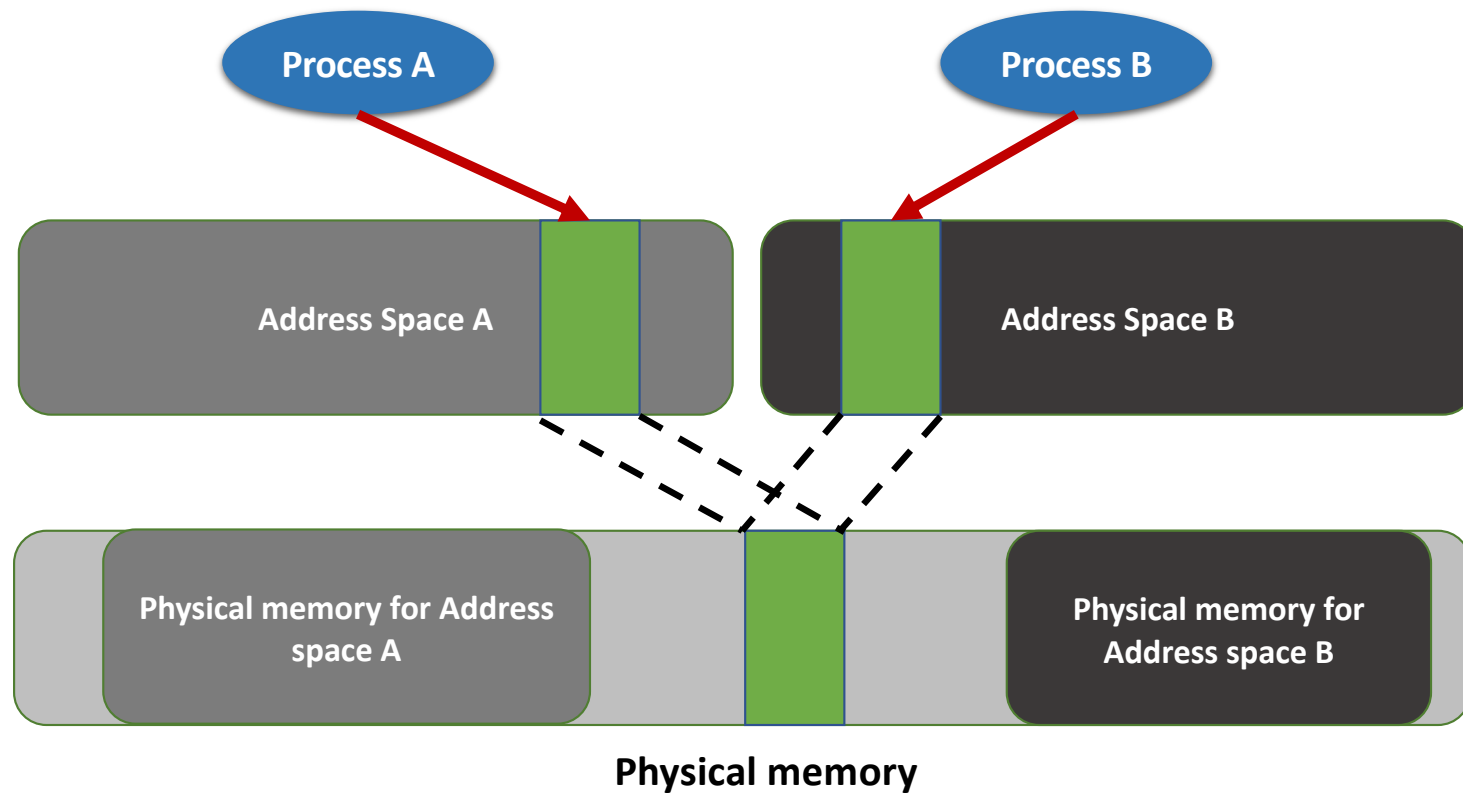# Lecture 5
Synchronization

Prof. Yinqian Zhang

Spring 2024
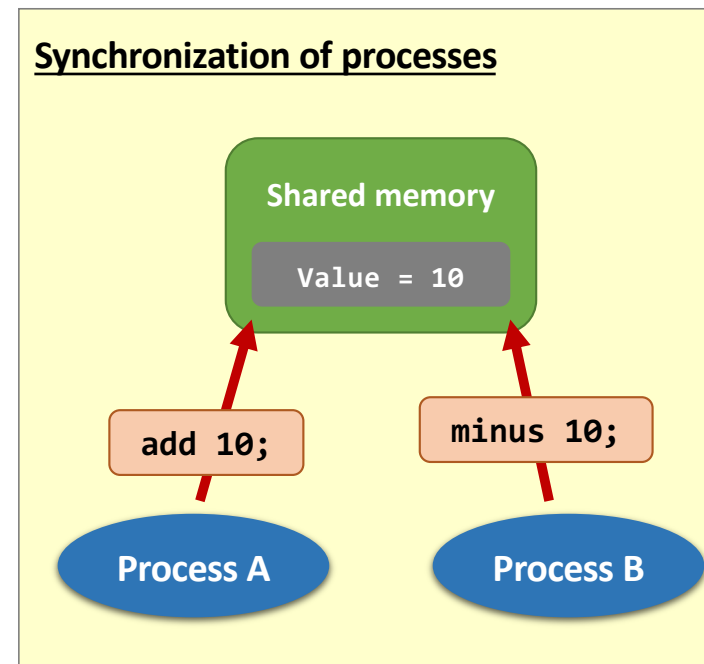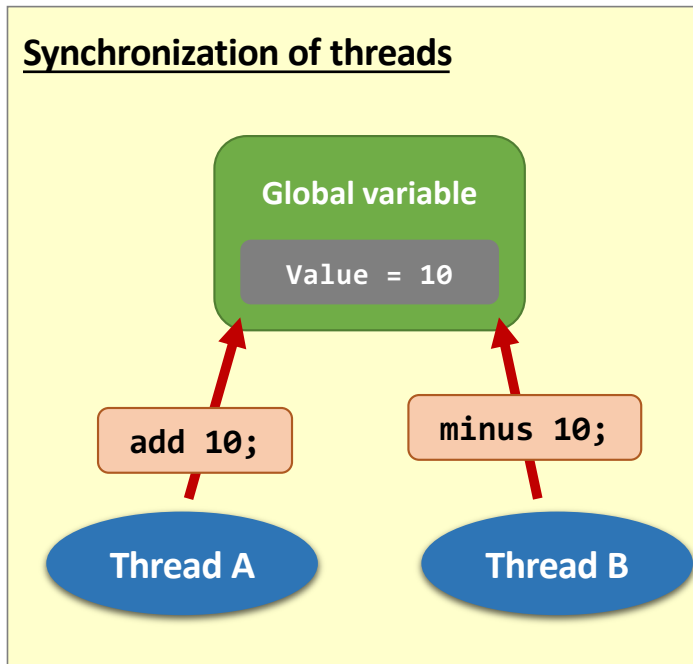
Process Communication

- 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

Process A

Process B

Address Space A

Address Space B

Physical memory for Address space A

Physical memory for Address space B

Physical memory

Synchronization of Threads/Processes

Process and thread synchronization can be considered in similar way

Synchronization of threads

Global variable

Value = 10

add 10;

minus 10;

Thread A

Thread B

Synchronization of processes

Shared memory

Value = 10

add 10;

minus 10;

