Chapter 6: Process Synchronization

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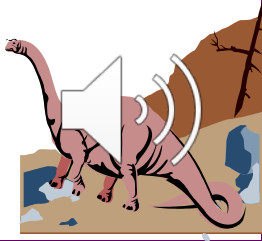
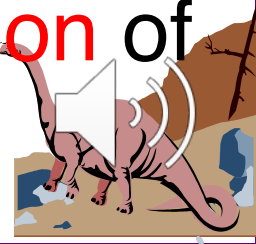
Chapter 6: Process Synchronization

- Background
- The Critical-Section Problem
- Synchronization Hardware
- Semaphores
- Classical Problems of Synchronization
- Conditional Variables and Monitors
- Synchronization Examples



Background

- Concurrent access to shared data may result in data inconsistency.
- Let us recall the concept of race condition
  - Several processes (threads) access and manipulate the same data concurrently and the outcome of the execution depends on the particular order in which the access takes place.
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes.



A Previously Used Example

```
volatile int counter = 0; // shared global variable

14  void *
15  mythread(void *arg)
16  {
17      printf("%s: begin\n", (char *) arg);
18      int i;
19      for (i = 0; i < 1e7; i++) {
20          counter = counter + 1;
21      }
22      printf("%s: done\n", (char *) arg);
23      return NULL;
24  }

32  int
33  main(int argc, char *argv[])
34  {
35      pthread_t p1, p2;
36      printf("main: begin (counter = %d)\n", counter);
37      Pthread_create(&p1, NULL, mythread, "A");
38      Pthread_create(&p2, NULL, mythread, "B");
39
40      // join waits for the threads to finish
41      Pthread_join(p1, NULL);
42      Pthread_join(p2, NULL);
43      printf("main: done with both (counter = %d)\n", counter);
44      return 0;
45  }
```

The output is non-deterministic. Why?

Another Example: Revisit the Producer Consumer Problem

- Shared-memory solution to bounded-buffer problem (Chapter 3)
  - The code can only use N-1 items in the buffer

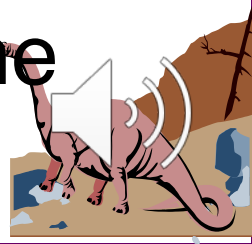
Producer:

```
while (1) {
  while (((in+1) % BUF_SIZE) == out) ;
  ……
  in = (in+1) % BUF_SIZE;
}
```

Consumer:

```
while (1) {
  while (in == out) ;
  ……
  out = (out+1) % BUF_SIZE;
}
```

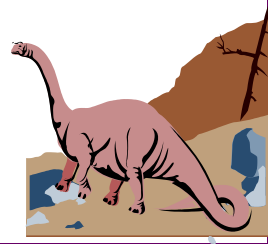
- We modify the above code by adding a variable *counter*, such that all items in the buffer can be used



Bounded-Buffer Solution

- Shared data

```
#define BUF_SIZE 10
typedef struct {
    . . .
} item;
item buffer[BUF_SIZE];
int in = 0;
int out = 0;
int counter = 0;
```



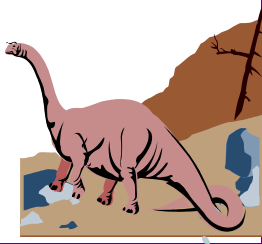
Bounded-Buffer Solution

- Producer process

```
item nextProduced;

while (1) {
   while (counter == BUF_SIZE)
      ; /* do nothing */
   buffer[in] = nextProduced;
   in = (in + 1) % BUF_SIZE;
   counter++;
}
```

- Consumer process

```
item nextConsumed;

while (1) {
   while (counter == 0)
      ; /* do nothing */
   nextConsumed = buffer[out];
   out = (out + 1) % BUF_SIZE;
   counter--;
}
```



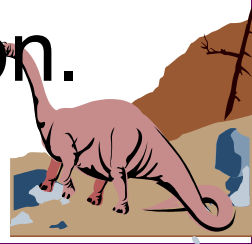
Critical Shared Data

- Counter is a piece of critical shared data
- The statements

  counter++;
  counter--;

  must be performed *atomically*.

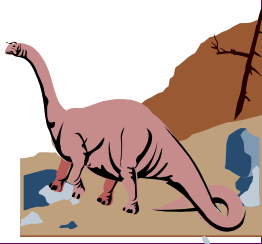
- Atomic operation means an operation that completes in its entirety without interruption.



Difficult to Implement the Atomic Guarantee

- However, the statement "**count++**" may be implemented in machine language as:
  register1 = counter
  register1 = register1 + 1
  counter = register1

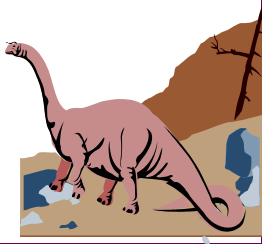
- The statement "**count--**" may be implemented in machine language as:
  register2 = counter
  register2 = register2 – 1
  counter = register2



Potential Data Inconsistency

- If both the producer and consumer attempt to update the buffer concurrently, the assembly language statements may get interleaved.

- Interleaving depends upon how the producer and consumer processes are scheduled.



Potential Data Inconsistency

- Assume **counter** is initially 5. One interleaving of statements is:

  producer: **register1 = counter** (*register1 = 5*)
  producer: **register1 = register1 + 1** (*register1 = 6*)
  consumer: **register2 = counter** (*register2 = 5*)
  consumer: **register2 = register2 – 1** (*register2 = 4*)
  producer: **counter = register1** (*counter = 6*)
  consumer: **counter = register2** (*counter = 4*)

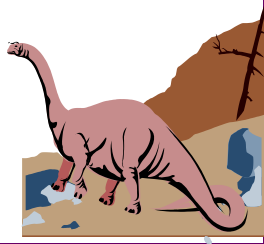
- The value of **count** may be either 4 or 6, where the correct result should be 5.

Producer

```
register1 = counter

register1 = register1 + 1

counter = register1
```

Consumer

```
register2 = counter

register2 = register2 – 1

counter = register2
```



Another Example——ATM

```
function withdraw($amount)
{
    $balance = getBalance();
    if ($amount <= $balance) {
        $balance = $balance - $amount;
        saveBalance($balance);
        echo “The amount you withdraw:$amount”;
    } else {
        echo “Sorry, you don’t have enough money”;
    }
}
```

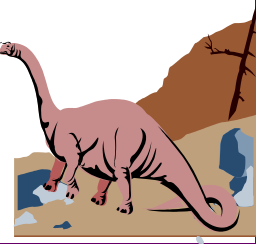
If you only have 1000 yuan, how to take out 1800 yuan?

Another Example——ATM

Assume account $balance = 1000

```
Call function withdraw(900)
{
   $balance = getBalance();

   if (900 <= $balance) {
      $balance = $balance - $amount;
      saveBalance($balance);
      echo "The amount you withdraw:$amount";
   } else {
      echo "Sorry, you don't have enough money";
   }
}
```

```
Call function withdraw(900)
{
      $balance = getBalance();

   if (900 <= $balance) {
      $balance = $balance - $amount;
      saveBalance($balance);
      echo "The amount you withdraw:$amount";
   } else {
      echo "Sorry, you don't have enough money";
   }
}
```



Time Of Check To Time Of Use (TOCTTOU)

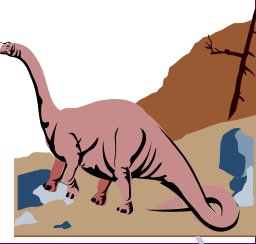
- In software development, TOCTTOU is a class of software bug caused by changes in a system between the checking of a condition(e.g. enough money?) and use of the results of that check(e.g. give money?).

- TOCTTOU states that race condition can occur if the state of the system changes between the moment when some condition was checked by a process and a moment when the action was taken based on that condition by the same process.

Concept of Race Condition

- **Race condition** occurs, if:
  - **two or more processes/threads access and manipulate the same data concurrently, and**
  - **the outcome of the execution depends on the particular order in which the access takes place.**

- To prevent race conditions, concurrent processes must be **synchronized**.



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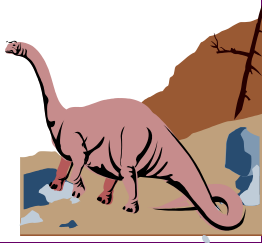
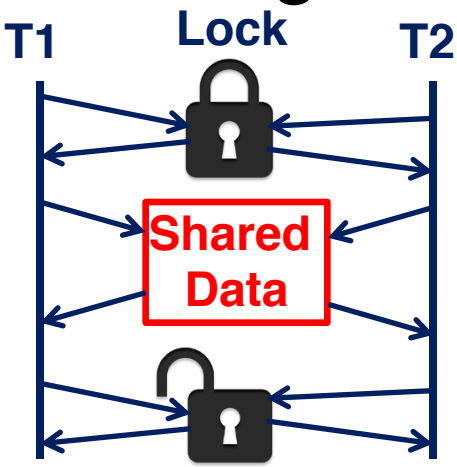


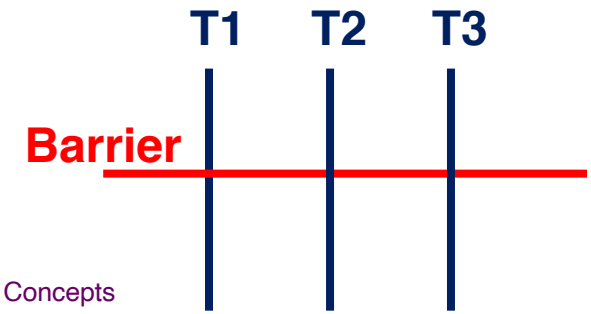
Three Typical Mechanisms of Process Synchronization

