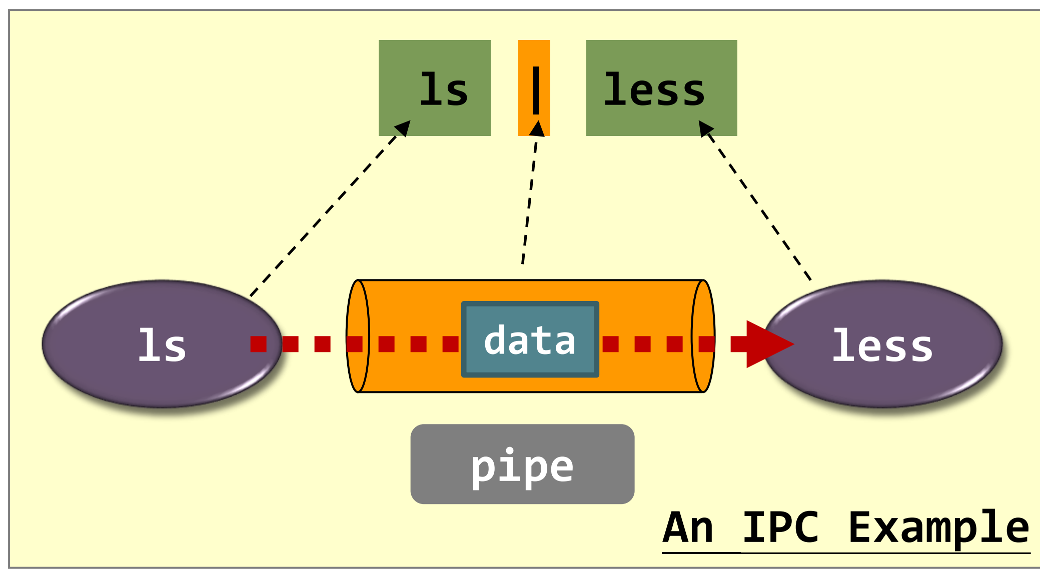
Lecture 6: Synchronization

Bo Tang @ 2020, Spring

Inter-process Communication (IPC)

- Pipe
  - Unidirectional
  - Between processes with a common ancestor (e.g., ls | less; ancestor=shell)
- Signal
  - More kernel-level
  - Limited (SIGCHLD, SIG…)

Pipe is a **shared object** between two processes.

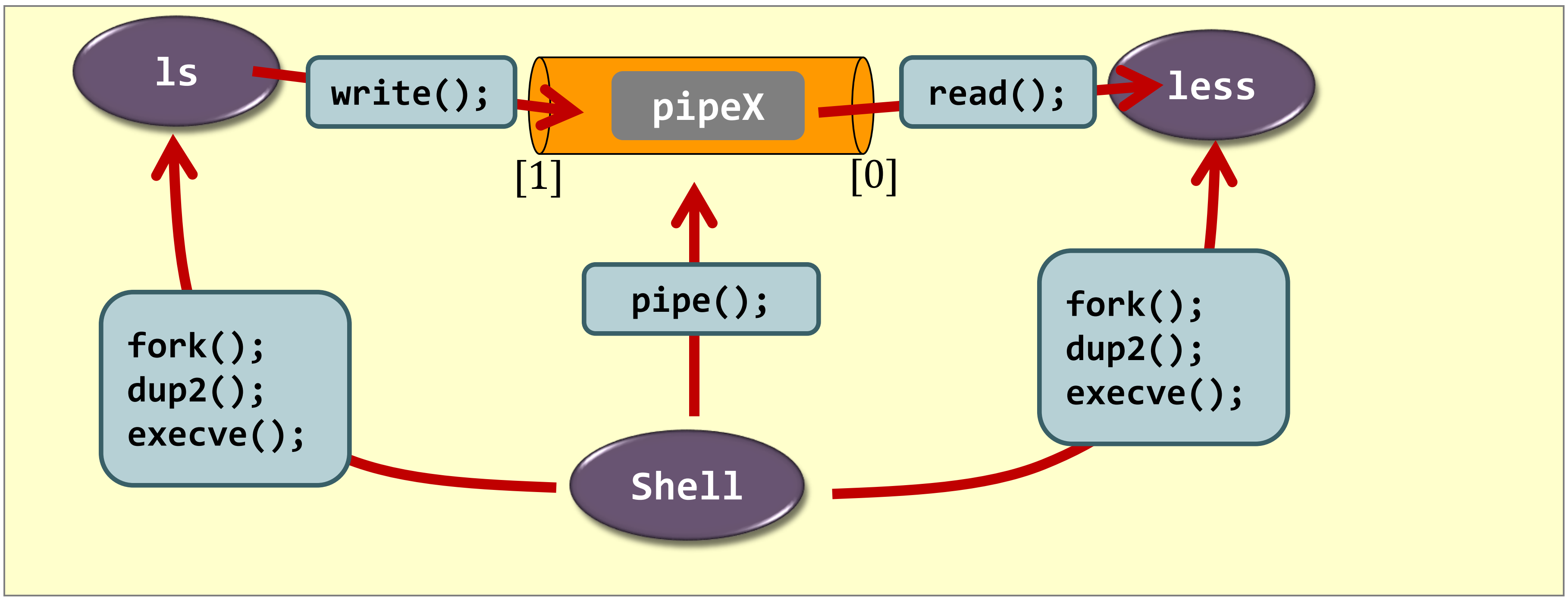


Programming “ls | less”

```
fork();
if (pid==0) { // child; “ls”
  //dup2: replace “ls” default stdout
    by the write end of the pipe
  dup2(pipeX[1], STDOUT_FILENO);
  execlp(“ls”, “ls”, NULL);
} else … //parent; “less”
```

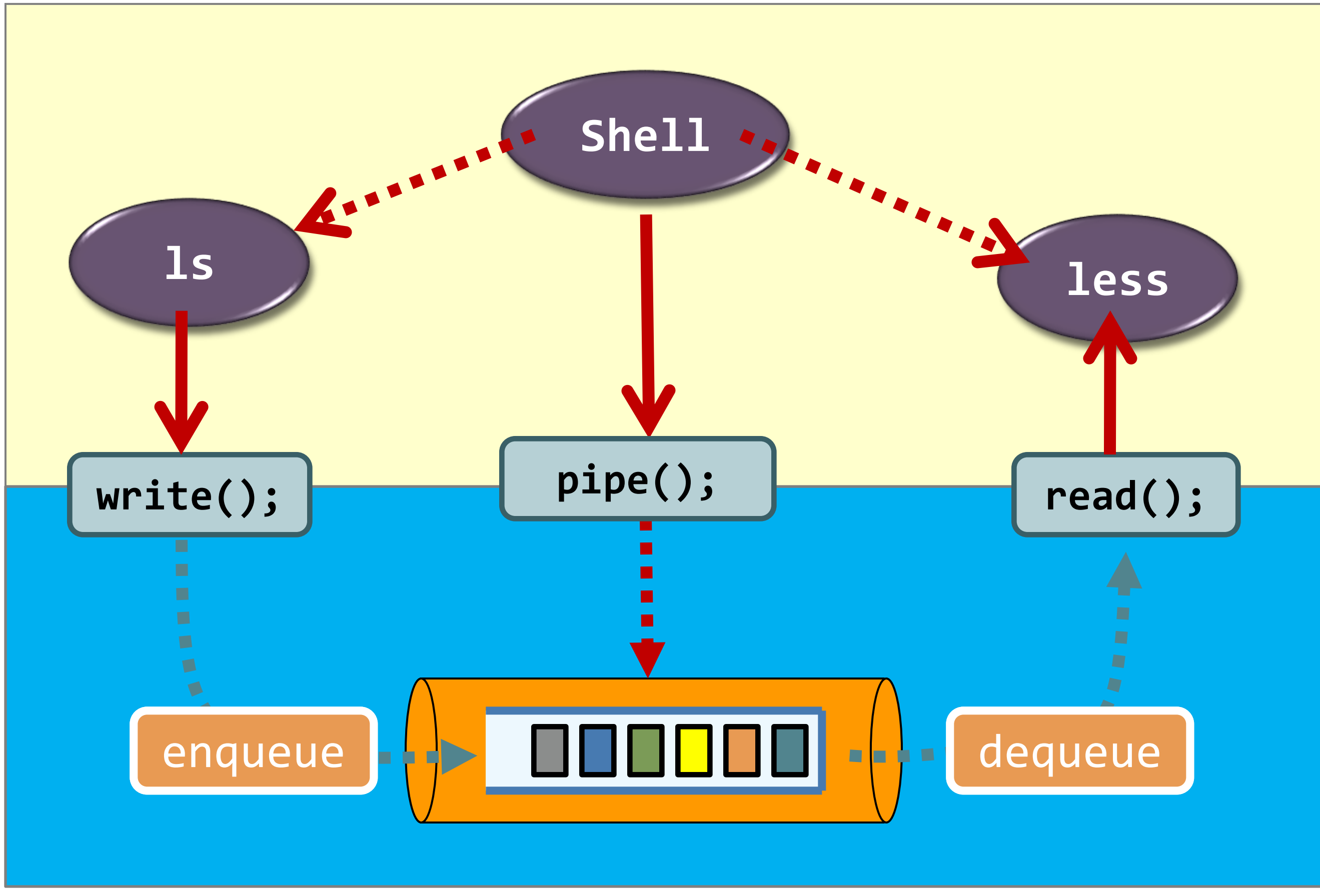
In UNIX*, “everything is a file”

- Every resource that can read/write is represented as a file. E.g.,
    - Network, Disk, Keyboard
- A “file” is indexed by a number called *file descriptor*



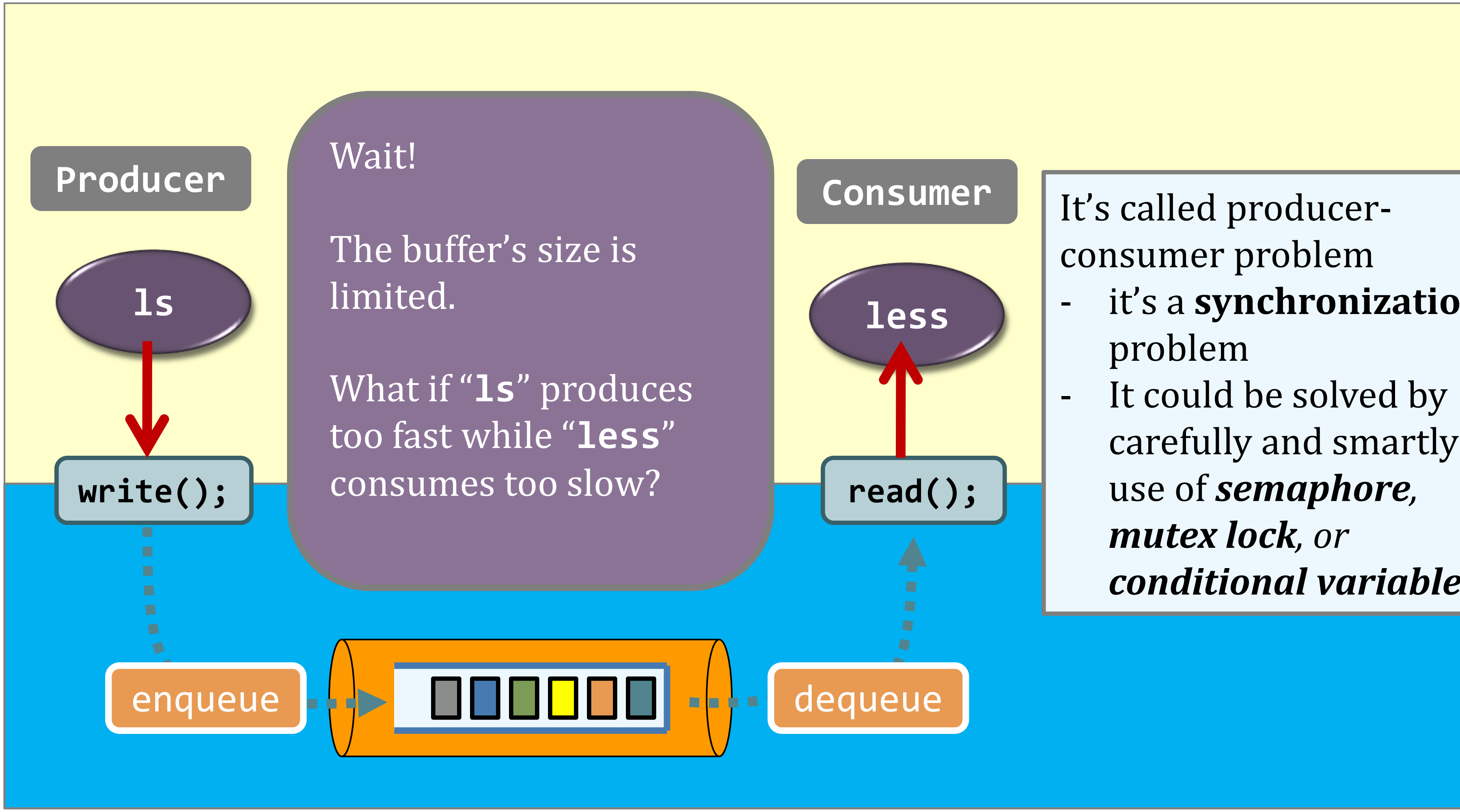
https://en.wikipedia.org/wiki/Everything_is_a_file

"ls | less" in kernel



The **pipe()** system call creates a piece of **shared FIFO queue in the kernel space**!

Synchronization problems



Wait!

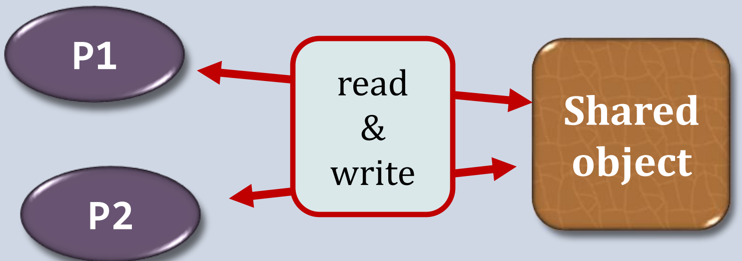
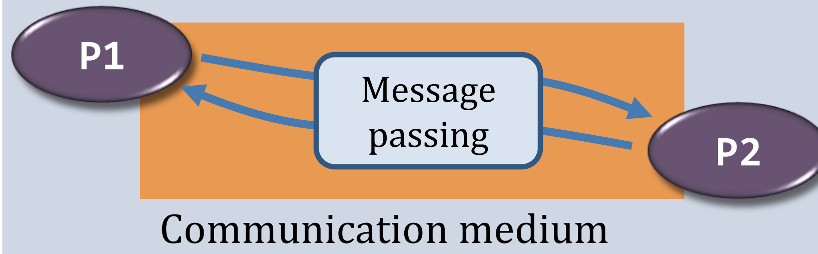
The buffer's size is limited.

What if "**`ls`**" produces too fast while "**`less`**" consumes too slow?

It's called producer-consumer problem

- it's a **synchronization** problem
- It could be solved by carefully and smartly use of ***semaphore***, ***mutex lock***, *or* ***conditional variable***

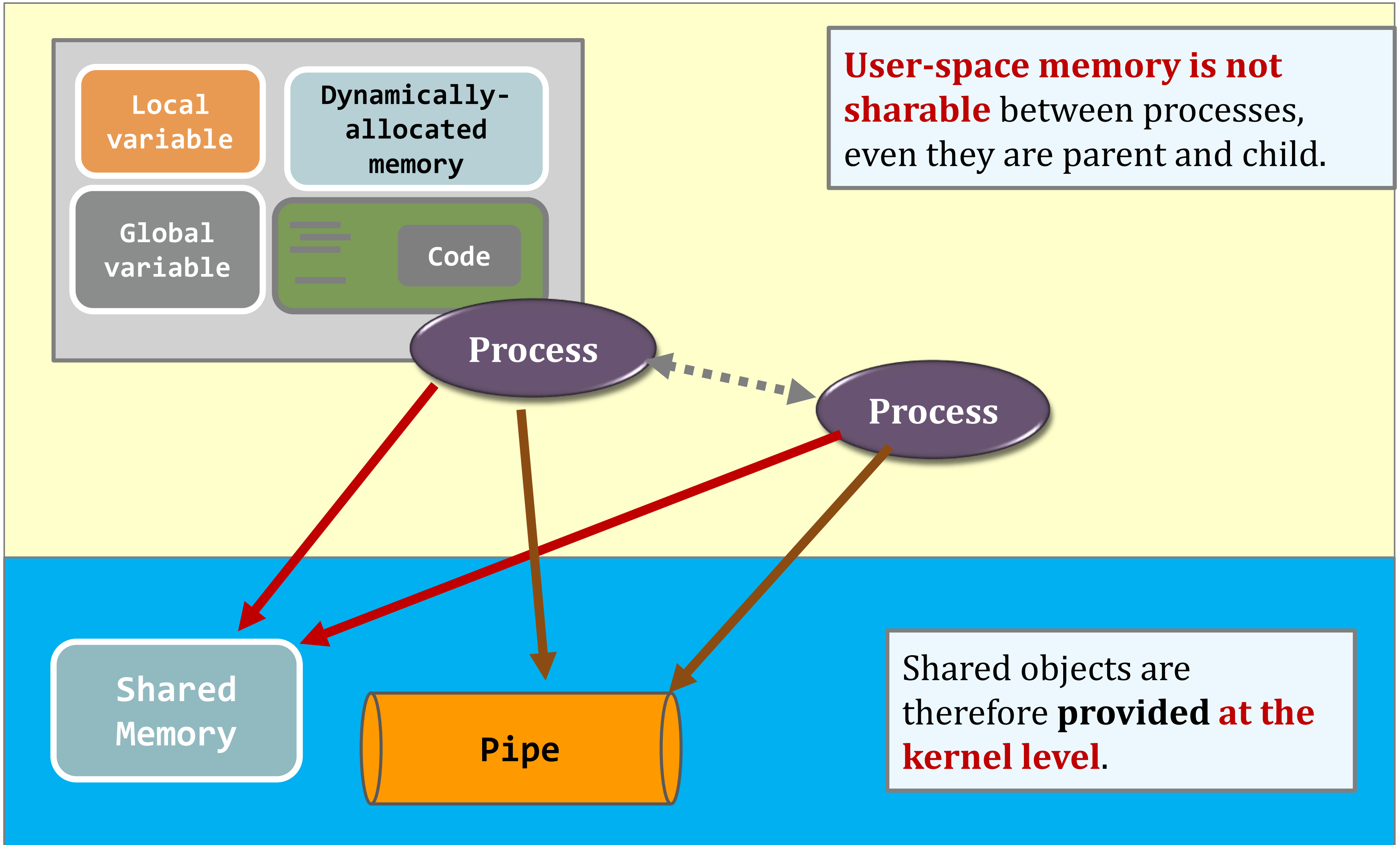
Summary of IPC models

Shared Objects	Message Passing
	
• shared files (on disk; slow) • pipes (restricted, but OS takes care of synchronization for you) • shared memory (primitive, general, but synchronization is on you) • shared address space (threading)	• socket programming • message passing interface (MPI) library for computing clusters.
- Usually single-node communication - More efficient - Need to take great care of synchronization because of sharing the same object	- Usually multi-node communication - Less efficient - Less troublesome in synchronization - But need to care of other faults (e.g., what if a network link is broken?)