Process A

Process B

Synchronization of Threads/Processes
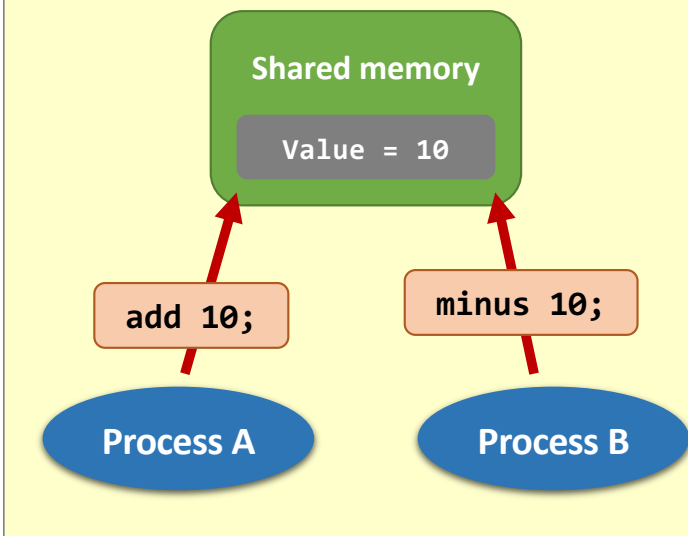
High-level language for Program A

```
1   attach to the shared memory X;
2   add 10 to X;
3   exit;
```
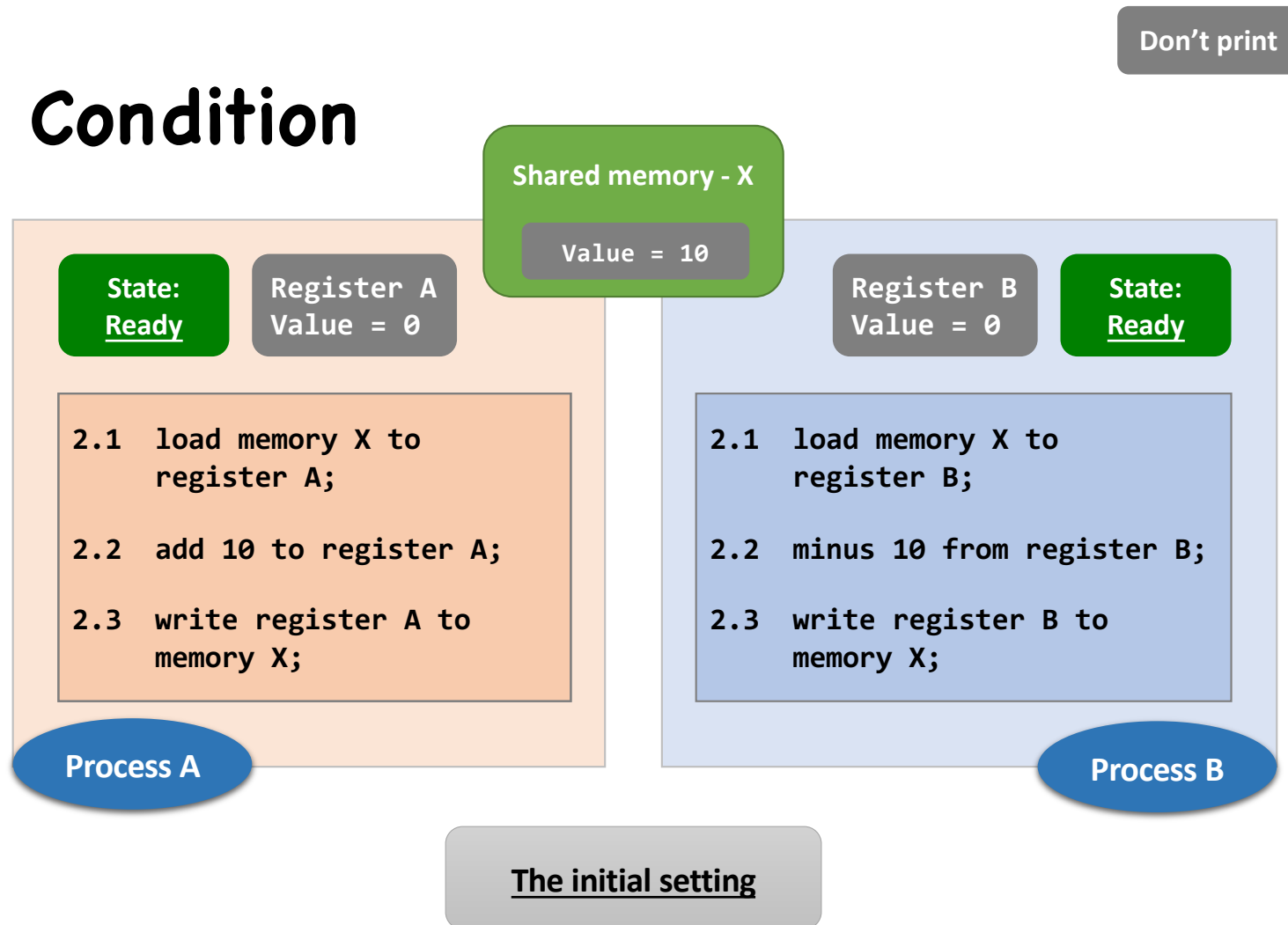
Partial low-level language for Program A

```
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

Shared memory

Value = 10

add 10;

minus 10;

Process A

Process B

Race Condition

Shared memory - X

Value = 10

State: Ready **Register A Value = 0**

Register B Value = 0 **State: Ready**

Process A

2.1 load memory X to register A;

2.2 add 10 to register A;

2.3 write register A to memory X;

Process B

2.1 load memory X to register B;

2.2 minus 10 from register B;

2.3 write register B to memory X;

The initial setting

Normal Execution

Shared memory - X

Value = 10

Process A

State: **Running**

Register A
Value = 10

1

2.1	load memory X to register A;
2.2	add 10 to register A;
2.3	write register A to memory X;

Process B

Register B
Value = 0

State: **Ready**

2.1	load memory X to register B;
2.2	minus 10 from register B;
2.3	write register B to memory X;

Execution Flow #1, Step 1

Normal Execution

Shared memory - X

Value = 10

Process A

State: **Running**

Register A Value = 20

1 2.1 load memory X to register A;

2 2.2 add 10 to register A;

2.3 write register A to memory X;

Process B

Register B Value = 0

State: **Ready**

2.1 load memory X to register B;

2.2 minus 10 from register B;

2.3 write register B to memory X;

Execution Flow #1, Step 2

Normal Execution

Shared memory - X

Value = 20

Process A

State: **Running**

Register A
Value = 20

1 **2.1 load memory X to register A;**

2 **2.2 add 10 to register A;**

3 **2.3 write register A to memory X;**

Process B

Register B
Value = 0

State: **Ready**

2.1 load memory X to register B;

2.2 minus 10 from register B;

2.3 write register B to memory X;

Execution Flow #1, Step 3

9

Normal Execution

Shared memory - X

Value = 20

Process A

State: **Ready**

Register A Value = 20

1 2.1 load memory X to register A;

2 2.2 add 10 to register A;

3 2.3 write register A to memory X;

Process B

Register B Value = 10

State: **Running**

4 2.1 load memory X to register B;

5 2.2 minus 10 from register B;

2.3 write register B to memory X;

Execution Flow #1, Step 5

Normal Execution

Shared memory - X

Value = 10

Process A

State: **Ready**

Register A
Value = 20

1   2.1   load memory X to register A;

2   2.2   add 10 to register A;

3   2.3   write register A to memory X;

Process B

Register B
Value = 10

State: **Running**

4   2.1   load memory X to register B;

5   2.2   minus 10 from register B;

6   2.3   write register B to memory X;

Execution Flow #1, Step 6

Abnormal Execution

Shared memory - X

`Value = 10`

Process A

State: <u>Running</u>

Register A
Value = 10

1	2.1	load memory X to register A;
	2.2	add 10 to register A;
	2.3	write register A to memory X;

Process B

Register B
Value = 0

State: <u>Ready</u>

2.1	load memory X to register B;
2.2	minus 10 from register B;
2.3	write register B to memory X;

Execution Flow #2, Step 1

13

Abnormal Execution

Shared memory - X

Value = 10

Process A

State: **Ready**

Register A
Value = 10

2.1 load memory X to register A;

2.2 add 10 to register A;

2.3 write register A to memory X;

Process B

Register B
Value = 10

State: **Running**

2.1 load memory X to register B;

2.2 minus 10 from register B;

2.3 write register B to memory B;

Context Switching

Execution Flow #2, Step 2

Abnormal Execution

Shared memory - X

`Value = 10`

Process A

State: Ready	Register A Value = 10

1 2.1 load memory X to register A;

2.2 add 10 to register A;

2.3 write register A to memory X;

Process B

Register B Value = 0	State: Running

2.1 load memory X to register B; 2

2.2 minus 10 from register B; 3

2.3 write register B to memory B;

Execution Flow #2, Step 3

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Abnormal Execution

Shared memory - X

Value = 0

State: __Running__

Register A Value = 10

Register B Value = 0

State: __Ready__

①

2.1   load memory X to register A;

2.2   add 10 to register A;

2.3   write register A to memory X;

②

2.1   load memory X to register B;

③

2.2   minus 10 from register B;

④

2.3   write register B to memory B;

Process A

Context Switching

Process B

Execution Flow #2, Step 4

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Abnormal Execution

Shared memory - X

Value = 0

State: Running

Register A Value = 20

1 | 2.1 load memory X to register A;
5 | 2.2 add 10 to register A;
2.3 write register A to memory X;

Process A

Register B Value = 0

State: Ready

2.1 load memory X to register B; | **2**
2.2 minus 10 from register B; | **3**
2.3 write register B to memory B; | **4**

Process B

Execution Flow #2, Step 5

Abnormal Execution

Shared memory - X

Value = 20

State: Running

Register A Value = 20

Register B Value = 0

State: Ready

Process A

Process B

1. 2.1 load memory X to register A;
5. 2.2 add 10 to register A;
6. 2.3 write register A to memory X;

2. 2.1 load memory X to register B;
3. 2.2 minus 10 from register B;
4. 2.3 write register B to memory B;

BUG!! T**he result is 20, but not 10**!

"Add 10" and "minus 10" for "value" is not **atomic**!
The execution result totally depends on the execution sequences

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 memory

How to resolve race condition?

add 10;

minus 10;

Process A

Process B

Solution: **mutual exclusion**

When one process access the shared memory, no one else could access it.

A set of processes would not have the problem of race condition if **mutual exclusion is guaranteed**.

Shared memory

add 10;

minus 10;

Process A

Process B
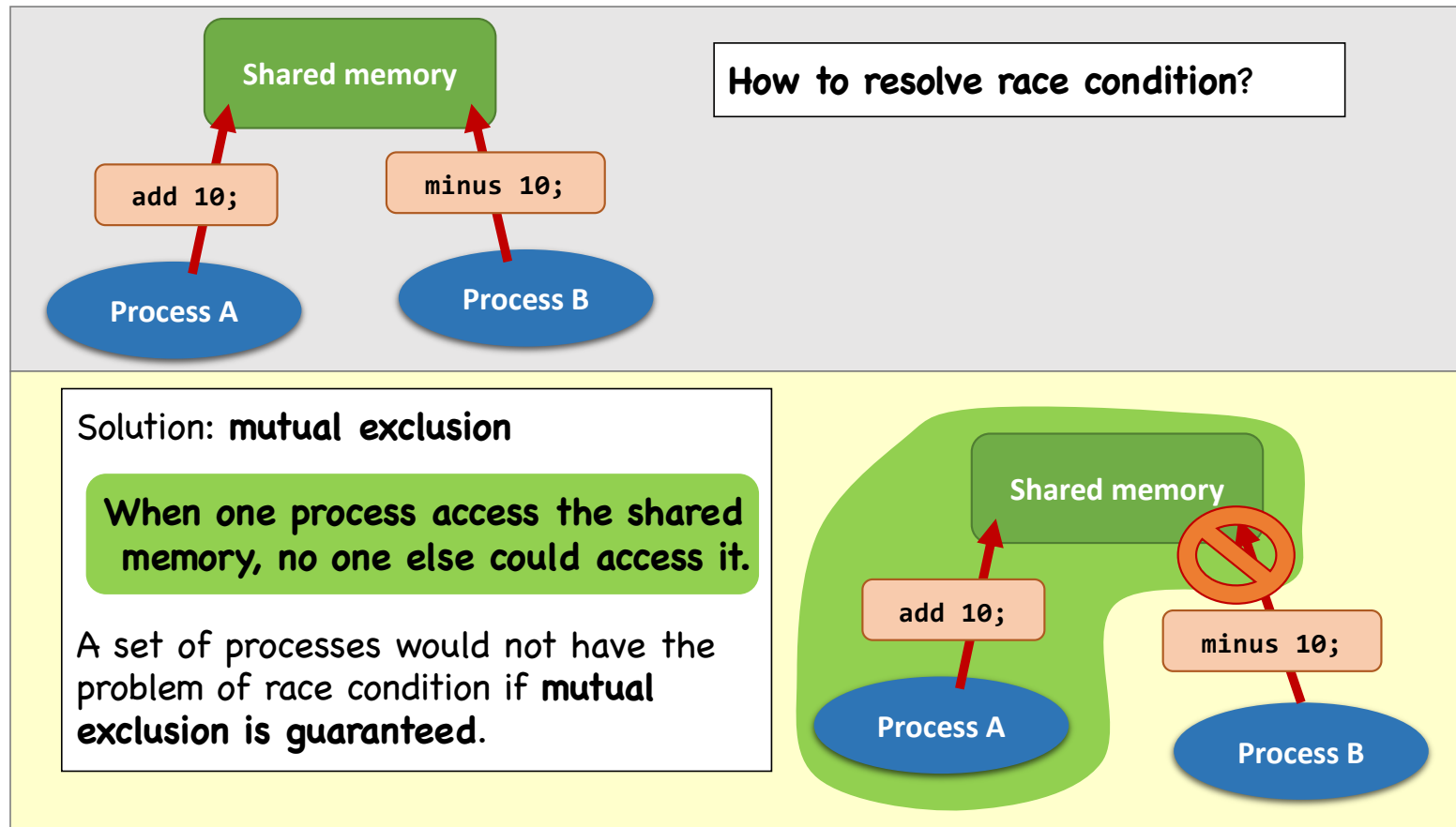
Solution: Mutual Exclusion

- 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

Program code

Section entry

critical section

......

Reading

Writing

Shared Object

......

Section exit

Declaring the start of the critical section.

As if telling other processes that:
"**I start accessing the shared object.**"

Critical section is the code segment that is accessing the shared object.

Declaring the end of the critical section.

As if telling other processes that:
"**I finish accessing the shared object.**"

Critical Section: Realizing Mutual Exclusion

Process A

Need a section entry here

2.1 load memory X to register A;

2.2 add 10 to register A;

2.3 write register A to memory X;

Need a section exit here

Process B

Need a section entry here

2.1 load memory X to register B;

2.2 minus 10 from register B;

2.3 write register B to memory X;

Need a section exit here

When process A is entering **its critical section**, process B cannot enter **its critical section.**

A Typical Mutual Exclusion Scenario

Keys

- Critical section entry
- Inside Critical section
- Critical section exit

Process A

Process B

BLOCKED

B tries to enter its critical section but A is in its critical section.

A leaves its critical section and B resumes execution accordingly.
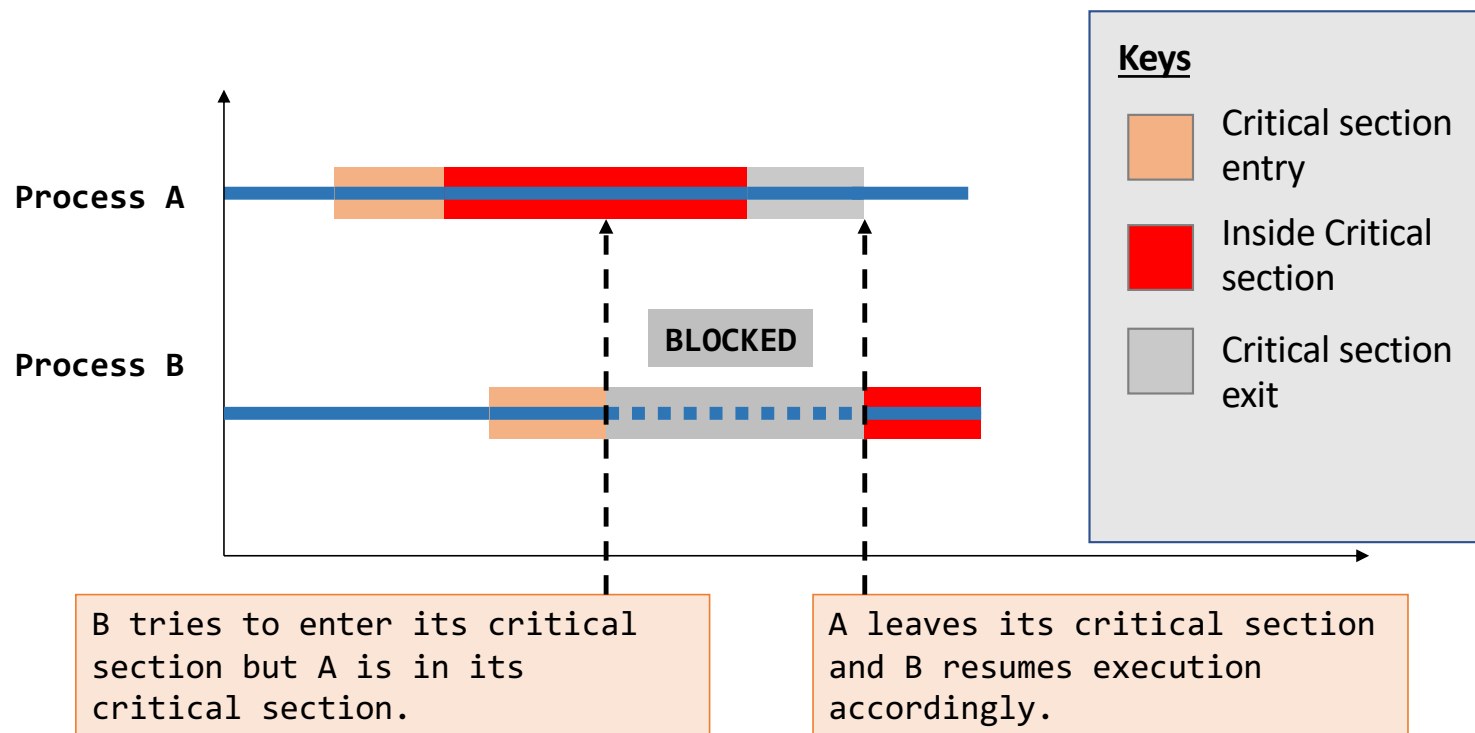
Summary

- 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!!!!)

Program Code

Interrupt disabled

Critical Section

Interrupt enabled

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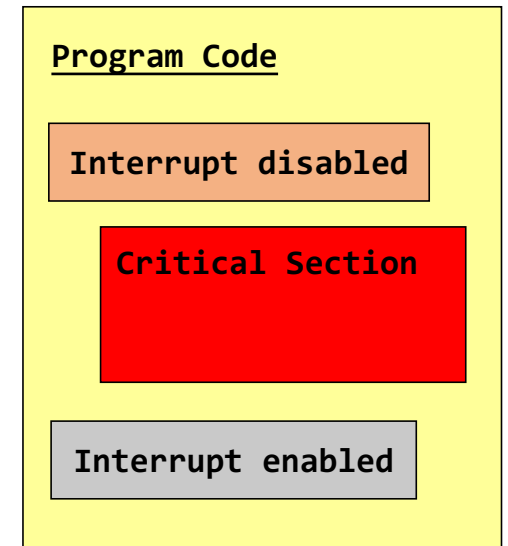
Solution: Locks

- 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

Shared object "turn"   `initial value = 0`

Process 0:
```
1   while (TRUE) {
2     while( turn != 0 )
3       ; /* busy waiting */
4     critical_section();
5     turn = 1;
6     remainder_section();
7   }
```

Process 0

Process 1:
```
1   while (TRUE) {
2     while( turn != 1 )
3       ; /* busy waiting */
4     critical_section();
5     turn = 0;
6     remainder_section();
7   }
```

Process1

Spin-based Locks (Cont'd)

turn = 0   turn = 0

Process 0

Process 1

turn = 1

The order of executing the critical section is **alternating**.

Shared object "turn"   `initial Value = 0`