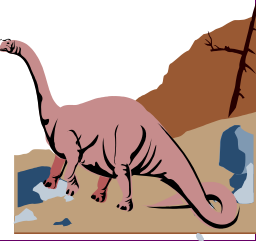
- Locks for shared memory programming
  - Exclusive Lock



  - Shared Lock:
    - ✓Readers can share a lock, but readers and writers must access the data mutually exclusively

- There are other synchronization primitives for shared memory programming, e.g., Barrier





OS Support to Implement an Exclusive Lock for Threads

- Using Mutex: Sleeping of threads Instead of spinning that wastes CPU cycles

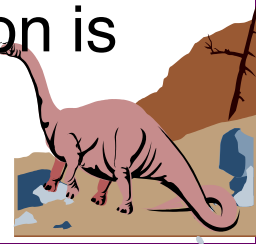
- APIs of POSIX Thread for exclusive lock

  int pthread_mutex_lock(pthread_mutex_t* mutex)
  int pthread_mutex_unlock(pthread_mutex_t* mutex)

- An Example

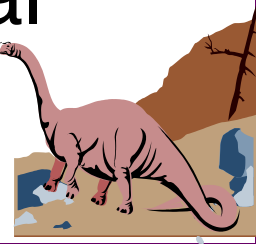
  Give a demonstration

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
pthread_mutex_lock(&lock);
counter = counter+1; // or whatever your critical section is
pthread_mutex_unlock(&lock);
```



The Critical-Section Problem: An Use Case of Exclusive Lock

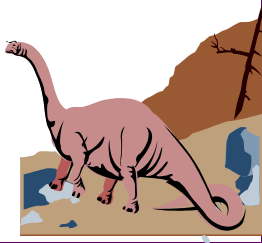
- Multiple processes all competing to use some shared data
- Each process has a code segment, called *critical section*, in which the shared data is accessed.
- Problem – ensure that when one process is executing in its critical section, no other process is allowed to execute in its critical section.



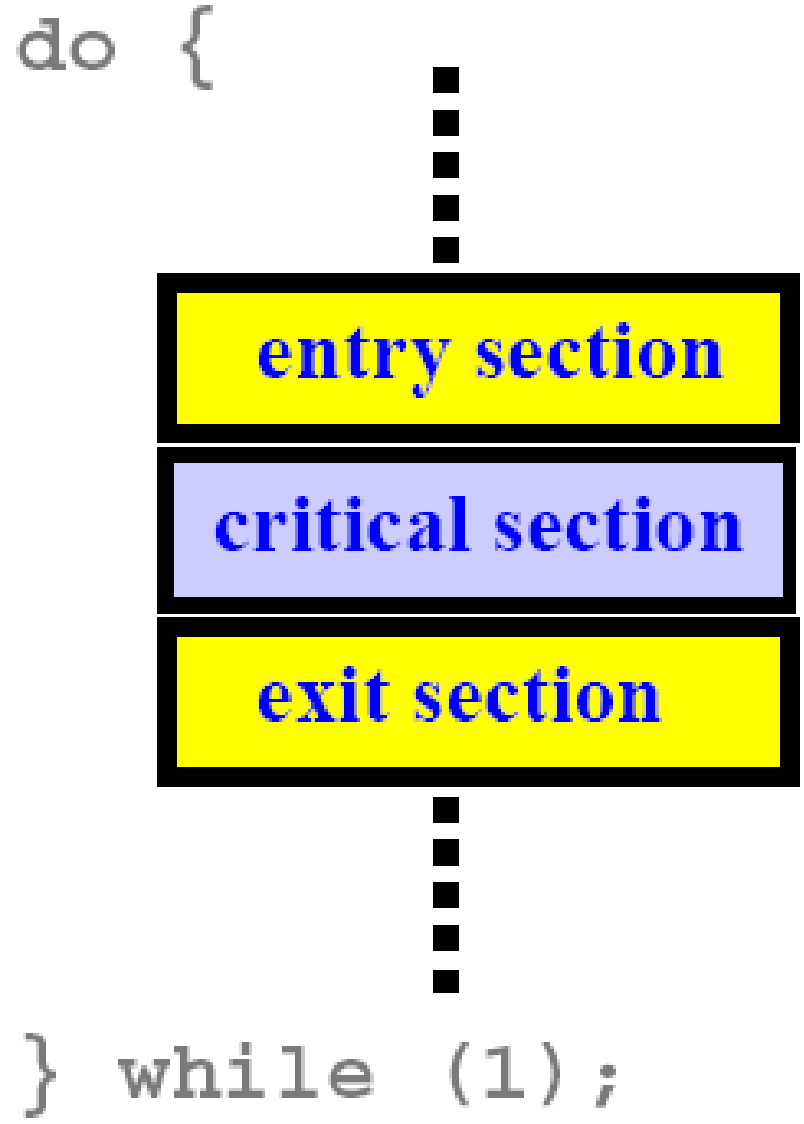
Critical Section and Mutual Exclusion

- Thus, the execution of critical sections must be *mutually exclusive* (e.g., at most one process can be in its critical section at any time).

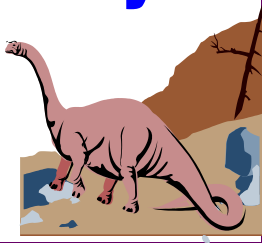
- The *critical-section problem* is to design a protocol that processes can use to cooperate.



The Critical Section Protocol



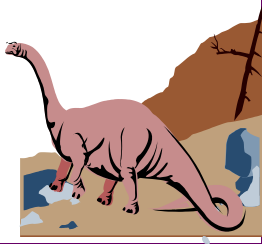
- A critical section protocol consists of **two** parts: an ***entry section (or lock)*** and an ***exit section (or unlock)***.
- Between them is the critical section that must run in a **mutually exclusive** way.



Solution to Critical-Section Problem

- Any solution to the critical section problem must satisfy the following three conditions:
  - **Mutual Exclusion**
  - **Progress**
  - **Bounded Waiting**

- Moreover, the correctness of the solution cannot depend on relative speed of processes and scheduling policy.

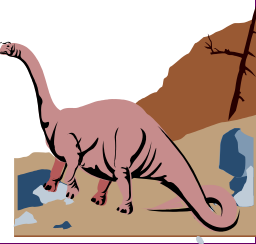


Mutual Exclusion

- If a process P is executing in its critical section, then *no* other processes can be executing in their critical sections.
- The entry protocol should be capable of blocking processes that wish to enter but cannot.
- Moreover, when the process that is executing in its critical section exits, the entry protocol must be able to know this fact and allows a waiting process to enter.

Progress

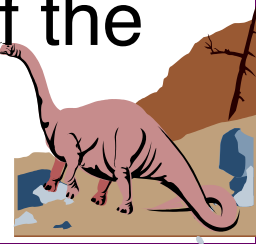
- If no process is executing in its critical section and some processes wish to enter their critical sections, then
  - Only those processes that are waiting to enter can participate in the competition (to enter their critical sections).
  - No other process can influence this decision.
  - This decision cannot be postponed indefinitely.



Bounded Waiting

- After a process made a request to enter its critical section and before it is granted the permission to enter, there exists a *bound* on the number of times that other processes are allowed to enter.

- Hence, even though a process may be blocked by other waiting processes, it will not be waiting forever.
  - Assume that each process executes at a nonzero speed
  - No assumption concerning relative speed of the *n* processes

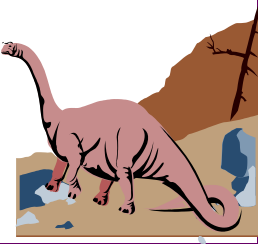


Solve the Problem without any OS Support

- Consider a simple case of only 2 processes, P_0 and P_1
- General structure of process P_i (and P_j)

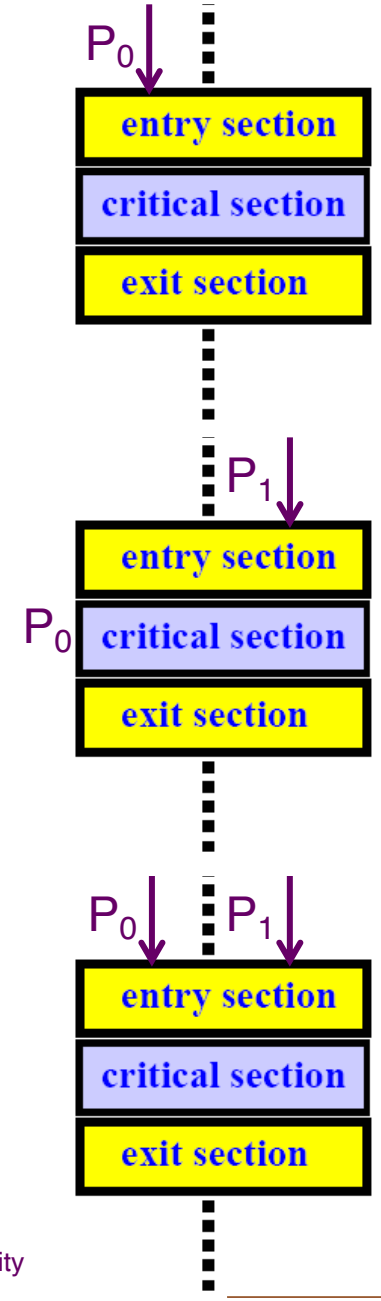
```
do {    entry section

            critical section

        exit section

            remainder section

} while (1);
```

- Processes may share some common variables to synchronize their actions.



Consider Three Test Cases

- Case 1: One process repeatedly attempts to enter the critical section (CS)
  - Progress Test: Whether P_0's repeated entering of CS is independent of P_1's attempt
- Case 2: One process is already in the critical section, and meanwhile the other process attempts to enter
  - Mutual Exclusive Test: P_0 safely block P_1 out
- Case 3: Two processes try to enter the critical section simultaneously
  - Progress Test: Whether it is possible for the two processes to block each other's entry
  - Mutual Exclusive Test: Whether it is possible for them to both enter the section

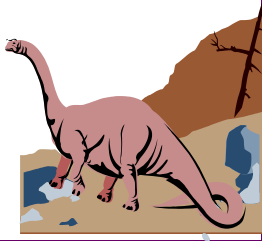


Our First Attempt: Algorithm 1

- Shared variables:
  - **boolean lock**; *// initially **lock = false***
  - **lock = true** $\Rightarrow$ the critical section has been locked
- Process P_i :