Inter-process communication (IPC)

- What, why, and how?
- The problem: race condition

Evil source: the shared objects.



User-space memory is not sharable between processes, even they are parent and child.

Shared objects are therefore **provided at the kernel level**.

Evil source: the shared objects.

- Kernel provides you “pipe” to do **one-way** data flow between **2 processes** from the **same ancestor**
  - Super restrictive
- Other IPC problems beyond pipe?
  - You have to use shared memory directly
    - **concurrent access may yield <u>unpredictable outcomes</u>**!
    - Kernel will not take care of that for you
    - You take care of that

Race Condition: Understanding the problem

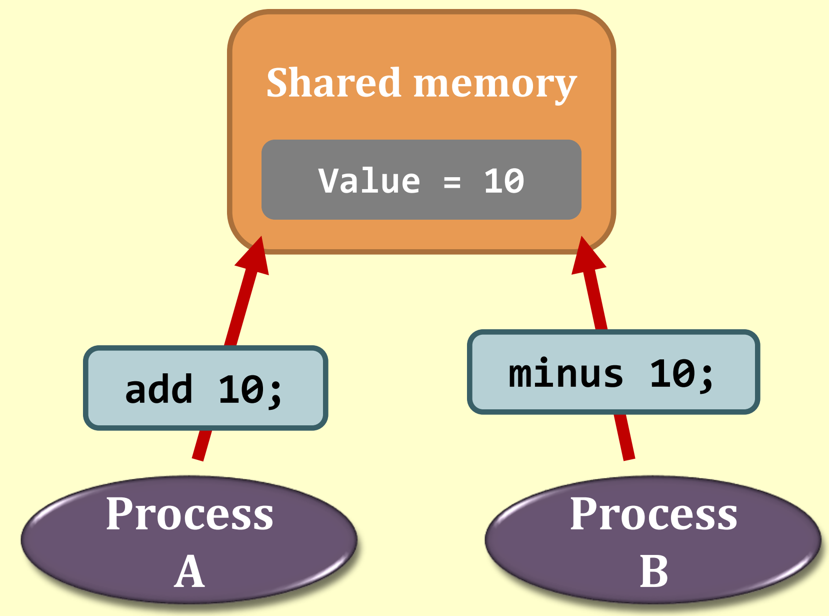
High-level language for Program A

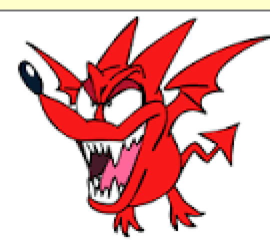
```
1   attach to the shared memory X;
2   add 10 to X;
3   exit;
```

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

Shared memory - X

Value = 10

Process A

State: Ready

Register A Value = 0

```
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;
```

The initial setting

Problem not yet arise...

Don't print

Shared memory - X

Value = 10

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 A

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;
```

Process B

Execution Flow #1, Step 1

Problem not yet arise…

Don't print

Shared memory - X

`Value = 10`

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 A


```
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;
```

Process B

Execution Flow #1, Step 2

Don't print

Problem not yet arise…

Shared memory - X

Value = 20

State: Running

Register A
Value = 20

Register B
Value = 0

State: Ready

Process A

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

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

Don't print

Problem not yet arise...

Shared memory - X

`Value = 20`

State: Ready

`Register A Value = 20`

Register B Value = 20

State: Running

Process A:

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:

4
```
2.1   load memory X to
      register B;

2.2   minus 10 from register B;

2.3   write register B to
      memory X;
```

Process A → **Context Switching** → **Process B**

Execution Flow #1, Step 4

Problem not yet arise…

Don't print

Shared memory - X

`Value = 20`

State: Ready

`Register A Value = 20`

`Register B Value = 10`

State: Running

Process A

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

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

Problem not yet arise…

Shared memory - X

`Value = 10`

State: Ready

`Register A Value = 20`

`Register B Value = 10`

State: Running

Process A

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

`2.1 load memory X to register B;` 4

`2.2 minus 10 from register B;` 5

`2.3 write register B to memory X;` 6

Execution Flow #1, Step 6

Problem arise…

Don't print

Shared memory - X

Value = 10

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;
```

```
2.1   load memory X to
      register B;

2.2   minus 10 from register B;

2.3   write register B to
      memory X;
```

Process A

Process B

Execution Flow #2, Step 1

Problem arise…

Don't print

Shared memory - X

`Value = 10`

State: <u>Ready</u>

`Register A Value = 10`

State: <u>Running</u>

`Register B 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 A

2

```
2.1   load memory X to
      register B;

2.2   minus 10 from register B;

2.3   write register B to
      memory B;
```

Process B

Context Switching

<u>Execution Flow #2, Step 2</u>

Problem arise…

Don't print

Shared memory - X

`Value = 10`

State: Running

`Register A Value = 20`

`Register B Value = 10`

State: Ready

1

3

```
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;

2.2   minus 10 from register B;

2.3   write register B to
      memory X;
```

Process A

Context Switching

Process B

Execution Flow #2, Step 3

Problem arise…

Don’t print

Shared memory - X

`Value = 10`

State: Ready

```
Register A
Value = 20
```

1, 3 (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 A

```
Register B
Value = 0
```

State: Running

2, 4 (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;
```

Process B

Context Switching

Execution Flow #2, Step 4

Problem arise…

Shared memory - X

Value = 10

State: Ready

Register A
Value = 20

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

Process A

Register B
Value = 0

State: Running

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

Process B

1 2 3 4

BUG!! No matter which process runs next, **the result is either 0 or 20, but not 10**!

The final result depends on the execution sequence!

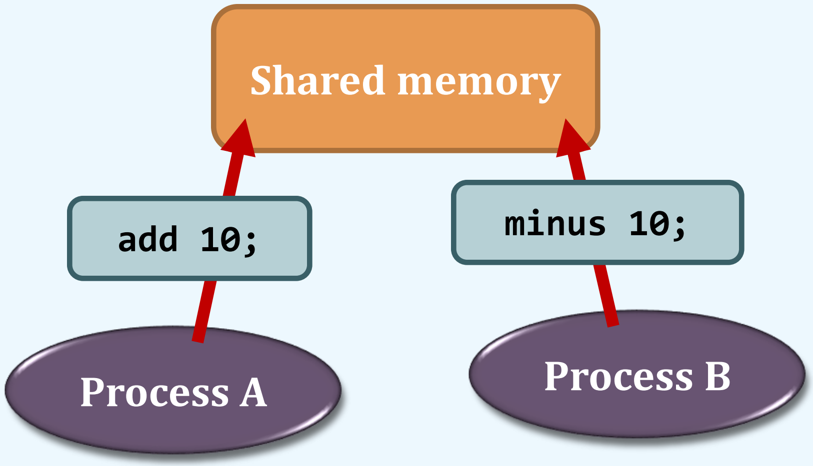
Race condition

- The above scenario is called the **race condition**.
  - May happen whenever "**shared object**" + "**multiple processes**" + "**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.

Inter-process communication (IPC)

- What, why, and how?
- The problem: race condition.
- **How to resolve** race condition **on a shared object?**
  - **Mutual Exclusion**

Mutual Exclusion – the cure

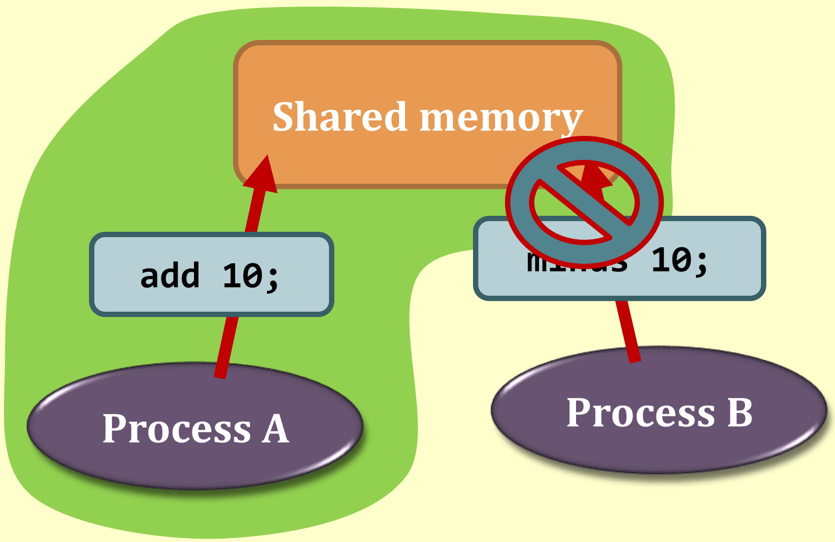


How to resolve race condition?

Solution: **mutual exclusion**

When I'm playing with the shared memory, no one could touch it.

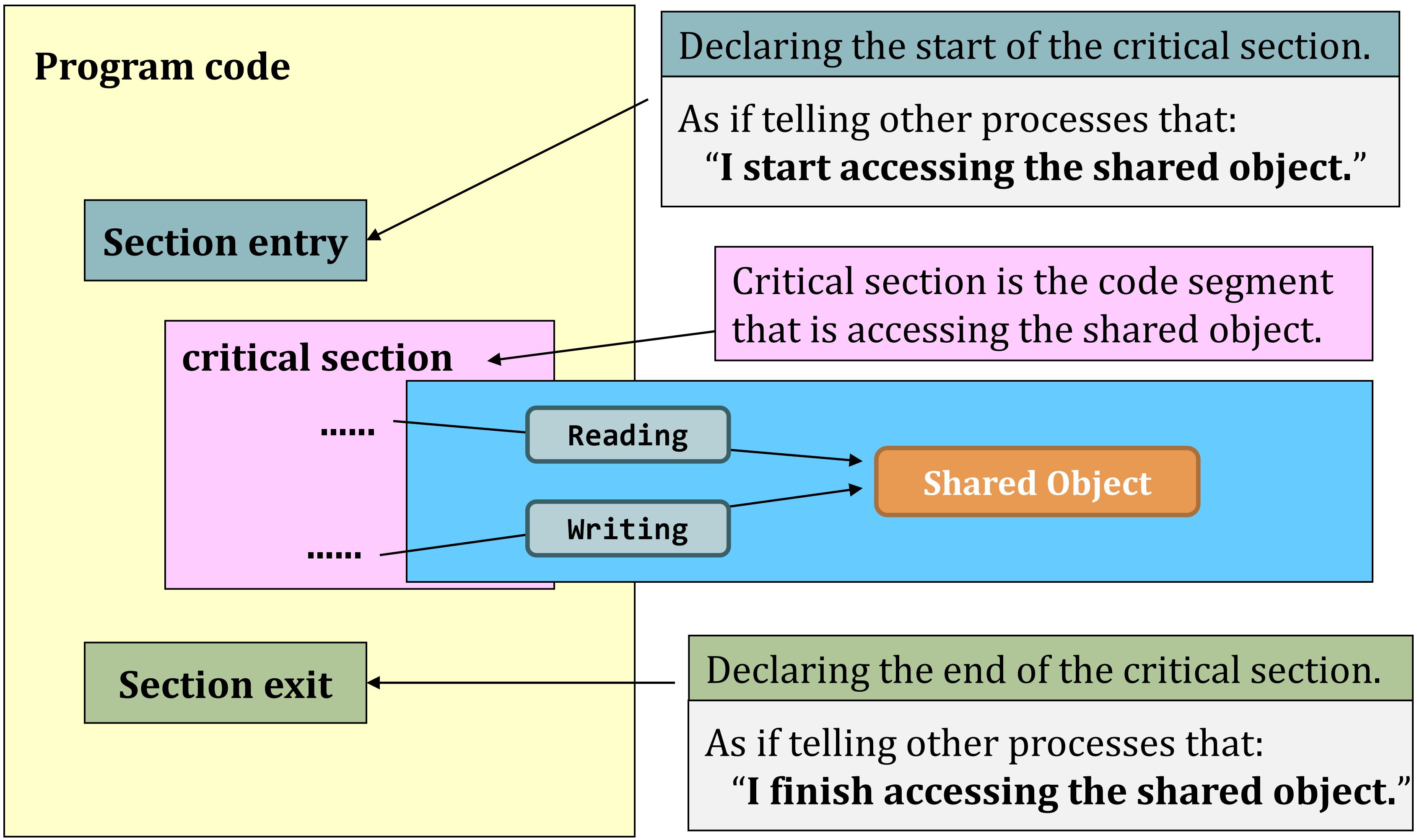
A set of processes would not have the problem of race condition *if* ***mutual exclusion is guaranteed***.



Solution – Mutual exclusion

- Shared object is still sharable, but
- Not to share the “shared object” at the same time
- Share the “shared object” one by one

Critical Section – the realization



Critical Section (CS) – the realization

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 A

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

Process B

Important: Process A vs. Process B

A's CS != B's CS

That is, when process A is entering **her CS**, process B cannot enter **his CS.**

What's really matter is the section entry/exit

Set of blocked processes, waiting to

Shared Object

Certainly, you want mutual exclusion!

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.

Summary

- **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**.

Summary

- **Implementing section entry and exit** is a challenge.
  - The entry and the exit are **the core parts that guarantee mutual exclusion**, but not the critical section.
  - Unless they are correctly implemented, race condition would appear.
- **Mutual exclusion hinders the performance of parallel computations.**

Entry and exit implementation - requirements

- **<u>Requirement #1</u>. Mutual Exclusion**
  - No two processes could be simultaneously go inside their own critical sections.
- **<u>Requirement #2</u>. Bounded Waiting**
  - One a process starts trying to enter her CS, there is a bound on the number of times other processes can enter theirs.

Entry and exit implementation - requirements

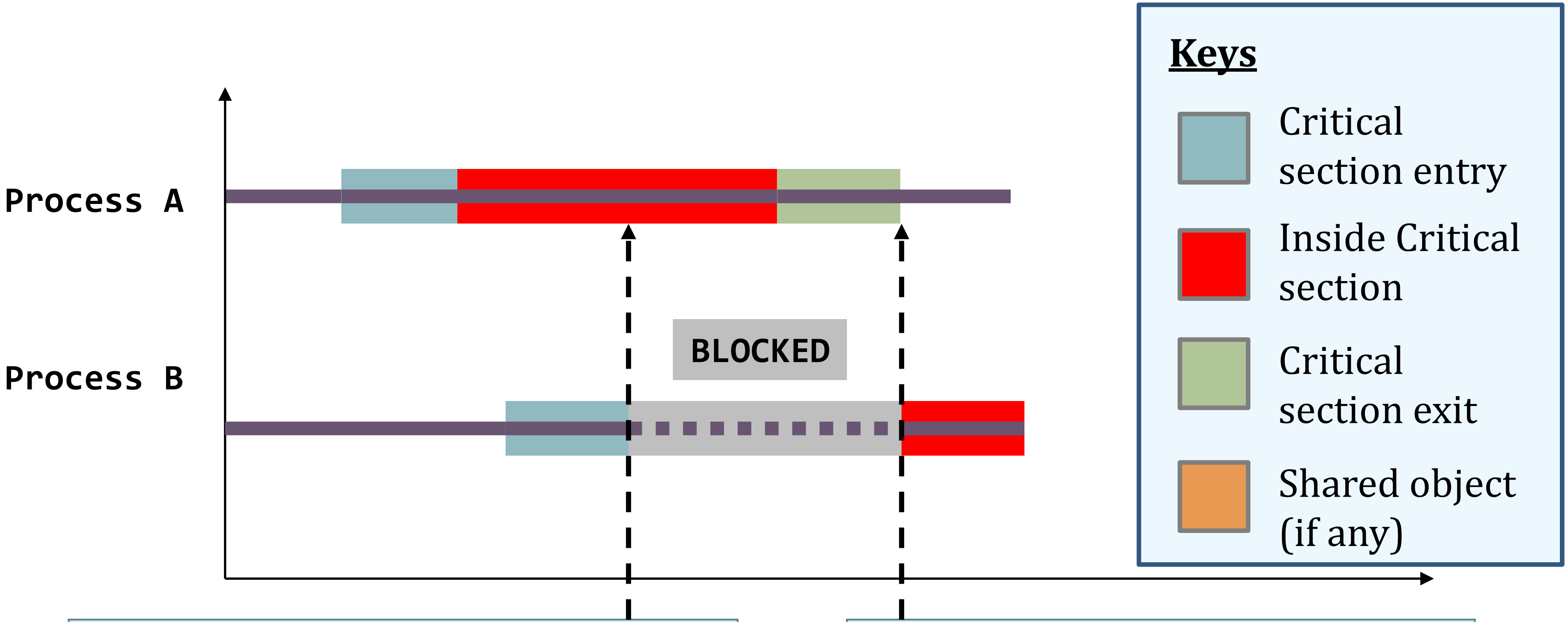
- **<u>Requirement #3</u>. Progress**
  - Say no process currently in C.S.
  - One of the processes trying to enter will eventually get in

https://en.wikipedia.org/wiki/Non-blocking_algorithm

Progress vs. bounded waiting

- If no process can enter C.S, do not have *progress*
- If A waiting to enter its C.S, while B repeated leaves and re-enters its C.S *and infinitum*
- A does not have *bounded waiting (but B is having progress)*

A typical mutual exclusion scenario



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

A leaves its critical section and B resumes execution accordingly.

Achieving Mutual Exclusion

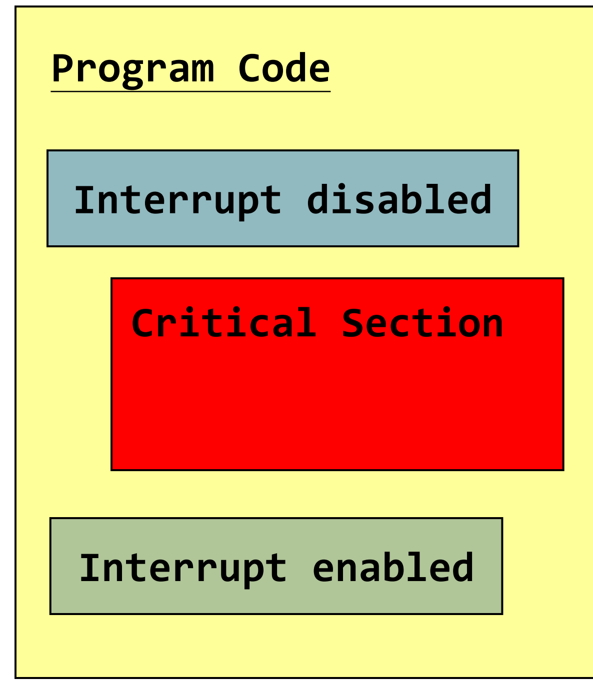
- Lock-based
  - Spin-based lock
    - E.g., use of "`pThread_spin_lock`"
      - What is inside?
        - **Basic spinning using 1 shared variable**
        - **Spin using 2 shared variables + good algorithm (=Peterson's solution)**
        - Spin using atomic instructions + smart algorithm (=Ticket, MCS algorithm, etc.)
  - Sleep-based lock
    - E.g., **POSIX `semaphore`**, `pThread_mutex_lock`
      - What is inside?
        - wait, yield(), atomic instructions + smart algorithm
- Lock-free

User-level synchronization

- You can treat that as:
  - You add some more global variables and write some while-loop smartly
  - Proper use of some library functions (e.g., pthread library)
  - You follow some synchronization “algorithm” to work on your case
  - …

#0 – disabling interrupt for the whole CS

- **Aim**
  - To **disable context switching** when the process is inside the critical section.
- **Effect**
  - When a process is in its critical section, no other processes could be able to run.
- **Correctness?**
  - **Uni-core: Correct but not permissible**
    - at userspace: what if one writes a CS that loops infinitely and the other process (e.g., the shell) never gets the context switch back to kill it?
    - At 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!!!!)



#1: Basic Spin lock (busy waiting)

- **Aim.**
  - Loop on yet another shared object, **`turn`**, to detect the status of other processes

Shared object "turn" `initial value = 0`

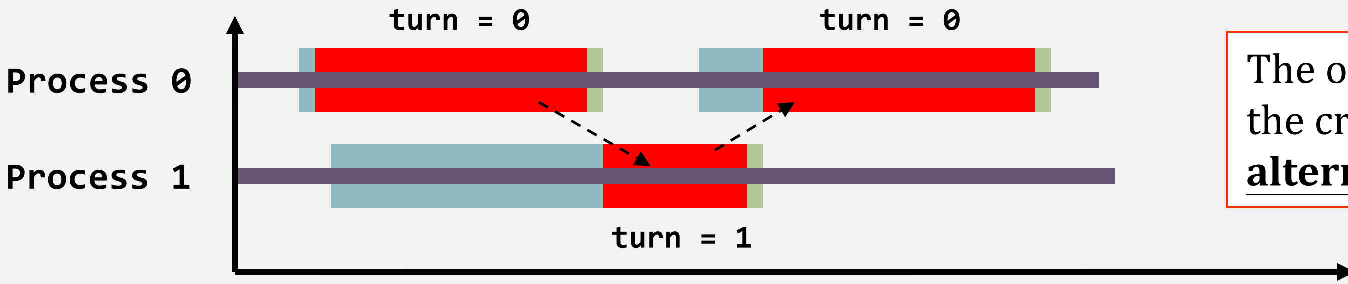
```
while (TRUE) {
  while( turn != 0 )
    ; /* busy waiting */
  critical_section();
  turn = 1;
  remainder_section();
}
```

Process 0