```
1   while (TRUE) {
2       while( turn != 0 )
3          ; /* busy waiting */

4       critical_section();

5       turn = 1;

6       remainder_section();
7   }
```

Process 0

```
1   while (TRUE) {
2       while( turn != 1 )
3          ; /* busy waiting */

4       critical_section();

5       turn = 0;

6       remainder_section();
7   }
```

Process1

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Spin-based Locks (Cont'd)

The order of executing the critical section is **alternating**.

- 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 <u>turn=1</u>
  - Process0 finishes its **remainder_section()**, go back to top of the loop
    - It can't enter its cs() (as <u>turn=1</u>)
    - That is, process0 gets blocked, but <u>Process1 is outside its cs()</u>, it is at its **remainder_section_slow()**

```
1  while (TRUE) {
2    while( turn != 0 )
3      ; /* busy waiting */

4    cs();

5    turn = 1;

6    remainder_section();
7  }
```

Process 0

```
1  while (TRUE) {
2    while( turn != 1 )
3      ; /* busy waiting */

4    cs();

5    turn = 0;

6    remainder_section_slow ();
7  }
```
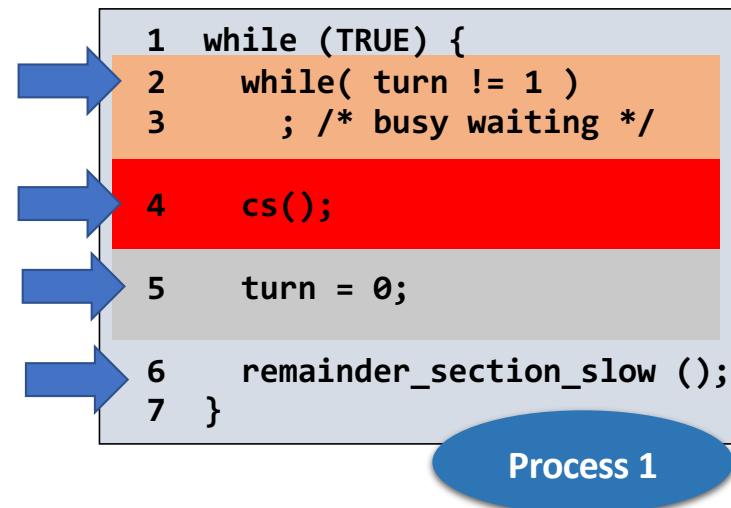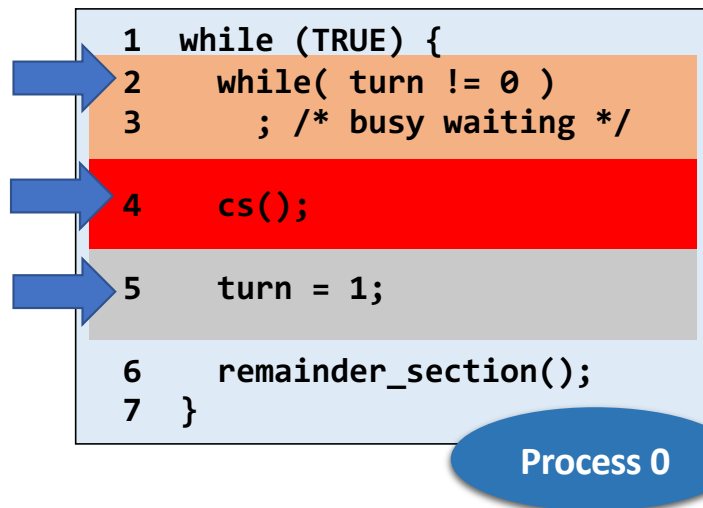
Process 1

Turn = 1

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 <u>turn=1</u>
  - Process0 finishes its **remainder_section()**, go back to top of the loop
    - It can't enter its cs() (as <u>turn=1</u>)
    - That is, process0 gets blocked, but <u>Process1 is outside its cs()</u>, it is at its **remainder_section-slow()**

Has to wait...

```
1   while (TRUE) {
2      while( turn != 0 )
3         ; /* busy waiting */

4      cs();

5      turn = 1;

6      remainder_section();
7   }
```

Process 0

```
1   while (TRUE) {
2      while( turn != 1 )
3         ; /* busy waiting */

4      cs();

5      turn = 0;

6      remainder_section_slow ();
7   }
```

Process 1

Turn = 1

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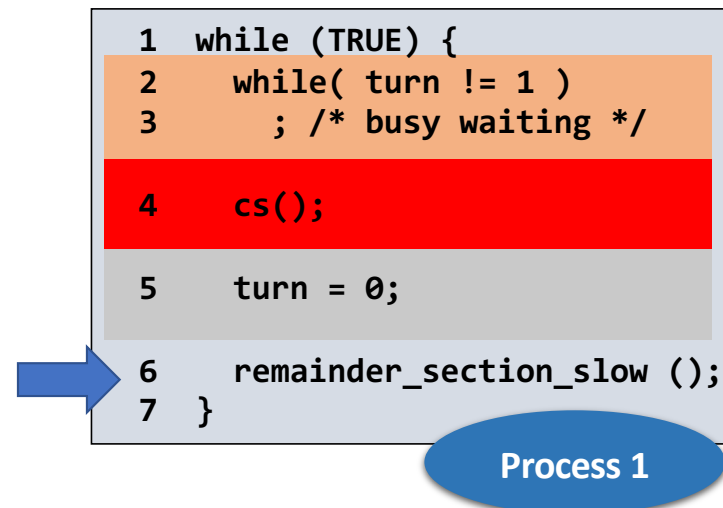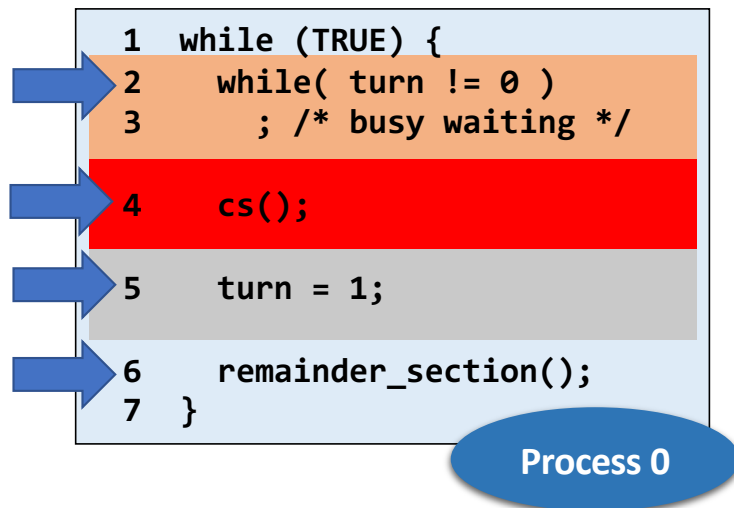
Peterson's Solution: Improved Spin-based Locks

```
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  }
```

Process 0	Process 1

lock() {
Interested[0] = true
turn = 1;
 //interested[1]=false;
 //no while and return; }	

Critical Section	
Context Switching	

	lock() {
	 interested[1]=true;
	 turn = 0;
	 while (turn = 0 &
	 interested[0]=true)
	     busy waiting!

Context Switching	
Critical Section cont'	

unlock() {
 Interested[0]=false;
}	

Context Switching	
	exit while loop
	Critical Section

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  }
```

Process 0	Process 1

lock() {
 interested[0]=TRUE;
 turn = 1;	

Context Switching	

	lock() {
	 interested[1]=TRUE;
	 turn = 0;

Context Switching	

turn == 1 ? //line 9
 false
 no busy waiting	

Critical Section	
Context Switching	

	turn == 0? //line 9
	 && interested[0]=true?
	 busy waiting!

...
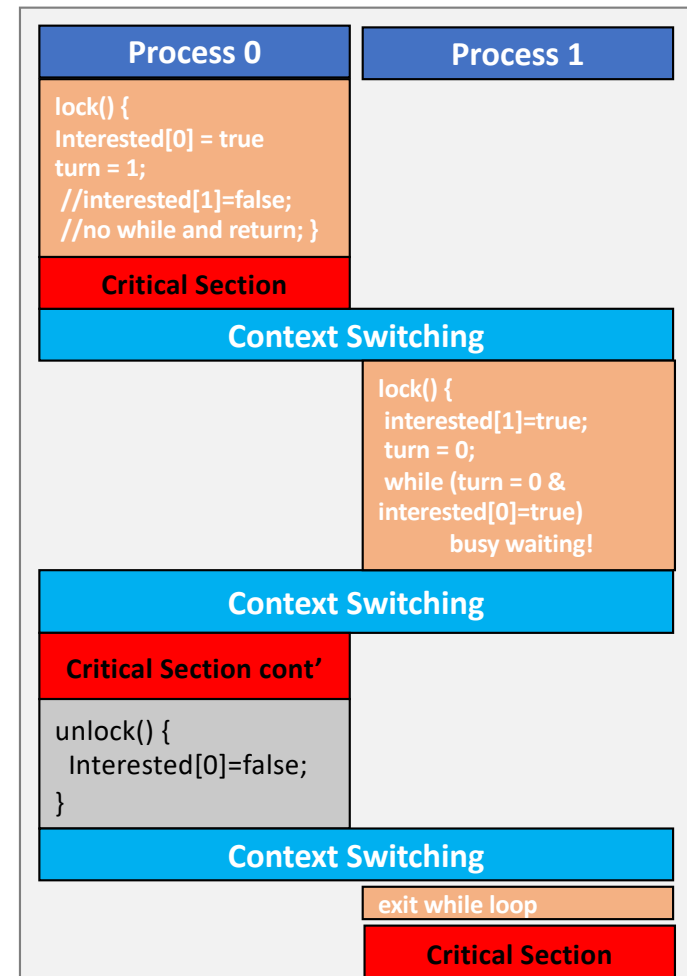
Peterson's Solution Summary

- 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 = 0, 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

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, ... n-1, 0, 1, ..., 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

High priority process created with preemption

Not scheduled for a long time.

Low-priority process

Because it has a higher priority, it takes the CPU for busy waiting (do nothing)

High-priority process
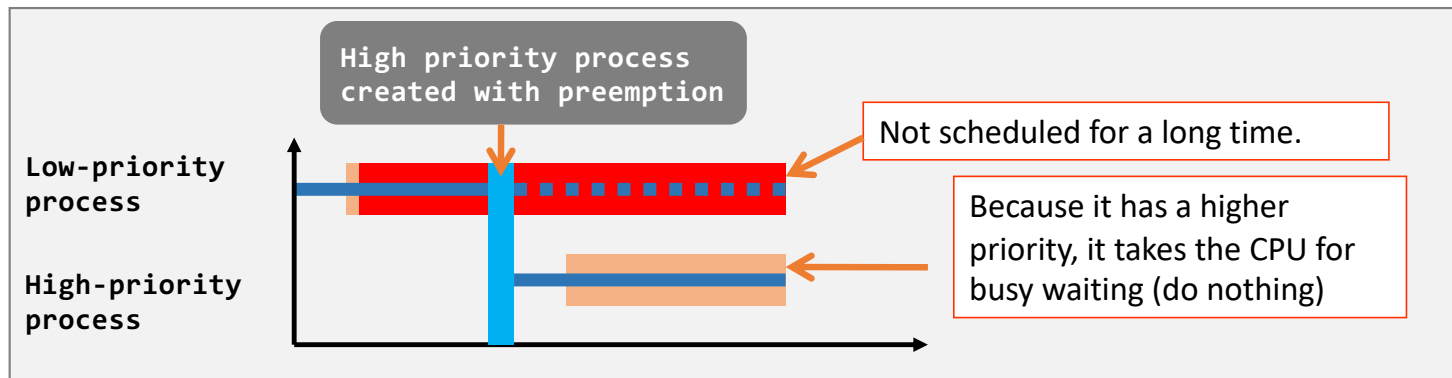
Sleep-based Lock: Semaphore

- 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  }
```

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Semaphore Example

Process **1234**

Assuming someone else (process **1357**) has already taken the only one resource:
X = 1 (initial) => **X** = 0
Now, process **1234** arrives

Sem_wait(X)

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  }
```