```
do {    while (lock) ; // if locked then wait
        lock = true;  // acquire the lock
          critical section
        lock = false; // release the lock
          remainder section
} while (1);
```

- Does not satisfy mutual exclusion. Why?



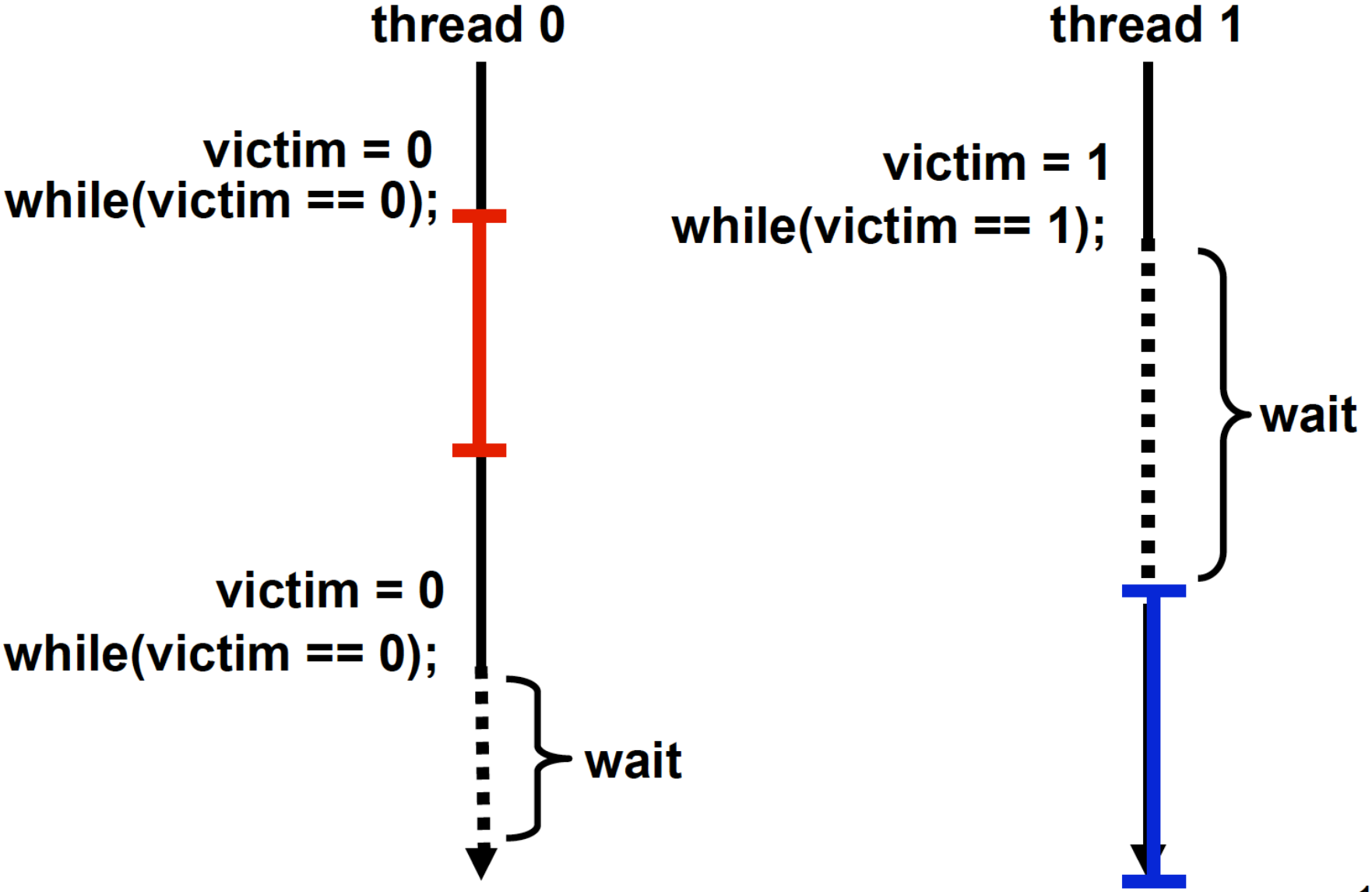
Our Second Attempt: Algorithm 2

- Shared variables:
  - **int victim**; initially **victim = 0 (or victim = 1)**
- Process P_i:

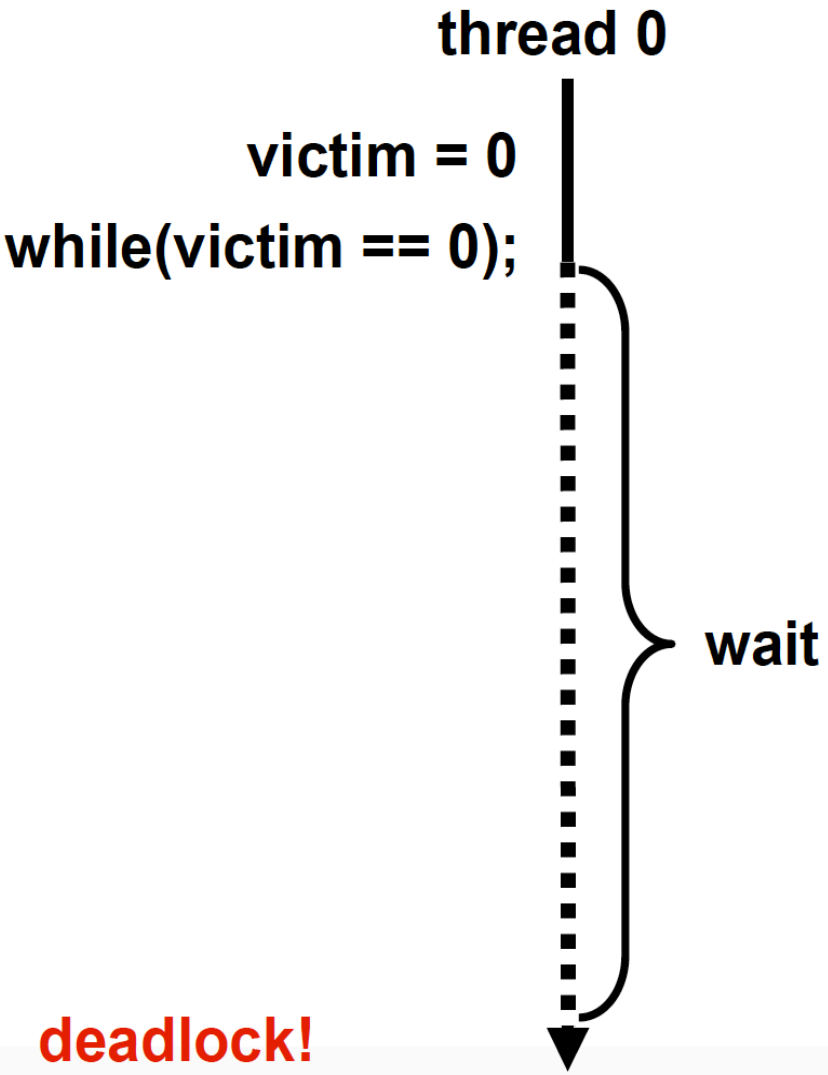
```
do {victim = i;          // determine who is the victim
    while (victim == i) ; // if I am victim, then wait
    critical section  // assume empty
    // do nothing for CS exit
    remainder section
} while (1);
```

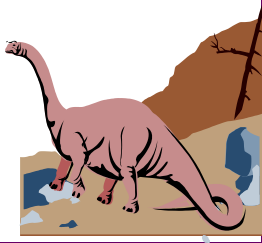
- Processes are forced to run in an alternating way
- Satisfies mutual exclusion, but not progress

Alternating and Atomic Execution of Algorithm 2



Deadlock of Algorithm 2





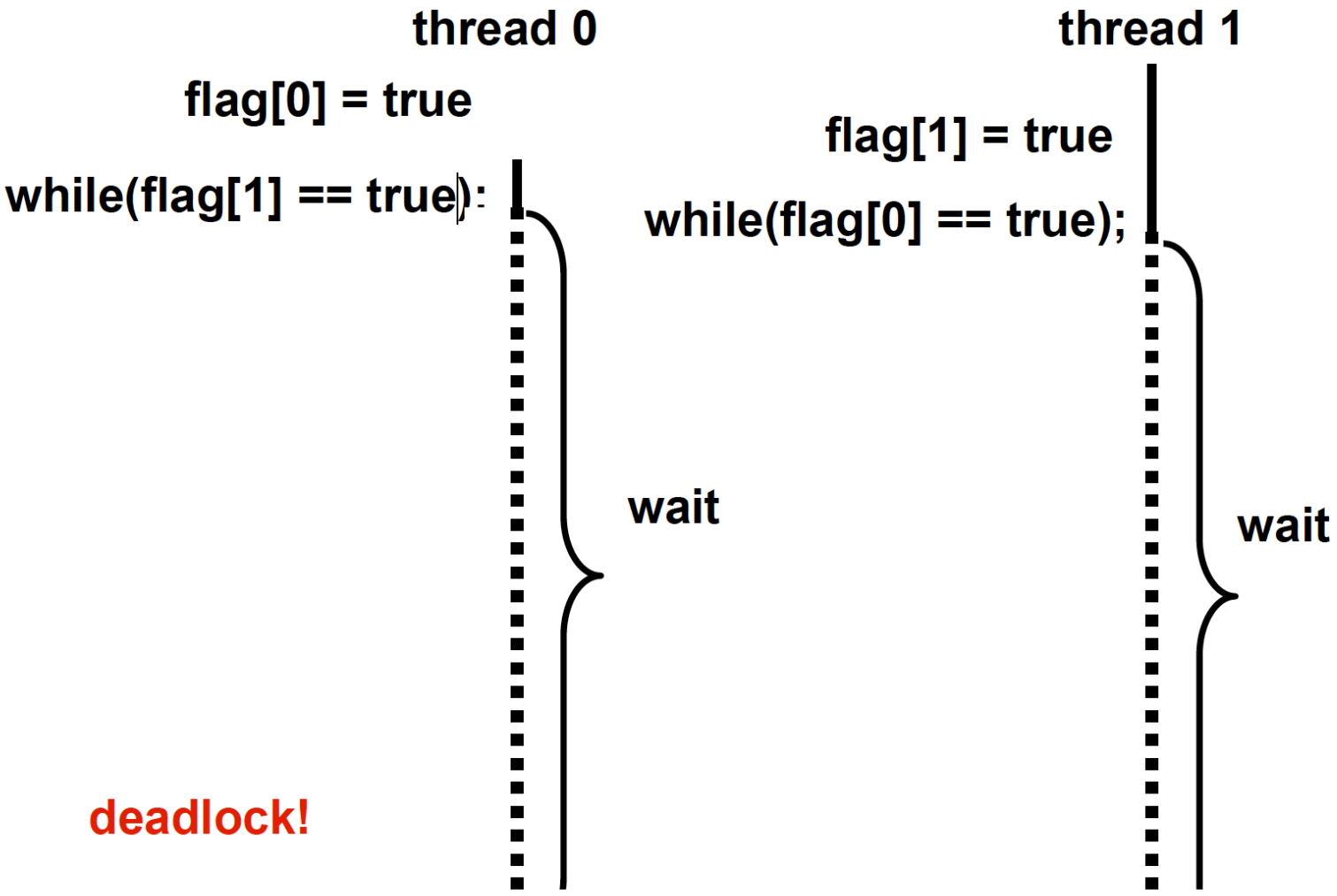
Another Failed Attempt: Algorithm 3

- Shared variables:
  - **boolean flag[2];** *// initially **flag[0] = flag[1] = false***
  - **flag[i] = true** $\Rightarrow$ P_i *wants to enter its critical section*
- Process P_i