```
while (TRUE) {
  while( turn != 1 )
    ; /* busy waiting */
  critical_section();
  turn = 0;
  remainder_section();
}
```

Process1

#1: Basic Spin lock (busy waiting)



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

Shared object "turn" `initial Value = 0`

Process 0

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

    critical_section();

    turn = 1;

    remainder_section();
}
```

Process1

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

    critical_section();

    turn = 0;

    remainder_section();
}
```

#1: Basic Spin lock (busy waiting)

- Correct
  - but it wastes CPU resources
  - OK for short waiting
    - Especially these days we have multi-core
      - Will not block other irrelevant processes a lot
    - Ok when spin-time < context-switch-overhead
- Impose a "strict alternation" order
  - Sometimes you give me my turn but I'm not ready to enter CS yet
    - Then you have to wait long

#1: Basic Spin lock (busy waiting)

- You can wrap them as lock() and unlock() functions
- In fact, some nice people wrap their super efficient implementation of the spinlock concept as pthread_mutex_lock() and pthread_mutex_unlock() functions

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

    critical_section();

    turn = 1;

    remainder_section();
}
```

```
while (TRUE) {
    lock();

    critical_section();

    unlock();

    remainder_section();
}
```

#1: Basic Spin lock violates *progress*

- 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()`

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

  cs();

  turn = 1;

  remainder_section();
}
```

Process 0

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

  cs();

  turn = 0;

  remainder_section_slow ();
}
```

Process 1

#2: Spin Smarter (by Peterson's solution)

- Highlight:
  - Use one more extra shared object: **`interested`**
    - If I don't show interest
      - I let you **all** go
    - If we both show interest
      - Take turns

Shared objects:
- turn &
- "interested[2]"

#2: Spin Smarter (by Peterson's solution)

```
int turn;                            /* who is last enter cs */
int interested[2] = {FALSE,FALSE};  /* express interest to enter cs*/

void lock( int process ) {  /* process is 0 or 1 */
  int other;                         /* number of the other process */
  other = 1-process;                 /* other is 1 or 0 */
  interested[process] = TRUE;        /* express interest */
  turn = process;
  while ( turn == process &&
          interested[other] == TRUE )
    ;    /* busy waiting */
}

void unlock( int process ) {    /* process: who is leaving */
  interested[process] = FALSE;    /* I just left critical region */
}
```

#2: Spin Smarter (by Peterson's solution)

```
int turn;
int interested[2] = {FALSE,FALSE};

void lock( int process ) {
  int other;
  other = 1-process;
  interested[process] = TRUE;
  turn = process;
  while ( turn == process &&
          interested[other] == TRUE )
     ;    /* busy waiting */
}

void unlock( int process ) {
  interested[process] = FALSE;
}
```

Express interest to enter CS

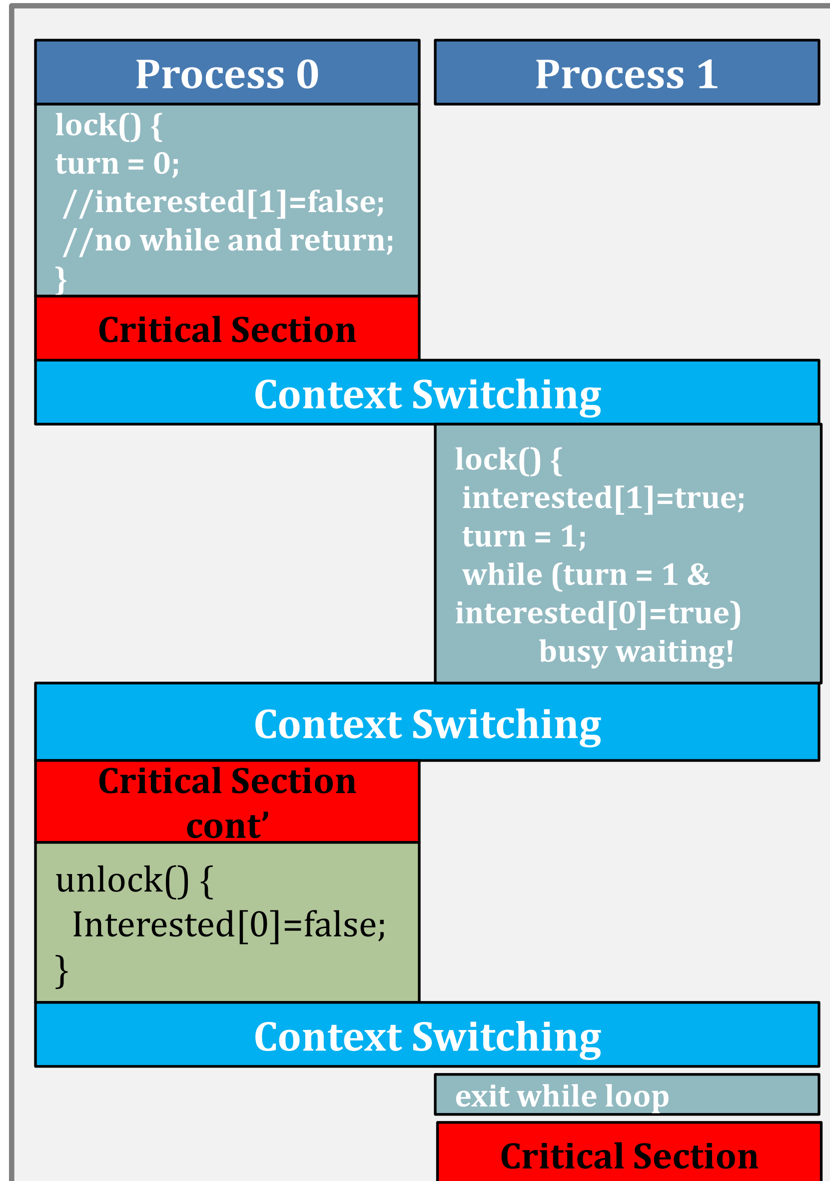
If others not show interest, I can always go ahead

#2: Spin Smarter (by Peterson's solution)

```
int turn;
int interested[2] = {FALSE,FALSE};

void lock( int process ) {
  int other;
  other = 1-process;
  interested[process] = TRUE;
  turn = process;
  while ( turn == process &&
              interested[other] == TRUE )
     ;    /* busy waiting */
}

void unlock( int process ) {
  interested[process] = FALSE;
}
```



#2: Spin Smarter (by Peterson's solution) (another case)

```
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 = process;
9     while ( turn == process &&
                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 = 0;	

Context Switching	

	lock() {
	interested[1]=true;
	turn = 1;

Context Switching	

turn == 0 ? //line 9
false
no busy waiting	

Critical Section	
Context Switching	

	turn == 1? //line 9
	&& interested[0]=true?
	busy waiting!

...

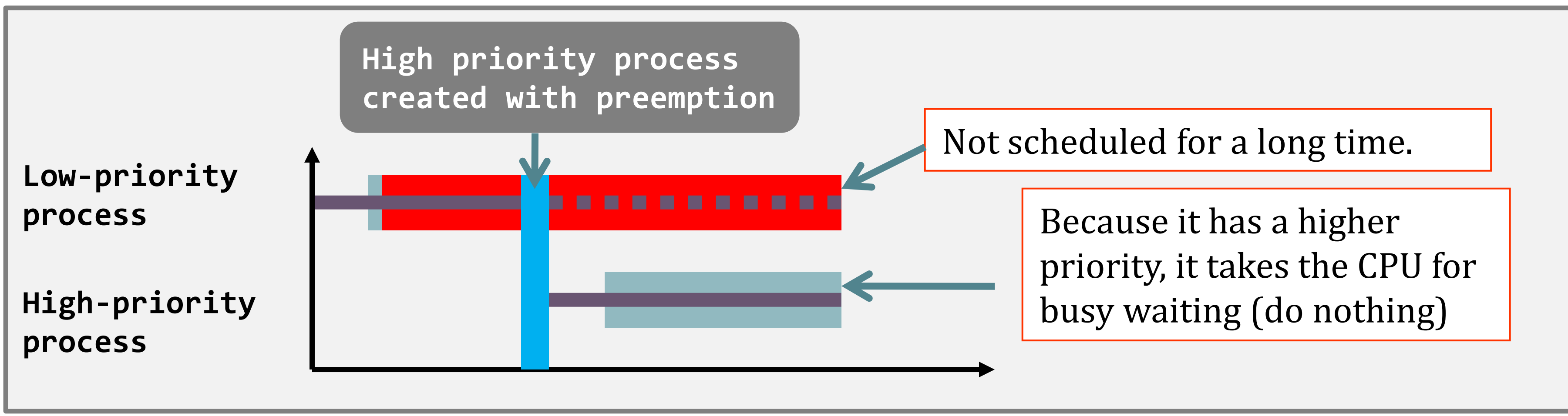
Spin Smarter (by Peterson's solution)

- = Busy waiting
  + shared variable **turn** for mutual exclusion
  + shared variables **interest** to resolve strict alternation
- Wikipedia:
  - *"It satisfies the three essential criteria to solve the critical section problem, provided that changes to the variables turn, interest[0], and interest[1] propagate immediately and atomically."*
- Suffer from **priority inversion problem**

Does it work for >2 processes?
https://en.wikipedia.org/wiki/Peterson's_algorithm

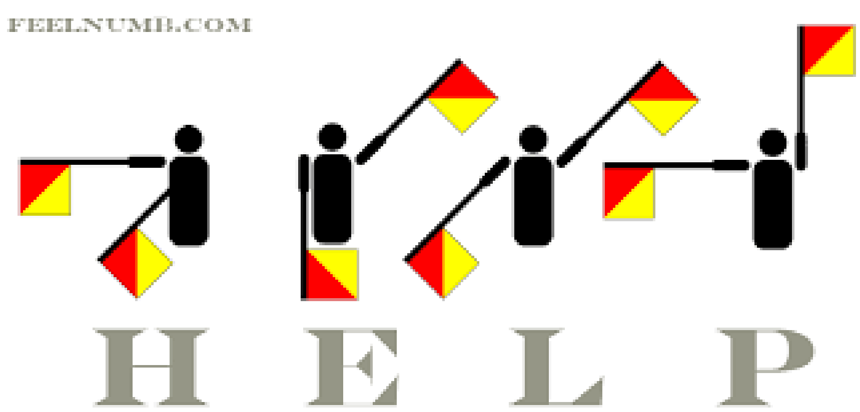
Peterson spinlock suffers from Priority Inversion

- 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** can not **`lock`** (because **L** has not **`unlock`**)
    - So, **H** gets the CPU to do nothing but spinning



#3: Sleep-based lock: Semaphore

- Semaphore is just a struct
  - Include
    - 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
  - Need to interact with scheduler (must involve kernel, e.g., syscall)
  - Implement uninterruptable **section entry/exit**
    - Section entry/exit function are **short**
      - **Compared with Implementation #0 (uninterruptable throughout the whole CS)**



https://en.wikipedia.org/wiki/Semaphore_(programming) check out the library analogy

Semaphore logical view

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

Section Entry: sem_wait()

