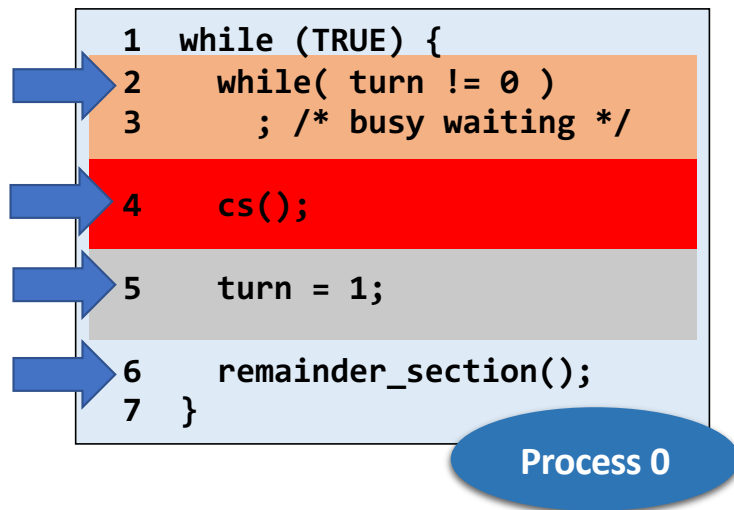


- **Correct but waste CPU resources**
 - OK for short waiting (spin-time < context-switch-overhead)
 - Especially these days we have multi-core
 - Will not block other irrelevant processes a lot
- Impose a "strict alternating" order
 - Sometimes you give me my turn but I'm not ready to enter critical section yet

Spin-based Locks: Progress Violation

- Consider the following sequence:
 - Process0 leaves cs(), set turn=1
 - Process1 enters cs(), leaves cs(), set turn=0, work on remainder_section-slow()
 - Process0 loops back and enters cs() again, leaves cs(), set turn=1
 - Process0 finishes its remainder_section(), go back to top of the loop
 - It can't enter its cs() (as turn=1)
 - That is, process0 gets blocked, but Process1 is outside its cs(), it is at its remainder_section-slow()

Has to wait...



Turn = 1

p1进入block
不如p0频繁

表明一个进程是否想进critical section

Peterson's Solution: Improved Spin-based Locks

```
1  int turn;                                /* whose turn is it next */
2  int interested[2] = {FALSE,FALSE}; /* express interest to enter cs*/
3
4  void lock( int process ) { /* process is 0 or 1 */
5      int other;                /* number of the other process */
6      other = 1-process;        /* other is 1 or 0 */
7      interested[process] = TRUE; /* express interest */
8      turn = other;
9      while ( turn == other &&
              interested[other] == TRUE )
10         ; /* busy waiting */
11 }
12
13 void unlock( int process ) { /* process: who is leaving */
14     interested[process] = FALSE; /* I just left critical region */
15 }
```

Peterson's Solution: Improved Spin-based Locks

```
1  int turn;
2  int interested[2] = {FALSE,FALSE};
3
4  void lock( int process ) {
5      int other;
6      other = 1-process;
7      interested[process] = TRUE;
8      turn = other;
9      while ( turn == other &&
              interested[other] == TRUE )
10         ;    /* busy waiting */
11 }
12
13 void unlock( int process ) {
14     interested[process] = FALSE;
15 }
```

Express interest to enter CS

Being polite and let other go first

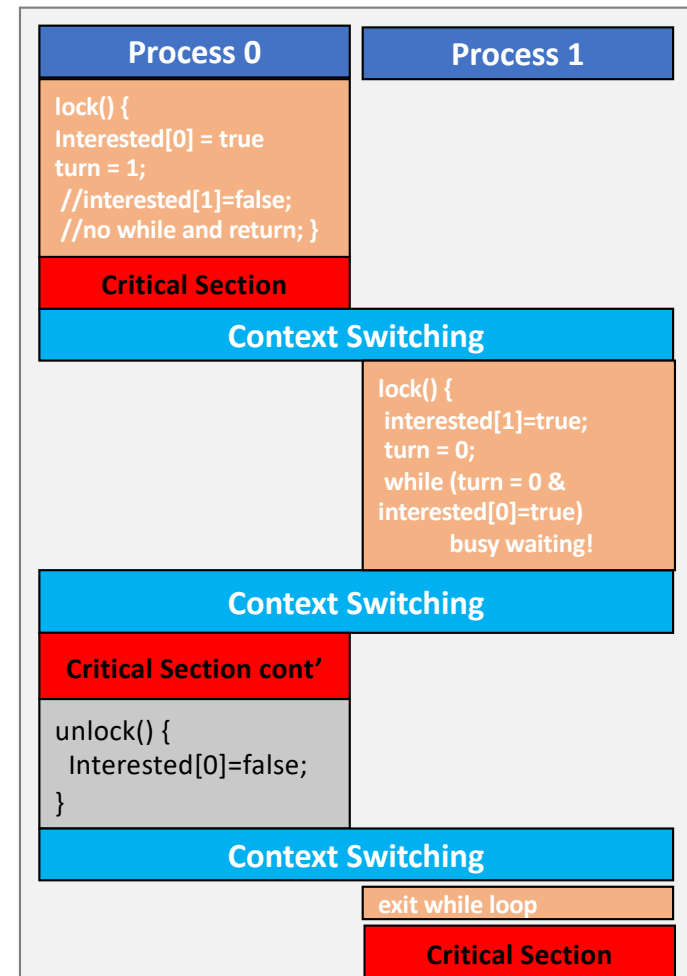
If other is not interested, I can always go ahead

Peterson's Solution

```

1  int turn;
2  int interested[2] = {FALSE, FALSE};
3
4  void lock( int process ) {
5      int other;
6      other = 1-process;
7      interested[process] = TRUE;
8      turn = other;
9      while ( turn == other &&
              interested[other] == TRUE )
10         ;    /* busy waiting */
11 }
12
13 void unlock( int process ) {
14     interested[process] = FALSE;
15 }

```

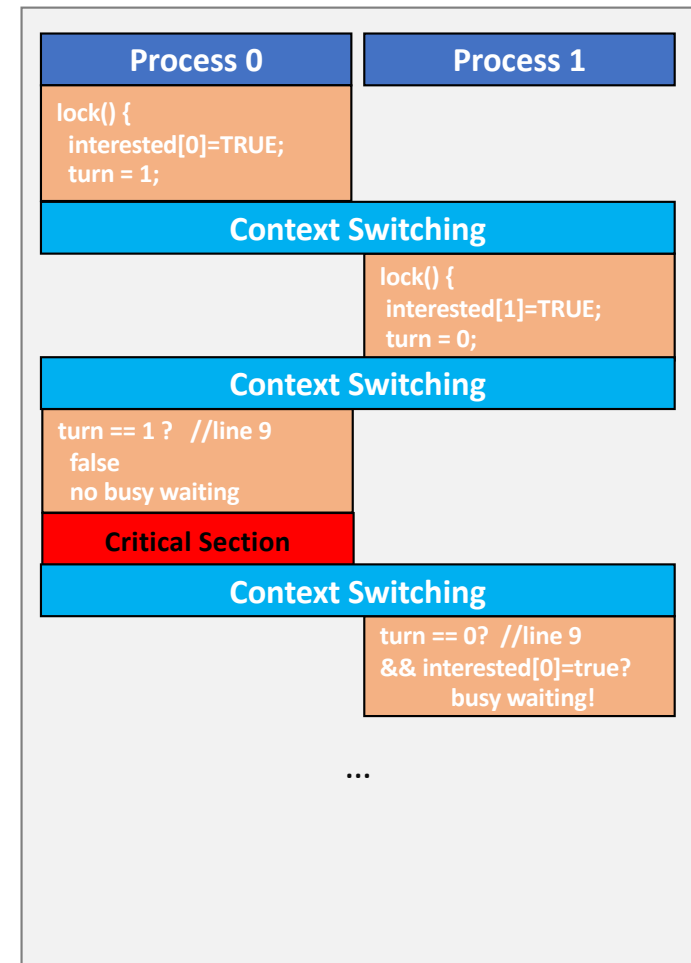


Peterson's Solution

```

1  int turn;
2  int interested[2] = {FALSE,FALSE};
3
4  void lock( int process ) {
5      int other;
6      other = 1-process;
7      interested[process] = TRUE;
8      turn = other;
9      while ( turn == other &&
              interested[other] == TRUE )
10         ;    /* busy waiting */
11 }
12
13 void unlock( int process ) {
14     interested[process] = FALSE;
15 }

```



Peterson's Solution Summary

- Mutual exclusion
 - `interested[0] == interested[1] == true`
 - `turn == 0` or `turn == 1`, not both
- Progress
 - If only P_0 to enter critical section
 - `interested[1] == false`, thus P_0 enters critical section
 - If both P_0 and P_1 to enter critical section
 - `interested[0] == interested[1] == true` and (`turn == 0` or `turn == 1`)
 - One of P_0 and P_1 will be selected
- Bounded-waiting
 - If both P_0 and P_1 to enter critical section, and P_0 selected first
 - When P_0 exit, `interested[0] = false`
 - If P_1 runs fast: `interested[0] == false`, P_1 enters critical section
 - If P_0 runs fast: `interested[0] = true`, but `turn = 1`, P_1 enters critical section

Multi-Process Mutual Exclusion

```
do {  
    waiting[i] = TRUE;  
    key = TRUE;  
    while (waiting[i] && key)  
        key = test_and_set(&lock);  
    waiting[i] = FALSE;  
    // critical section  
  
    j = (i + 1) % n;  
    while ((j != i) && !waiting[j])  
        j = (j + 1) % n;  
    if (j == i)  
        lock = FALSE;  
    else  
        waiting[j] = FALSE;  
    // remainder section  
} while (TRUE);
```

Multi-Process Mutual Exclusion (Cont'd)

- Support n processes
 - boolean waiting[n]
 - boolean lock
 - initially FALSE
- A process can enter the critical section if either **waiting[i] == FALSE** or **key == FALSE**
 - key is local variable
 - All process must execute **test_and_set()** at least once
 - The first one call **test_and_set()** with lock==FALSE wins
 - key = FALSE
 - lock == TRUE after the first process executes **test_and_set()**
 - key = TRUE
- *Mutual exclusion and progress are satisfied*

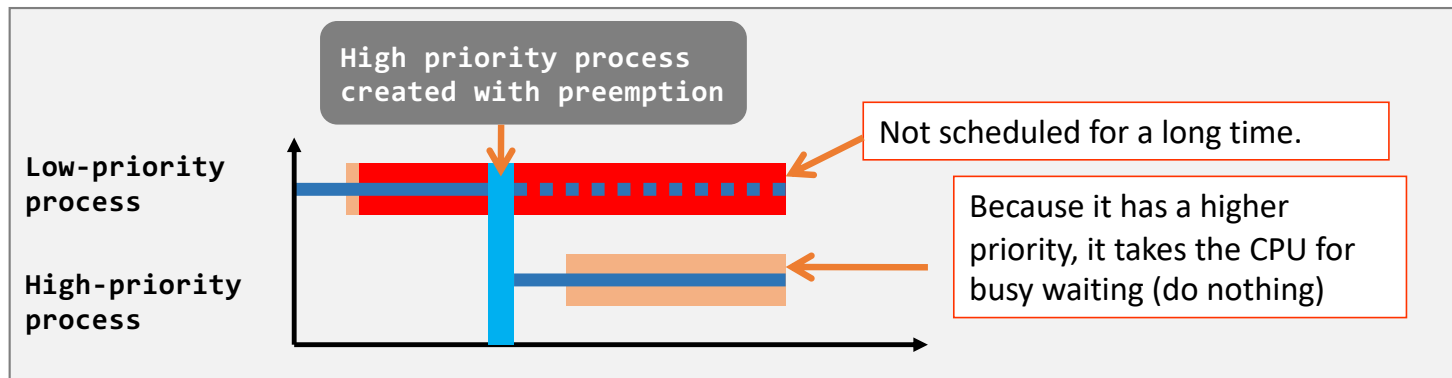
note: key/lock

Multi-Process Mutual Exclusion (Cont'd)