Semaphore **X**
Value = -1

1234

Waiting List

Semaphore Example

Process **1357**

Process **1234**

post(X)

wakeup

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 X
Value = 0

1234

Waiting List

Semaphore Example

Process 1234

Section Entry: sem_wait()

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

return
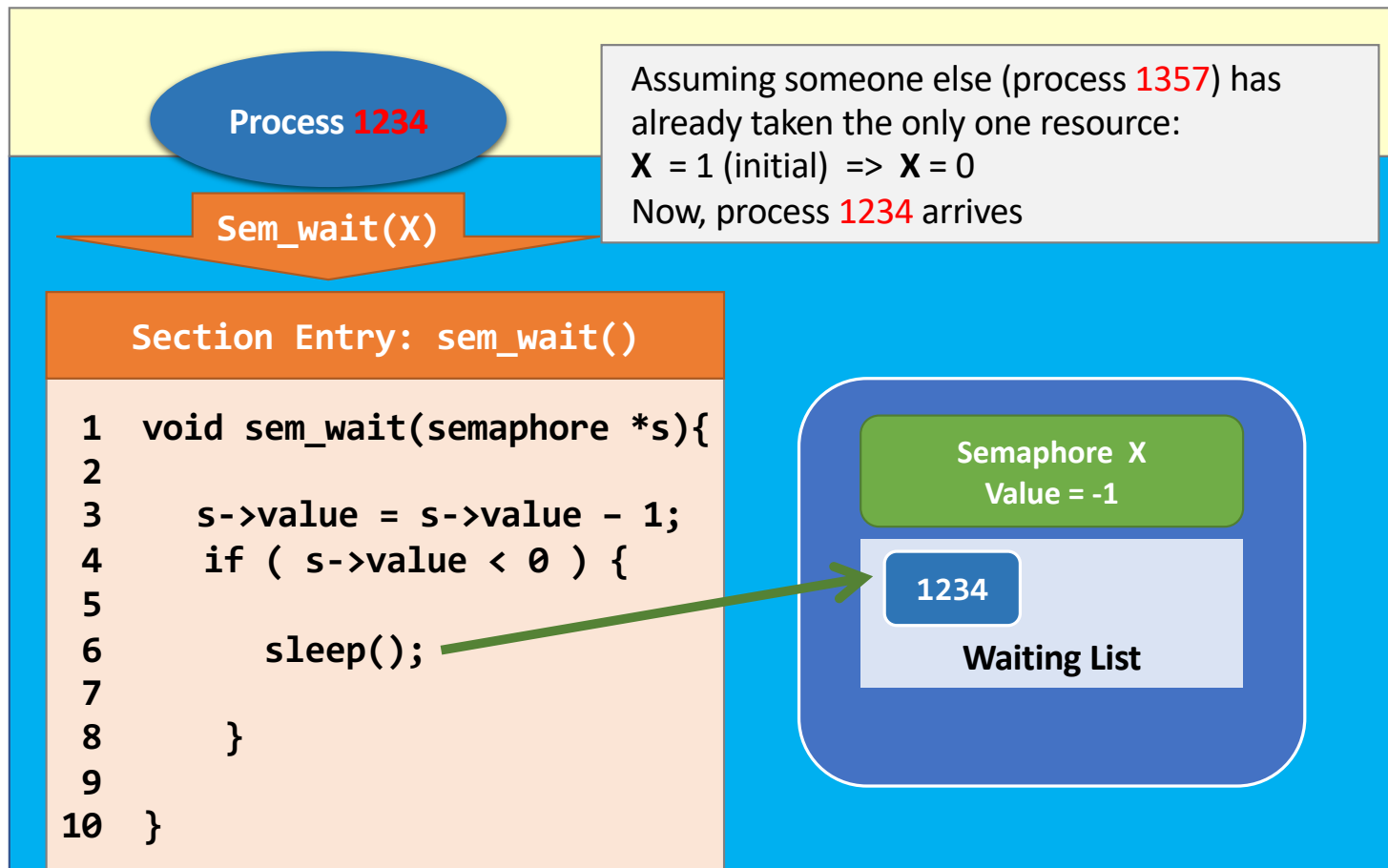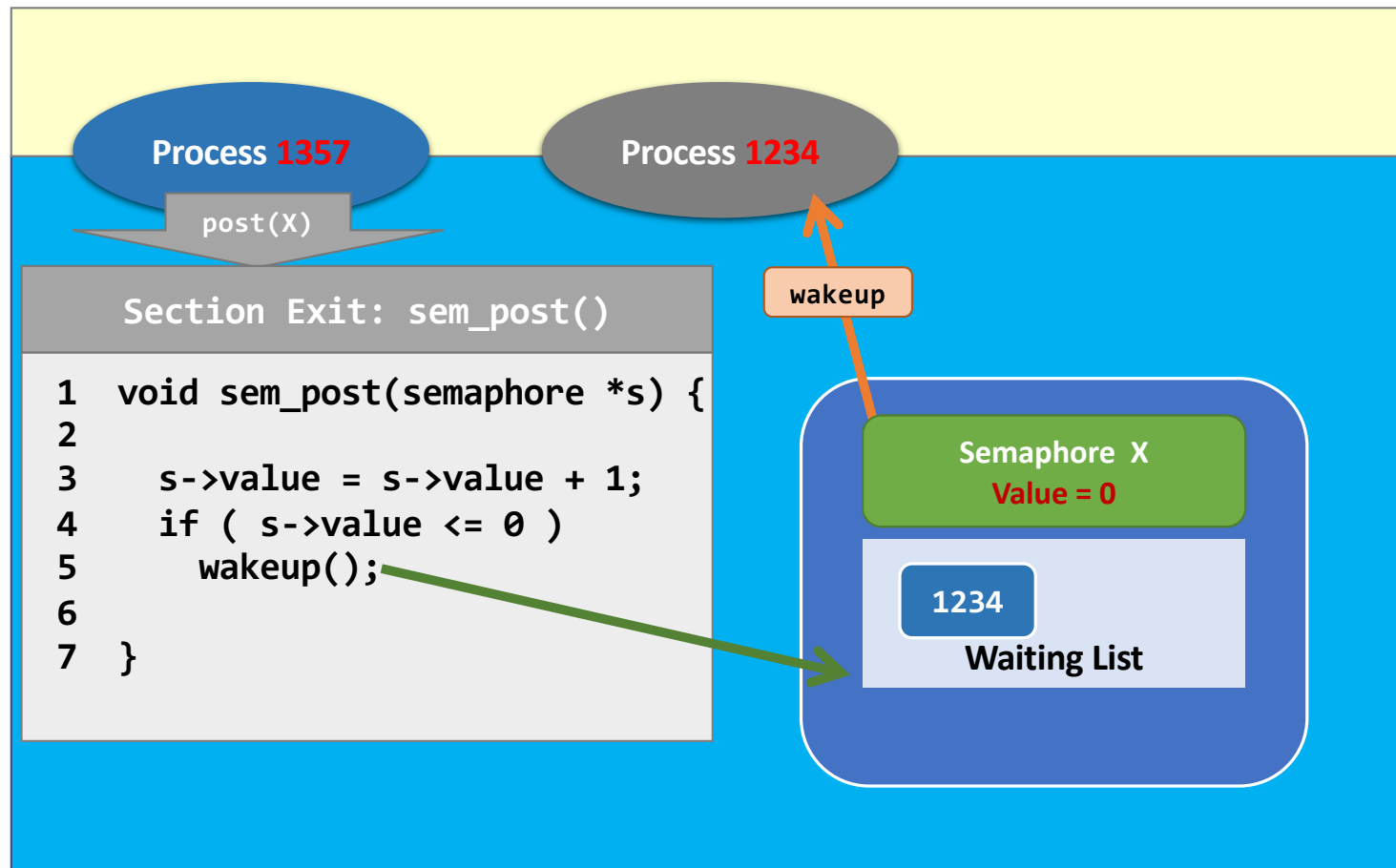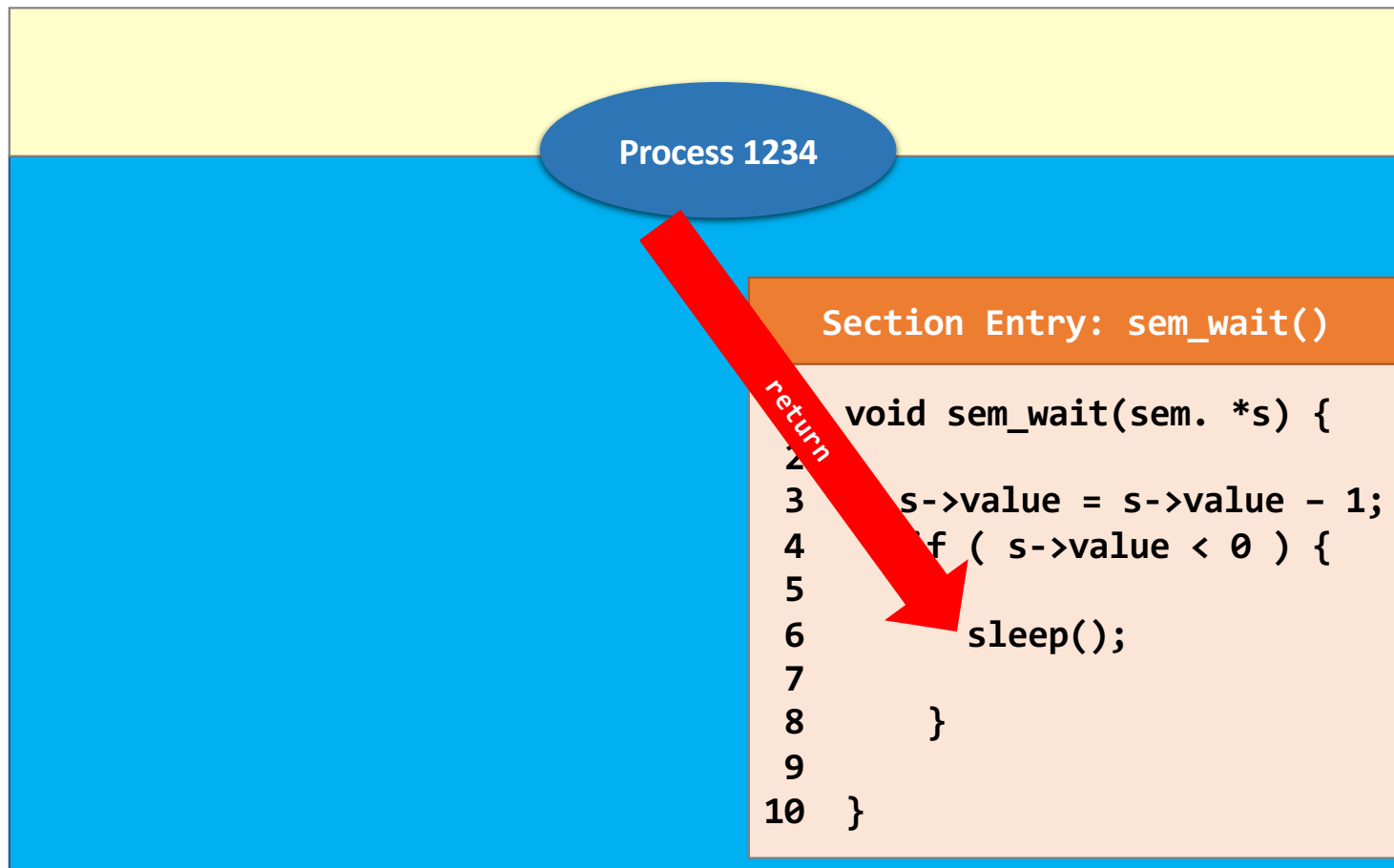
Using Semaphore in User Process


```
semaphore *s;  /* from kernel */
s->value = 1; /* initial value */
```

```
1   while(TRUE) {
2       sem_wait(s);      entry
3       critical_section();
4       sem_post(s);
                          exit
5   }
```