```
void sem_wait(semaphore *s) {
   disable_interrupt();
   *s = *s - 1;
   if ( *s < 0 ) {
      enable_interrupt();
      sleep();
      disable_interrupt();
   }
   enable_interrupt();
}
```

Initialize **s** = 1

"sem_**wait(s)**"

- I wait until I get <u>an</u> **s** (i.e., **wait(s)** only returns when I get <u>an</u> **s**)
- Implementation:
  # of **s**--;
  sleep if # of **s** < 0;

<u>Important 1</u>
s can be a plural

<u>Important 2</u>
This wait is different from parent's folk wait(child). When programming, it is sem_wait()

"sem_**post(s)**"

- I notify the others that one **s** is added
- Implementation:
  # of **s**++;
  If someone is waiting **s**, wakeup one of them

Section Exit: sem_post()

```
void sem_post(semaphore *s) {
   disable_interrupt();
   *s = *s + 1;
   if ( *s <= 0 )
      wakeup();
   enable_interrupt();
}
```

Example

Process
1234

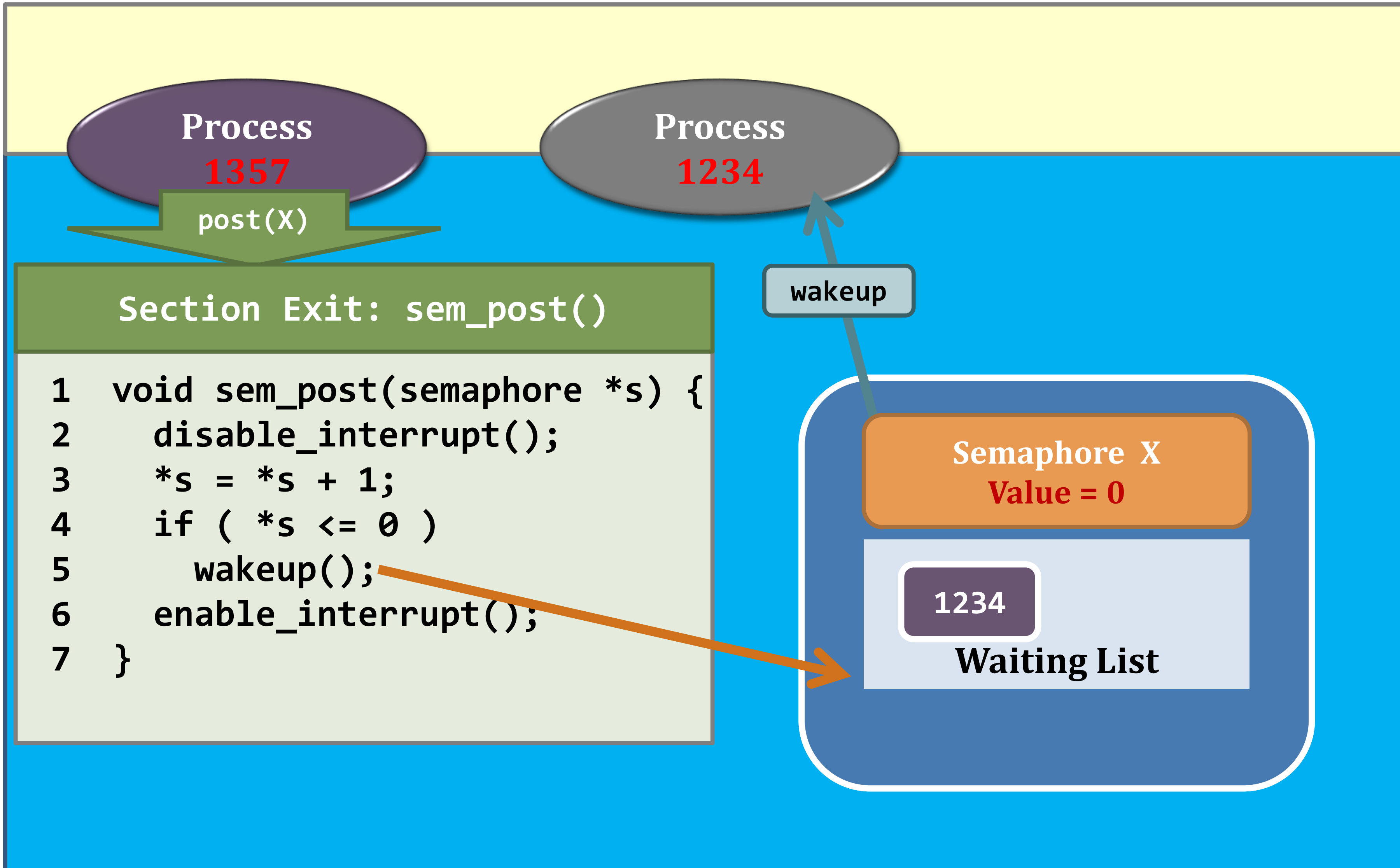
`Sem_wait(X)`

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

Section Entry: sem_wait()

```
void sem_wait(semaphore *s){
    disable_interrupt();
   *s = *s - 1;
    if ( *s < 0 ) {
        enable_interrupt();
        sleep();
        disable_interrupt();
     }
    enable_interrupt();
}
```

Example


Process
1357
post(X)
Process
1234
wakeup
Section Exit: sem_post()
void sem_post(semaphore *s) {
disable_interrupt();
*s = *s + 1;
if (*s <= 0)
wakeup();
enable_interrupt();
}
Semaphore X
Value = 0
1234
Waiting List

Example

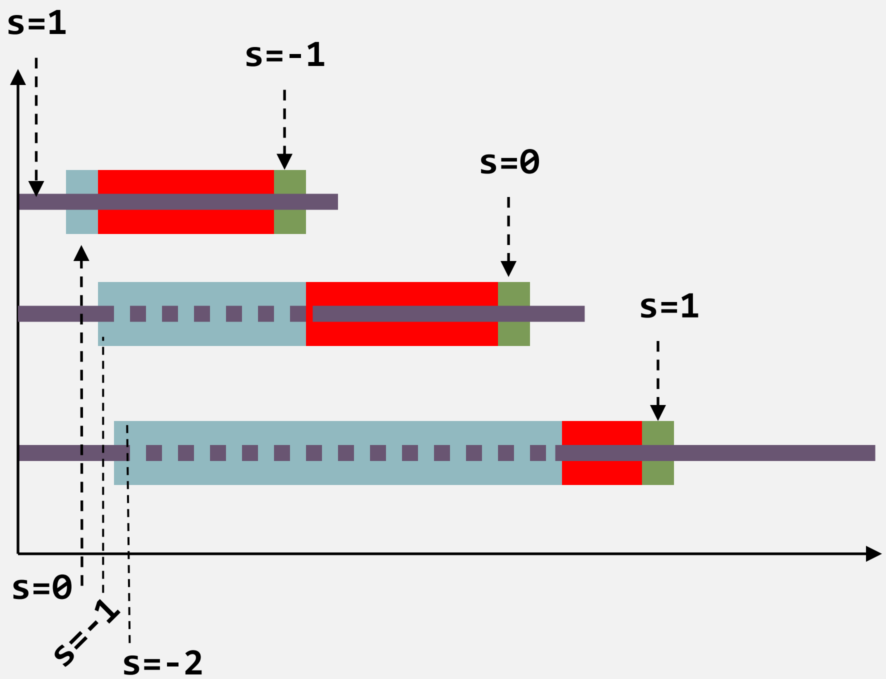
Process 1234

return

Section Entry: sem_wait()

```
void sem_wait(sem. *s) {
    disable_interrupt();
    *s = *s - 1;
    if ( *s < 0 ) {
        enable_interrupt();
        sleep();
        disable_interrupt();
     }
    enable_interrupt();
}
```

Using Semaphore (user-level)




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

```
while(TRUE) {
    sem_wait(s);
    critical_section();
    sem_post(s);
}
```

entry

exit

Using Semaphore beyond mutual exclusion

- Can also be used as a synchronization primitive to solve IPC problems
  - E.g., make sure "ls" waits until "less" consumes things from the pipe (otherwise the pipe will overflow)

Which one is the shared object in this picture?

Achieving Mutual Exclusion

- Lock-based
  - Spin-based lock
    - E.g., use of "`pThread_spin_lock`"
      - What is it inside?
        - **Basic spinning using 1 shared variable**
        - **Spin using 2 shared variables + good algorithm (=Peterson's solution)**
        - Spin using atomic instructions + smart algorithm (=Ticket, MCS algorithm, etc.)
  - Sleep-based lock
    - E.g., **POSIX `semaphore`**, `pThread_mutex_lock`
      - What is it inside?
        - wait, yield(), atomic instructions + smart algorithm
- Lock-free

IPC / Synchronization problems

	Properties	Examples
Producer-Consumer Problem	Two classes of processes: **producer** and **consumer**; At least one producer and one consumer. [Single-Object Synchronization]	Pipe, Named Pipe
Dining Philosopher Problem	They are all running the same program; At least two processes. [Multi-Object Synchronization]	Cross-road traffic control
Reader Writer Problem	Multiple reads, 1 write	…
…		

Named Pipe (a.k.a. FIFO in Linux)
- Like Shared File (so **multiple** producers and consumers; unlike pipe)
- Like Pipe (unidirectional)
- In-memory (unlike file)
- Use like pipe (more restrictive; unlike shared memory)

Inter-process communication (IPC)
- Classic IPC problems.
- Producer-consumer problem.

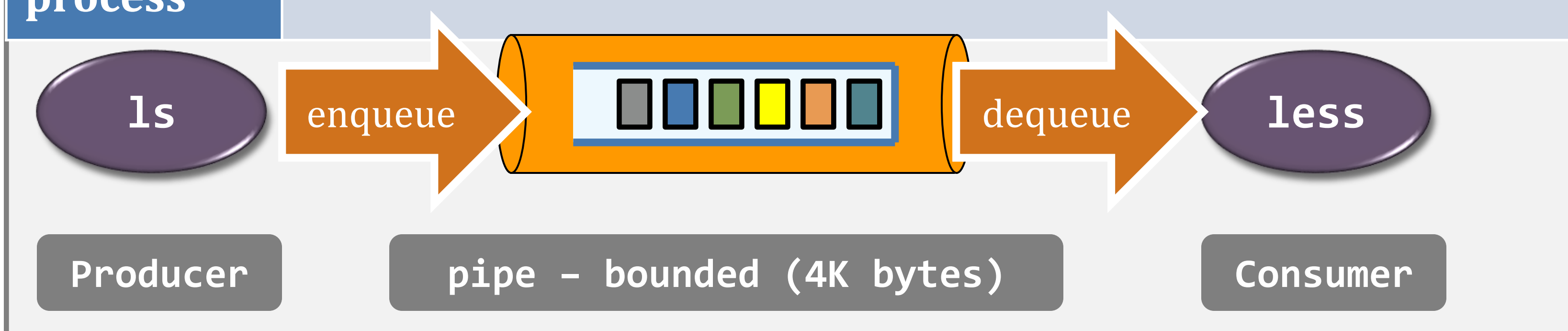
In the following, we demonstrate how to use semaphore to solve some IPC problems.

Semaphore is not the only way. You might use (i) lock + condition variable, (ii) use X more shared variables (like Peterson's solution) directly, ...

Producer-consumer problem – introduction

- 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 that 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.



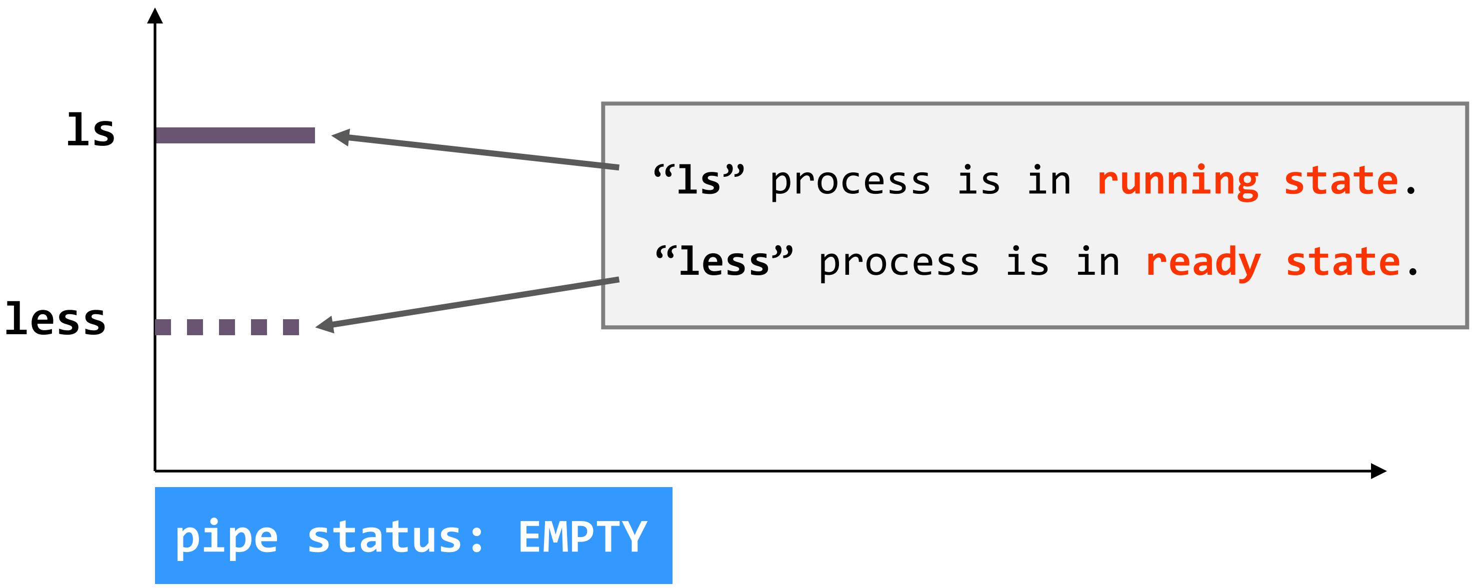
Producer-consumer problem – introduction

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.

Producer-consumer problem – pipe

Assumptions

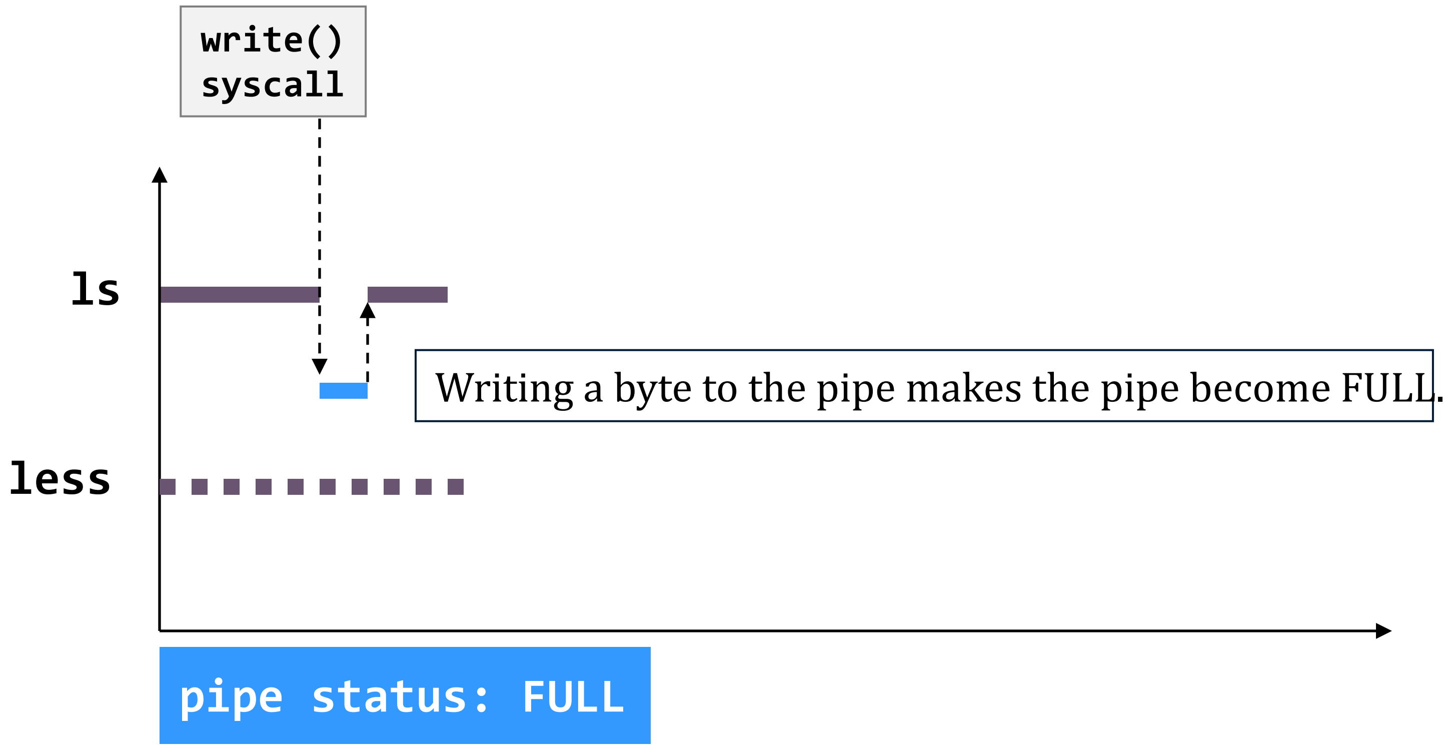
- The pipe is a queue of **1 byte** only!
- Each **write()** system call writes **1 byte** to the pipe.
- Each **read()** system call reads **1 byte** from the pipe.



Producer-consumer problem – pipe

Assumptions