- When a process leaves the critical section
- It scans the array `waiting[n]` in a cyclic order ($i+1, i+2, \dots, n-1, 0, 1, \dots, i-1$)
- The first process with `waiting[j] == TRUE` enters the critical section next
- Bounded-waiting: Any process waiting to enter its critical section will do so within $n-1$ turns.
- If no other process to enter critical section: $i==j$
 - `lock = FALSE`

Priority Inversion

- Priority/Preemptive Scheduling (Linux, Windows... all OS...)
 - A low priority process **L** is inside the critical region, but ...
 - A high priority process **H** gets the CPU and wants to enter the critical region.
 - But **H** cannot **lock** (because **L** has not **unlock**)
 - So, **H** gets the CPU to do nothing but spinning



Sleep-based Lock: Semaphore

- Semaphore is just a struct, which includes
 - an integer that counts the # of resources available
 - Can do more than solving mutual exclusion
 - a wait-list
- The trick is still the section entry/exit function implementation
 - Must involve kernel (for sleep)
 - Implement uninterruptable **section entry/exit**
 - Disable interrupts (on single core)
 - Atomic instructions (on multiple cores)

Semaphore

```
typedef struct {  
    int value;  
    list process_id;  
} semaphore;
```

Section Entry: sem_wait()

```
1 void sem_wait(semaphore *s) {  
2  
3     s->value = s->value - 1;  
4     if ( s->value < 0 ) {  
5  
6         sleep();  
7  
8     }  
9  
10 }
```

Initialize **s->value** = 1

“sem_wait(s)”

- I wait until **s->value** ≥ 0
(i.e., **sem_wait(s)** only returns when **s->value** ≥ 0)

Important

This wait is different from parent's folk **wait(child)**. When programming, it is **sem_wait()**

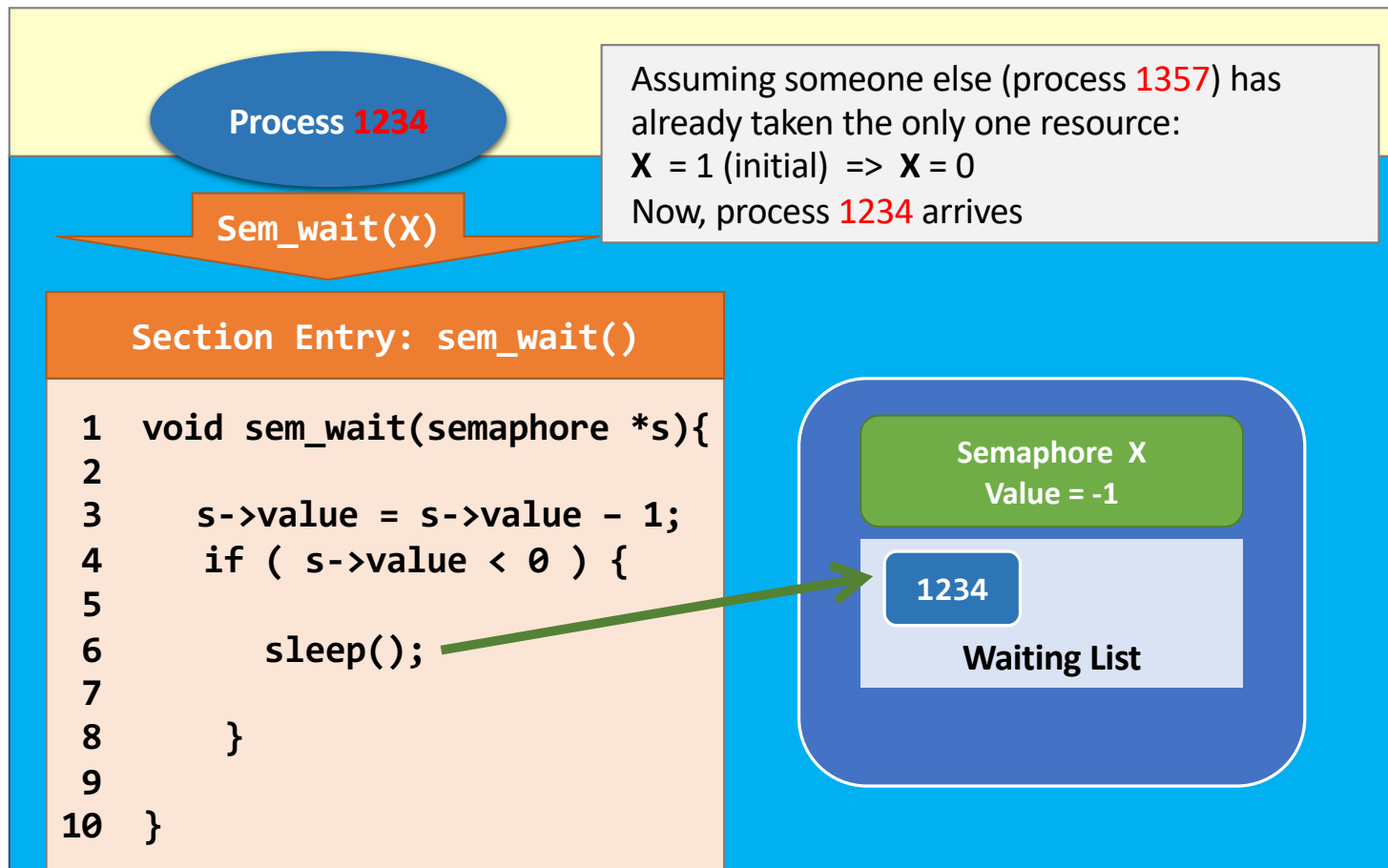
“sem_post(s)”

- I notify the others (if anyone waiting) that **s->value** ≤ 0

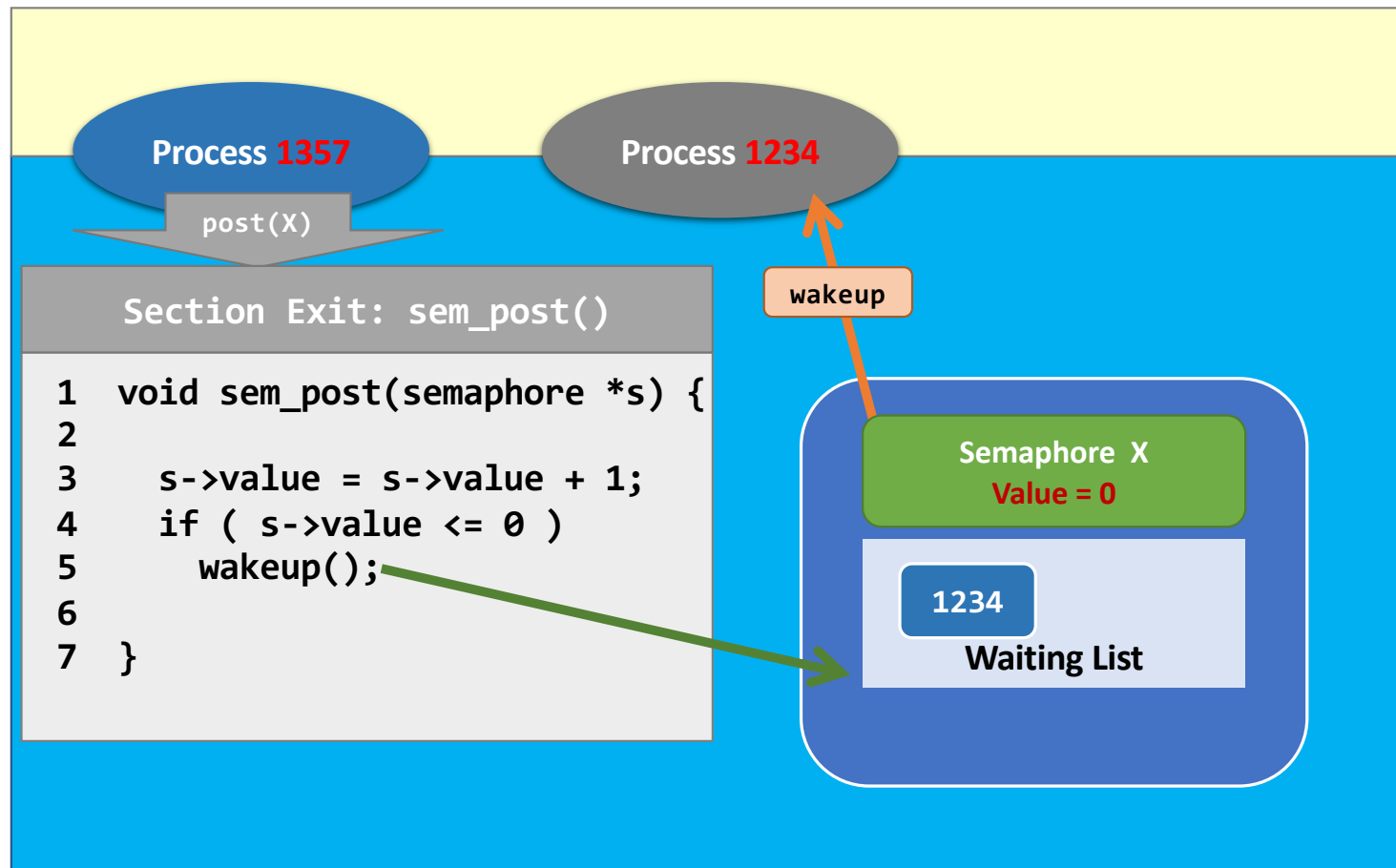
Section Exit: sem_post()

```
1 void sem_post(semaphore *s) {  
2  
3     s->value = s->value + 1;  
4     if ( s->value <= 0 )  
5         wakeup();  
6  
7 }
```