```
do {flag[i] = true;      // I want to enter
    while (flag[1-i]) ; // If you also want, then I wait
    critical section
    flag[i] = false;    // I leave
    remainder section
} while (1);
```

- Can satisfy mutual exclusion, but not progress requirement. Why?

Deadlock Problem of Algorithm 3

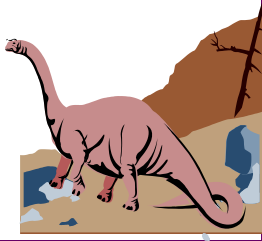


Is the Following Algorithm Correct?

- What if we change the location of the statement: **flag[i] = true**?
- Process P_i:

```
do {      while (flag[1-i]) ;
          flag[i] = true;
           critical section
          flag[i] = false;
            remainder section
} while (1);
```

- Does not satisfy mutual exclusion



Comparison of Algorithms 1, 2, 3

Critical Section Algorithms	Test Case 1: P_0 serialized enter	Test Case 2: P_0, P_1 serialized enter	Test Case 3: P_0, P_1 concurrent enter
Algorithm 1 with a shared ***lock*** variable	√	√	× (ME)
Algorithm 2 with a shared ***victim*** variable	×(Progress)	√	√
Algorithm 3 with two shared ***flag[2]*** variables	√	√	×(Progress)
Peterson's Algorithm, with a shared ***victim*** variable and two shared ***flag[2]*** variables	√	√	√

Combine the advantages of Algorithms 2 and 3

Peterson's Algorithm

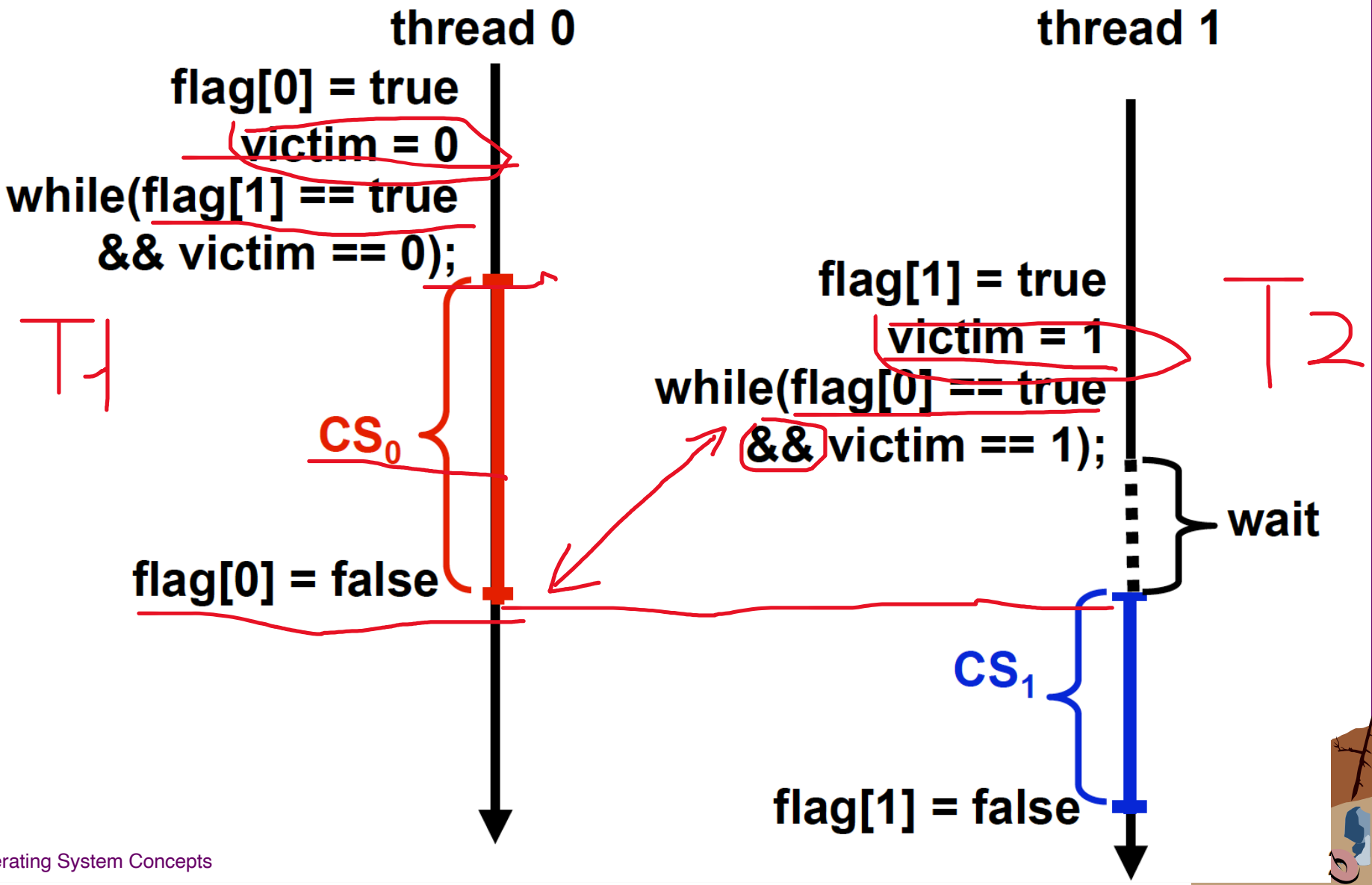
- Combined shared variables of algorithms 2, 3.
- Process P_i