```
- The pipe is a queue of 1 byte only!
- Each write() system call writes 1 byte to the pipe.
- Each read() system call reads 1 byte from the pipe.
```



Producer-consumer problem – pipe

Assumptions

- The pipe is a queue of **1 byte** only!
- Each **write()** system call writes **1 byte** to the pipe.
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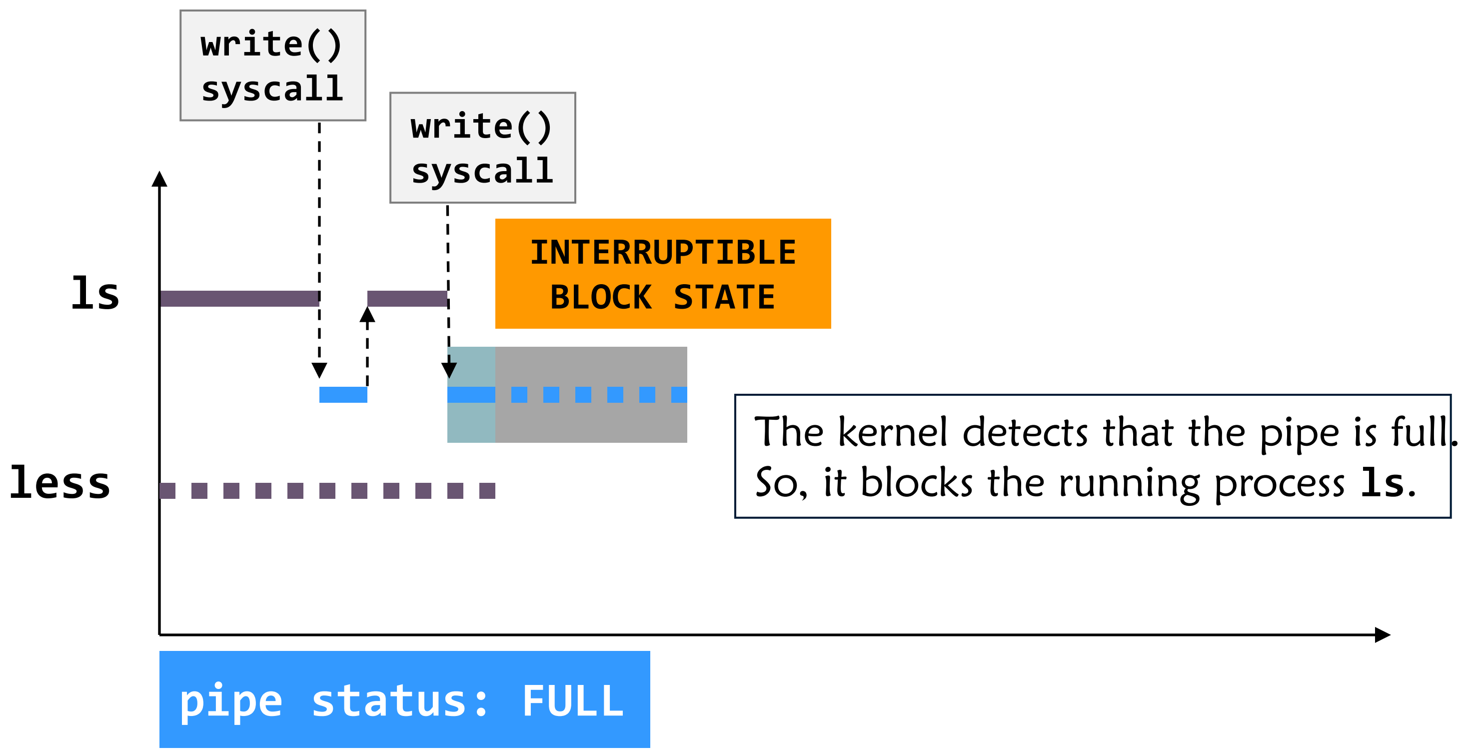
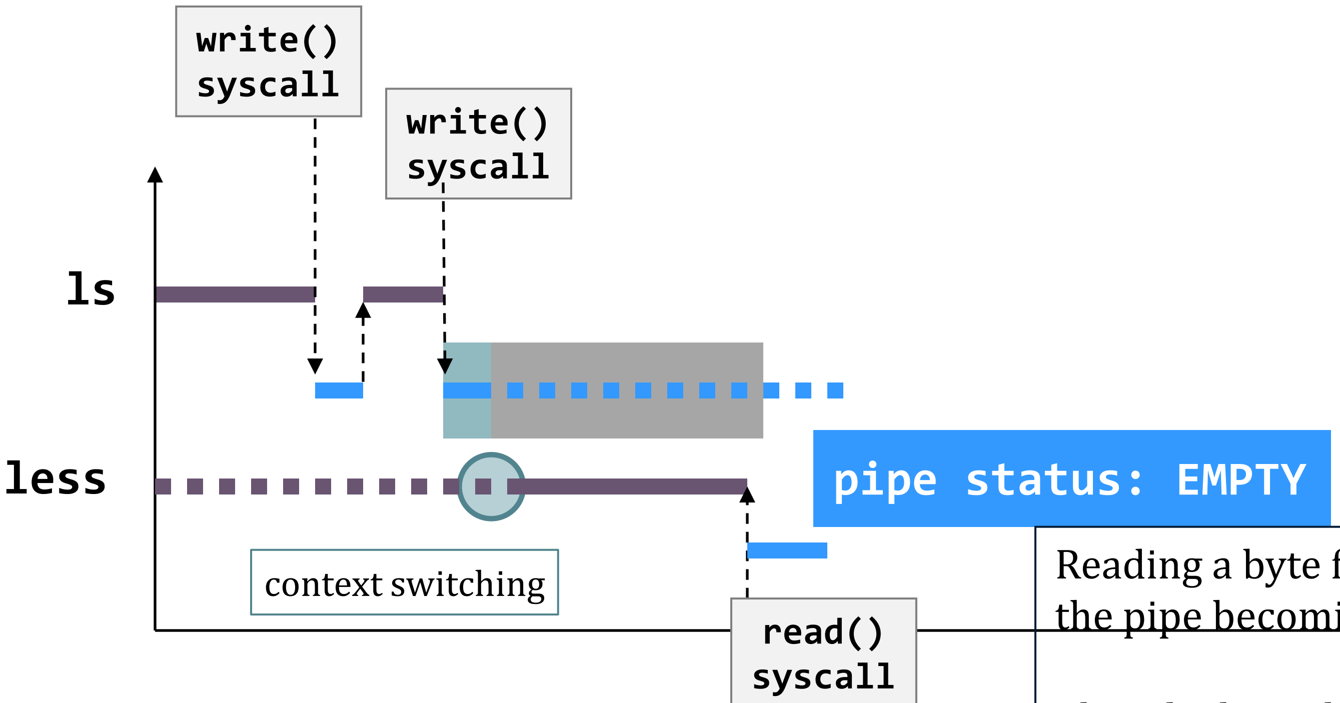


Producer-consumer problem – pipe

Assumptions

```
- The pipe is a queue of 1 byte only!
- Each write() system call writes 1 byte to the pipe.
- Each read() system call reads 1 byte from the pipe.
```



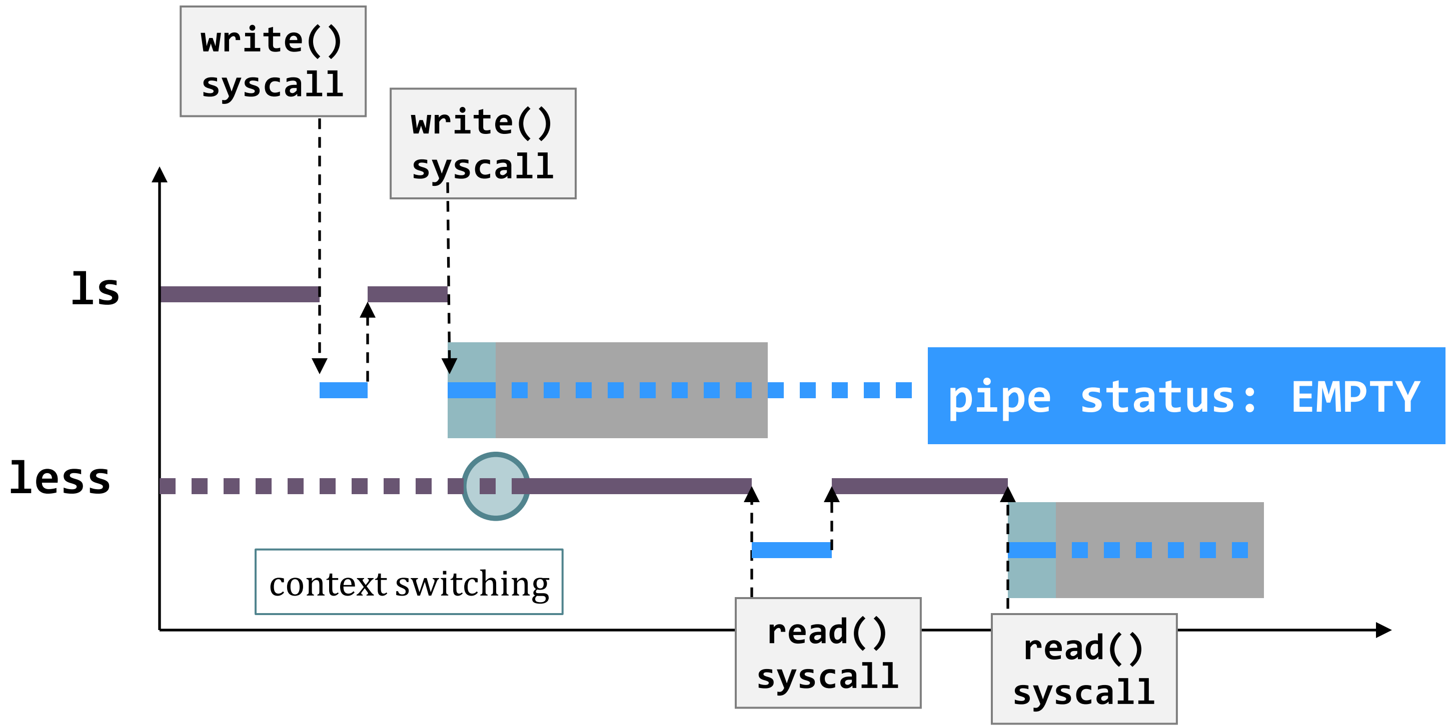
Reading a byte from the pipe makes the pipe becoming EMPTY.

Plus, the kernel **removes the interruptible block state** from the "**ls**" process.

Producer-consumer problem – pipe

Assumptions

- The pipe is a queue of **1 byte** only!
- Each **write()** system call writes **1 byte** to the pipe.
- Each **read()** system call reads **1 byte** from the pipe.



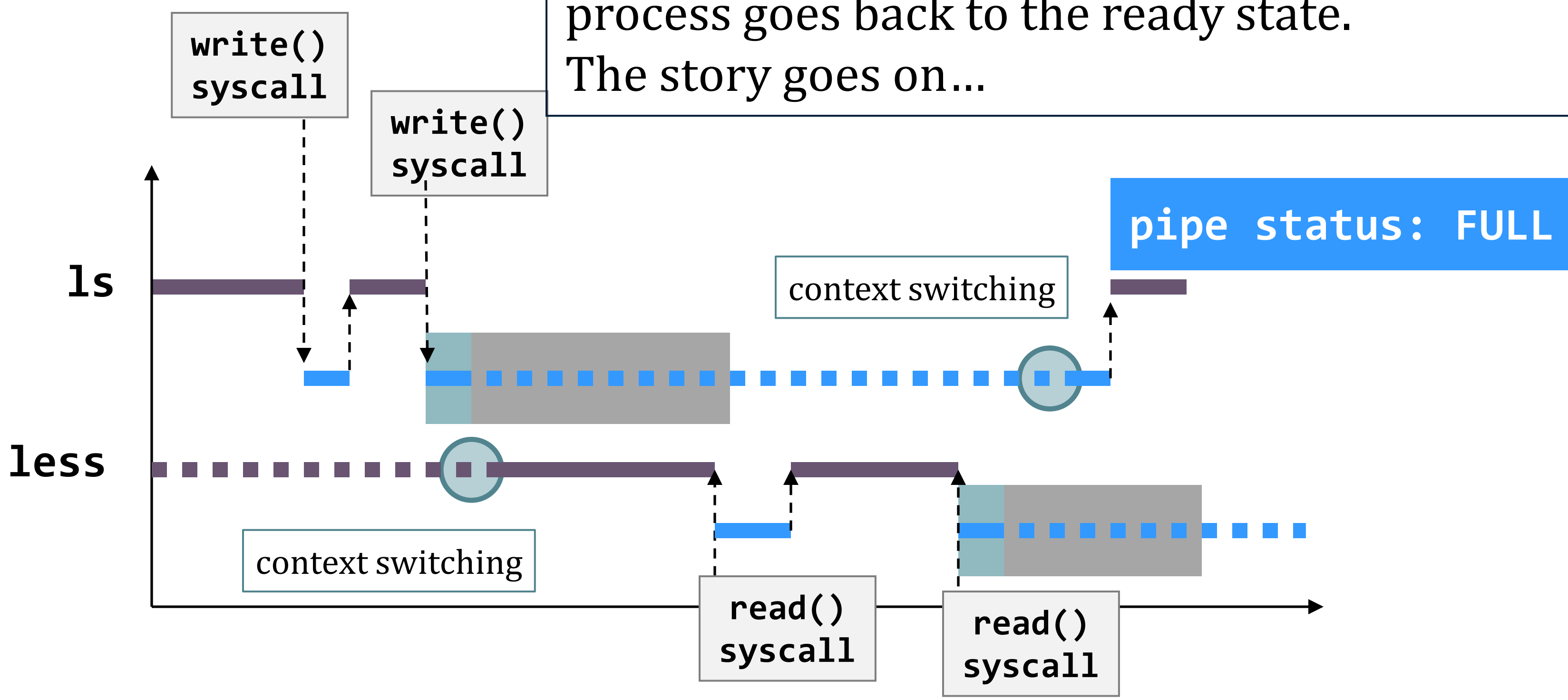
The kernel detects that the pipe is empty.
So, it blocks the running process **less**.

Producer-consumer problem – pipe

When "**`ls`**" process goes back to the running state, it **immediately writes a byte to the pipe so as to complete the execution of the `write()` system call**.

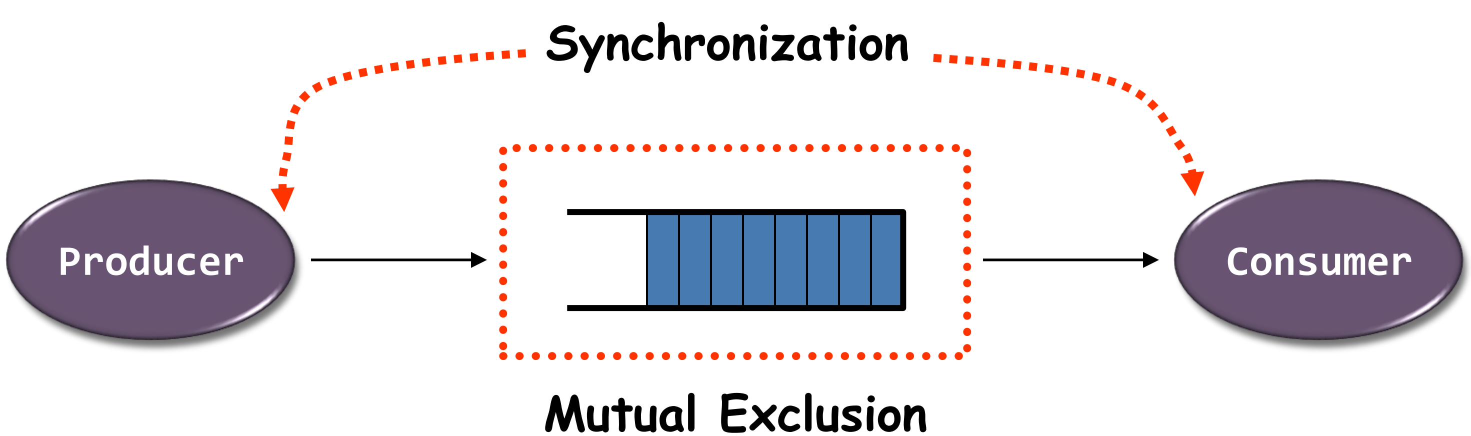
Then, the pipe is no longer empty, and the "**`less`**" process goes back to the ready state.

The story goes on…



Producer-consumer problem: semaphore

- The Producer-consumer problem is **more general** than the pipe story
  - *Pipe cannot work with >1 producers/consumers*
- The problem can be divided into two sub-problems.
  - Mutual exclusion.
    - The buffer is a shared object. **Mutual exclusion** is needed. Done by one binary semaphore
  - Synchronization.
    - Because the buffer's size is bounded, **coordination** is needed. Done by two 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



Producer-consumer problem: semaphore

Shared object

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

Note

The size of the bounded buffer is “N”.

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

Producer function