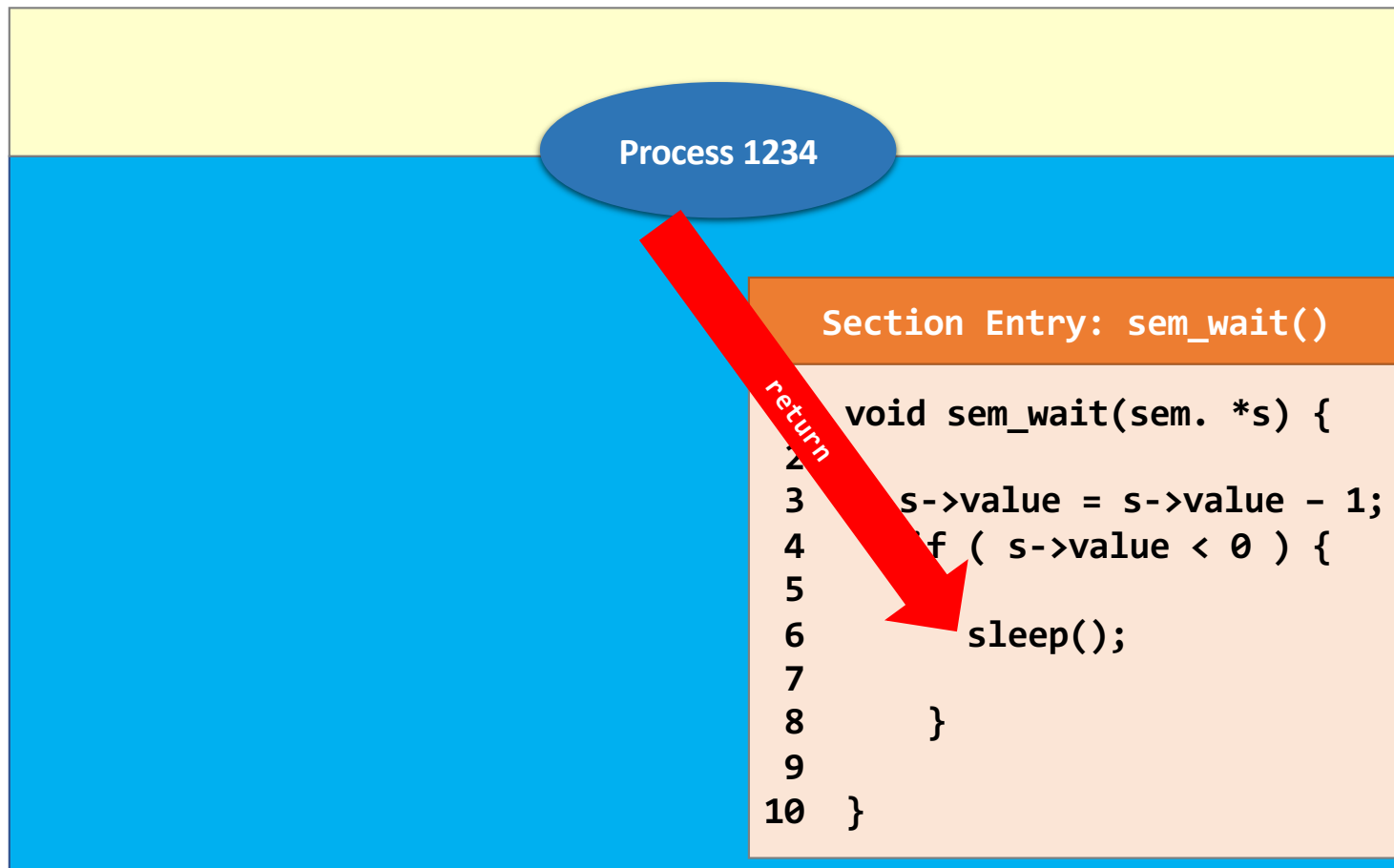
Semaphore Example



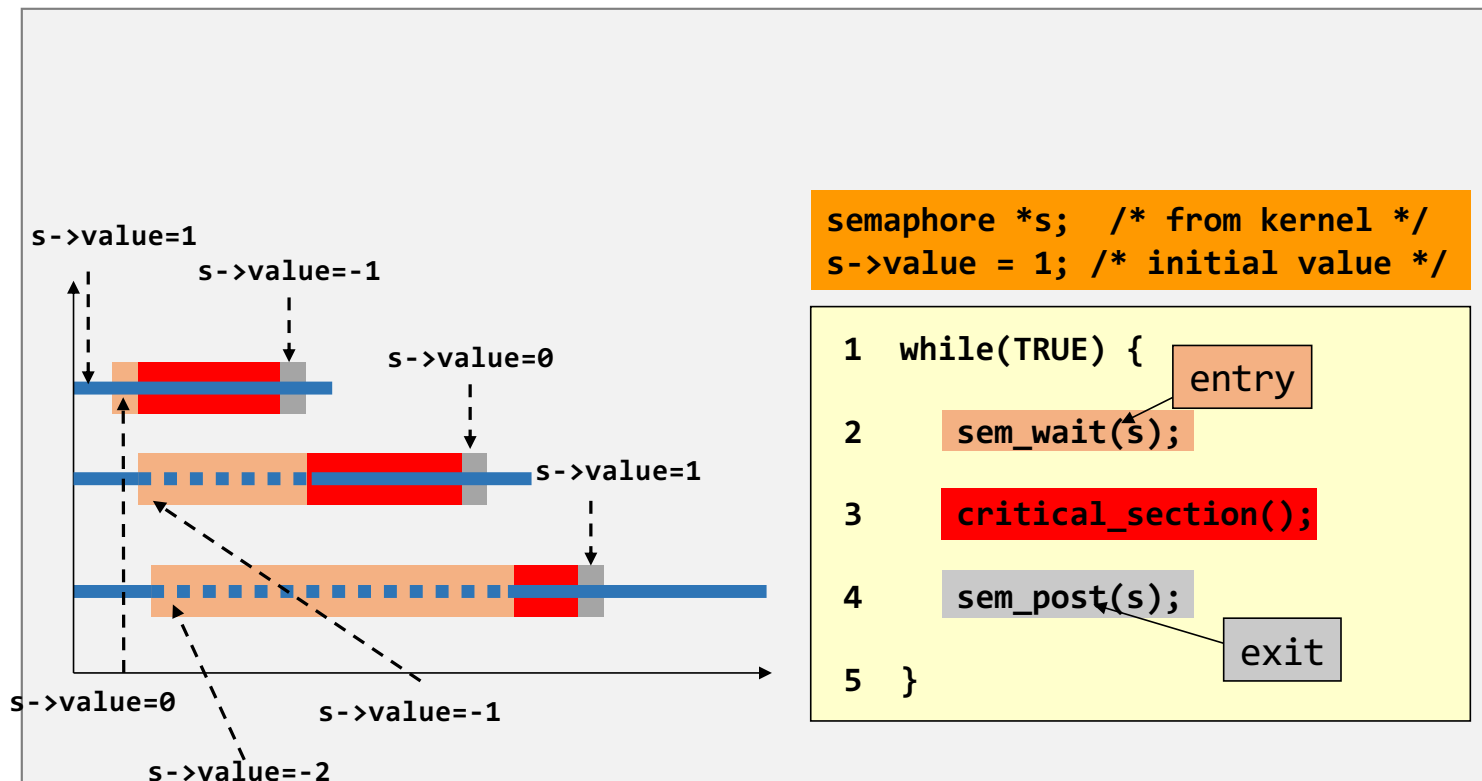
Semaphore Example



Semaphore Example



Using Semaphore in User Process



Semaphore Implementation

- Must guarantee that no two processes can execute `sem_wait()` and `sem_post()` on the same semaphore at the same time
- Thus, implementation becomes the critical section problem where the wait and signal code are placed in the critical section.
 - Need to disable interrupt on single-processor machine
 - use atomic instruction `cmp_xchg()` on multi-core architecture

Example: Atomic increment: `atomic_inc(addr)`

////////// implemented as //////////

```
do {  
    int old = *addr;  
    int new = old + 1;  
} while (cmp_xchg(addr, old, new) != old);
```

期中考：atomic incr

key: do-while, cmp_xchg

都执行，中间不给打断：如果被打断，重新执行

```
///one single instruction with the following  
///semantics  
void cmp_xchg(int *addr, int expected_value,  
int new_value)  
{  
    int temp = *addr;  
    if(*addr == expected_value)  
        *addr = new_value;  
    return temp;  
}
```

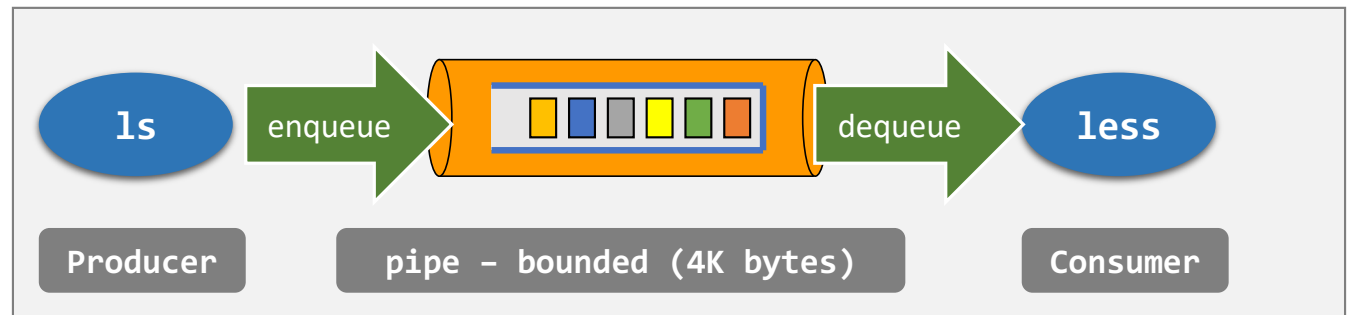
Using Semaphore beyond Mutual Exclusion

- Producer-Consumer Problem
 - Two types of processes: producer and consumer;
 - At least one producer and one consumer.
- Dining Philosopher Problem
 - Only one type of process
 - At least two processes.
- Reader Writer Problem
 - Multiple readers, one writer

Producer-consumer Problem

- Also known as the bounded-buffer problem.
- Single-object synchronization

A bounded buffer	-It is a shared object; -Its size is bounded, say N slots. -It is a queue (imagine that it is an array implementation of queue).
A producer process	-It produces a unit of data, and -writes a piece of data to the tail of the buffer at one time.
A consumer process	-It removes a unit of data from the head of the bounded buffer at one time.



Producer-consumer Problem

Requirement #1

When the producer wants to
(a) put a new item in the buffer, but
(b) **the buffer is already full...**

Then, **the producer should wait.**

The consumer should notify the producer after she has dequeued an item.

Requirement #2

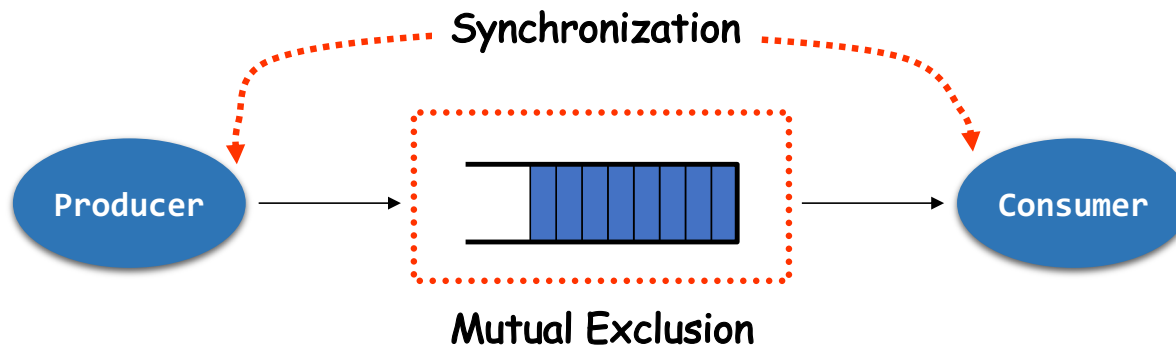
When the consumer wants to
(a) consumes an item from the buffer, but
(b) **the buffer is empty...**

Then, **the consumer should wait.**

The producer should notify the consumer after she has enqueued an item.

Solving Producer-consumer Problem with Semaphore

- The problem can be divided into two sub-problems.
 - Mutual exclusion with one **binary semaphore**
 - The buffer is a shared object.
 - Synchronization with two **counting semaphores**
 - Notify the producer to stop producing when the buffer is full
 - In other words, notify the producer to produce when the buffer is NOT full
 - Notify the consumer to stop eating when the buffer is empty
 - In other words, notify the consumer to consume when the buffer is NOT empty



Solving Producer-consumer Problem with Semaphore

Shared object
<pre>#define N 100 semaphore mutex = 1; semaphore avail = N; semaphore fill = 0;</pre>

Note

The size of the bounded buffer is “N”.

fill : number of occupied slots in buffer

avail: number of empty slots in buffer

Abstraction of semaphore as integer!