```
do {    flag[i] = true;   // I'm interested
        victim = i;       // you go first
        while (flag[1-i] and victim == i) ;

          critical section

        flag[i] = false; // I'm not interested
                         // any more

          remainder section

} while (1);
```

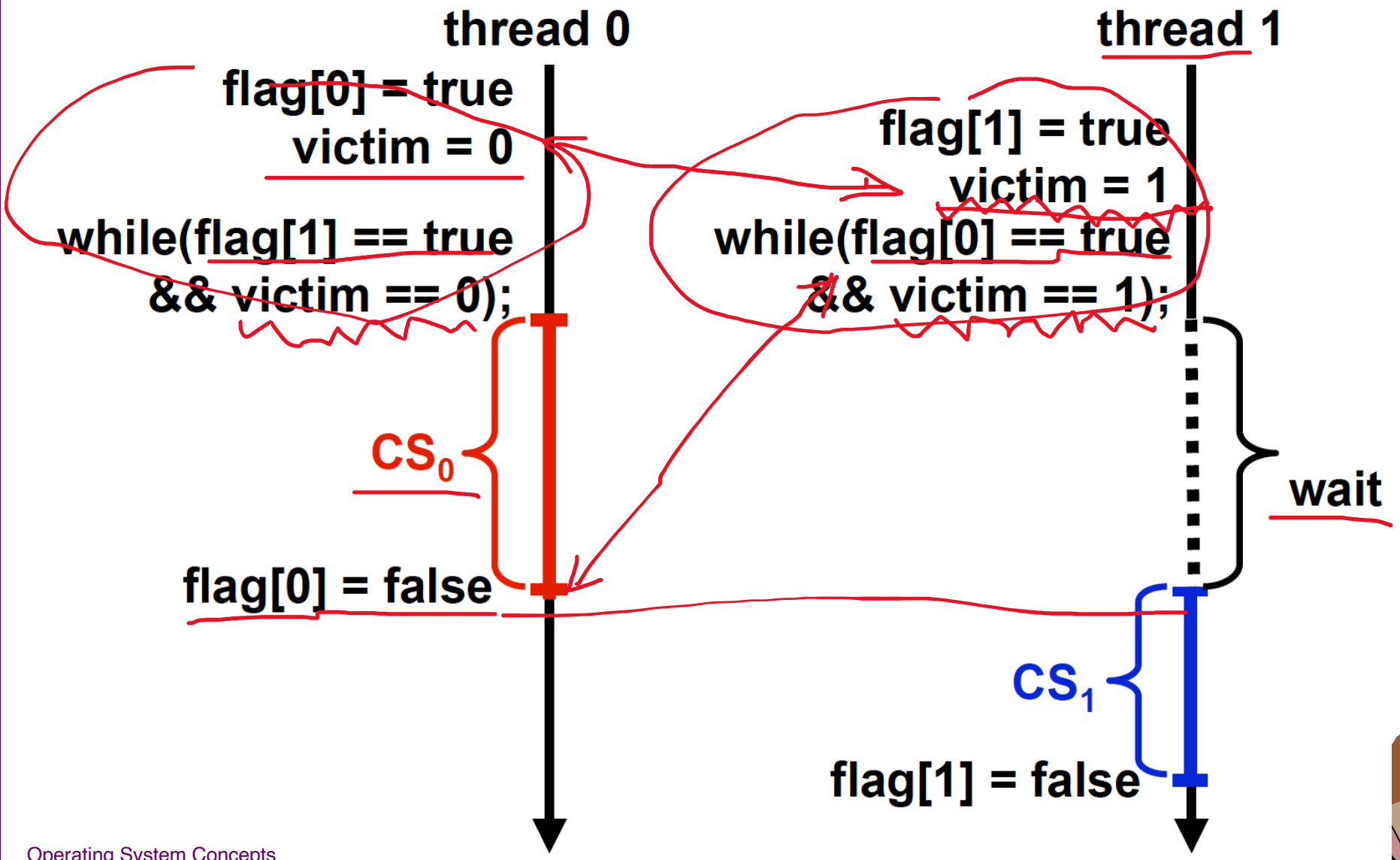
Gary Peterson. Myths about the Mutual Exclusion Problem. Information Processing Letters, 12(3):115-116, 1981.

- Meet all the three requirements; Can solve the critical-section problem for two processes.

Peterson's Lock: Serialized Acquires

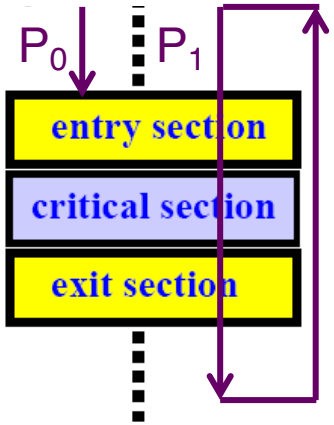


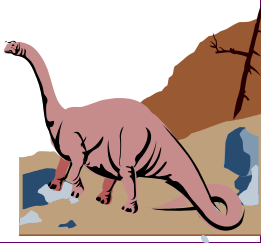
Peterson's Lock: Concurrent Acquires



Test the Bounded Waiting Property

- **Recall:** After a process made a request to enter its critical section and before it is granted the permission to enter, there exists a *bound* on the number of times that other processes are allowed to enter.
- Test Case: Two processes attempt to enter the critical section simultaneously
  - Assume P0 is slow, while P1 is fast
  - Can P1 repeatedly grab the exclusive lock, causing P0 to starve?
    - ✓If yes/no, the solution of critical section cannot/can satisfy bounded waiting property

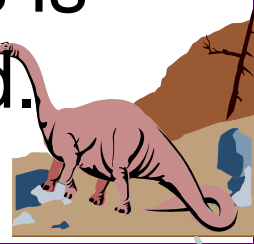




Proof of Peterson's Algorithm

- The mutual exclusion requirement is assured.
- The progress requirement is assured. The victim variable is only considered when both processes are using, or trying to use, the resource.
- Deadlock is not possible. If both processes are testing the while condition, one of them must be the victim. The other process will proceed.
- Finally, bounded waiting is assured. When a process that has exited the CS reenters, it will mark itself as the victim. If the other process is already waiting, it will be the next to proceed.

https://en.wikipedia.org/wiki/Peterson%27s_algorithm

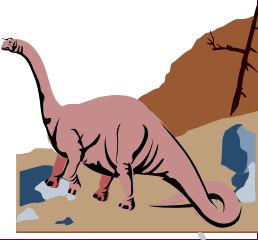


Quiz: Is the following code correct?

- What if we change **victim = i** to **victim = j**?

```
do {        flag[i] = true;   // I'm interested
            victim = j;       // I go first
            while (flag[j] and victim == i) ;
                    critical section
            flag[i] = false; // I'm not interested
                    remainder section
} while (1);
```

  - Can the code satisfy mutual exclusion?
  - Can the code satisfy progress?
  - Can the code satisfy bounded waiting?

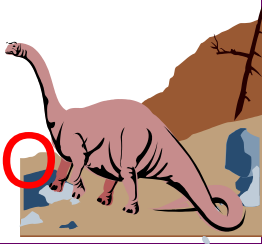


Quiz: Is the following code correct?

- What if we change **victim = i** to **victim = j**?

```
do {        flag[i] = true;   // I'm interested
            victim = j;       // I go first
            while (flag[j] and victim == i) ;
                    critical section
            flag[i] = false; // I'm not interested
                    remainder section
} while (1);
```

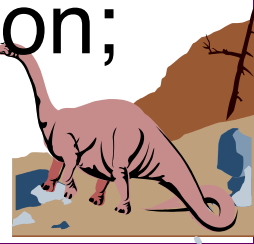
  - Can the code satisfy mutual exclusion? NO
  - Can the code satisfy progress? YES
  - Can the code satisfy bounded waiting? NO



Lamport's Bakery Algorithm

Solve the critical section problem for an arbitrary number of processes

- Before entering its critical section, process receives a number. Holder of the smallest number enters the critical section.
- If processes P_i and P_j receive the same number, if $i < j$, then P_i is served first; else P_j is served first.
- The numbering scheme always generates numbers in increasing order of enumeration; i.e., 1,2,3,3,3,3,4,5...



Bakery Algorithm

- Notation
  - $(a,b) < (c,d)$ if $a < c$ or if $a = c$ and $b < d$
  - max $(a_0, \ldots, a_{n-1})$ is a number, k, such that $k \geq a_i$ for $i = 0, \ldots, n-1$

- Shared data

  boolean choosing[n];

  int number[n];

  Data structures are initialized to **false** and **0** respectively

Bakery Algorithm

```
do {
    choosing[i] = true;
    number[i] = max(number[0], number[1], …,
                    number[n – 1]) + 1;
    choosing[i] = false;
    for (j = 0; j < n; j++) {
      while (choosing[j]) ;
      while ( (number[j] != 0) &&
              ((number[j], j) <  (number[i], i)) ) ;
    }
       critical section
    number[i] = 0;
       remainder section
} while (1);
```

Get a ticket first

Which parts are the entry and exit sections?

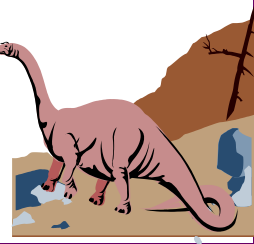
What is the use of choosing[]?

What if we remove the choosing[]?