```
void producer(void) {
    int item;

    while(TRUE) {
        item = produce_item();
        wait(&avail);
        wait(&mutex);
        insert_item(item);
        post(&mutex);
        post(&fill);
    }
}
```

Consumer Function

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

    while(TRUE) {
        wait(&fill);
        wait(&mutex);
        item = remove_item();
        post(&mutex);
        post(&avail);
        //consume the item;
    }
}
```

Producer-consumer problem: 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 }
```

Producer-consumer problem: 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  }
```

Producer-consumer problem – 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

```
void producer(void) {
    int item;

    while(TRUE) {
        item = produce_item();
        wait(&avail);
        wait(&mutex);
        insert_item(item);
        post(&mutex);
        post(&fill);
    }
}
```

Consumer Function

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

    while(TRUE) {
        wait(&fill);
        wait(&mutex);
        item = remove_item();
        post(&mutex);
        post(&avail);
    //consume the item;
    }
}
```

Producer-consumer problem – question #1

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

```
wait s--
post s++
So,
• producer s-- by wait
• consumer s++ by post
Problem solved?
```

Producer function

```
void producer(void) {
    int item;

    while(TRUE) {
        item = produce_item();
        wait(&avail);
        wait(&mutex);
        insert_item(item);
        post(&mutex);
        ~~post(&fill);~~
    }
}
```

Consumer Function

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

    while(TRUE) {
        ~~wait(&fill);~~
        wait(&mutex);
        item = remove_item();
        post(&mutex);
        post(&avail);
    //consume the item;
    }
}
```

Producer-consumer problem – question #1

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

```
wait s--
post s++
So,
y wait
y post
```

If consumer gets CPU first, it removes item from NULL

ERROR

Producer function

```
void producer(void) {
    int item;

    while(TRUE) {
        item = produce_item();
        wait(&avail);
        wait(&mutex);
        insert_item(item);
        post(&mutex);
        ~~post(&fill);~~
    }
}
```

Consumer Function

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

    while(TRUE) {
        ~~wait(&fill);~~
        wait(&mutex);
        item = remove_item();
        post(&mutex);
        post(&avail);
    //consume the item;
    }
}
```

Producer-consumer problem – 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;
```

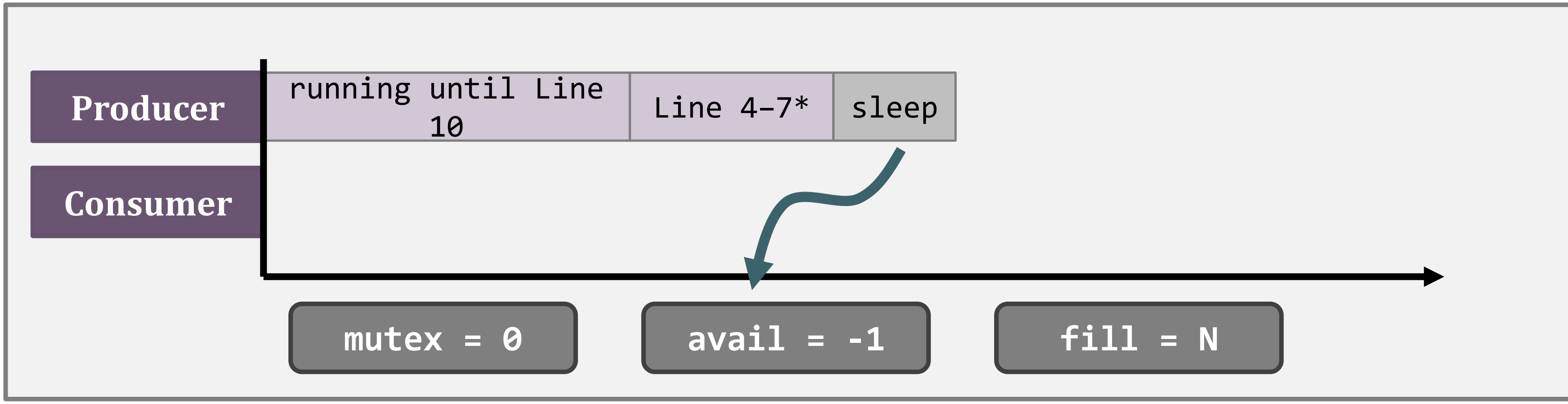
Producer function

```
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

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

    while(TRUE) {
        wait(&fill);
        wait(&mutex);
        item = remove_item();
        post(&mutex);
        post(&avail);
        //consume the item
    }
}
```

Producer-consumer problem – question #2



Producer function

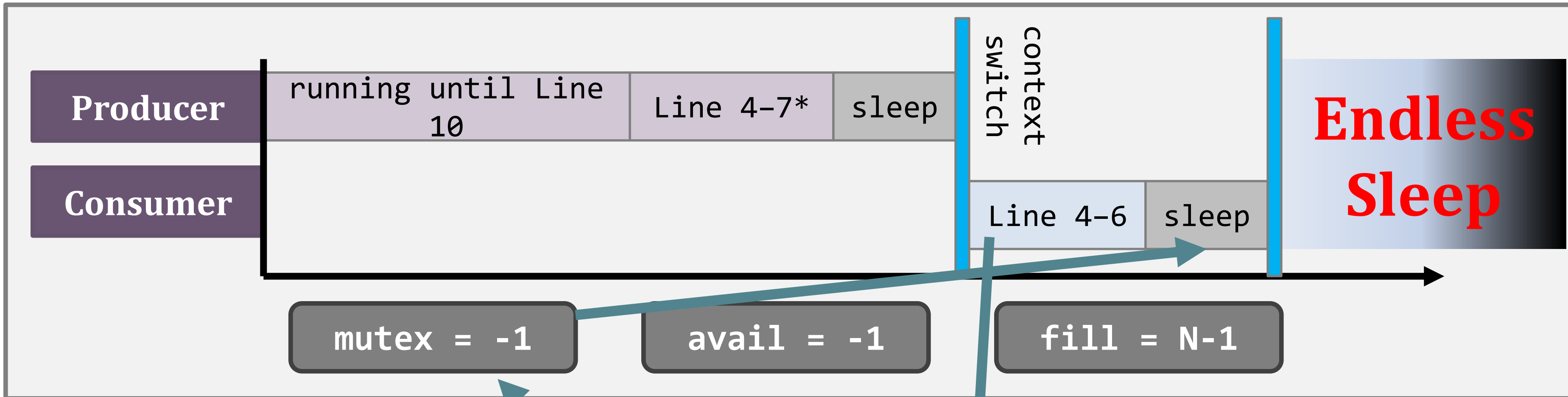
```
1   void producer(void) {
2       int item;
3
4       while(TRUE) {
5           item = produce_item();
6*          wait(&mutex);
7*          wait(&avail);
8           insert_item(item);
9           post(&mutex);
10          post(&fill);
11      }
12  }
```

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  }
```

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

Producer-consumer problem – 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);  !sleep with lock!
8           insert_item(item);
9           post(&mutex);
10          post(&fill);
11      }
12  }
```

Consumer Function

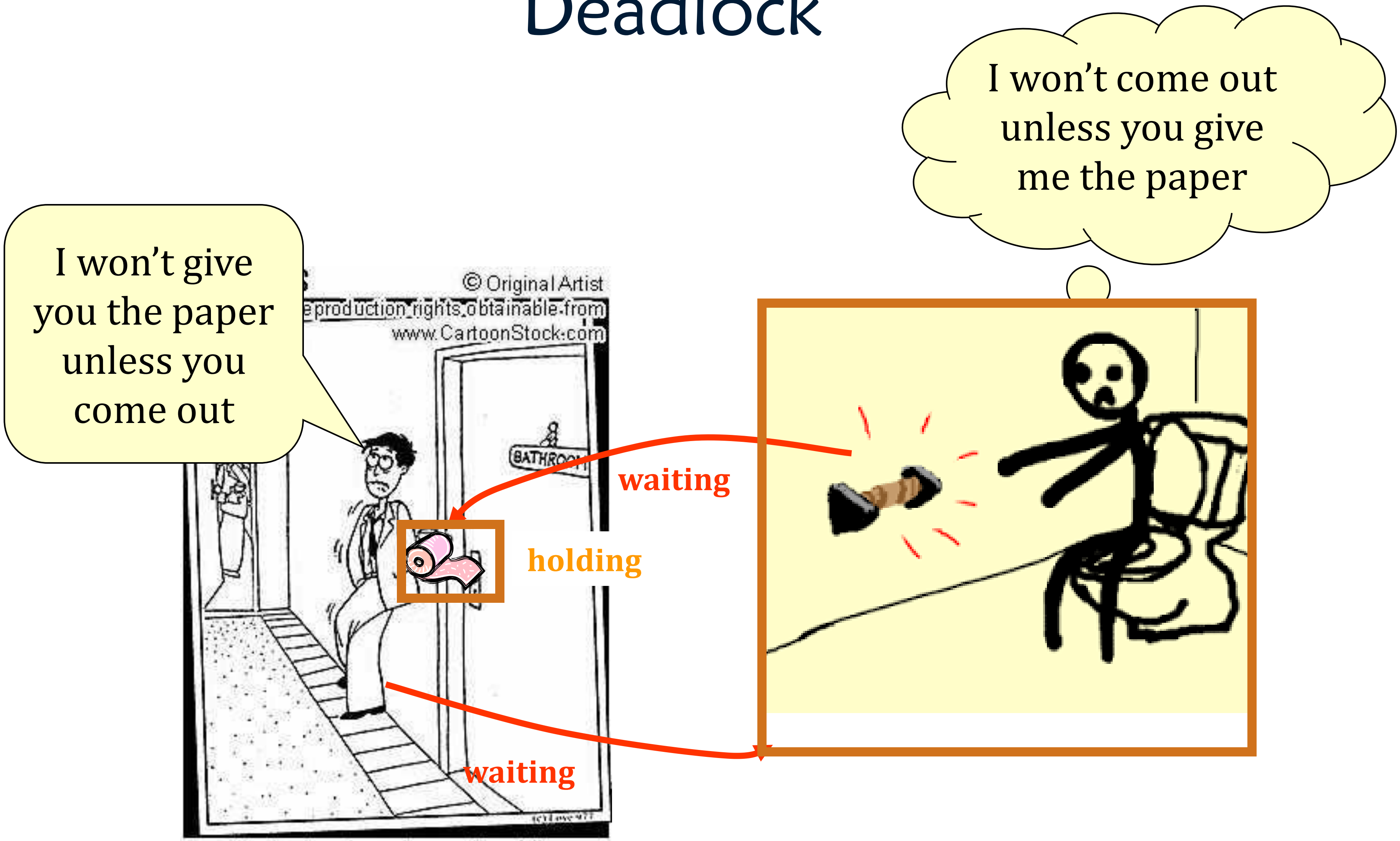
```
1   void consumer(void) {
2       int item;
3
4       while(TRUE) {
5           wait(&fill);
6           wait(&mutex);
7           item = remove_item();
8           post(&mutex);
9           post(&avail);
10          //consume the item
11      }
12  }
```

Producer-consumer problem – 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.

Deadlock



I won't give you the paper unless you come out
I won't come out unless you give me the paper
© Original Artist
www.CartoonStock.com
waiting
holding
waiting

Summary on producer-consumer problem

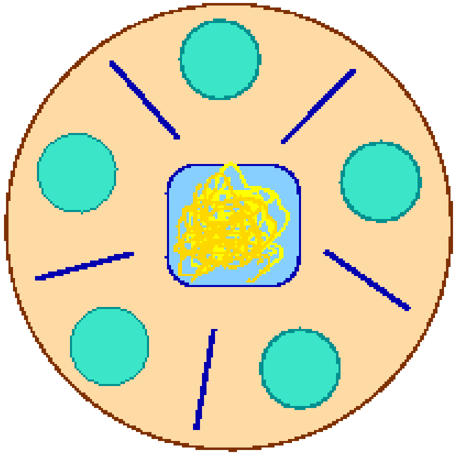
- How to avoid race condition on the shared buffer?
  - E.g., Use a **binary semaphore**.
- How to achieve synchronization?
  - E.g., Use two semaphores: fill and avail

Inter-process communication (IPC)

- **Classic IPC problems.**
  - **Producer-consumer problem.**
  - **Dining philosopher problem.**

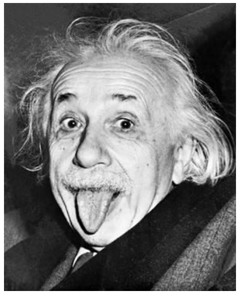
Dining philosopher – introduction

- 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 ....