Producer function
<pre>1 void producer(void) { 2 int item; 3 4 while(TRUE) { 5 item = produce_item(); 6 wait(&avail); 7 wait(&mutex); 8 insert_item(item); 9 post(&mutex); 10 post(&fill); 11 } 12 }</pre>

Consumer Function
<pre>1 void consumer(void) { 2 int item; 3 4 while(TRUE) { 5 wait(&fill); 6 wait(&mutex); 7 item = remove_item(); 8 post(&mutex); 9 post(&avail); 10 //consume the item; 11 } 12 }</pre>

Solving Producer-consumer Problem with Semaphore

Note

6: (Producer) I wait for an **avail**able slot and acquire it if I can

10: (Producer) I **notify** the others that I have **filled** the buffer

Producer function

```
1 void producer(void) {  
2     int item;  
3  
4     while(TRUE) {  
5         item = produce_item();  
6         wait(&avail);  
7         wait(&mutex);  
8         insert_item(item);  
9         post(&mutex);  
10        post(&fill);  
11    }  
12 }
```

Solving Producer-consumer Problem with Semaphore

Note

6: (Producer) I wait for an **available** slot and acquire it if I can

10: (Producer) I **notify** the others that I have **filled** the buffer

Note

5: (Consumer) I wait for someone to **fill** up the buffer and proceed if I can

9: (Consumer) I **notify** the others that I have made the buffer with a new **available** slot

Producer function

```
1 void producer(void) {
2     int item;
3
4     while(TRUE) {
5         item = produce_item();
6         wait(&avail);
7         wait(&mutex);
8         insert_item(item);
9         post(&mutex);
10        post(&fill);
11    }
12 }
```

Consumer Function

```
1 void consumer(void) {
2     int item;
3
4     while(TRUE) {
5         wait(&fill);
6         wait(&mutex);
7         item = remove_item();
8         post(&mutex);
9         post(&avail);
10        //consume the item;
11    }
12 }
```

Question 1

Necessary to use both “avail” and “fill”?

Let us try to remove semaphore fill?

Shared object

```
#define N 100
typedef int semaphore;
semaphore mutex = 1;
semaphore avail = N;
semaphore fill = 0;
```

Producer function

```
1 void producer(void) {
2     int item;
3
4     while(TRUE) {
5         item = produce_item();
6         wait(&avail);
7         wait(&mutex);
8         insert_item(item);
9         post(&mutex);
10        post(&fill);
11    }
12 }
```

Consumer Function

```
1 void consumer(void) {
2     int item;
3
4     while(TRUE) {
5         wait(&fill);
6         wait(&mutex);
7         item = remove_item();
8         post(&mutex);
9         post(&avail);
10        //consume the item;
11    }
12 }
```

Question 1

Just view wait(avail) as -- resource?
Just view post(avail) as ++ resource?

so
• producer avail-- by wait
• consumer avail++ by post
Problem solved?

Producer function

```
1 void producer(void) {  
2     int item;  
3  
4     while(TRUE) {  
5         item = produce_item();  
6         wait(&avail);  
7         wait(&mutex);  
8         insert_item(item);  
9         post(&mutex);  
10        post(&fill);  
11    }  
12 }
```

Consumer Function

```
1 void consumer(void) {  
2     int item;  
3  
4     while(TRUE) {  
5         wait(&fill);  
6         wait(&mutex);  
7         item = remove_item();  
8         post(&mutex);  
9         post(&avail);  
10        //consume the item;  
11    }  
12 }
```

Question 1

Just view wait(avail) as -- resource?
Just view post(avail) as ++ resource?

so
• producer avail-- by wait
• consumer avail++ by post

If consumer gets CPU first, it removes item from NULL

ERROR

Producer function

```
1 void producer(void) {  
2     int item;  
3  
4     while(TRUE) {  
5         item = produce_item();  
6         wait(&avail);  
7         wait(&mutex);  
8         insert_item(item);  
9         post(&mutex);  
10        post(&fill);  
11    }  
12 }
```

Consumer Function

```
1 void consumer(void) {  
2     int item;  
3  
4     while(TRUE) {  
5         wait(&fill);  
6         wait(&mutex);  
7         item = remove_item();  
8         post(&mutex);  
9         post(&avail);  
10        //consume the item;  
11    }  
12 }
```

Question 2

Question #2.

Can we swap Lines 6 & 7 of the producer?

Let us simulate what will happen with the modified code!

Shared object

```
#define N 100
semaphore mutex = 1;
semaphore avail = N;
semaphore fill = 0;
```

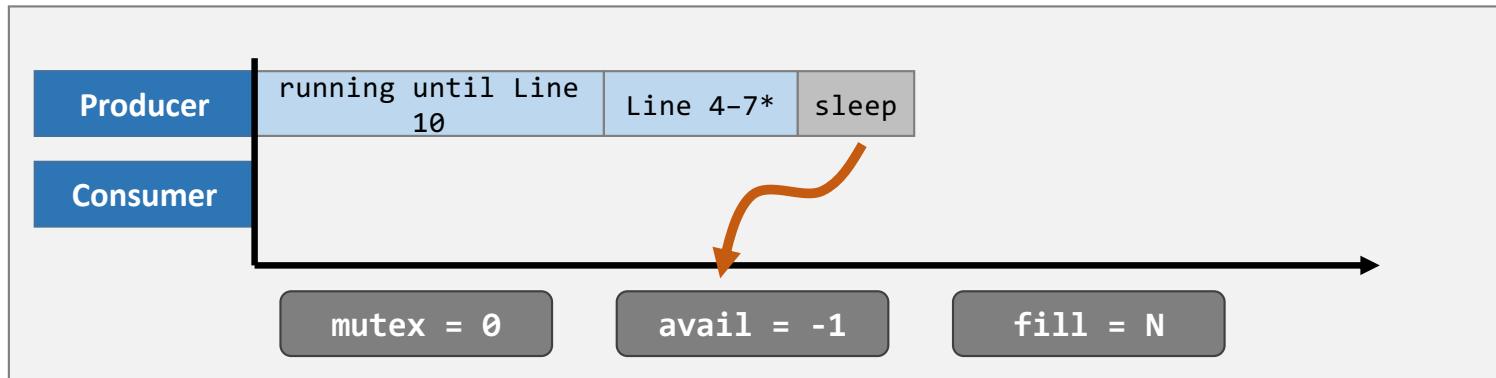
Producer function

```
1 void producer(void) {
2     int item;
3
4     while(TRUE) {
5         item = produce_item();
6*      wait(&mutex);
7*      wait(&avail);
8         insert_item(item);
9         post(&mutex);
10        post(&fill);
11    }
12 }
```

Consumer Function

```
1 void consumer(void) {
2     int item;
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4     while(TRUE) {
5         wait(&fill);
6         wait(&mutex);
7         item = remove_item();
8         post(&mutex);
9         post(&avail);
10        //consume the item
11    }
12 }
```

Question 2

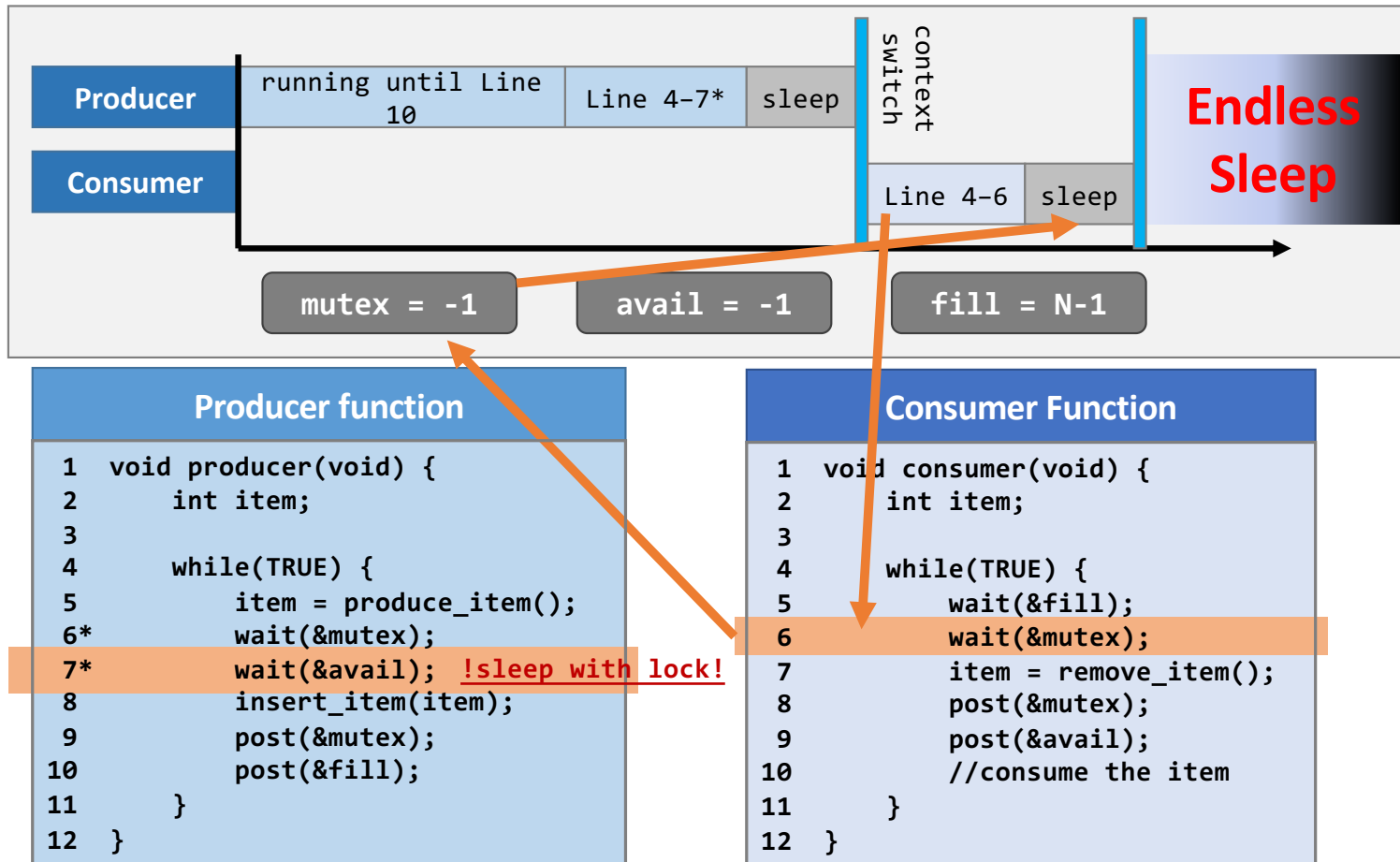


Producer function	
1	void producer(void) {
2	int item;
3	
4	while(TRUE) {
5	item = produce_item();
6*	wait(&mutex);
7*	wait(&avail);
8	insert_item(item);
9	post(&mutex);
10	post(&fill);
11	}
12	}

