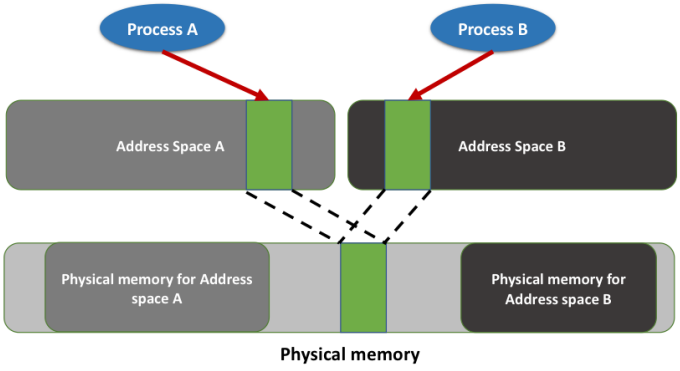
Process Communication

- 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

同一进程中的线程共享部分内存空间 (global、static、heap)

不同进程之间要通信

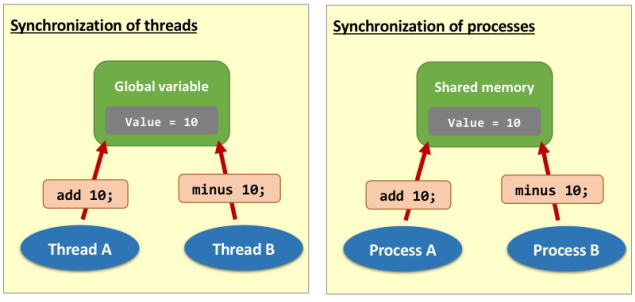
Shared memory between Processes



可以映射到相同的物理内存.

Synchronization of Threads / Processes

Process and thread synchronization can be considered in similar way



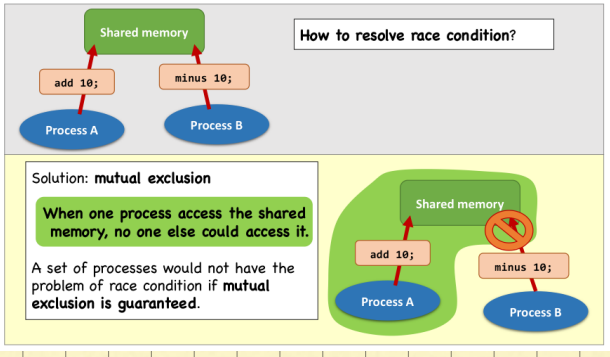
线程与进程的同步是类似的.

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.

结果取决于顺序

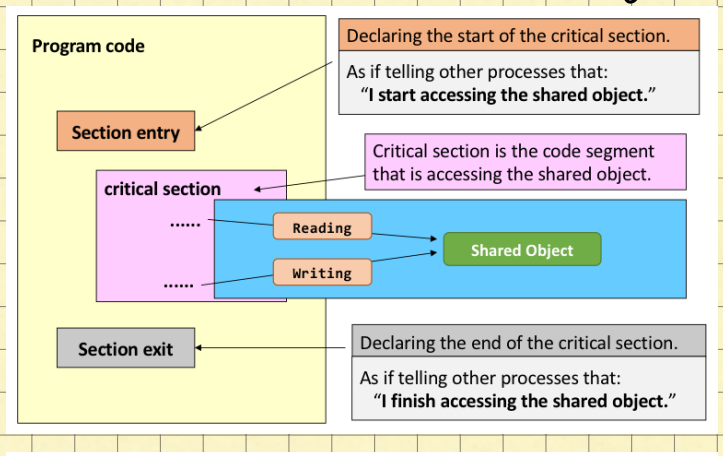
Solution: Mutual Exclusion 互斥



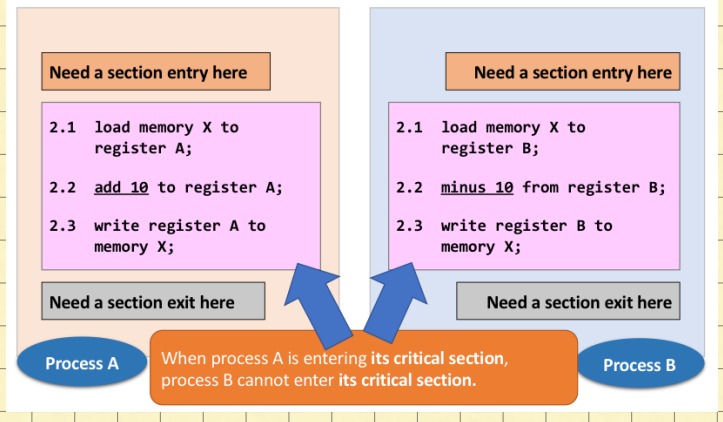
- Shared object is still sharable, but
- Do not access the "shared object" **at the same time**
- Access the "shared object" one by one

当有进程访问了共享内存，其他进程不能访问.