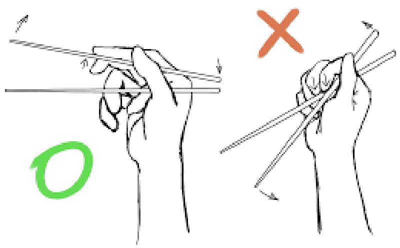


It's a multi-object synchronization problem

Dining philosopher – introduction



Philosophers



Chopsticks

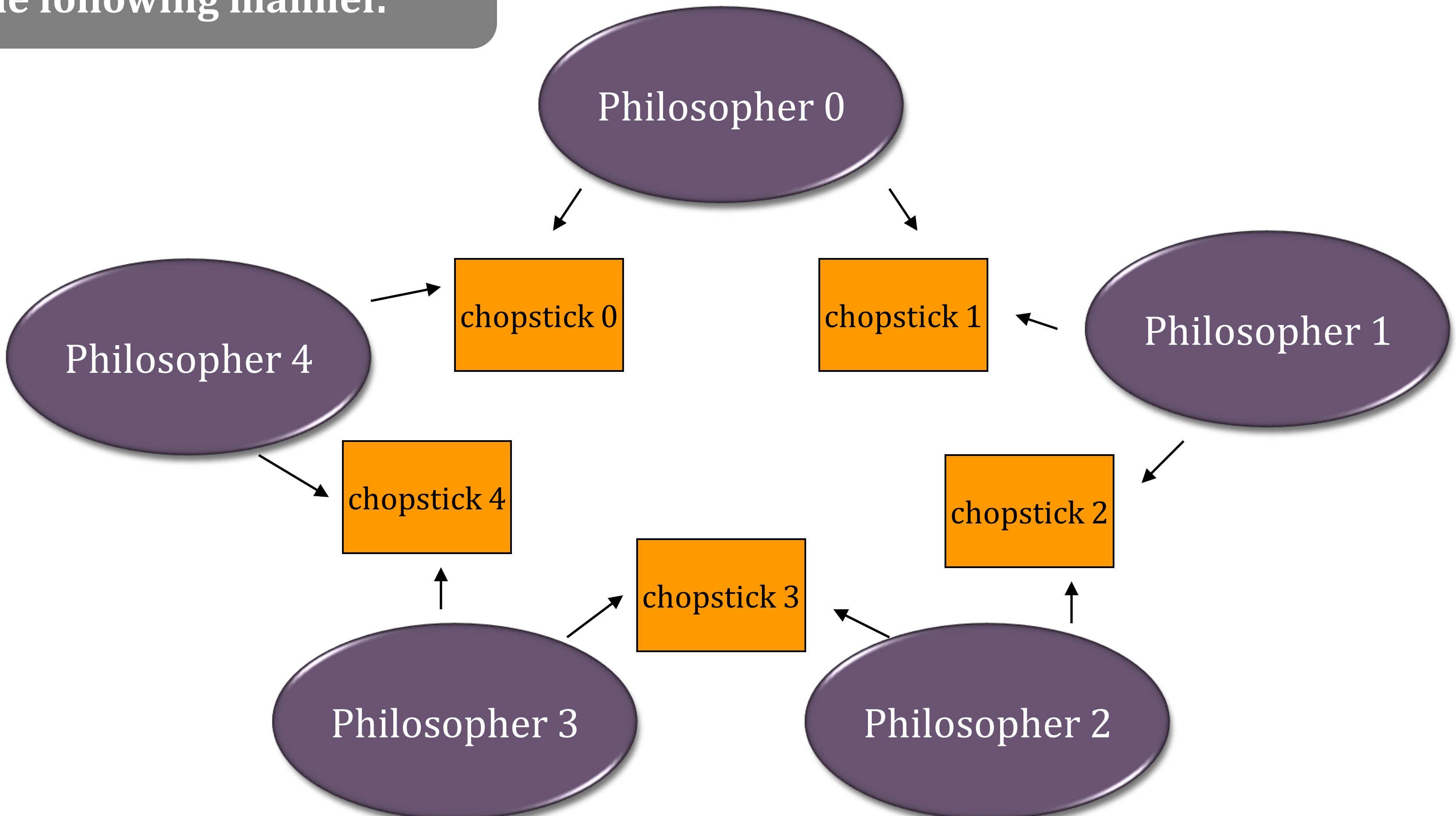
Process

Shared Object

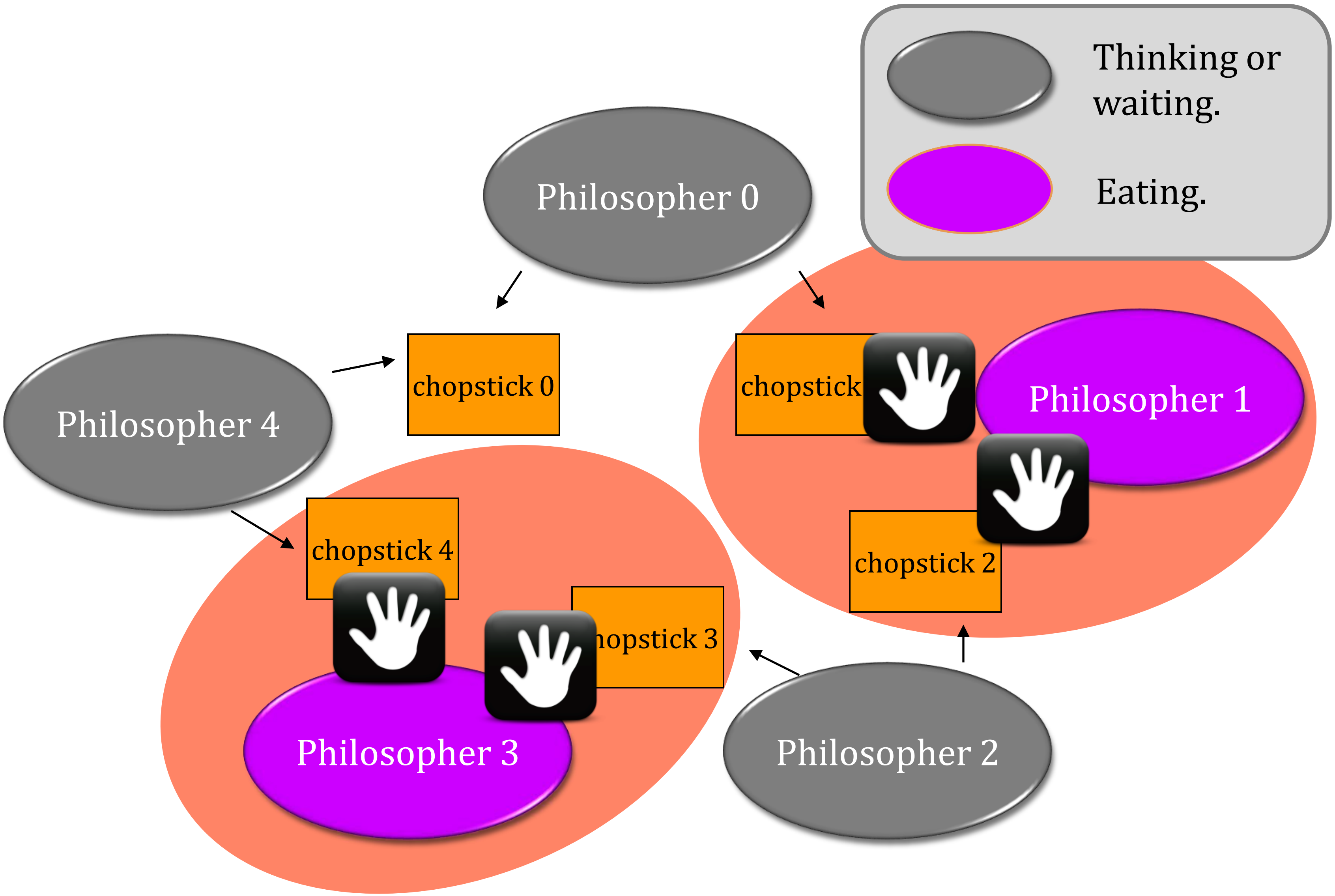
A process needs two shared resources in order to do some work

Dining philosopher – introduction

The chopsticks are arranged in the following manner.



Dining philosopher – introduction



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 all your chopsticks.

Dining philosopher – meeting 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

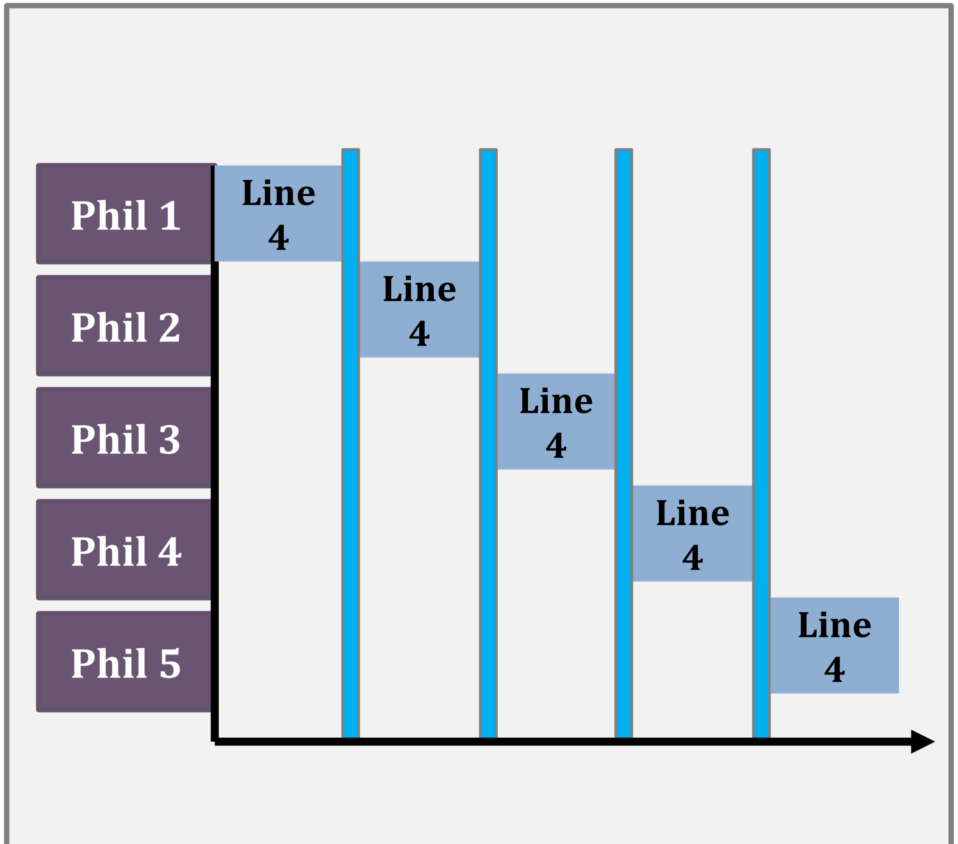
Section Exit

Main Function

```
void philosopher(int i) {
    while (TRUE) {
        think();

        take_chopstick(i);
        take_chopstick((i+1) % N);

        eat();

        put_chopstick(i);
        put_chopstick((i+1) % N);
    }
}
```

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

- **<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 – meeting 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

- Before we present the final solution, let us see what problems we have.

Problems
<u>**Model each chopstick as a semaphore is intuitive, but may cause deadlock**</u>
<u>**Using `sleep()` to avoid deadlock is effective, yet creating starvation.**</u>

Dining philosopher – before the final solution.

Philosopher 0
<u>EATING</u>

Philosopher 4
<u>CAN'T EAT</u>

Philosopher 1
<u>CAN'T EAT</u>

<u>Idea:</u>

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

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

Philosopher 3
<u>CAN EAT</u>

Philosopher 2
<u>CAN EAT</u>

Dining philosopher – the 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 – the 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

```
void philosopher(int i) {
    think();
    take_chopsticks(i);
    eat();
    put_chopsticks(i);
}
```

```
void wait(semaphore *s) {
   disable_interrupt();
    *s = *s - 1;
   if ( *s < 0 ) {
      enable_interrupt();
      sleep();
      disable_interrupt();
    }
   enable_interrupt();
}
```

Section entry

```
void take_chopsticks(int i) {
    wait(&mutex);
    state[i] = HUNGRY;
    captain(i);
    post(&mutex);
    wait(&p[i]);
}
```

Section exit

```
void put_chopsticks(int i) {
    wait(&mutex);
    state[i] = THINKING;
    captain(LEFT);
    captain(RIGHT);
    post(&mutex);
}
```

```
void post(semaphore *s) {
  disable_interrupt();
  *s = *s + 1;
  if ( *s <= 0 )
    wakeup();
  enable_interrupt();
}
```

Extremely important helper function

```
void captain(int i) {
    if(state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
        state[i] = EATING;
        post(&p[i]);
    }
}
```

Dining philosopher – 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

```
void take_chopsticks(int i) {
    wait(&mutex);
    state[i] = HUNGRY;
    captain(i);
    post(&mutex);
    wait(&p[i]);
}
```

<u>Critical Section</u>
The captain is “indivisible”

Extremely important helper function

```
void captain(int i) {
    if(state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
        state[i] = EATING;
        post(&p[i]);
    }
}
```

Dining philosopher – 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

```
void put_chopsticks(int i) {
    wait(&mutex);
    state[i] = THINKING;
    captain(LEFT);
    captain(RIGHT);
    post(&mutex);
}
```

Extremely important helper function

```
void captain(int i) {
    if(state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
        state[i] = EATING;
        post(&p[i]);
    }
}
```

Wake up the one who is sleeping

Dining philosopher – the final soluti

Don't print

An illustration: How can Philosopher 1 start eating?

Philosopher 0
<u>THINKING</u>

Philosopher 1
<u>THINKING</u>

Philosopher 4
<u>THINKING</u>

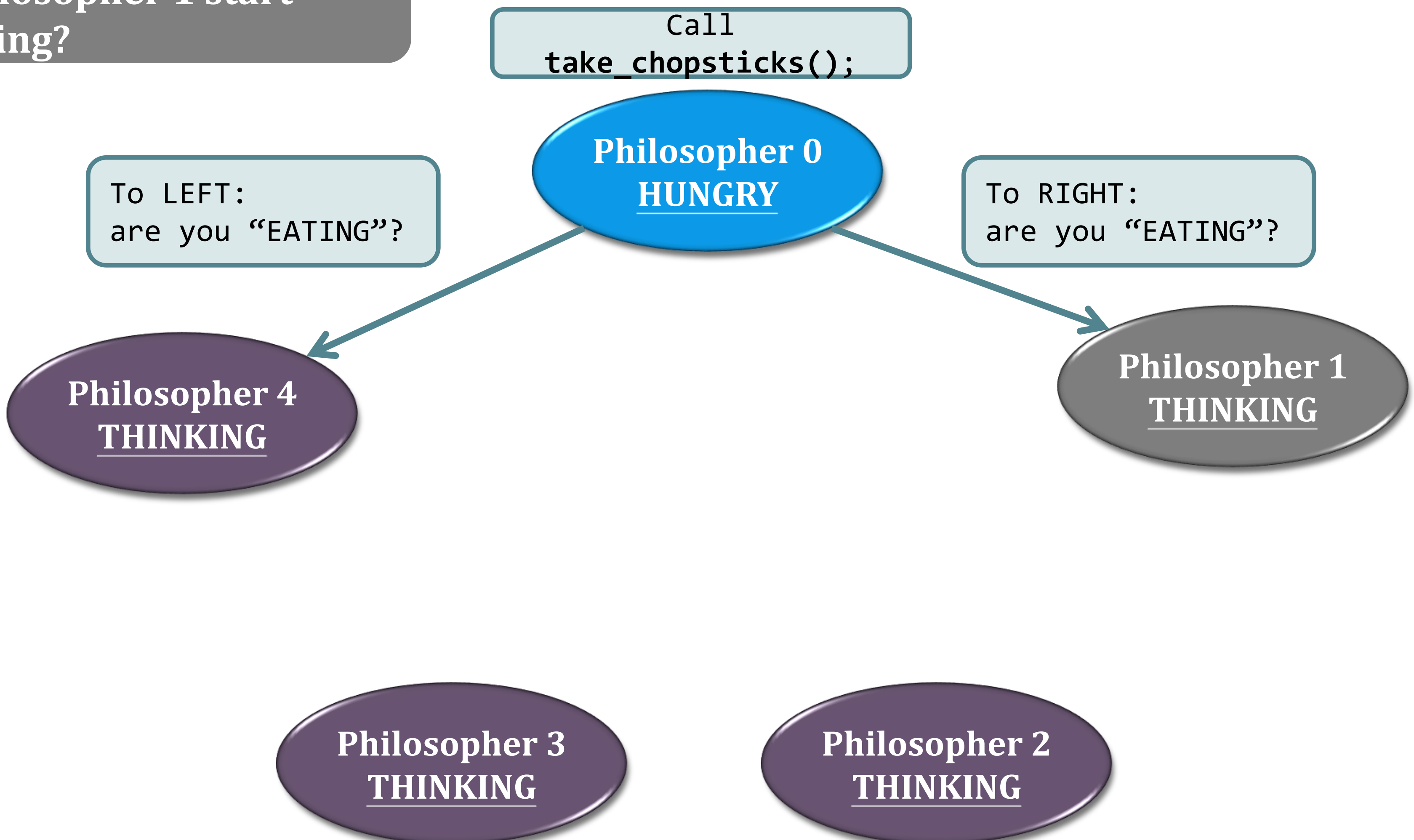
Philosopher 3
<u>THINKING</u>

Philosopher 2
<u>THINKING</u>

Dining philosopher – the final soluti

Don’t print

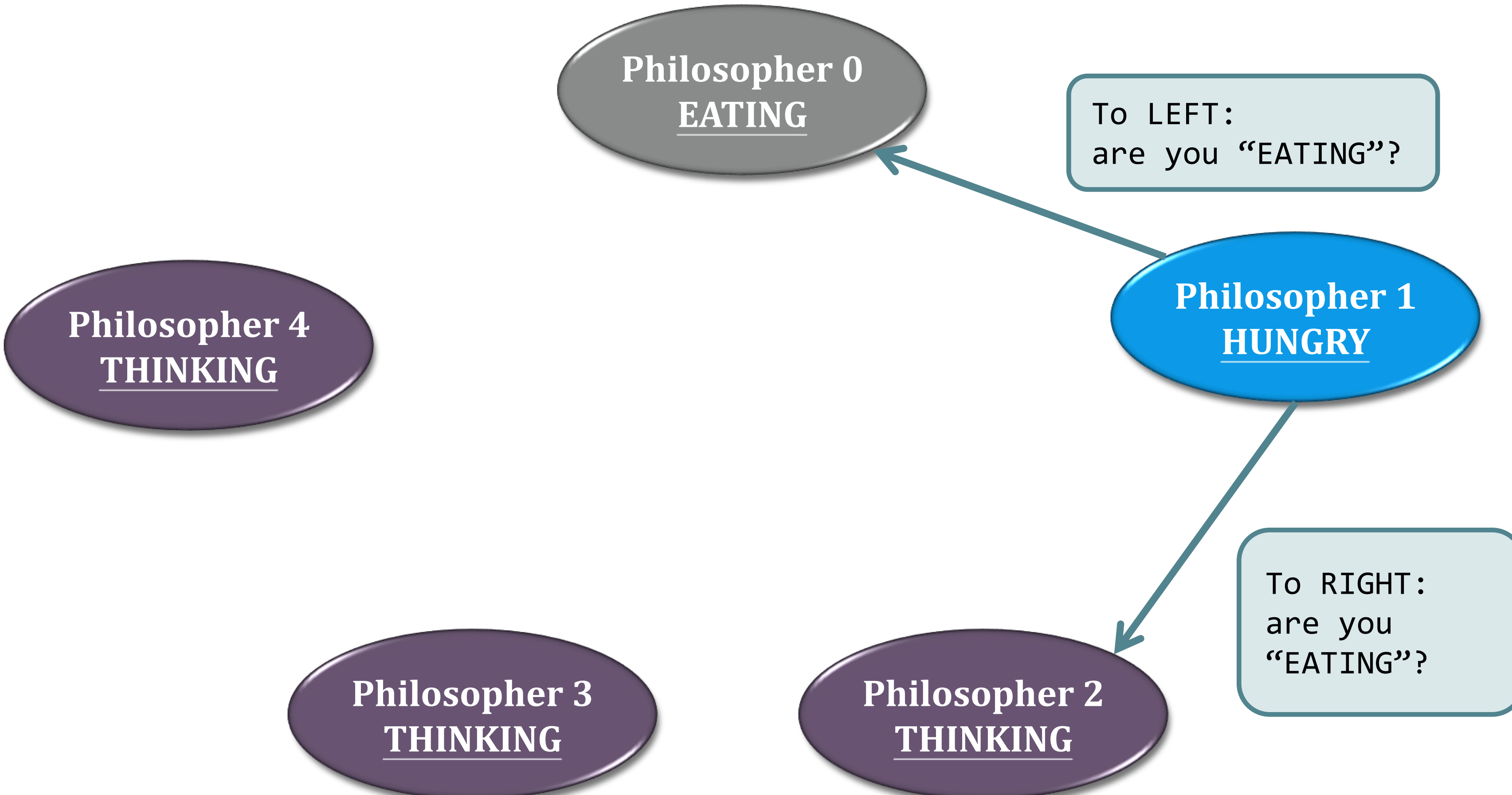
An illustration: How can Philosopher 1 start eating?