```
do {
        number[i] = max(number[0], number[1], …,
                                    number[n – 1]) + 1;
        for (j = 0; j < n; j++) {
          while ( (number[j] != 0) &&
                    ((number[j], j) <  (number[i], i)) ) ;
        }
           critical section
        number[i] = 0;
           remainder section
} while (1);
```

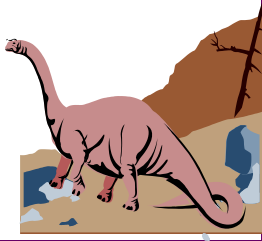
Can the above code satisfy the mutual exclusion and why?

Hint: two processes computed the same number[i].



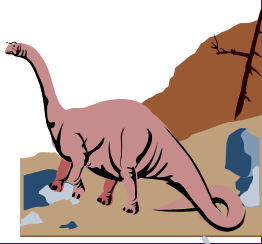
Chapter 6: Process Synchronization

- Background
- The Critical-Section Problem
- Synchronization Hardware to Build a Lock
- Semaphores
- Classical Problems of Synchronization
- Conditional Variables and Monitors
- Synchronization Examples

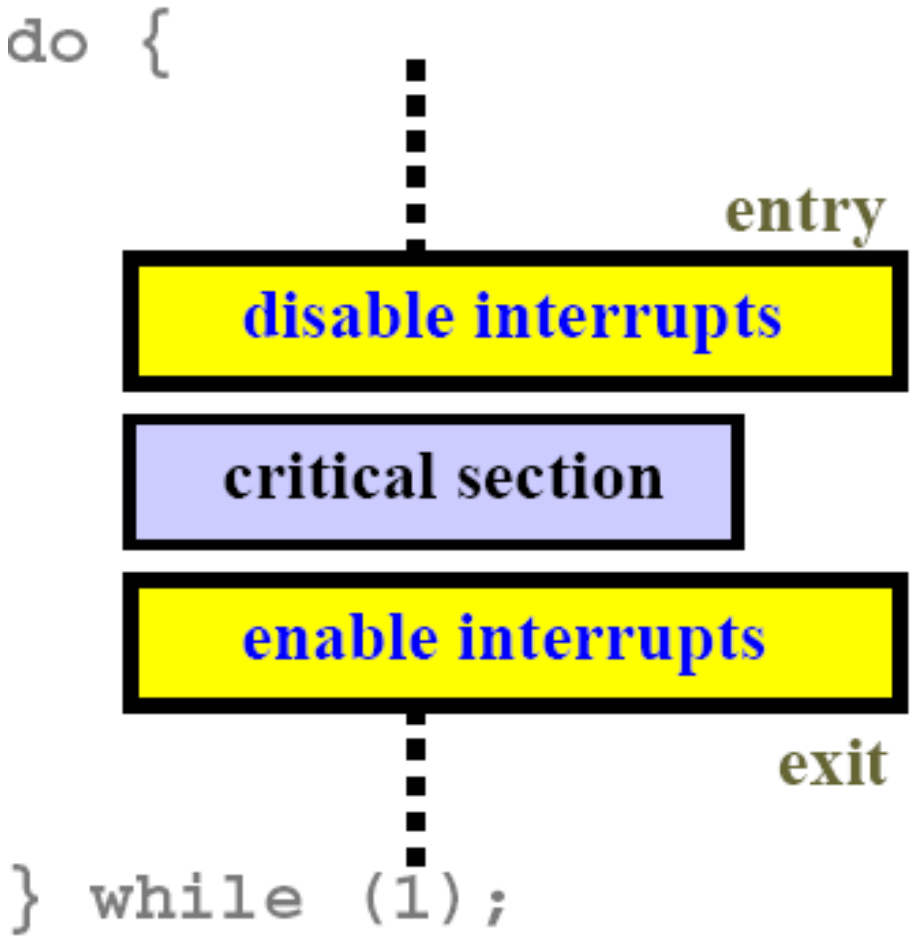


Hardware Support

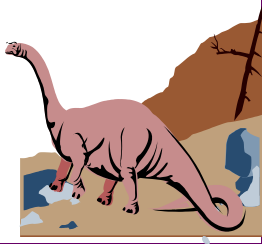
- There are two types of hardware synchronization supports:
  - Disabling/Enabling interrupts: This is slow and difficult to implement on multiprocessor systems.
  - Special machine instructions:
    - ✓Test and set (TAS)
    - ✓Swap



Interrupt Disabling



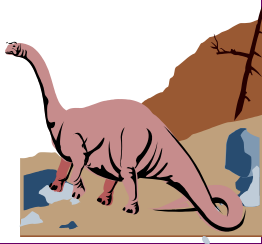
- Because interrupts are disabled, no context switch will occur in a critical section.
- Infeasible in a multiprocessor system because all CPUs must be informed.
- Some features that depend on interrupts (*e.g.*, clock) may not work properly.



Test-and-Set (TAS)

- Test and modify the content of a machine word atomically

```
boolean TestAndSet(boolean &target) {
    boolean rv = target;
    target = true;
    return rv;
}
```



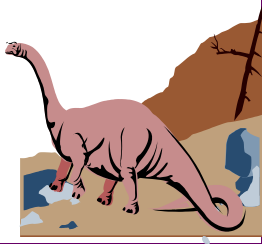
Mutual Exclusion with Test-and-Set

- Shared data:

  boolean lock = false;

- Process P_i

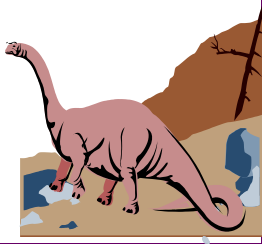
```
do {
   while (TestAndSet(lock)) ;
      critical section
   lock = false;
      remainder section
} while(1);
```



Atomic Swap

- Atomically swap two variables.

```
void Swap(boolean &a, boolean &b) {
   boolean temp = a;
   a = b;
   b = temp;
}
```



Mutual Exclusion with Swap

- Shared data (initialized to **false**):

  boolean lock = false;

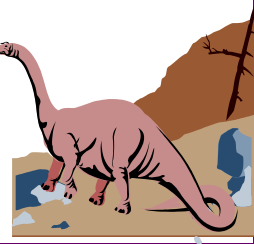
- local variable

  boolean key;

- Process P_i or Interrupt Handler TH_i

```
do {
    key = true;
    while (key == true)  Swap(lock,key);
        critical section
    lock = false;
        remainder section
} while(1);
```

Cannot satisfy bounded waiting. Why?



Bounded Waiting Mutual Exclusion with TestAndSet

- Shared data (initialized to **false**):

boolean lock = false; boolean waiting[n]; //init to false

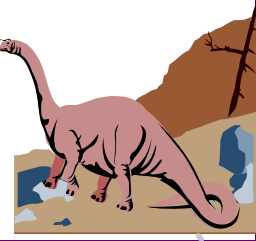
- local variable: **boolean key;**

Enter Critical Section (Lock)

```
waiting[i] = true;
key = true;
while (waiting[i] && key)
  key=TestAndSet(lock);
waiting[i] = false;
```

Leave Critical Section (unlock)