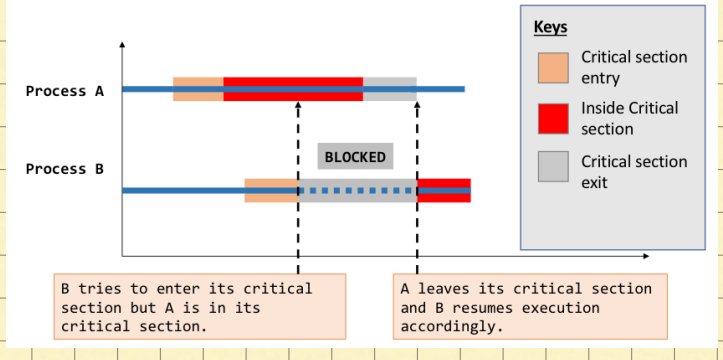
Critical Section: Realizing Mutual Exclusion



进入critical section后共享资源将会被锁定.
其他进程不能进入.



A Typical Mutual Exclusion Scenario



Summary

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

Critical Section Implementation

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

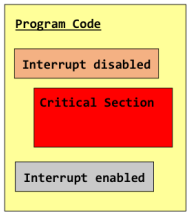
互斥

有界等待：
进程的等待时间有上限

进步：
想要进入critical section的进程最终都能进.

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!!!!)



在critical section中禁止中断，也不允许其他进程进入.

Solution : Locks

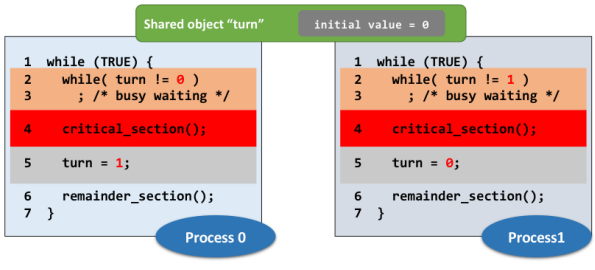
- Use yet another shared objects: **locks**
  - What about race condition on lock?
  - **Atomic instructions**: instructions that cannot be "interrupted", not even by instructions running on another core
- Spin-based locks
  - Process synchronization
    - Basic spinning using 1 shared variable
    - 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

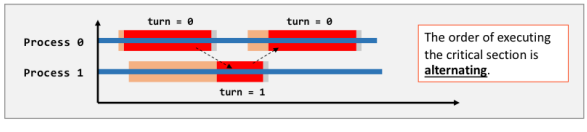
共享对象：锁
原子指令：不可被中断
自旋锁

睡眠锁

Spin-based Locks

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





- 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

交叉进入critical section

浪费CPU资源

Spin-based Locks: Progress Violation

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

```
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

32

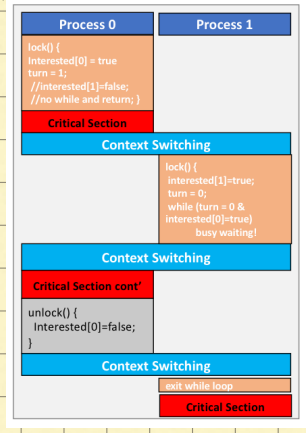
Peterson's Solution: Improved Spin-based Locks

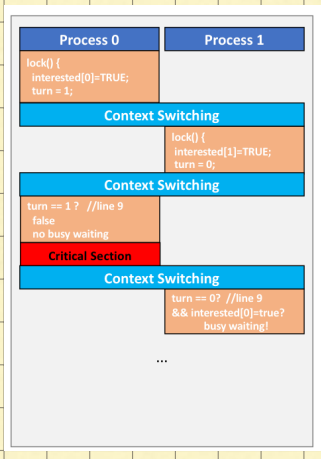
```
1  int turn;
2  int interested[2] = {FALSE,FALSE};
3
4  void lock( int process ) {
5    int other;
6    other = 1-process;
7    interested[process] = TRUE;
8    turn = other;
9    while ( turn == other &&
             interested[other] == TRUE
10     ;    /* busy waiting */
11 }
12
13 void unlock(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

检查了一遍头，有自己在waiting

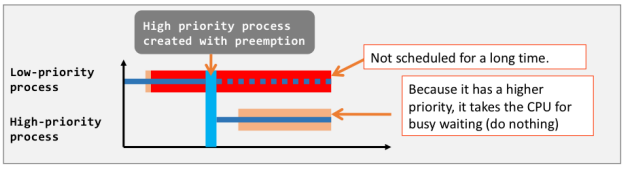
如果有其他的进程在waiting，就让其他进程先

- 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

- 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



低优先度进入了critical region，但高优先度抢占了CPU资源。

Sleep-based Locks: Semaphore 信号量

- 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)