s->value=1
s->value=-1
s->value=0
s->value=1
s->value=0
s->value=-1
s->value=-2
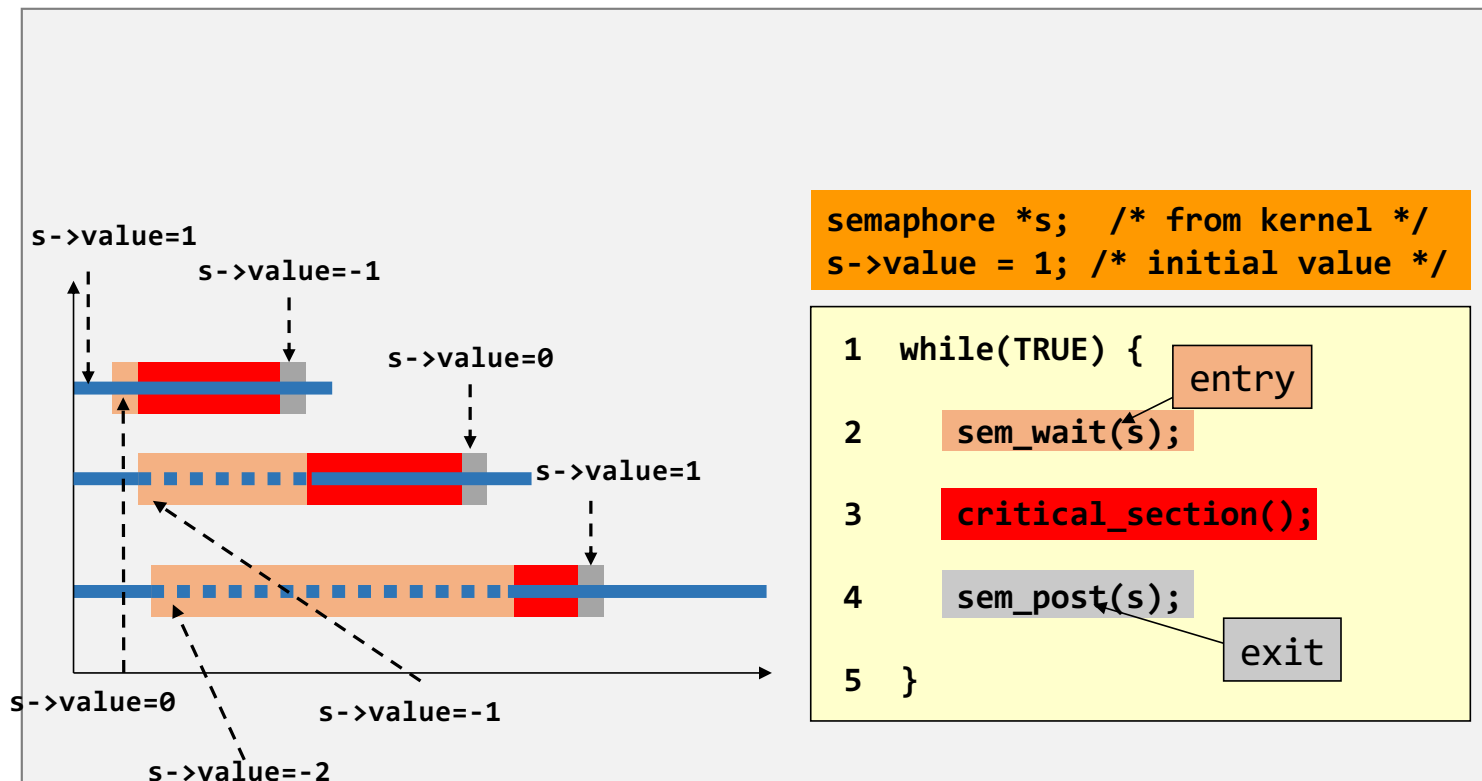
Semaphore Implementation

- 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);
```

```
///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.

ls → enqueue → [pipe buffer] → dequeue → less

Producer   pipe - bounded (4K bytes)   Consumer
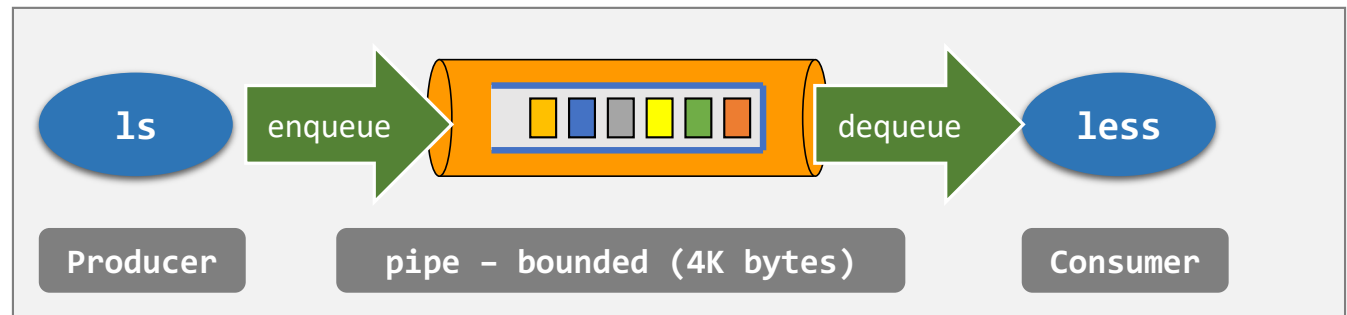
Producer-consumer Problem

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

Synchronization

Producer

Consumer

Mutual Exclusion
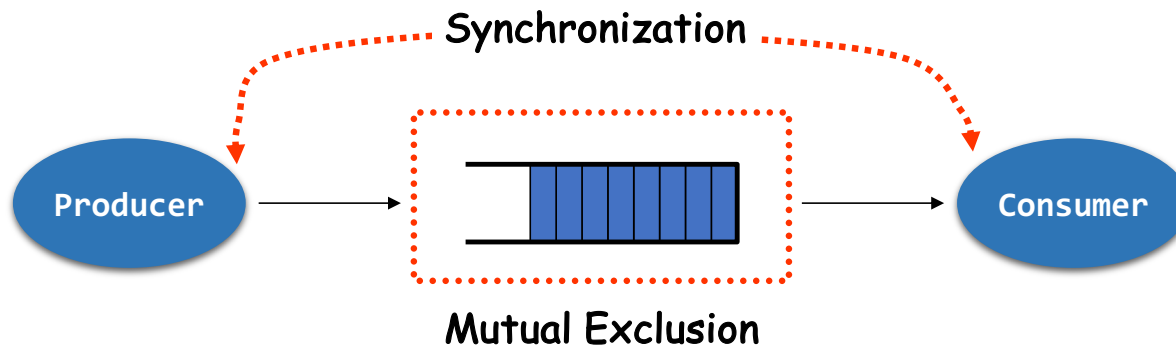
Solving Producer-consumer Problem with Semaphore

Shared object

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

Abstraction of semaphore as integer!

Note

<u>Note</u>

The size of the bounded buffer is "N".

fill : number of occupied slots in buffer
avail: number of empty slots in 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  }
```

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  }
```

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 **fill**ed 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 **avail**able slot and acquire it if I can

10: (Producer) I notify the others that I have **fill**ed 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 **avail**able 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 "<u>avail</u>" and "<u>fill</u>"?

Let us try to remove semaphore <u>fill</u>?

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

E R R O R
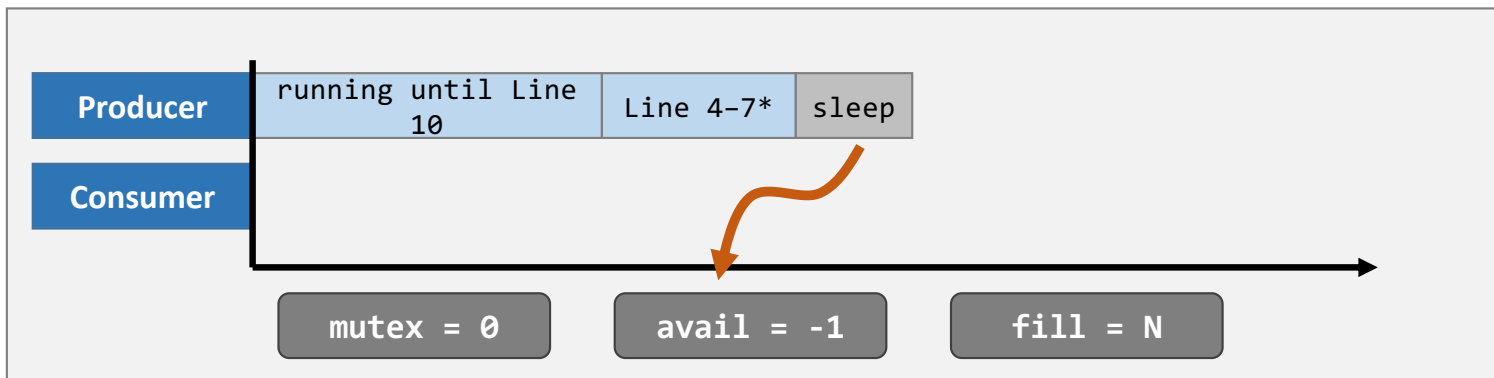
Producer function

```
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  }
```
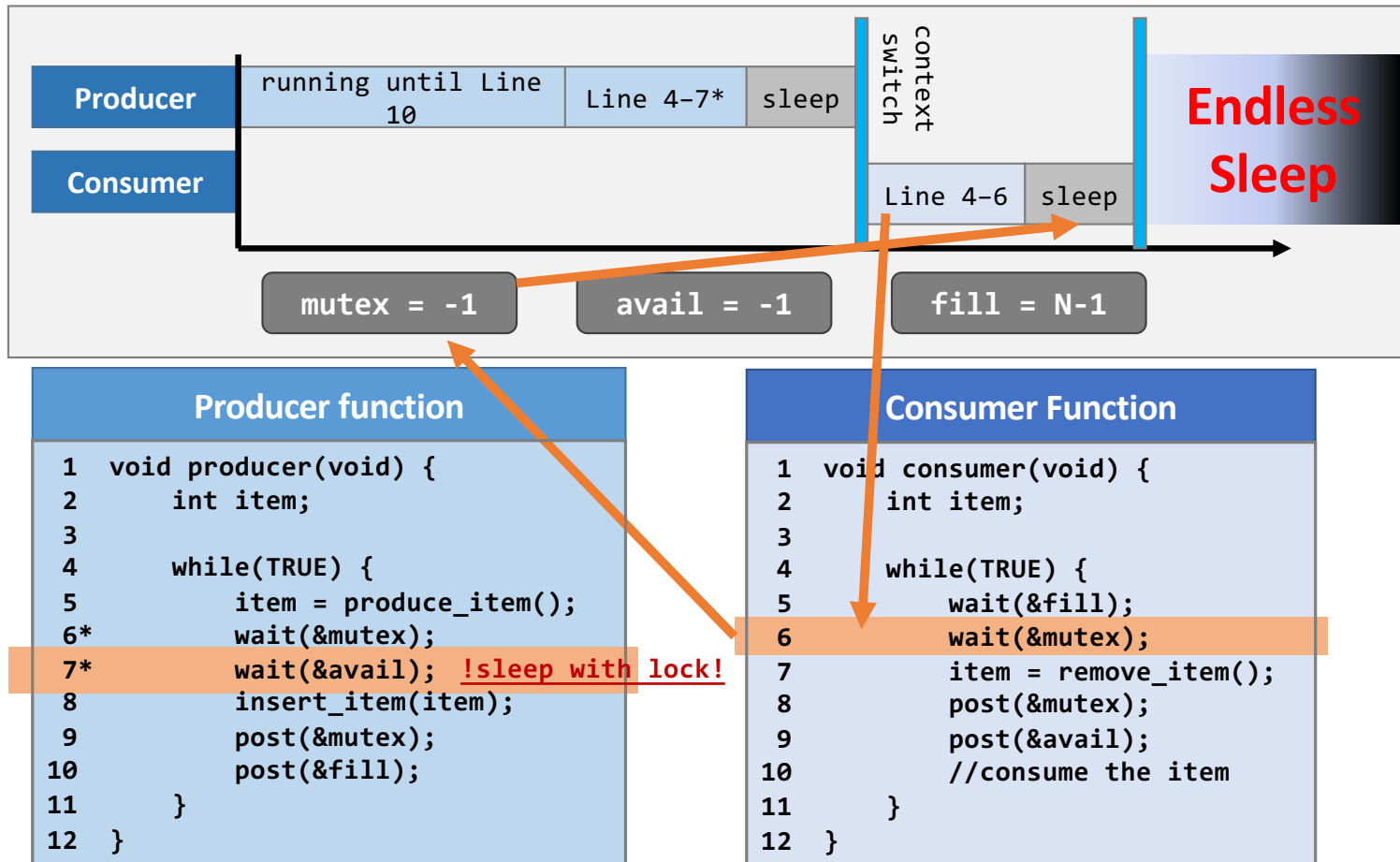
Question 2