```
j = (i+1)%n
while ((j!=i) && !waiting[j])
   j = (j+1)%n;
if (j == i)
   lock = false;
else
   waiting[j] = false;
```



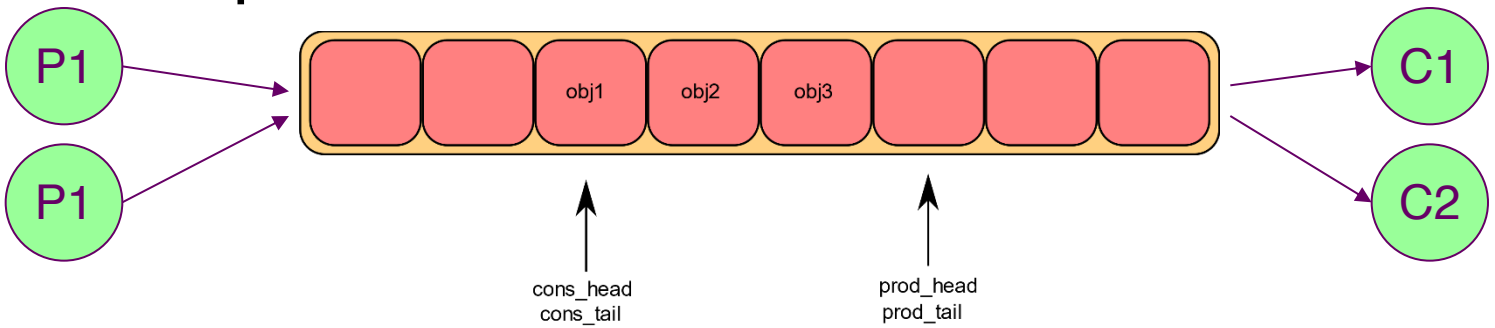
Question: What is a spinlock? Why spinlocks are not appropriate for single-processor systems yet are often used in multiprocessor system?

用忙等待方式实现的信号量称为自旋锁。自旋锁等待进入临界区需要占有CPU周期。在单处理器系统中，这将导致已进入临界区的那个进程得不到机会执行，反而使得想进临界区的进程等待更长时间。

在多处理器系统中，当临界区很短时，自旋锁是合适的。由于有多个处理器，忙等待的进程不影响在临界区中的进程在其他处理器上执行。由于临界区很短，在临界区里的进程很快就能离开临界区，其他忙等待的进程就可以进入它的临界区。这种情况下反而避免了由于阻塞和醒来导致的上下文切换开销。

DPDK Lockless Ring Buffer

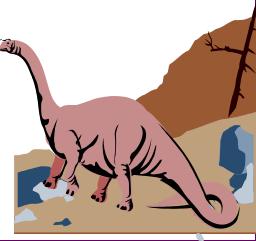
- High-Performance Applications:
  - Communication between multiple applications running on different CPU cores
  - Used by memory pool allocator that is shared by multiple CPU cores



http://dpdk.org/doc/guides/prog_guide/ring_lib.html

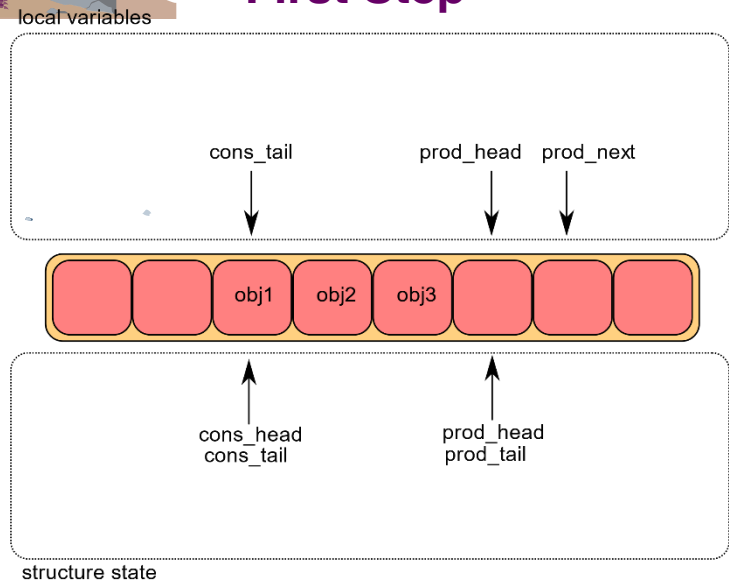
- The buffer enqueue and dequeue operations are implemented by using an atomic Compare-And-Swap (CAS) instruction

https://en.wikipedia.org/wiki/Compare-and-swap

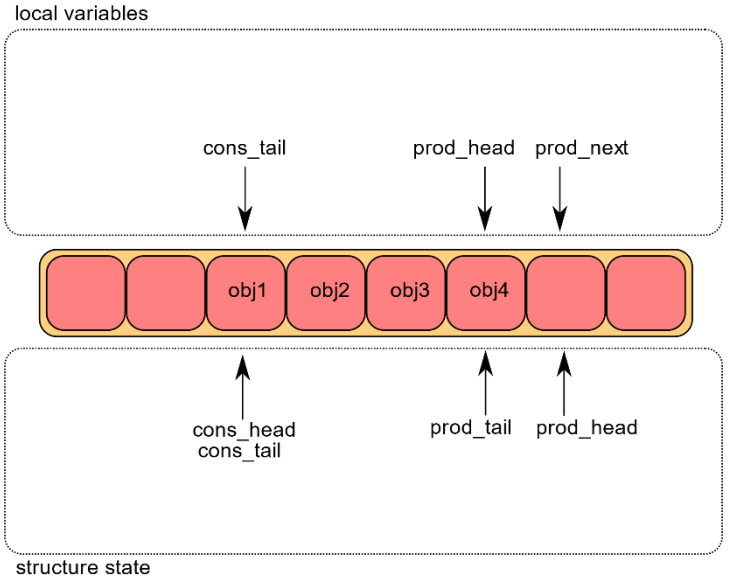


Single Producer Enqueue

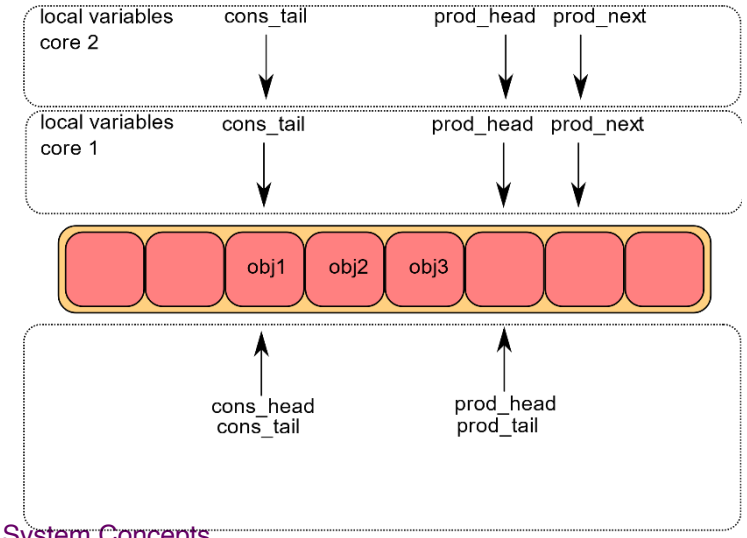
First Step

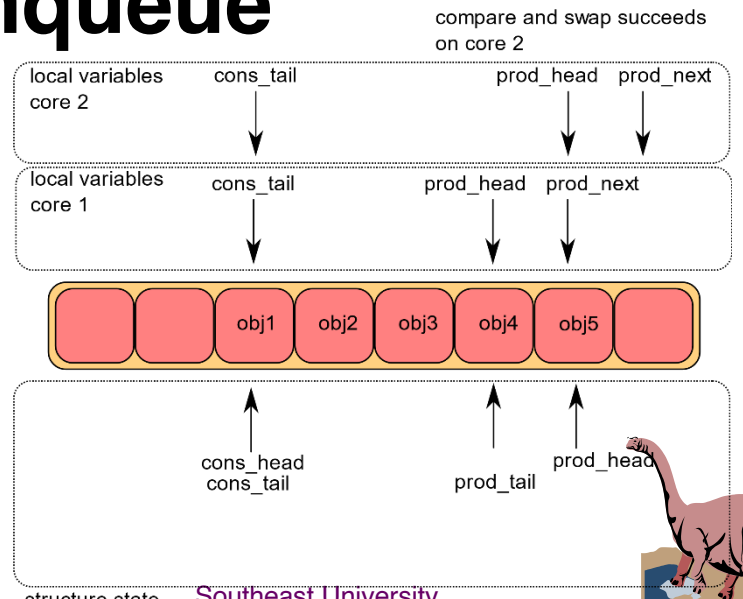


Second Step



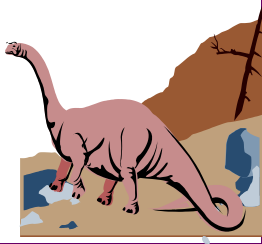
Multiple Producers Enqueue





Chapter 6: Process Synchronization

- Background
- The Critical-Section Problem
- Synchronization Hardware
- Semaphore as a generic synchronization tool
- Classical Problems of Synchronization
- Conditional Variables and Monitors
- Synchronization Examples



Dijkstra

- Edsger Wybe Dijkstra
  - (Dutch: [‘ɛtsxər ‘ʋibə ‘dɛikstra])
  - 11 May 1930 - 6 August 2002 (aged 72)
- Known for
  - Dijkstra's algorithm (single-source shortest path problem)
  - Structured programming, First implementation of ALGOL 60 (“Goto Statements Considered Harmful”)
  - Semaphores, Layered approach to operating system design, software-based paged virtual memory in
    - ✓THE multiprogramming system

Concept of Semaphore

- It is a synchronization tool that does not require busy waiting, but needs the support from kernel

  semop() - Unix, Linux System Call
  http://www.tutorialspoint.com/unix_system_calls/semop.htm

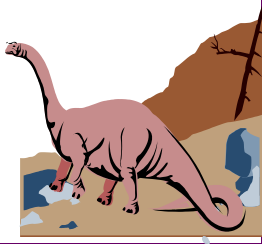
- Semaphore *S* — an integer variable
- It can only be accessed via two indivisible (atomic) operations: **wait** and **signal**
- They are functionally equivalent to the following busy-waiting operations.

***wait* (*S*):**

```
while S≤ 0 do no-op;
S--;
```

***signal* (*S*):**

```
S++;
```

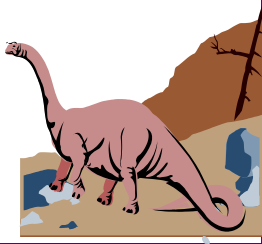


Semaphore Implementation

- Define a semaphore as a record

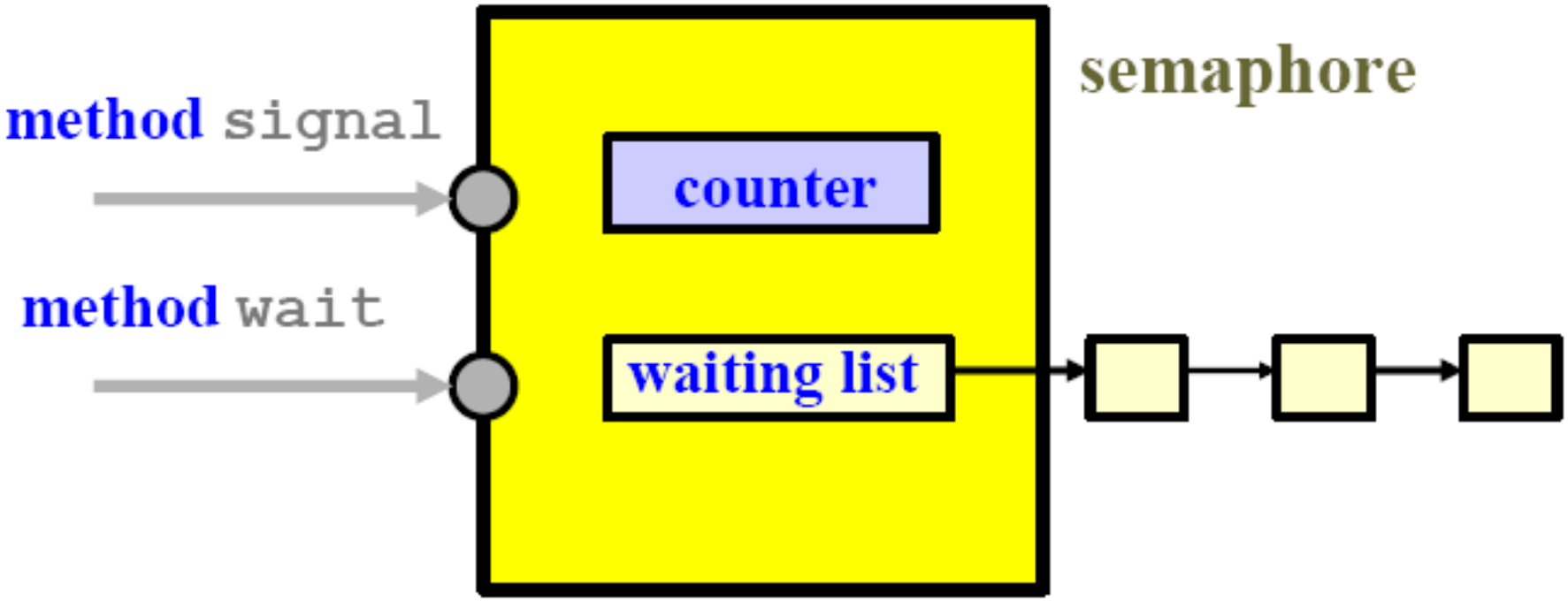
```
typedef struct {
   int counter;
   struct process *L;
   an in-kernel exclusive lock;
} semaphore;
```

- Assume two simple operations:
  - **block:** block the process that invokes it.
  - **wakeup(*P*):** resumes the execution of a blocked process *P*.



Semaphore Schematics

Semphore = counter + kernel mutex + waiting list



A useful way to think of a semaphore as used in the real-world systems is as a record of how many units of a particular resource are available,

Semaphore Implementation (1)

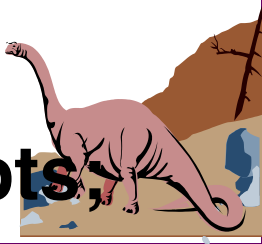
- Semaphore operations now defined as follows
  - Uniprocessor solution: disable interrupts. Recall that the only way the dispatcher regains control is through interrupts or through explicit requests.

wait(*S*):