Consider: producer gets the CPU to keep producing until the buffer is full

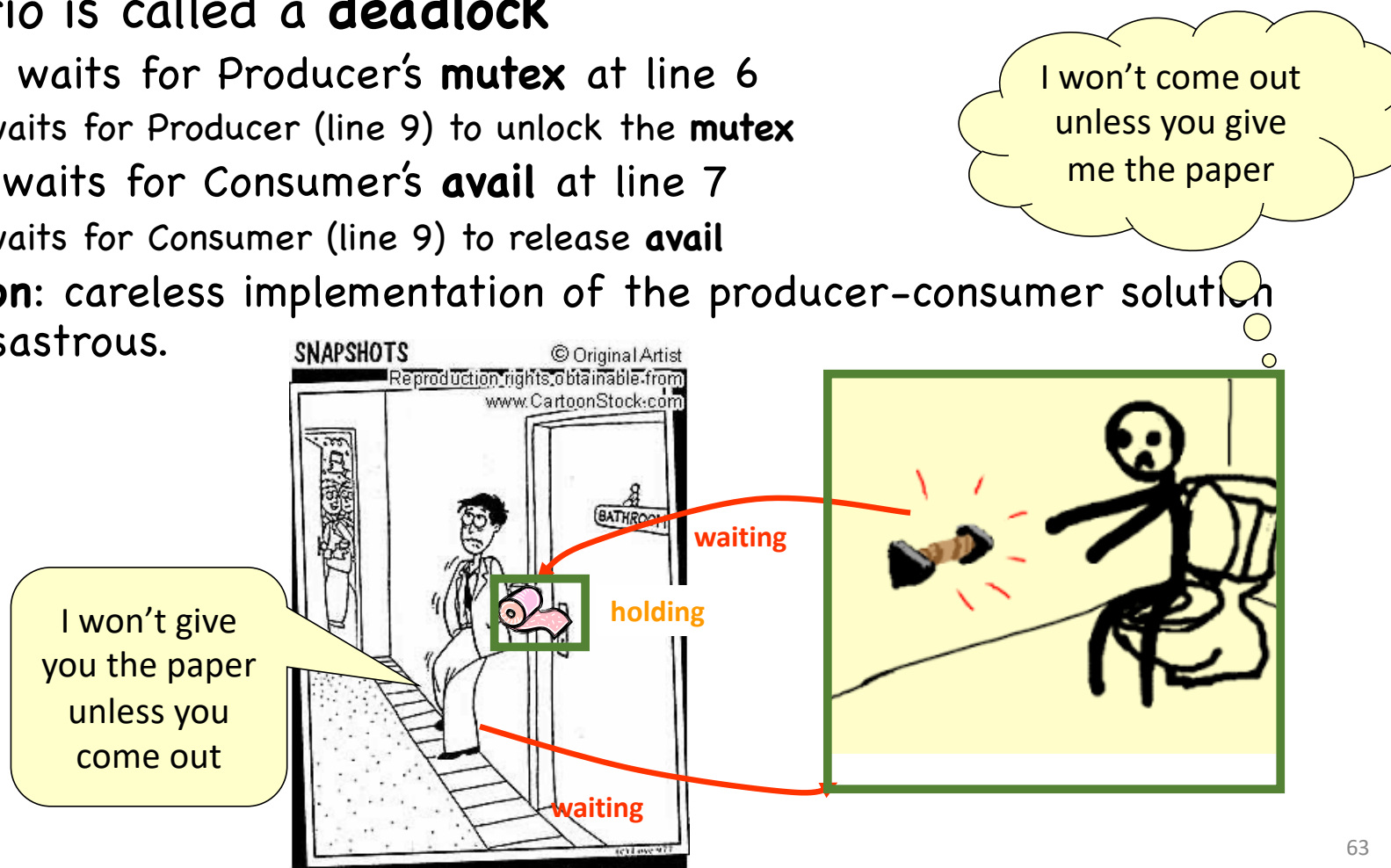
Consumer Function	
1	void consumer(void) {
2	int item;
3	
4	while(TRUE) {
5	wait(&fill);
6	wait(&mutex);
7	item = remove_item();
8	post(&mutex);
9	post(&avail);
10	//consume the item
11	}
12	}

Question 2



Question 2

- This scenario is called a **deadlock**
 - Consumer waits for Producer's **mutex** at line 6
 - i.e., it waits for Producer (line 9) to unlock the **mutex**
 - Producer waits for Consumer's **avail** at line 7
 - i.e., it waits for Consumer (line 9) to release **avail**
 - **Implication:** careless implementation of the producer-consumer solution can be disastrous.

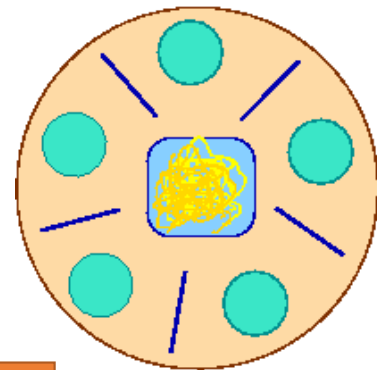


Summary on Producer-consumer Problem

- How to avoid race condition on the shared buffer?
 - E.g., Use a **binary semaphore**.
- How to achieve synchronization?
 - E.g., Use two **counting semaphores**: fill and avail

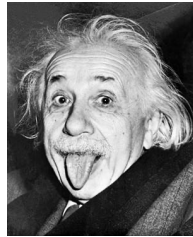
Dining Philosopher Problem

- 5 philosophers, 5 plates of spaghetti, and 5 chopsticks.
- The jobs of each philosopher are to think and to eat
- They **need exactly two chopsticks** in order to eat the spaghetti.
- Question: how to construct a synchronization protocol such that they
 - will not **starve to death**, and
 - will not result in any **deadlock scenarios**?
 - A waits for B's chopstick
 - B waits for C's chopstick
 - C waits for A's chopstick

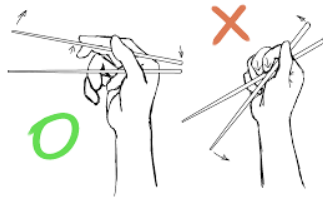


It's a multi-object synchronization problem

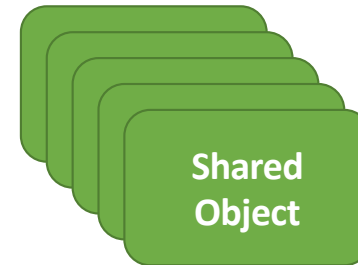
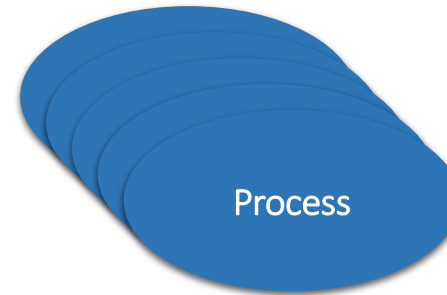
Dining Philosopher Problem



Philosophers



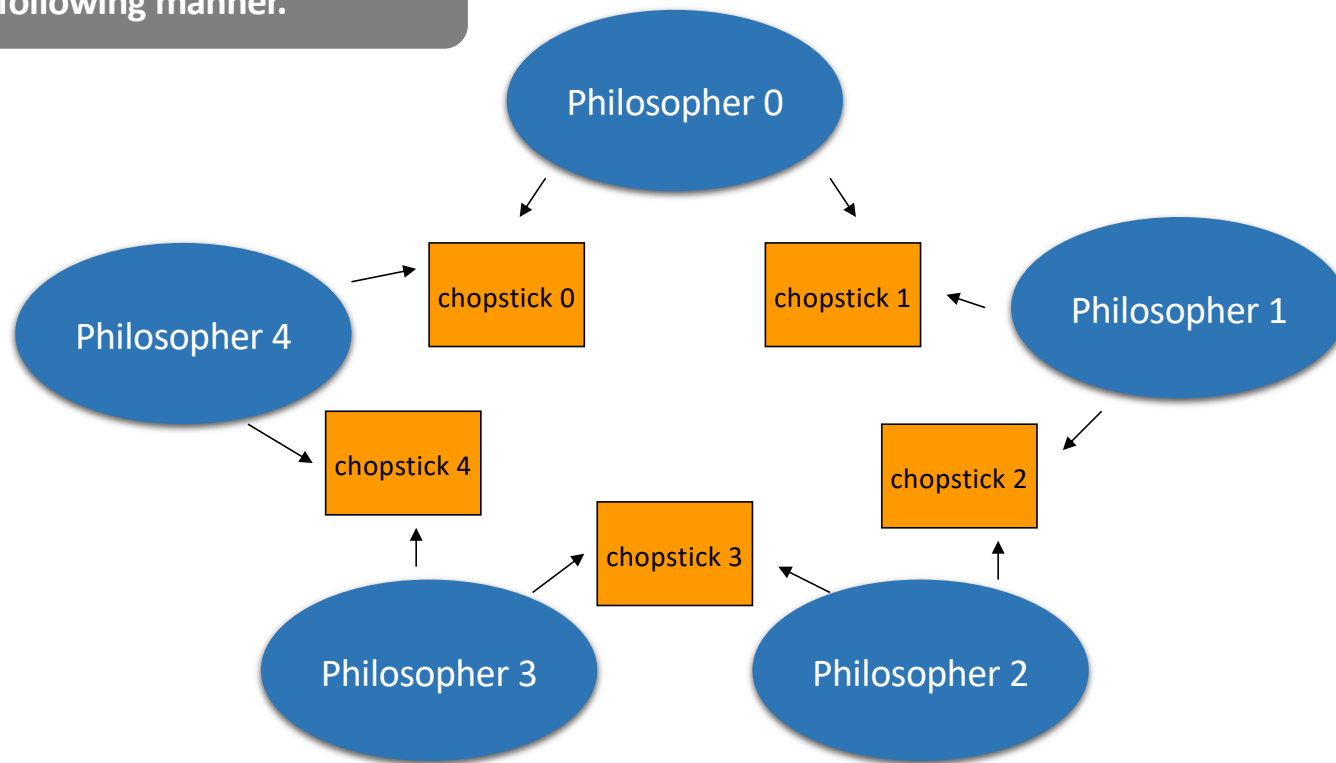
Chopsticks



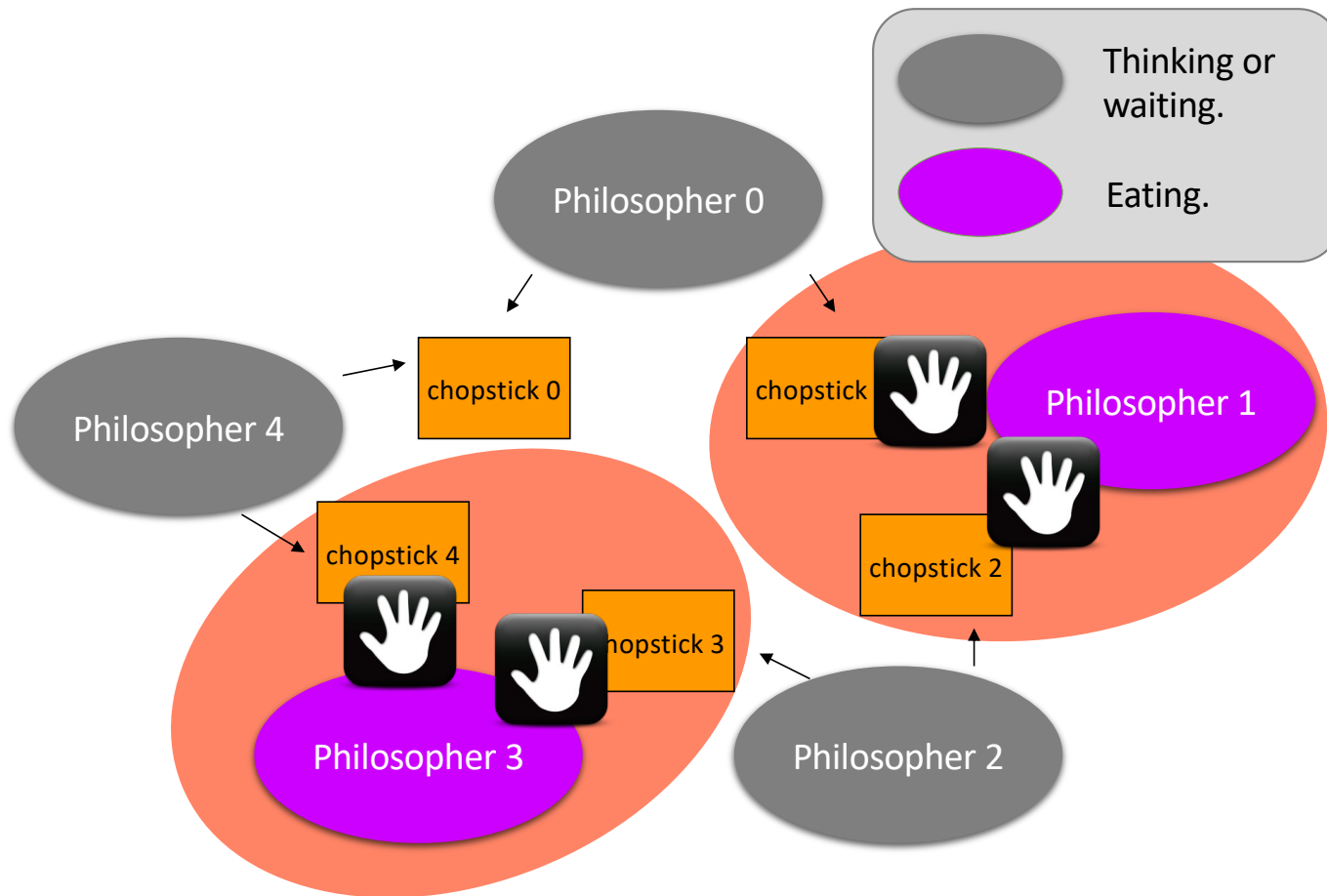
A process needs two shared resources in order to do some work

Dining Philosopher Problem

The chopsticks are arranged in the following manner.