Dining philosopher – the final soluti

Don't print

An illustration: How can Philosopher 1 start eating?



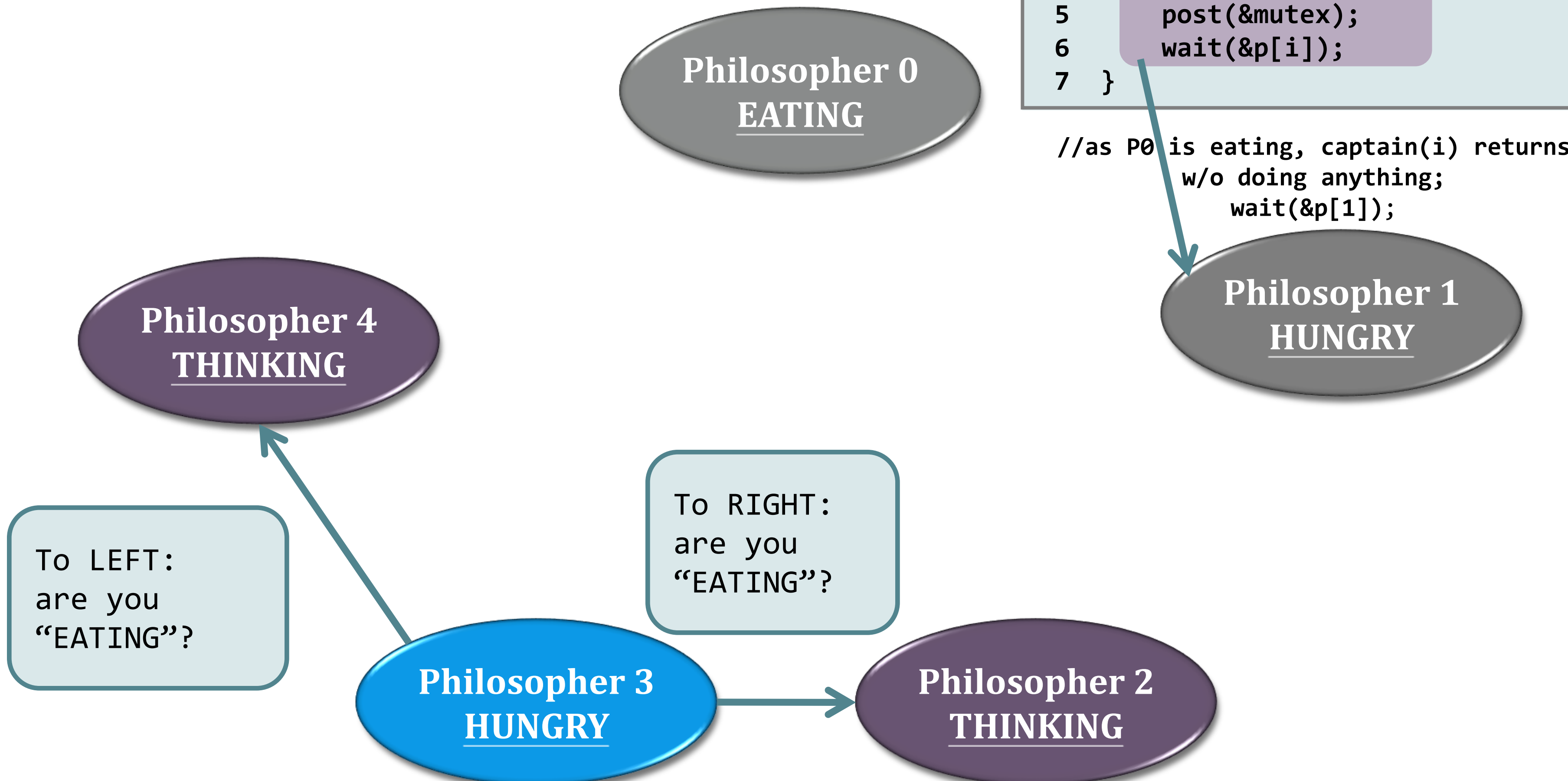
Dining philosopher – the final soluti

Don't print

An illustration: How can Philosopher 1 start eating?

Section entry

```
void take_chopsticks(int i) {
      wait(&mutex);
      state[i] = HUNGRY;
      captain(i);
      post(&mutex);
      wait(&p[i]);
}
```



Dining philosopher – the final soluti

Don't print

An illustration: How can Philosopher 1 start eating?

Philosopher 0
EATING

Philosopher 4
THINKING

Philosopher 1
HUNGRY

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

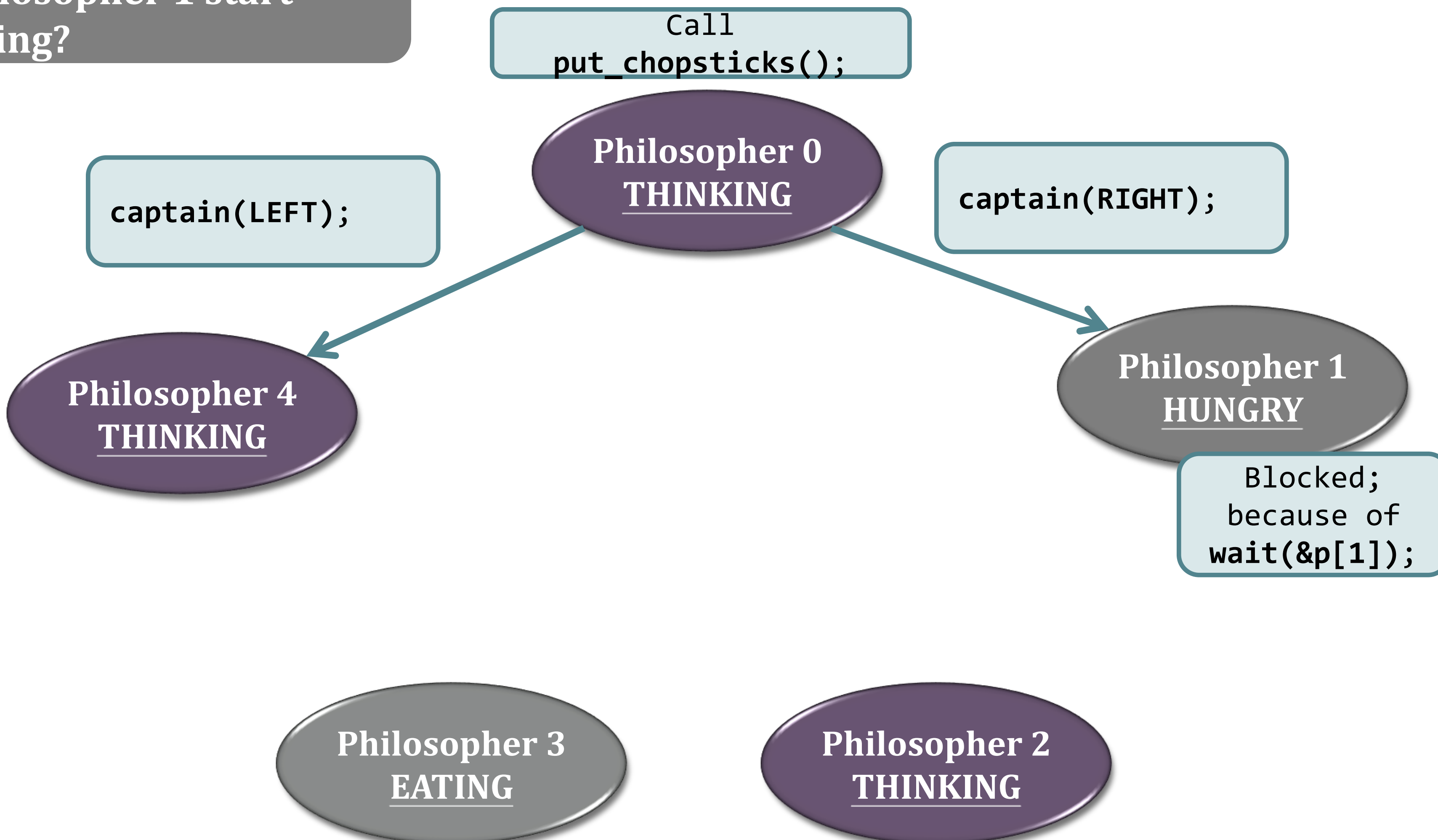
Philosopher 3
EATING

Philosopher 2
THINKING

Dining philosopher – the final soluti

Don’t print

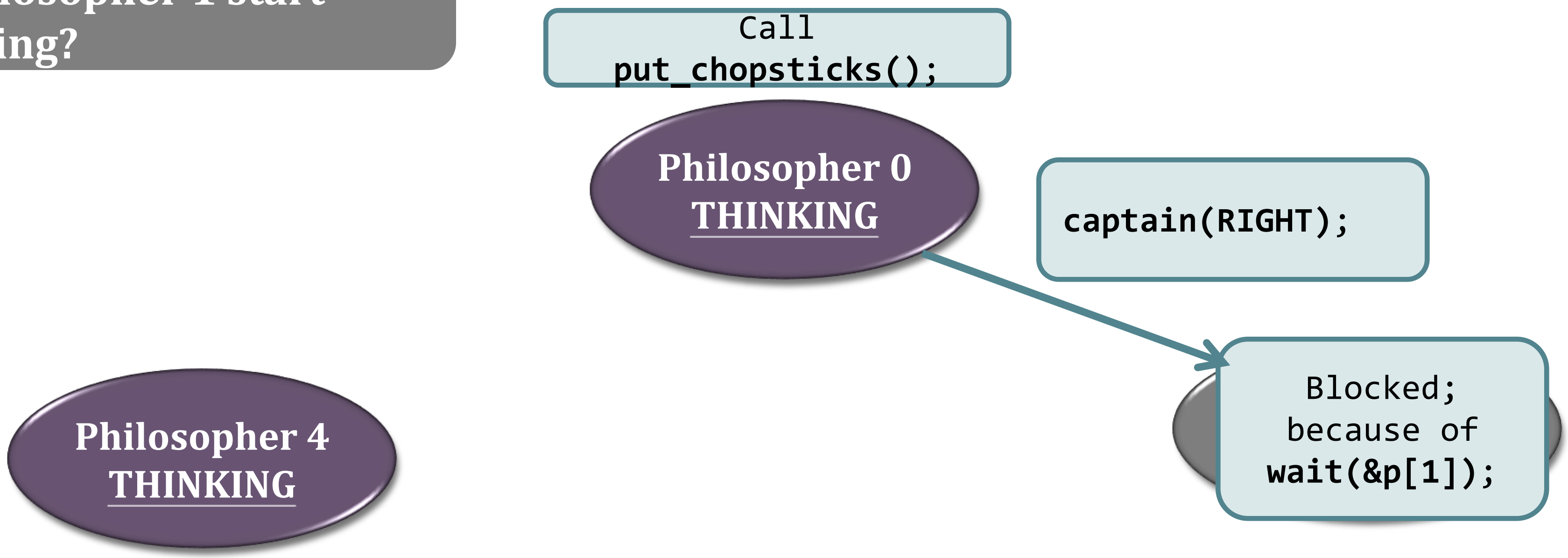
An illustration: How can Philosopher 1 start eating?



Dining philosopher – the final soluti

Don’t print

An illustration: How can Philosopher 1 start eating?




```
void captain(int i) {
    if(state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
        state[i] = EATING;
        post(&p[i]);
    }
}
```

Wake up !

Dining philosopher – the final soluti

Don't print

An illustration: How can Philosopher 1 start eating?

Section entry

```
void take_chopsticks(int i) {
    wait(&mutex);
    state[i] = HUNGRY;
    captain(i);
    post(&mutex);
    wait(&p[i]);
}
```

Wake up

Philosopher 0
THINKING

Philosopher 1
EATING

Philosopher 4
THINKING

Philosopher 3
EATING

Philosopher 2
THINKING

Dining philosopher – the core

5 philosophers $\rightarrow$ ideally how many chopsticks?

how many chopsticks do we have now?

Very common in today's cloud computing multi-tenancy model

Summary on IPC problems

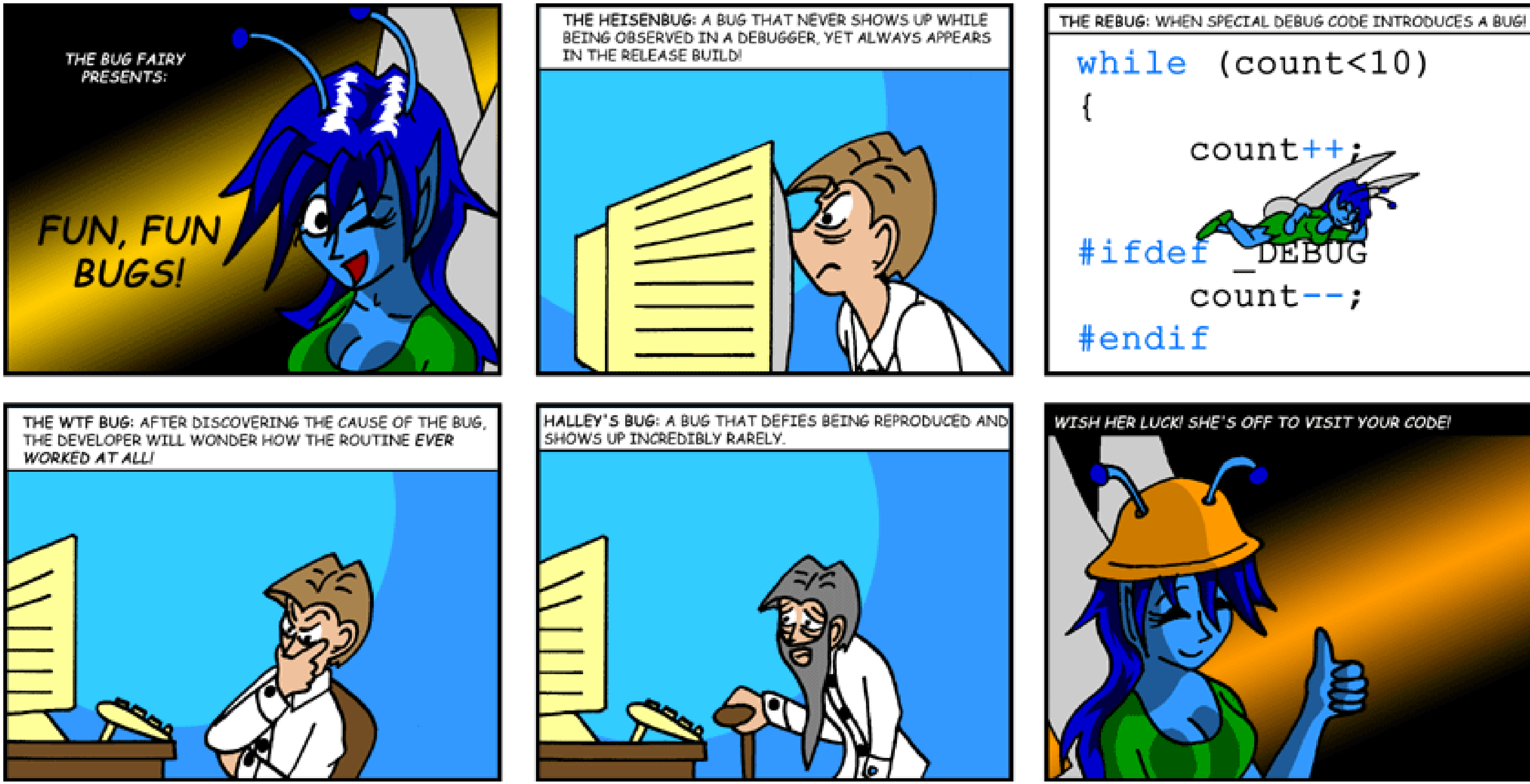
- The problems have the following properties in common:
  - Multiple number of processes;
  - Processes have to be synchronized in order to generate useful output;
  - Each resource may be shared as well as limited, and there may be more than one shared processes.

- The synchronization algorithms have the following requirements in common:
  - Guarantee mutual exclusion;
  - Uphold the correct synchronization among processes; and
  - (must be) Deadlock-free.

Heisenbugs

- Jim Gray, 1998 ACM Turing Award winner, coined that term
- You find your program P has a concurrency bug
- You insert ‘printf’ statements or GDB to debug P
- Then because of those debugging things added, P behaves normally when you are in debug mode

Heisenbugs


THE BUG FAIRY PRESENTS:
FUN, FUN BUGS!
THE HEISENBUG: A BUG THAT NEVER SHOWS UP WHILE BEING OBSERVED IN A DEBUGGER, YET ALWAYS APPEARS IN THE RELEASE BUILD!
THE REBUG: WHEN SPECIAL DEBUG CODE INTRODUCES A BUG!
while (count<10)
{
count++;
#ifdef _DEBUG
count--;
#endif
THE WTF BUG: AFTER DISCOVERING THE CAUSE OF THE BUG, THE DEVELOPER WILL WONDER HOW THE ROUTINE EVER WORKED AT ALL!
HALLEY'S BUG: A BUG THAT DEFIES BEING REPRODUCED AND SHOWS UP INCREDIBLY RARELY.
WISH HER LUCK! SHE'S OFF TO VISIT YOUR CODE!

Thank You!