资源数。
等待列表

必然，调用kernel
entry/exit中不能中断
①单核：禁用中断
②多核：原子指令。

Semaphore

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

Section Entry: sem_wait()

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

Initialize **s->value** = 1

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

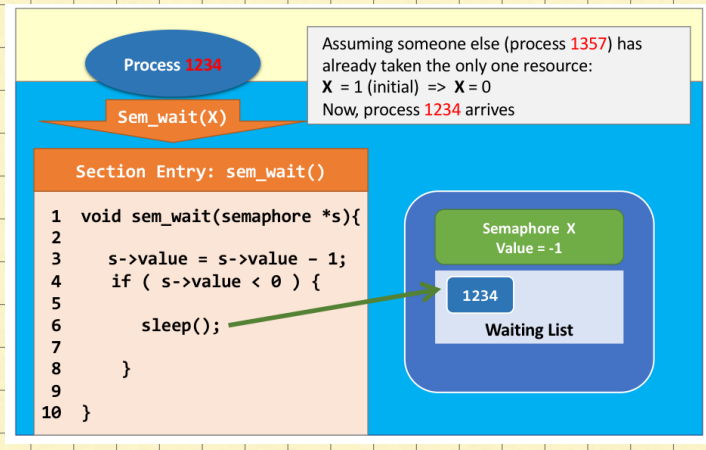
Important
This wait is different from parent's folk wait(child). When programming, it is sem_wait()

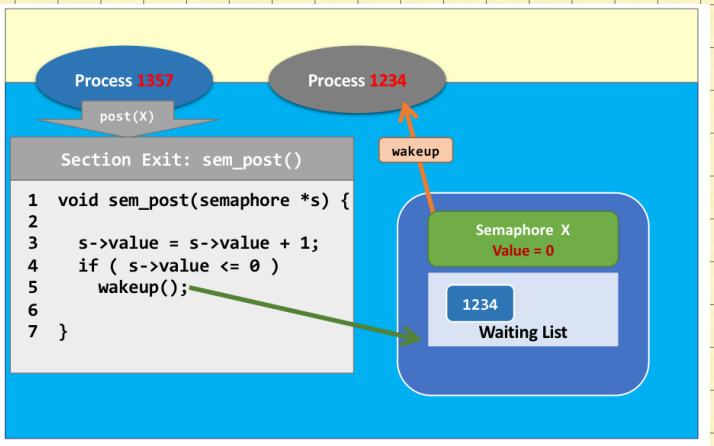
"sem_post(s)"
- I notify the others (if anyone waiting) that **s->value <= 0**

Section Exit: sem_post()

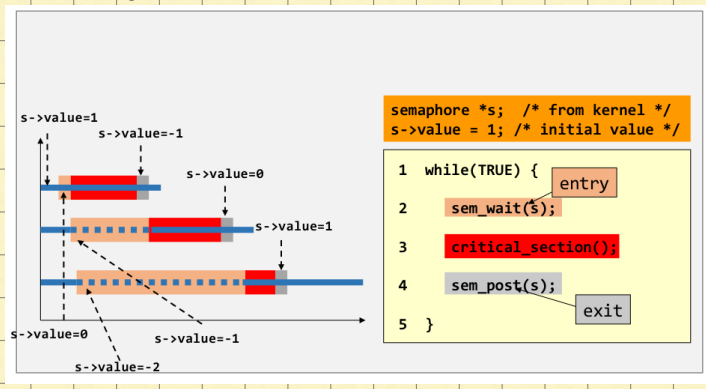
```
1  void sem_post(semaphore *s) {
2
3     s->value = s->value + 1;
4     if ( s->value <= 0 )
5        wakeup();
6
7  }
```

Semaphore Example





Using Semaphore in User Process



Semaphore Implementation

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

```
Example: Atomic increment: atomic_inc(addr)
////////////// implemented as /////////
do {
  int old = *addr;
  int new = old + 1;
} while (cmp_xchg(addr, old, new) != old);
```

```
///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;
        }
```

do...while保证了cmp_xchg是原子性的.

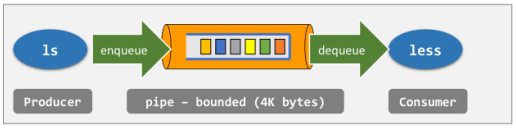
Using Semaphore beyond Mutual Exclusion

- 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.