Dining Philosopher Problem



Dining Philosopher – Requirement 1

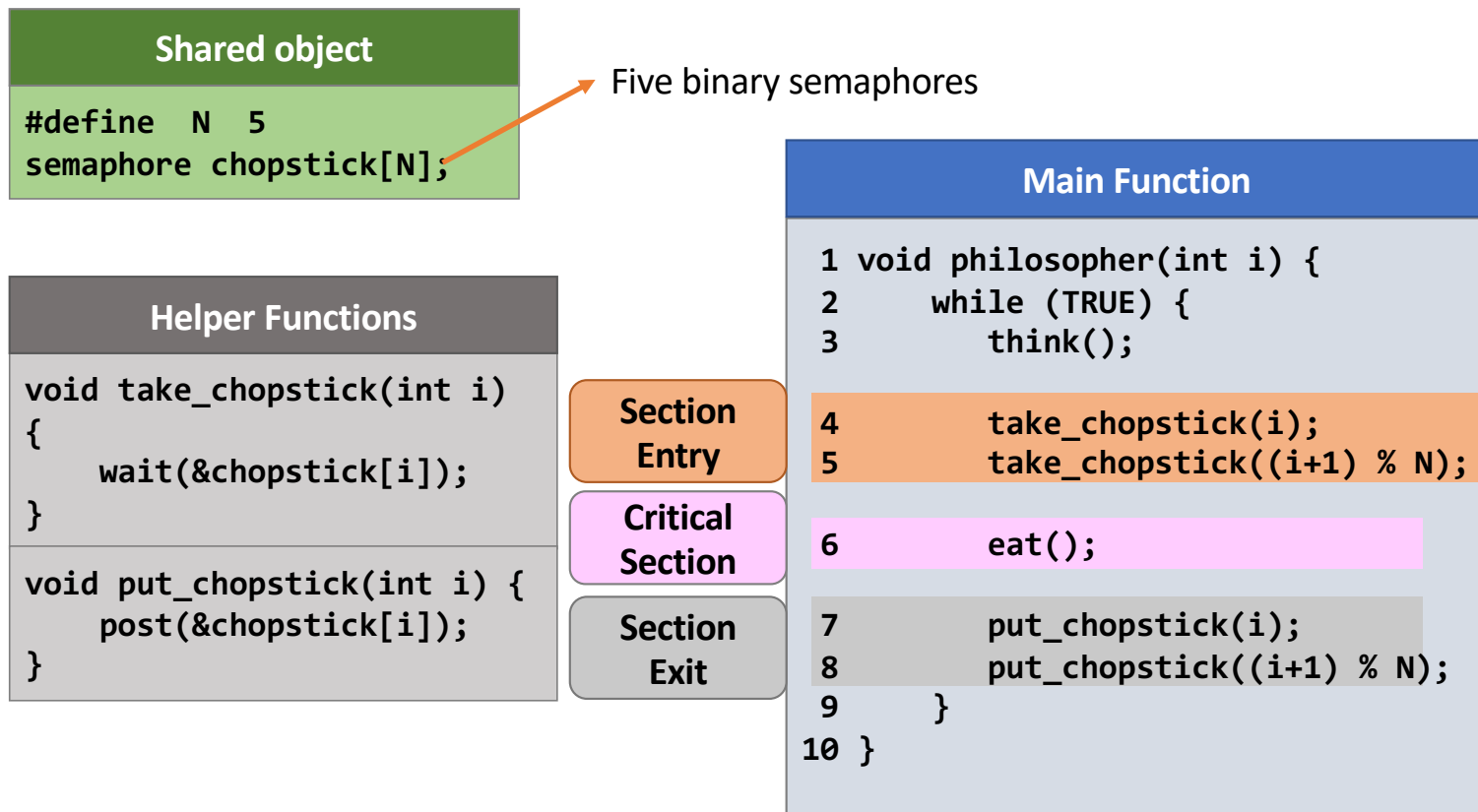
- Mutual exclusion

- While you are eating, people cannot steal your chopstick
- Two persons cannot hold the same chopstick

- Let's propose the following solution:

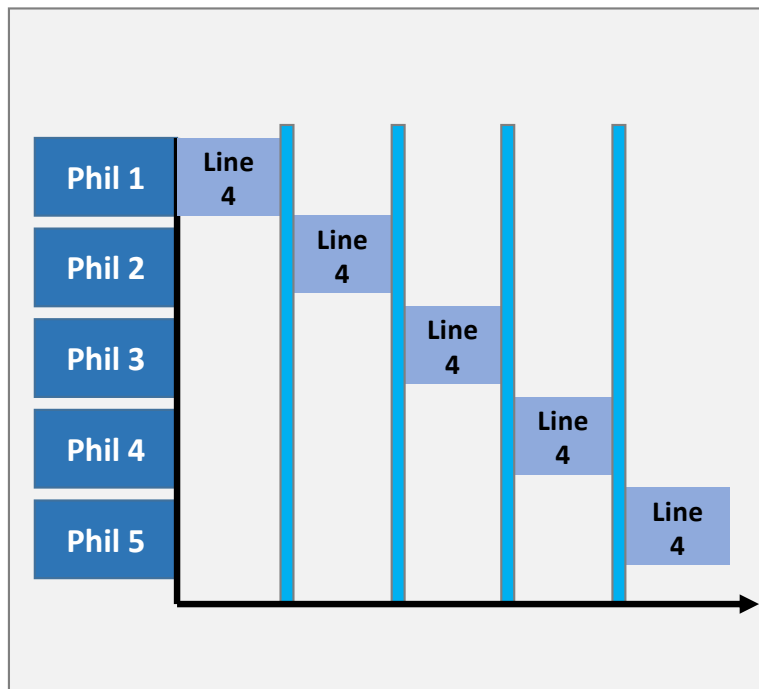
- When you are hungry, you have to check if anyone is using the chopsticks that you need.
- If yes, you wait.
- If no, **seize both chopsticks.**
- After eating, put down both your chopsticks.

Dining Philosopher – Requirement 1



Dining Philosopher – Deadlock

- Each philosopher finishes thinking at the same time and each first grabs her left chopstick
- All chopsticks[i]=0
- When executing line 5, all are waiting



Main Function	
1	void philosopher(int i) {
2	while (TRUE) {
3	think();
4	take_chopstick(i);
5	take_chopstick((i+1) % N);
6	eat();
7	put_chopstick(i);
8	put_chopstick((i+1) % N);
9	}
10	}

Dining Philosopher – Requirement 2

- Synchronization

- Should avoid **deadlock**.

- How about the following suggestions:

- First, a philosopher takes a chopstick.
 - If a philosopher finds that she cannot take the second chopstick, then she should put it down.
 - Then, the philosopher goes to sleep for a while.
 - When wake up, she retries
 - Loop until both chopsticks are seized.

Dining Philosopher – Requirement 2

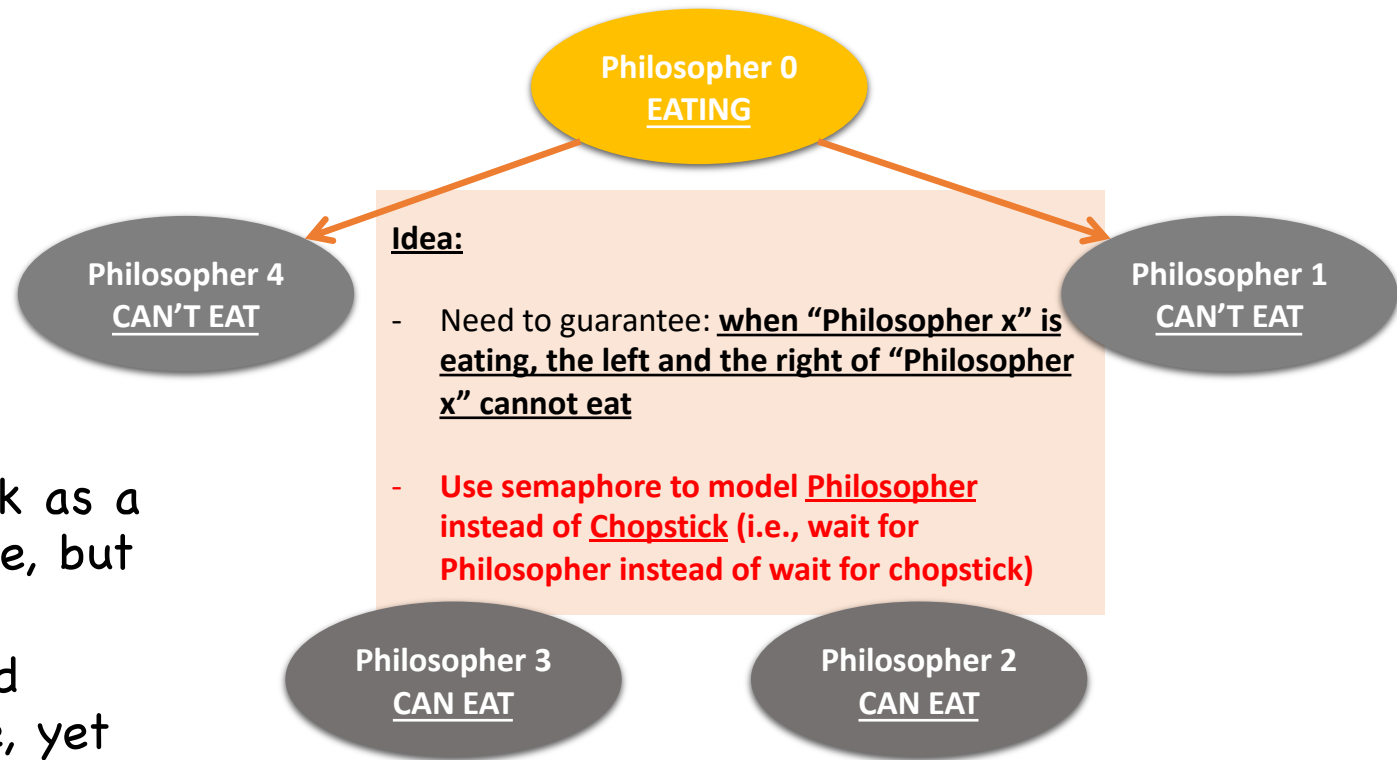
- **Potential Problem:**

- Philosophers are all busy (no deadlock), but no progress (starvation)

- **Imagine:**

- all pick up their left chopsticks,
- seeing their right chopsticks unavailable (because P1's right chopstick is taken by P2 as her left chopstick) and then putting down their left chopsticks,
- all sleep for a while
- all pick up their left chopsticks,