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  }
```

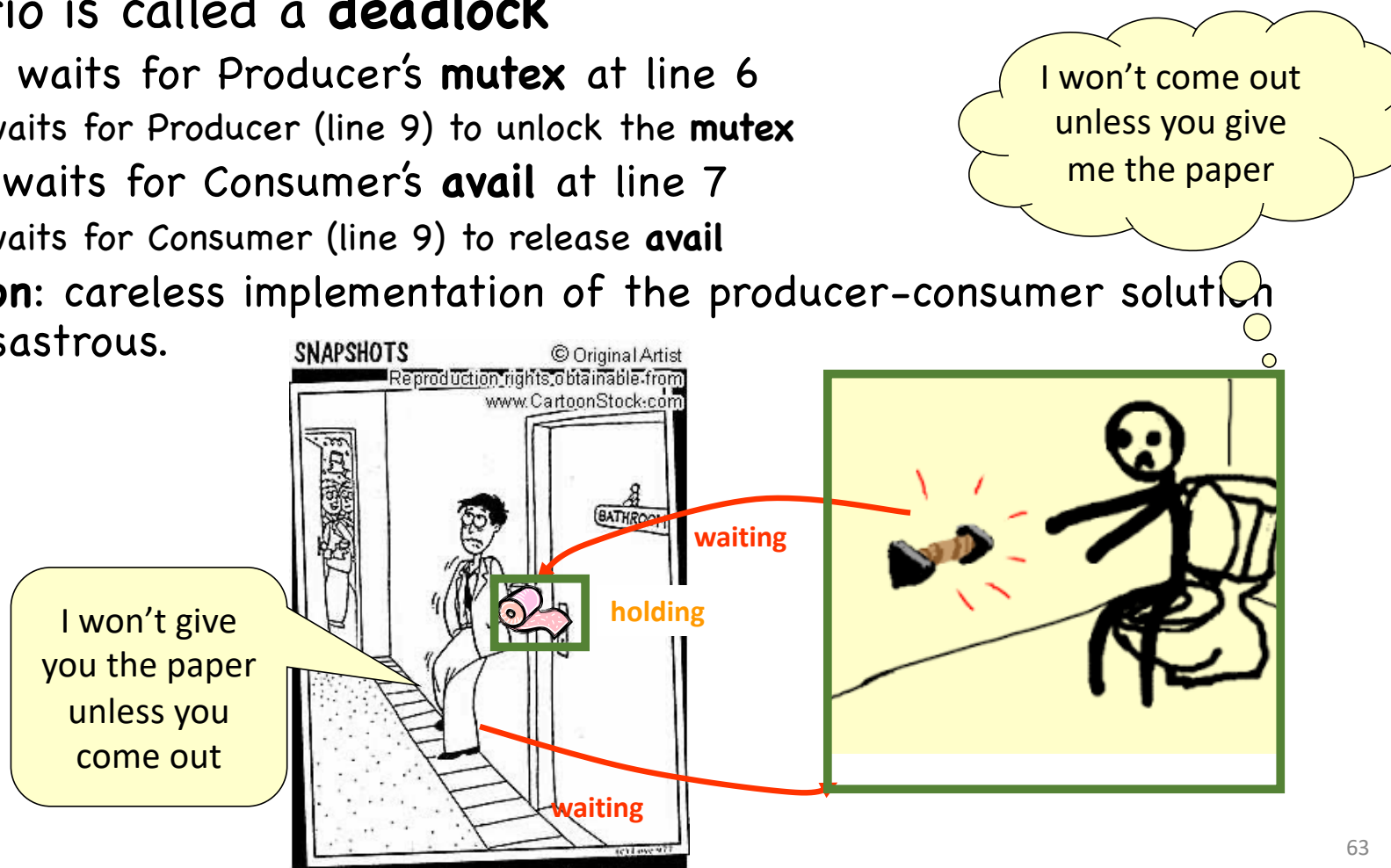**Consumer Function**

```
1   void consumer(void) {
2       int item;
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

Producer	running until Line 10	Line 4–7*	sleep
Consumer			

mutex = 0 **avail = -1** **fill = N**

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

Producer | running until Line 10 | Line 4-7* | sleep | context switch | **Endless Sleep**

Consumer | Line 4-6 | sleep

mutex = -1   avail = -1   fill = N-1

Producer function

```
1   void producer(void) {
2       int item;
3
4       while(TRUE) {
5           item = produce_item();
6*          wait(&mutex);
7*          wait(&avail);   !sleep with lock!
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

- 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 <u>to think</u> and <u>to eat</u>
- They **need exactly two chopsticks** in order to eat the spaghetti.
- Question: how to construct a <u>synchronization protocol</u> 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 ….
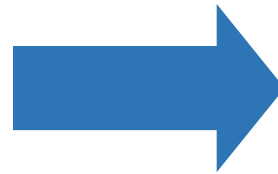

It's a multi-object synchronization problem

Dining Philosopher Problem
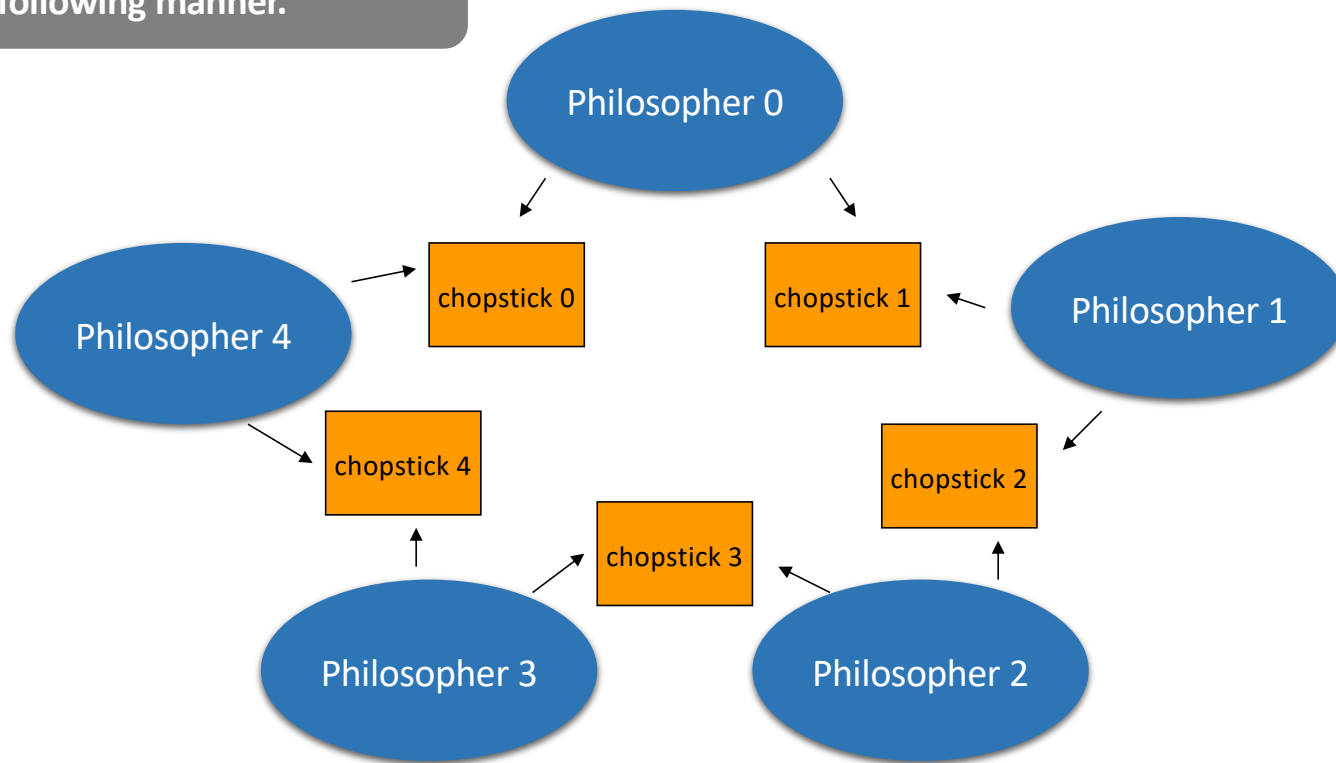

Philosophers

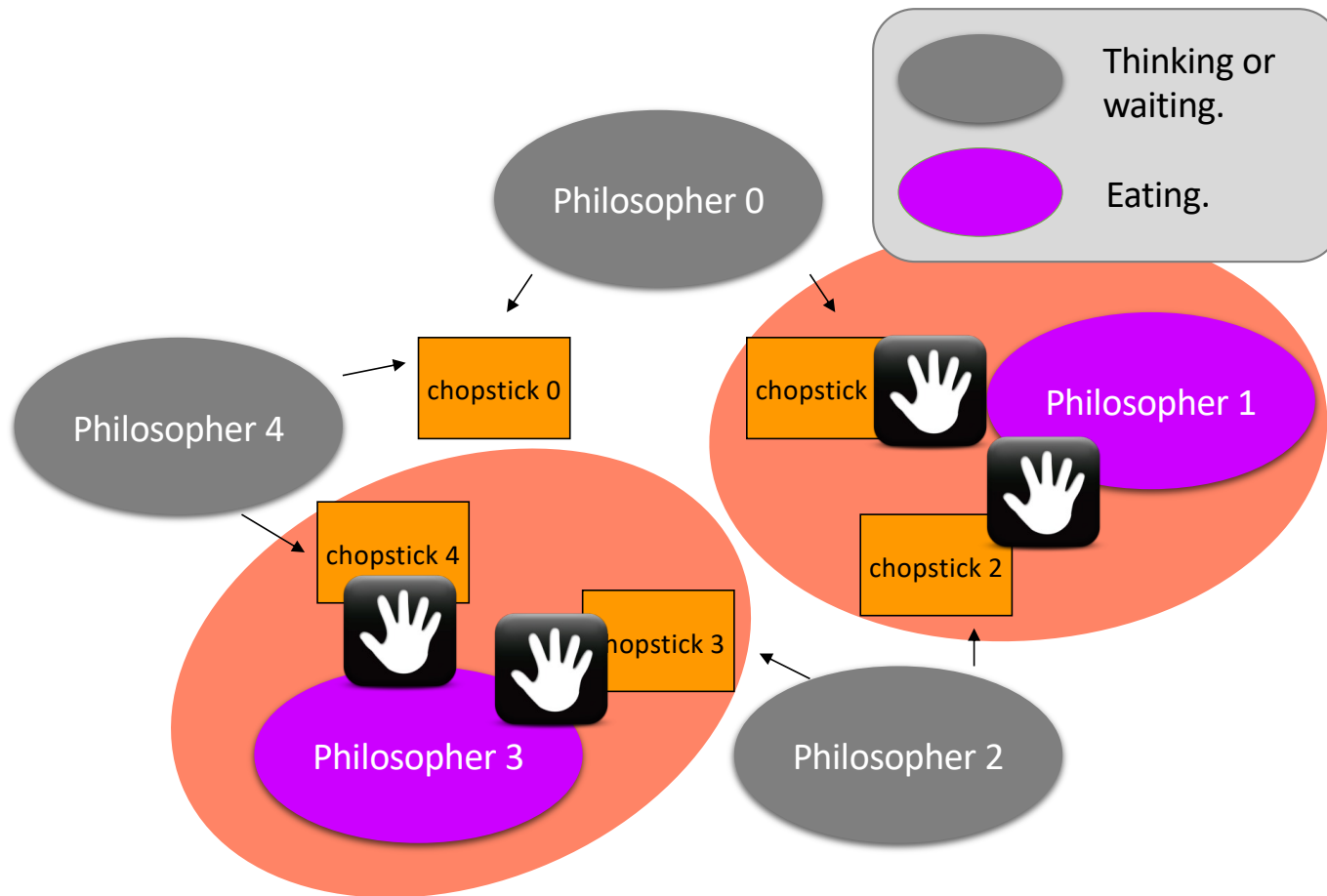Chopsticks

Process

Shared Object

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

Legend:
- Thinking or waiting. (gray ellipse)
- Eating. (magenta ellipse)

Philosopher 0
Philosopher 4
Philosopher 1
Philosopher 3
Philosopher 2

chopstick 0
chopstick (1)
chopstick 2
chopstick 4
chopstick 3

Dining Philosopher – Requirement 1
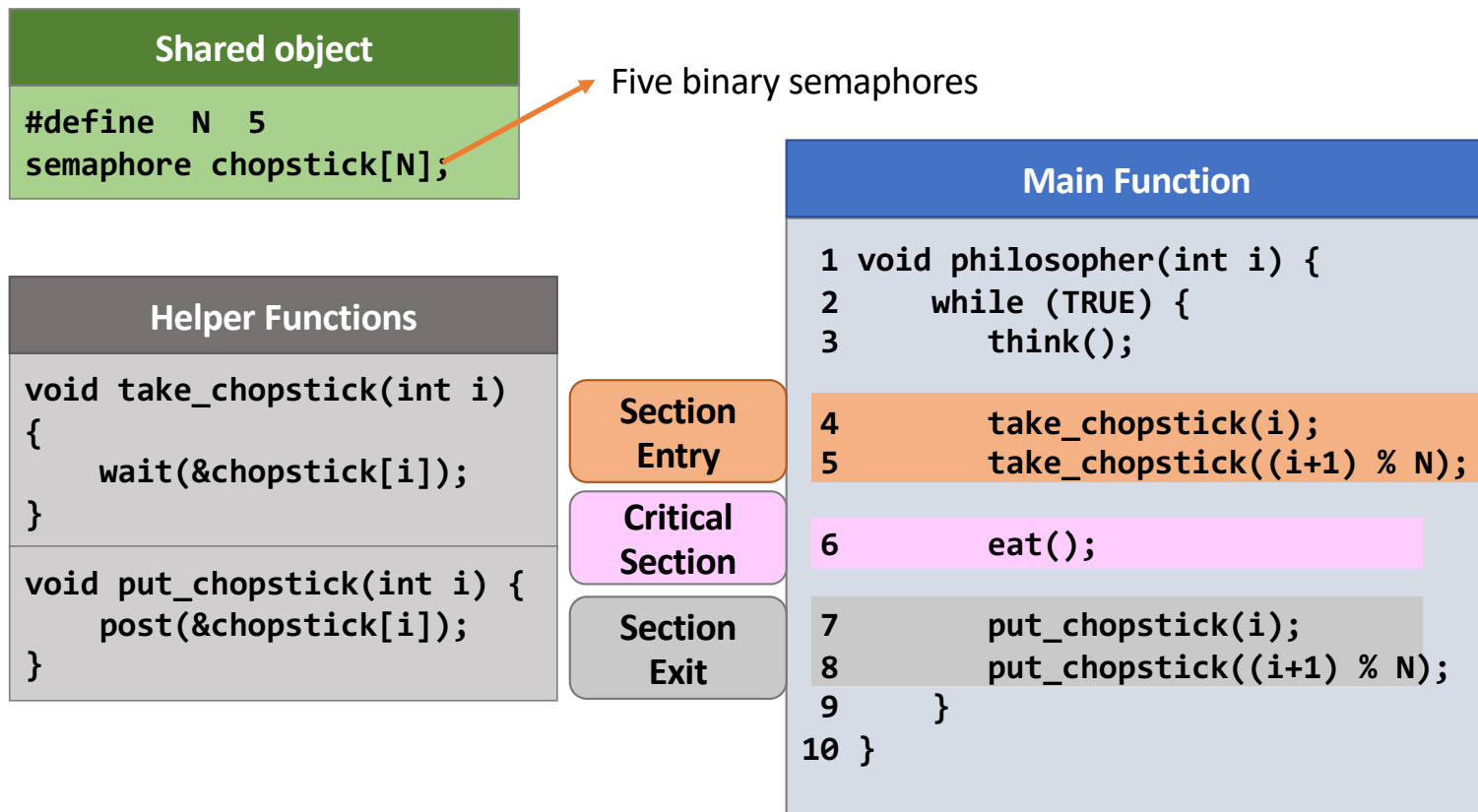
- **<u>Mutual exclusion</u>**
  - While you are eating, people cannot steal your chopstick
  - Two persons cannot hold the same chopstick
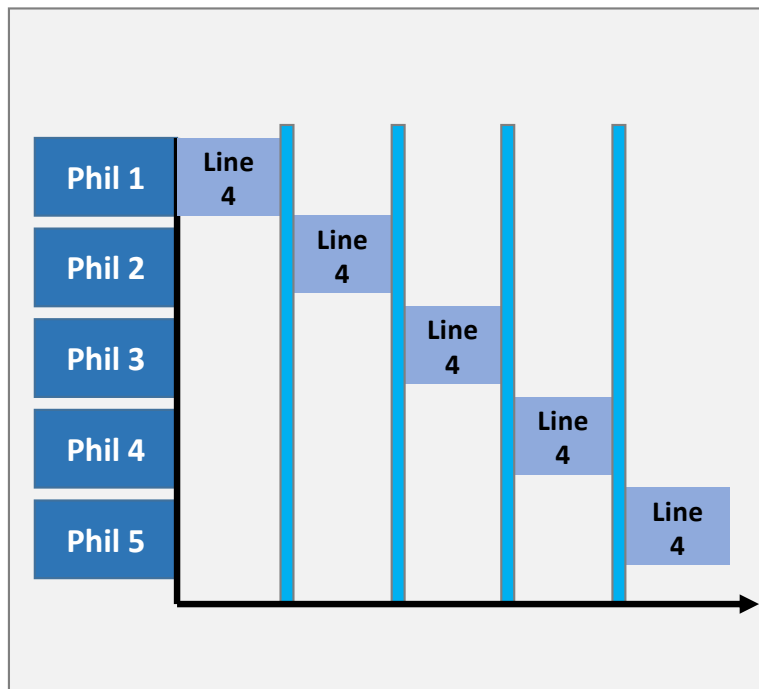
- Let's propose the following solution:
  - When you are hungry, you have to check if anyone is using the chopsticks that you need.
  - If yes, you wait.
  - If no, **seize both chopsticks**.
  - After eating, put down both your chopsticks.

Dining Philosopher – Requirement 1

Shared object