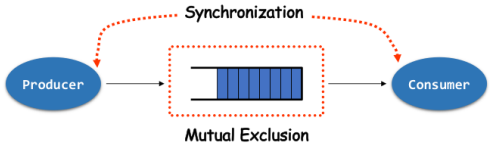
Requirement #1	When the **producer** wants to (a) put a new item in the buffer, but **(b) the buffer is already full**... Then, **the producer should wait**. **The consumer should notify the producer** after she has dequeued an item.
Requirement #2	When the **consumer** wants to (a) consumes an item 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.

当 buffer 满时，producer 不能塞新的 item，须等待直至 consumer 提醒

当 buffer 空时，consumer 不能取新的 item，须等待直至 producer 提醒

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



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

Abstraction of semaphore as integer!

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 }
```

Note

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

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

Note

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

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

Producer function

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

Consumer Function

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

Questions

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;
```

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

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

Problem solved?

If consumer gets CPU first, it removes item from NULL

ERROR

Producer function

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

Consumer Function

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

Question #2.
Can we swap Lines 6 & 7 of the producer?

Let us simulate what will happen with the modified code!

Shared object

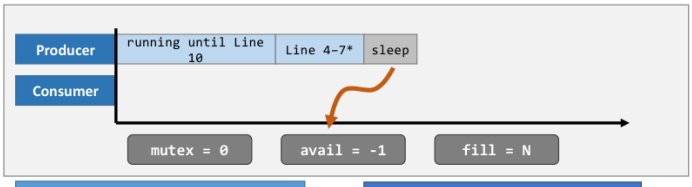
```
#define N 100
semaphore mutex = 1;
semaphore avail = N;
semaphore fill  = 0;
```

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 }
```



Producer function

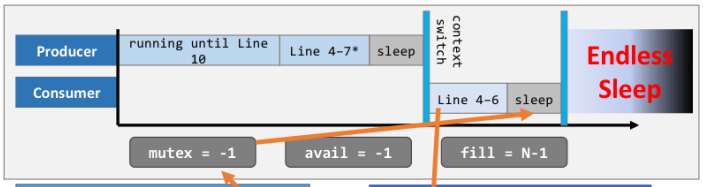
```
1  void producer(void) {
2      int item;
3
4      while(TRUE) {
5          item = produce_item();
6*         wait(&mutex);
7*         wait(&avail);
8          insert_item(item);
9          post(&mutex);
10         post(&fill);
11     }
12 }
```

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 }
```

producer 会在 critical section 内部睡着了



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 }
```

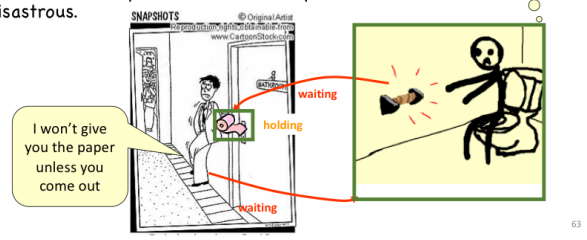
Consumer Function

```
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 }
```

consumer 无法进入 critical section，因为 producer 已经在内了。

死锁

- 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.



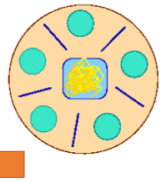
63

Summary of Producer-consumer Problem

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

Dining Philosopher Problem

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



It's a multi-object synchronization problem

Requirement 1

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

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

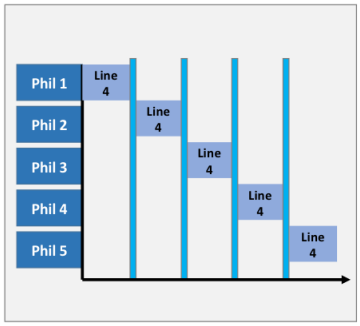
Main Function

```
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 }
```

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

都同时拿了左边的筷子，等待右边的筷子。



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 }
```

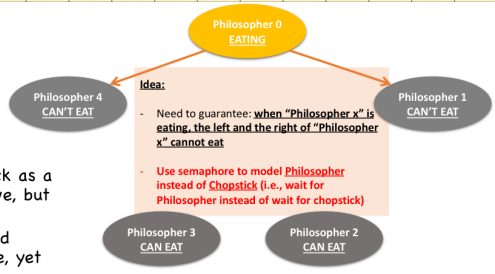
Requirement 2

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

- **Potential Problem:**
  - Philosophers are all busy (no deadlock), but no progress (starvation)
- Imagine:
  - all pick up their left chopsticks,
  - seeing their right chopsticks unavailable (because P1's right chopstick is taken by P2 as her left chopstick) and then putting down their left chopsticks,
  - all sleep for a while
  - all pick up their left chopsticks, ...

可能都饿着

Before the Final Solution



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

用 semaphore 模拟 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)

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 }
```

hungry

Tell the captain that you are hungry

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

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

Critical Section
The captain is "indivisible"

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  }
```

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 }
```

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