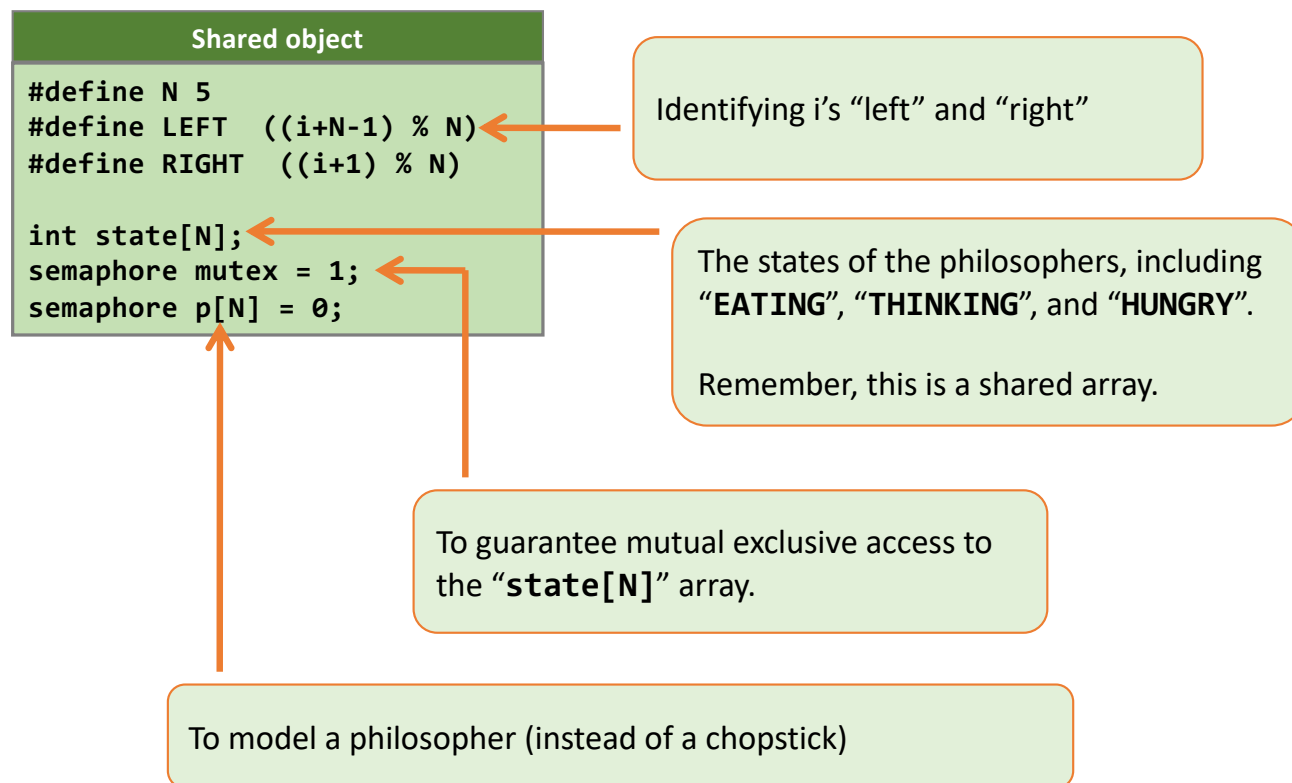
Dining Philosopher – before the Final Solution



• Two Problems

- Model each chopstick as a semaphore is intuitive, but may cause deadlock
- Using sleep() to avoid deadlock is effective, yet creating starvation.

Dining Philosopher – Final Solution



Dining Philosopher – Final Solution

<p>Shared object</p> <pre> #define N 5 #define LEFT ((i+N-1) % N) #define RIGHT ((i+1) % N) int state[N]; semaphore mutex = 1; semaphore p[N] = 0; </pre>	<p>Main function</p> <pre> 1 void philosopher(int i) { 2 think(); 3 take_chopsticks(i); 4 eat(); 5 put_chopsticks(i); 6 } </pre>	<pre> void wait(semaphore *s) { *s = *s - 1; if (*s < 0) { sleep(); } } </pre>
<p>Section entry</p> <pre> 1 void take_chopsticks(int i) { 2 wait(&mutex); 3 state[i] = HUNGRY; 4 captain(i); 5 post(&mutex); 6 wait(&p[i]); 7 } </pre>	<p>Section exit</p> <pre> 1 void put_chopsticks(int i) { 2 wait(&mutex); 3 state[i] = THINKING; 4 captain(LEFT); 5 captain(RIGHT); 6 post(&mutex); 7 } </pre>	<pre> void post(semaphore *s) { *s = *s + 1; if (*s <= 0) wakeup(); } </pre>
<p>Extremely important helper function</p> <pre> 1 void captain(int i) { 2 if(state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) { 3 state[i] = EATING; 4 post(&p[i]); 5 } 6 } </pre> <p>CS334 Operating Systems (H)</p>		

Dining Philosopher – Final Solution

hungry

Section entry

```
1 void take_chopsticks(int i) {
2     wait(&mutex);
3     state[i] = HUNGRY;
4     captain(i);
5     post(&mutex);
6     wait(&p[i]);
7 }
```

Tell the captain that you are hungry

If one of your neighbors is eating, the captain just does nothing for you and returns

Then, you wait for your chopsticks (later, the captain will notify you when chopsticks are available)

Critical Section

The captain is “indivisible”

Extremely important helper function

```
1 void captain(int i) {
2     if(state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
3         state[i] = EATING;
4         post(&p[i]);
5     }
6 }
```


Dining Philosopher – Final Solution

Finish eating

Tell the captain
Try to let your **left neighbor** to eat.

Tell the captain
Try to let your right **neighbor** to eat.

Section exit

```
1 void put_chopsticks(int i)
{
2     wait(&mutex);
3     state[i] = THINKING;
4     captain(LEFT);
5     captain(RIGHT);
6     post(&mutex);
7 }
```

Extremely important helper function

```
1 void captain(int i) {
2     if(state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
3         state[i] = EATING;
4         post(&p[i]);
5     }
6 }
```

Wake up the one who is sleeping

Dining Philosopher – Final Solution

Don't print

An illustration: How can
Philosopher 1 start eating?

Philosopher 0
THINKING

Philosopher 4
THINKING

Philosopher 1
THINKING

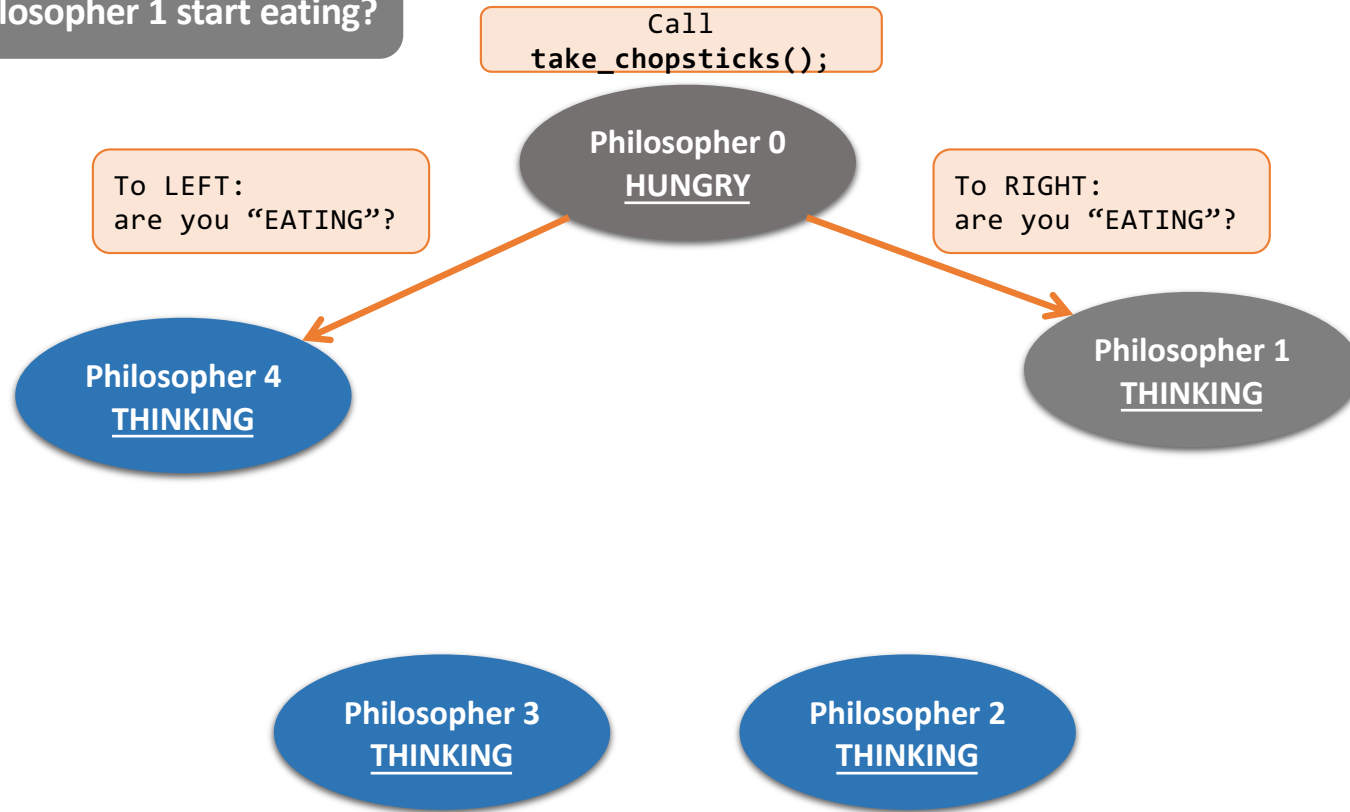
Philosopher 3
THINKING

Philosopher 2
THINKING

Dining Philosopher – Final Solution

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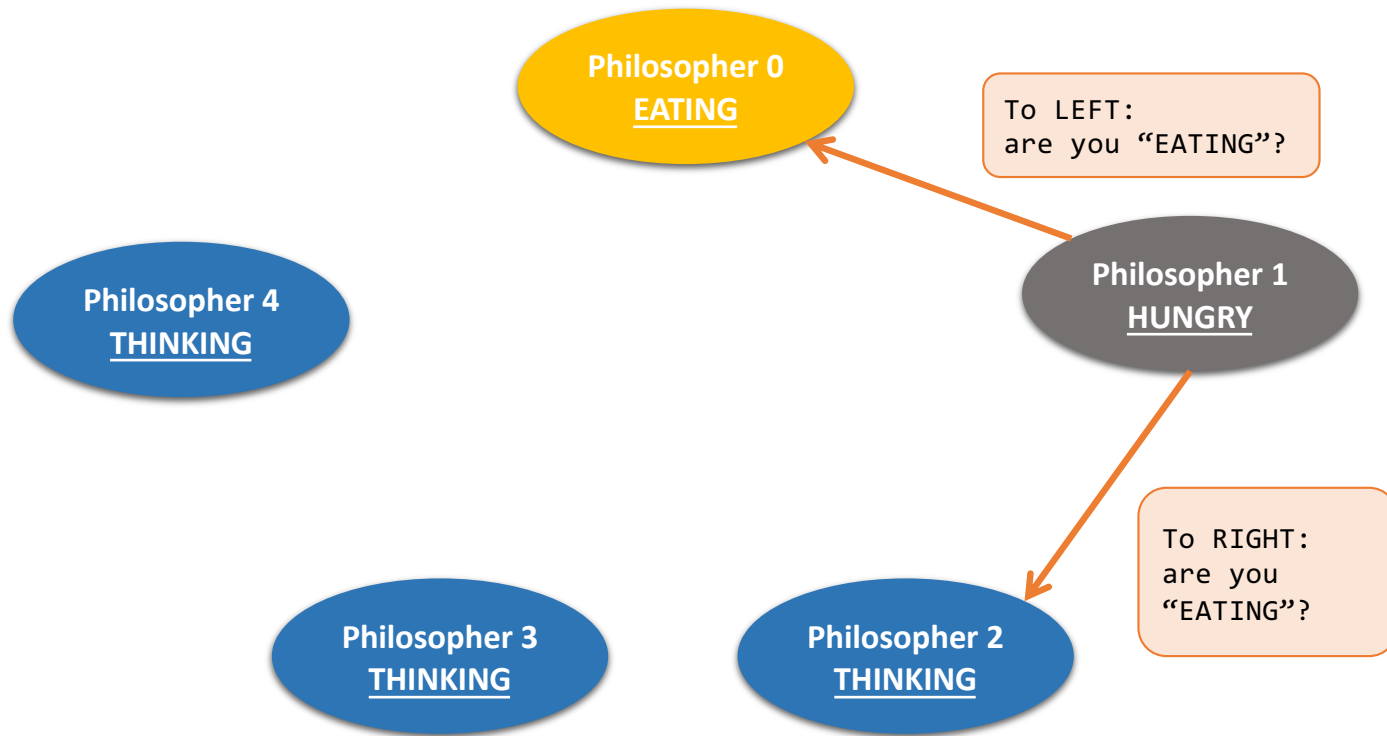
An illustration: How can
Philosopher 1 start eating?