```
#define  N  5
semaphore chopstick[N];
```

Five binary semaphores

Helper Functions

```
void take_chopstick(int i)
{
    wait(&chopstick[i]);
}
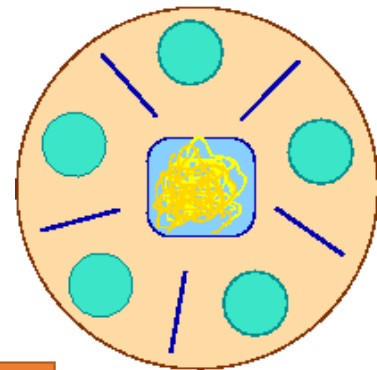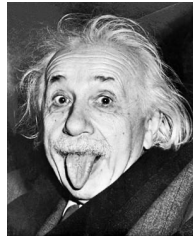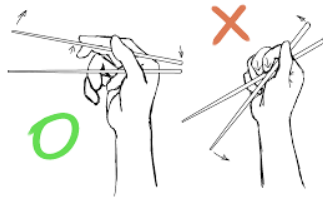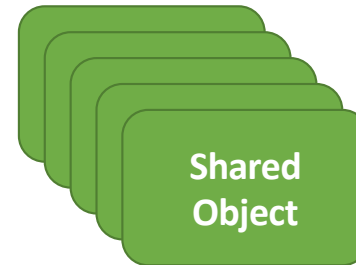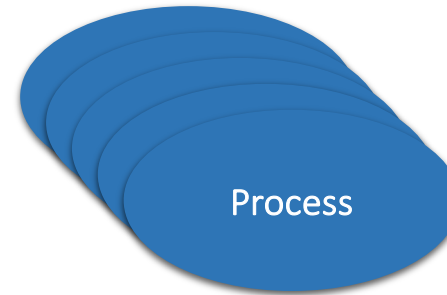
void put_chopstick(int i) {
    post(&chopstick[i]);
}
```

Section Entry

Critical Section

Section Exit

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 – 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

Phil 1	Line 4
Phil 2	Line 4
Phil 3	Line 4
Phil 4	Line 4
Phil 5	Line 4

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

- **<u>Synchronization</u>**
  - Should avoid **deadlock**.

- How about the following suggestions:
  - First, a philosopher **<u>takes a chopstick</u>**.
  - If a philosopher finds that she cannot take the second chopstick, then she should **<u>put it down</u>**.
  - Then, the philosopher **<u>goes to sleep</u>** for a while.
  - When wake up, she retries
  - Loop until both chopsticks are seized.

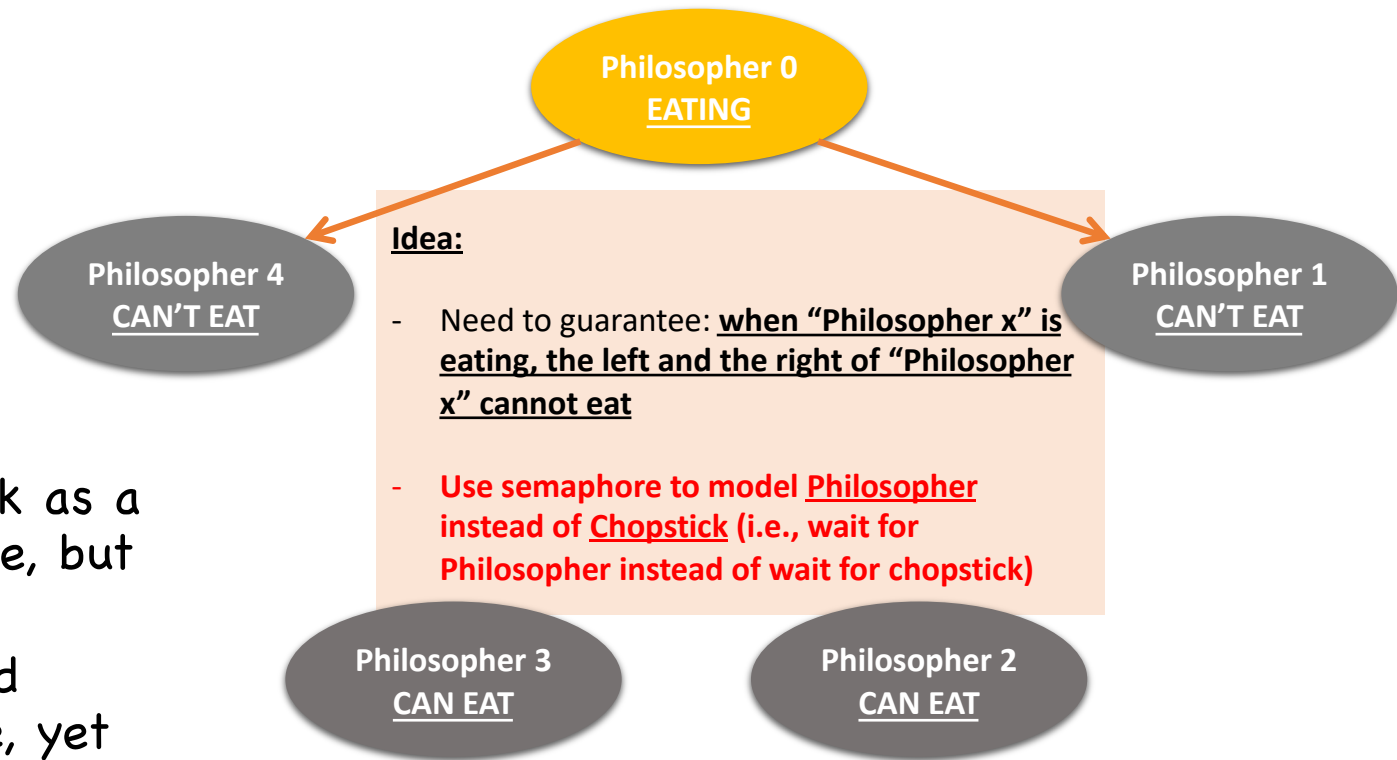# Dining Philosopher – Requirement 2

- **<u>Potential Problem:</u>**
  - Philosophers are all busy (no deadlock), but no progress (<u>starvation</u>)

- 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
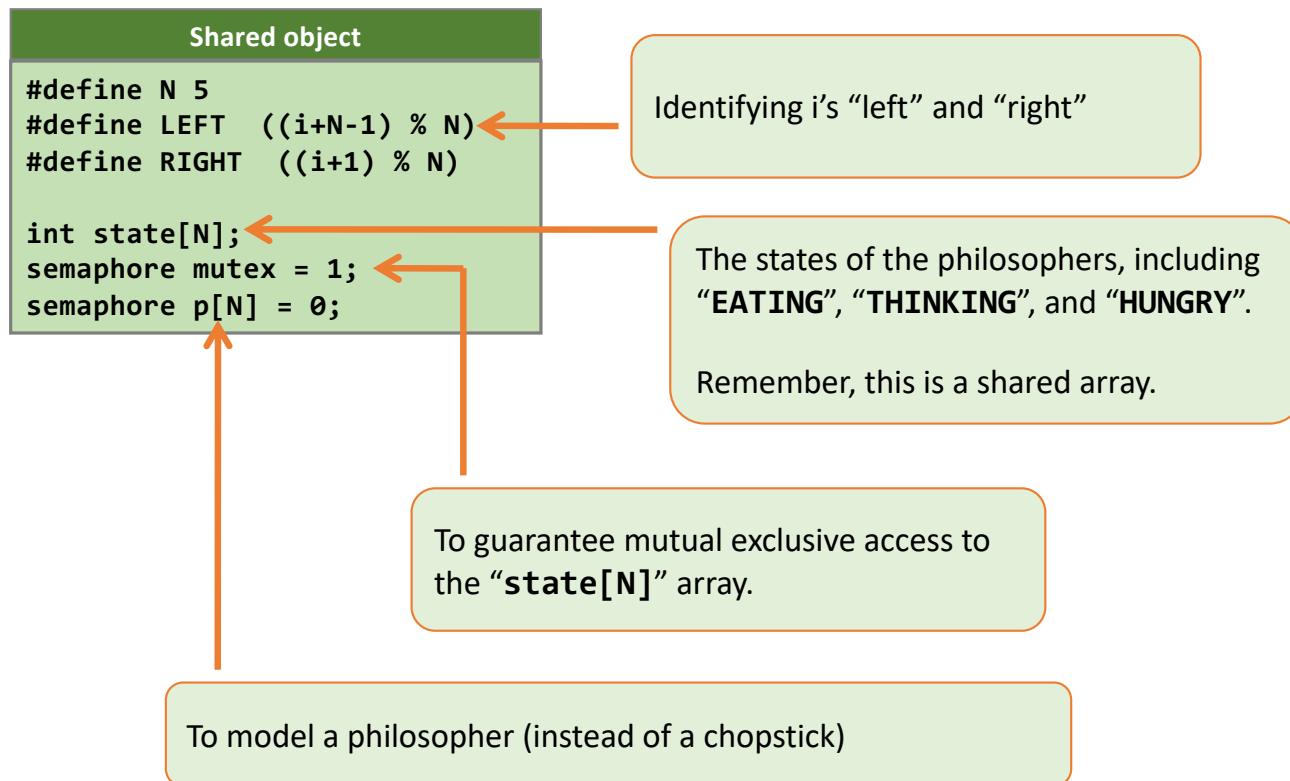 - all pick up their left chopsticks, ….

Dining Philosopher – before the Final Solution

Philosopher 0
EATING

Philosopher 4
CAN'T EAT

Philosopher 1
CAN'T EAT

Idea:

- Need to guarantee: **when "Philosopher x" is eating, the left and the right of "Philosopher x" cannot eat**

- **Use semaphore to model Philosopher instead of Chopstick (i.e., wait for Philosopher instead of wait for chopstick)**

Philosopher 3
CAN EAT

Philosopher 2
CAN EAT

- 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

Shared object

```
#define N 5
#define LEFT  ((i+N-1) % N)
#define RIGHT  ((i+1) % N)

int state[N];
semaphore mutex = 1;
semaphore p[N] = 0;
```

Identifying i's "left" and "right"

The states of the philosophers, including "**EATING**", "**THINKING**", and "**HUNGRY**".

Remember, this is a shared array.

To guarantee mutual exclusive access to the "**state[N]**" array.

To model a philosopher (instead of a chopstick)

Dining Philosopher – Final Solution

Shared object

```
#define N 5
#define LEFT   ((i+N-1) % N)
#define RIGHT  ((i+1) % N)

int state[N];
semaphore mutex = 1;
semaphore p[N] = 0;
```

Main function

```
1   void philosopher(int i) {
2       think();
3       take_chopsticks(i);
4       eat();
5       put_chopsticks(i);
6   }
```

```
void wait(semaphore *s) {

    *s = *s - 1;
    if ( *s < 0 ) {

        sleep();

    }

}
```

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   }
```

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   }
```

```
void post(semaphore *s) {

    *s = *s + 1;
    if ( *s <= 0 )
        wakeup();
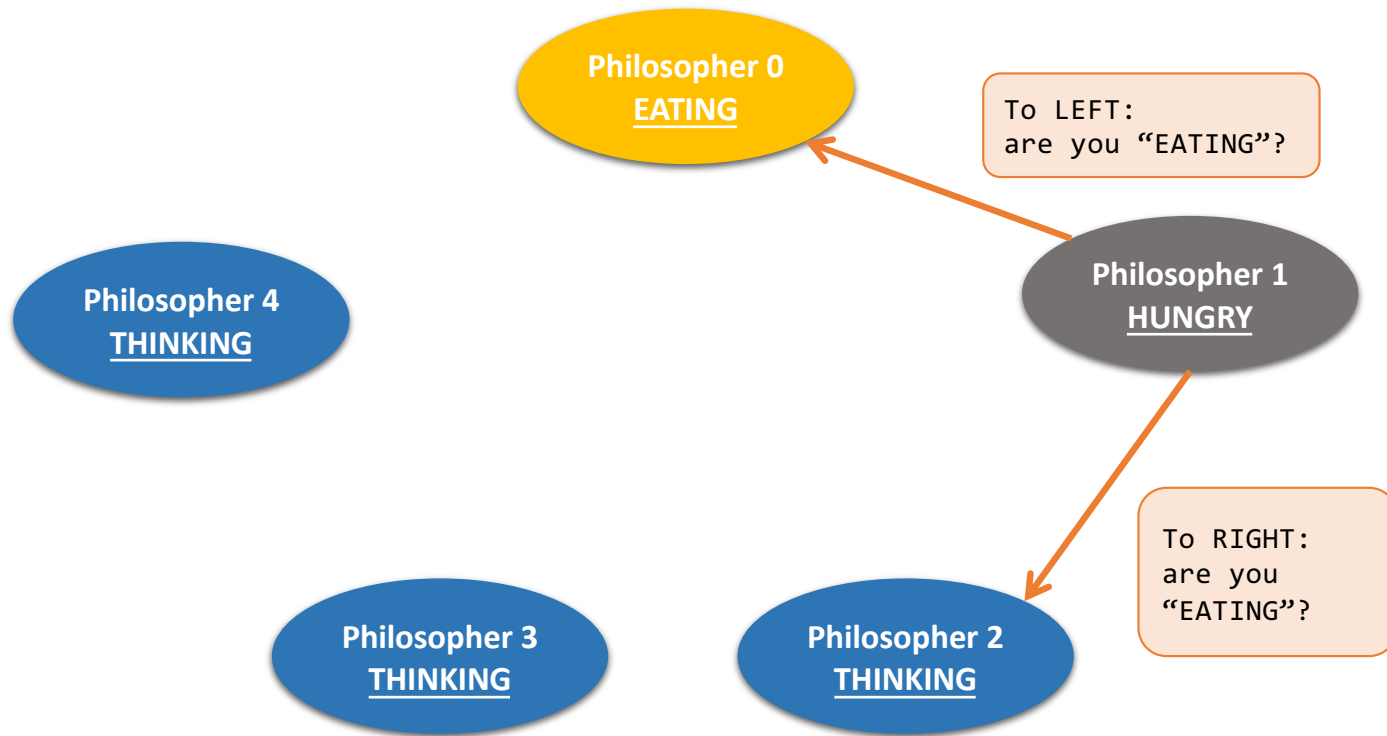
}
```

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 }
```

CS334 Operating Systems (H)

Dining Philosopher – Final Solution

hungry

Tell the captain that you are hungry

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

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

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  }
```

<u>Critical Section</u>
The captain is "indivisible"

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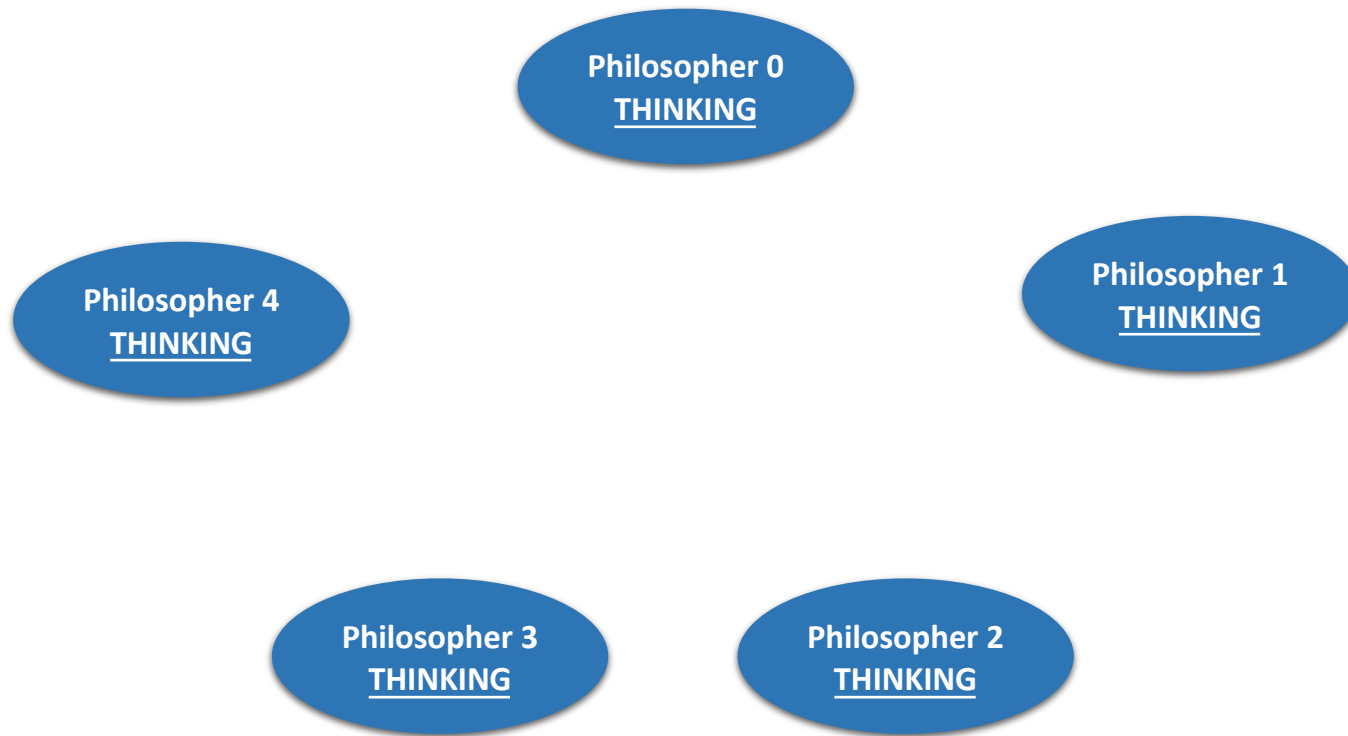
```
1 void captain(int i) {
2     if(state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
3         state[i] = EATING;
4         post(&p[i]);
5     }
6 }
```

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
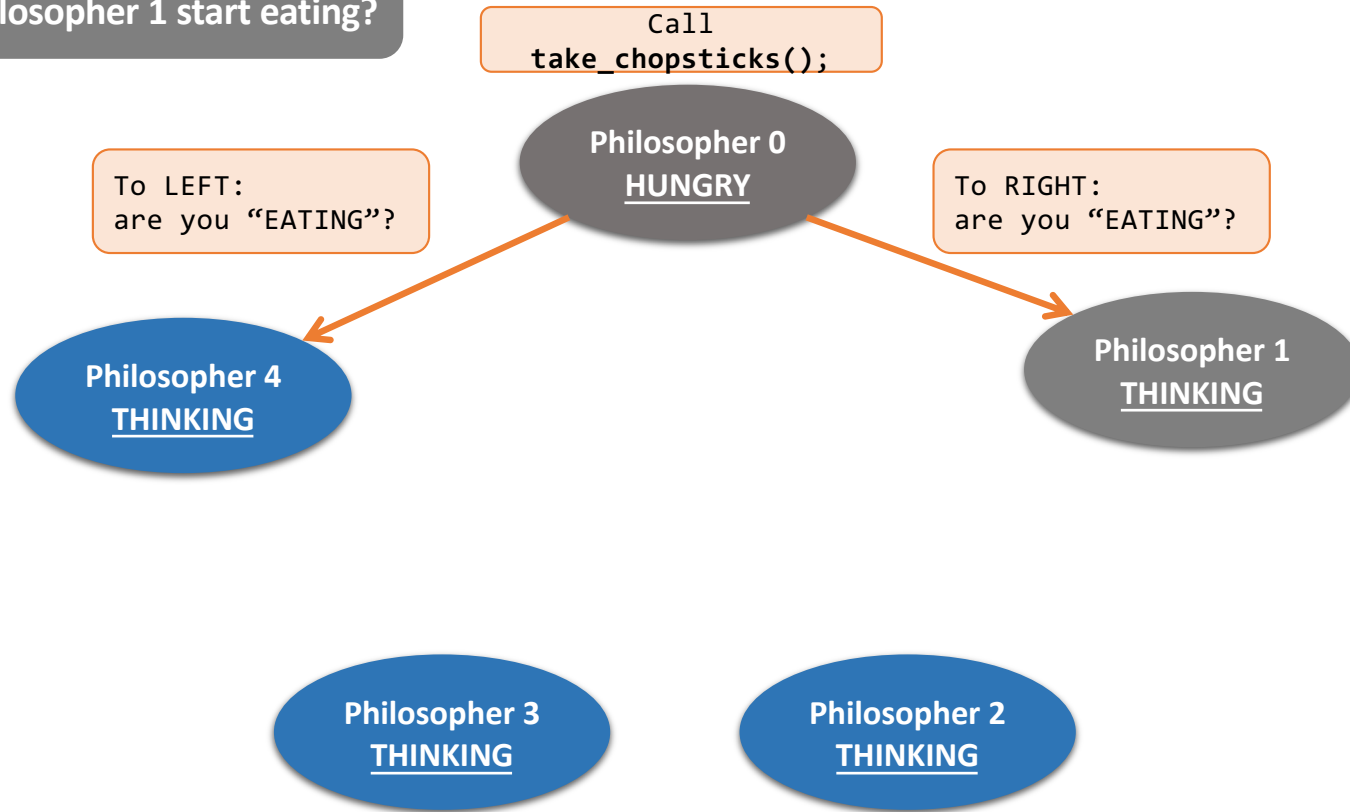
Dining Philosopher – Final Solution

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

An illustration: How can Philosopher 1 start eating?

Call
`take_chopsticks();`

Philosopher 0
HUNGRY

To LEFT:
are you "EATING"?

To RIGHT:
are you "EATING"?

Philosopher 4
THINKING

Philosopher 1
THINKING

Philosopher 3
THINKING

Philosopher 2
THINKING

Dining Philosopher – Final Solution

An illustration: How can Philosopher 1 start eating?

Philosopher 0
EATING

To LEFT:
are you "EATING"?

Philosopher 1
HUNGRY

Philosopher 4
THINKING

To RIGHT:
are you "EATING"?

Philosopher 3
THINKING

Philosopher 2
THINKING

81

Dining Philosopher – Final Solution

An illustration: How can Philosopher 1 start 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 0
EATING

Philosopher 1
HUNGRY

Philosopher 4
THINKING

To LEFT:
are you
"EATING"?

To RIGHT:
are you
"EATING"?

Philosopher 3
HUNGRY

Philosopher 2
THINKING

82

Dining Philosopher – Final Solution

An illustration: How can Philosopher 1 start eating?

Philosopher 0
EATING

Philosopher 4
THINKING

Philosopher 1
HUNGRY

```
Blocked;
because of
wait(&p[1]);
```

Philosopher 3
EATING

Philosopher 2
THINKING

83

Dining Philosopher – Final Solution

An illustration: How can Philosopher 1 start eating?

```
Call
put_chopsticks();
```

Philosopher 0
THINKING

```
captain(LEFT);
```

```
captain(RIGHT);
```

Philosopher 4
THINKING

Philosopher 1
HUNGRY

```
Blocked;
because of
wait(&p[1]);
```

Philosopher 3
EATING

Philosopher 2
THINKING

84

Dining Philosopher – Final Solution

An illustration: How can Philosopher 1 start eating?

Call
`put_chopsticks();`

Philosopher 0
THINKING

`captain(RIGHT);`

Blocked;
because of
`wait(&p[1]);`

Philosopher 4
THINKING

```
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 !

85

Dining Philosopher – Final Solution

An illustration: How can Philosopher 1 start 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   }
```

Wake up

Philosopher 0
THINKING

Philosopher 1
EATING

Philosopher 4
THINKING

Philosopher 3
EATING

Philosopher 2
THINKING

Thank you!