Dining Philosopher – Final Solution

Don't print

An illustration: How can
Philosopher 1 start eating?



Dining Philosopher – Final Solution

Don't print

An illustration: How can Philosopher 1 start eating?

Philosopher 0
EATING

```
Section entry
1 void take_chopsticks(int i) {
2     wait(&mutex);
3     state[i] = HUNGRY;
4     captain(i);
5     post(&mutex);
6     wait(&p[i]);
7 }
```

//as P0 is eating, captain(i) returns
w/o doing anything;
wait(&p[1]);

Philosopher 1
HUNGRY

Philosopher 4
THINKING

To LEFT:
are you
"EATING"?

Philosopher 3
HUNGRY

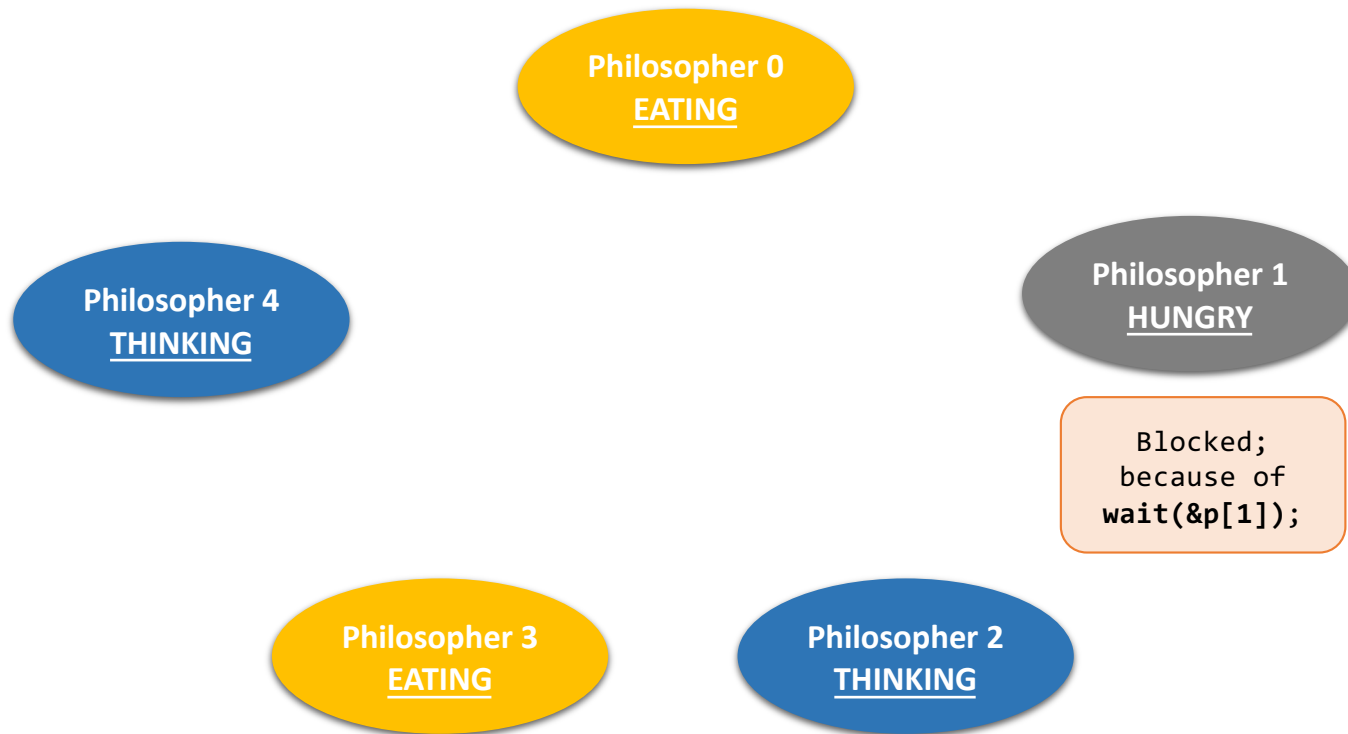
To RIGHT:
are you
"EATING"?

Philosopher 2
THINKING

Dining Philosopher – Final Solution

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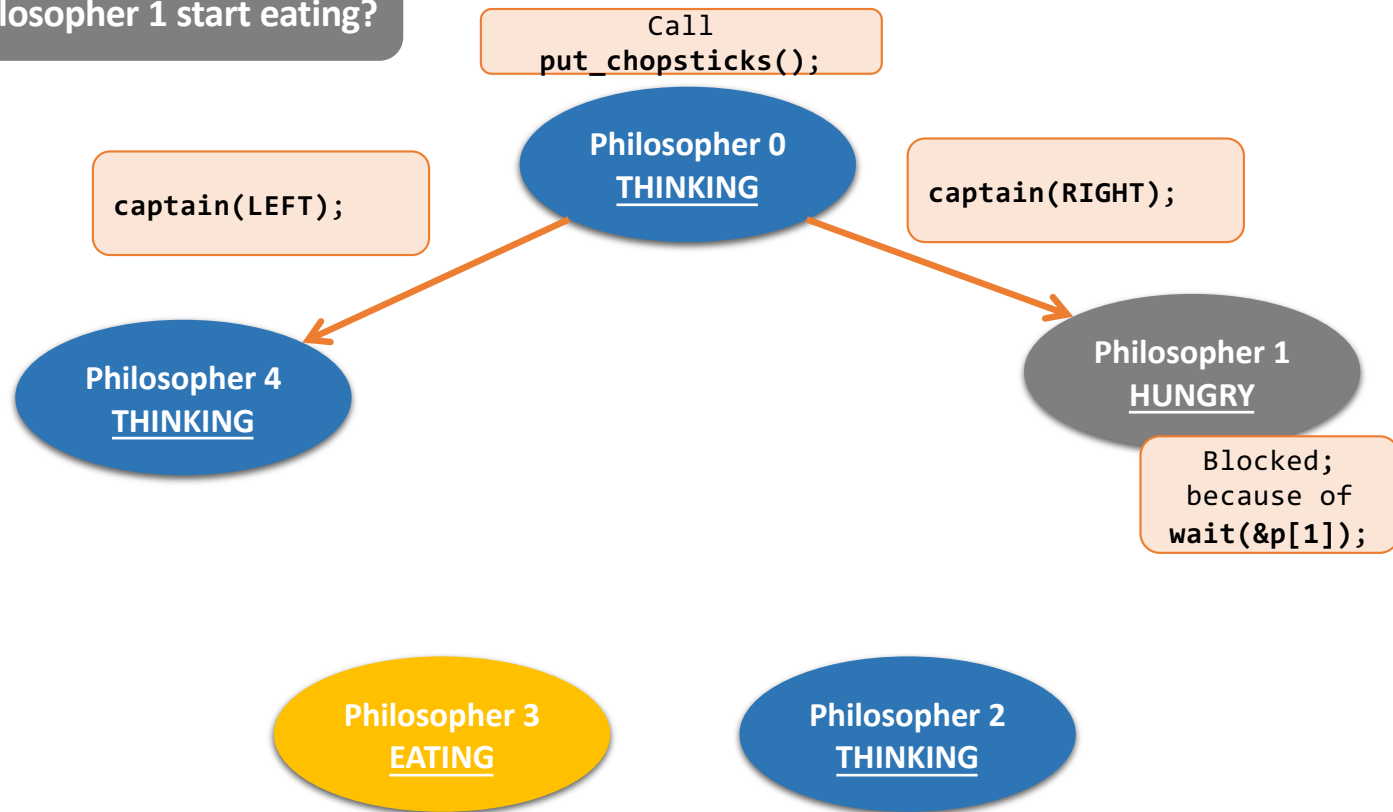
An illustration: How can
Philosopher 1 start eating?



Dining Philosopher – Final Solution

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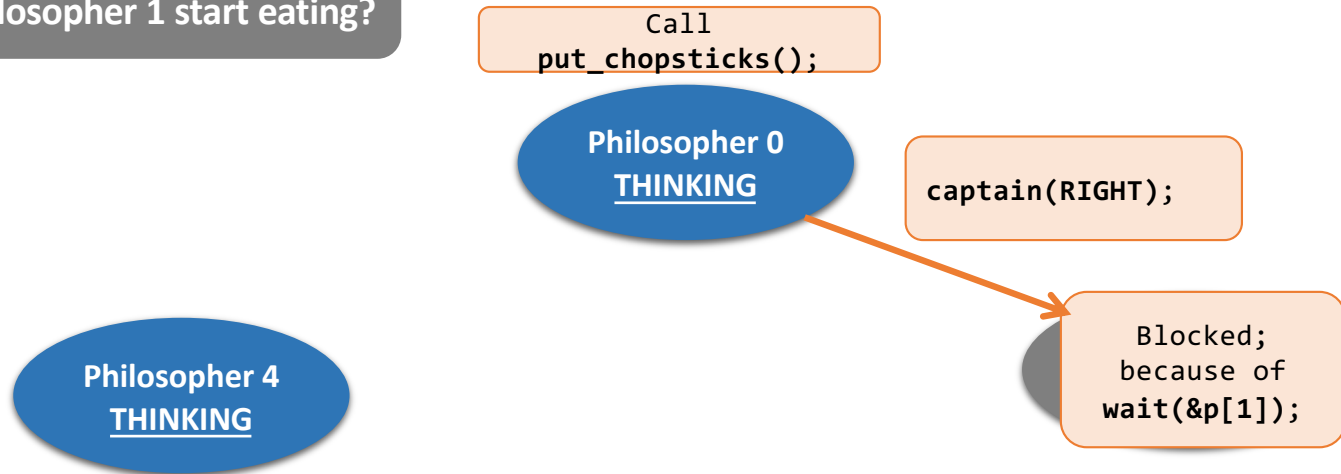
An illustration: How can
Philosopher 1 start eating?



Dining Philosopher – Final Solution

Don't print

An illustration: How can
Philosopher 1 start eating?



```
1 void captain(int i) {  
2     if(state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {  
3         state[i] = EATING;  
4         post(&p[i]); ← Wake up !  
5     }  
6 }
```


Dining Philosopher – Final Solution

Don't print

An illustration: How can
Philosopher 1 start eating?

Philosopher 0
THINKING

Philosopher 4
THINKING

Philosopher 3
EATING

Philosopher 2
THINKING

Wake up

Philosopher 1
EATING

Section entry

```
1 void take_chopsticks(int i) {  
2     wait(&mutex);  
3     state[i] = HUNGRY;  
4     captain(i);  
5     post(&mutex);  
6     wait(&p[i]);  
7 }
```