```
Disable interrupts;
S.counter--;
if (S.counter < 0) {
    add this process to S.L;
    block;
}
Enable interrupts;
```

signal(S):

```
Disable interrupts;
S.counter++;
if (S.counter <= 0) {
    remove a process P
    from S.L;
    wakeup(P);
}
Enable interrupts;
```



Semaphore Implementation (2)

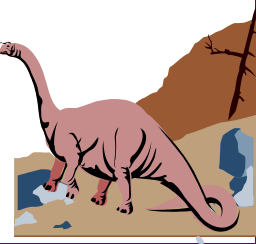
- What do we do in a multiprocessor platform to implement *wait(S)* and *signal(S)*?
  - Can't turn off interrupts to get low-level mutual exclusion
  - Suppose hardware provides atomic test-and-set instruction

wait(*S*):

```
while(TAS(S.lock));
S.counter--;
if (S.counter < 0) {
    add this process to S.L;
    block;
}
lock = 0;
```

signal(S):

```
while(TAS(S.lock));
S.counter++;
if (S.counter <= 0) {
    remove a process P
    from S.L;
    wakeup(P);
}
lock = 0;
```



POSIX Library's Support of Semaphore

- All POSIX semaphore functions and types are prototyped or defined in semaphore.h

  #include <semaphore.h>

- To define a semaphore object, use

  sem_t sem_name; OR sem_t * sem_pointer;

- For initialization, use either of the following APIs.

  int sem_init (sem_t *sem, int pshared, unsigned int initial_value);

  sem_t * sem_open (const char * name, int oflag, unsigned int initial_value);

- To increment/decrement the value of a semaphore,

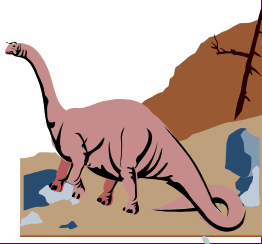
  int sem_wait (sem_t * sem_pointer);

  int sem_post (sem_t * sem_pointer);

Applications of Binary Semaphore: 1. Act as an Event Notification Tool

- Execute *B* in P_j only after *A* executed in P_i
- Use semaphore *flag*, which is initialized to 0
- Code:

P_i	P_j
⋮	⋮
A	*wait*(*flag*)
signal(*flag*)	*B*



Applications of Binary Semaphore: 2. Solve the Critical Section Problem

- Shared data: **semaphore lock;** // initially *lock*=1

- Process P_i:

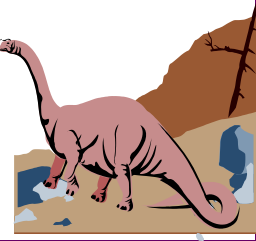
```
do {
        wait(lock);
            critical section
        signal(lock);
            remainder section
} while (1);
```

- **Give a demonstration about POSIX Semaphore**

Difference between Binary Semaphore and Mutex

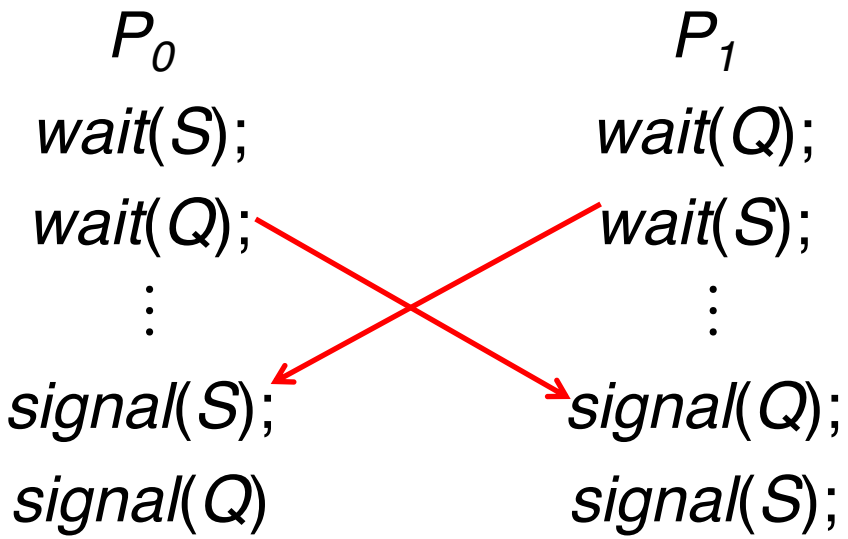
- Question: Is there any difference between binary semaphore and mutex, or they are essentially same?
- Answer: They're semantically the same, but in practice you will notice weird differences
  - Semaphore is implemented by process/thread blocking and wakeup
  - Mutex may be internally implemented by some kernels as spin locks, which could be more efficient on multi-processor systems but will slow down a single processor machine

http://gauss.ececs.uc.edu/Courses/c4029/extra/difference-between-semaphore-and-mutex.html



Side Effect of Semaphore: Deadlock and Starvation

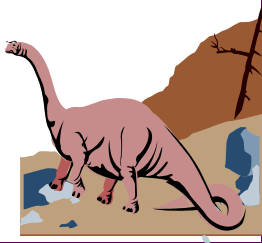
- **Deadlock** – two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes.
  - Example: Let *S* and *Q* be two semaphores initialized to 1



- **Starvation** – indefinite blocking. A process may never be removed from the semaphore queue in which it is waiting.

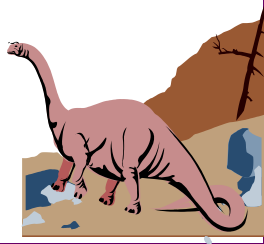
Chapter 6: Process Synchronization

- Background
- The Critical-Section Problem
- Synchronization Hardware
- Semaphores
- Classical Problems of Synchronization
- Conditional Variables and Monitors
- Synchronization Examples



Classical Problems of Synchronization

- Bounded-Buffer Problem (or called Producer-Consumer Problem)
- Readers and Writers Problem (or called Shared-Lock Problem)
- Dining-Philosophers Problem



Solution 1 for Producer-Consumer

- Shared variables besides the shared buffer

  semaphore fillCount, emptyCount;

  Initially:

  fillCount = 0, emptyCount = n

- **fillCount:** the number of items in the buffer
- **emptyCount:** the number of empty slots in the buffer

Solution 1 for Producer-Consumer

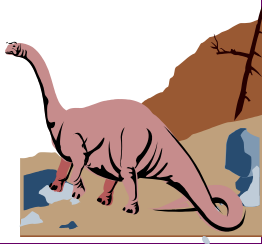
Producer:

```
do {
        ...
   produce an item in nextp
        ...
    wait(emptyCount);
    add nextp to buffer
    signal(fillCount);
} while (1);
```

Consumer:

```
do {
    wait(fillCount);
    remove an item from
    buffer to nextc
    signal(emptyCount);
        ...
    consume the item in nextc
        ...
} while (1);
```

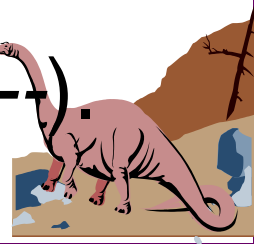
Question: Is this solution correct?



Solution 1 for Producer-Consumer

- This solution contains a serious race condition that can result in two or more processes modifying into the same variable *counter* (i.e., the variable recording the number of items in the buffer) at the same time.

- To understand how this is possible, recall how the procedures “add **nextp** to buffer” and “remove an item from buffer” are implemented (by *counter++* and *counter--*).



Solution 2 for Producer-Consumer

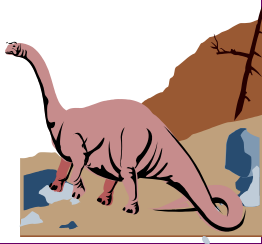
- Shared data

  semaphore fillCount, emptyCount, mutex;

  Initially:

  fillCount = 0, emptyCount = n, mutex = 1

- **mutex**: guarantee the mutual exclusive access of the shared buffer



Solution 2 for Producer-Consumer

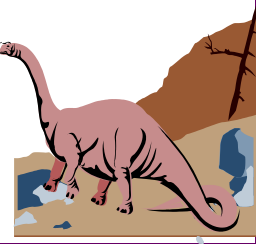
Producer:

```
do {
        ...
   produce an item in nextp
        ...
    wait(mutex);
    wait(emptyCount);
    add nextp to buffer
    signal(fillCount);
    signal(mutex);
} while (1);
```

Consumer:

```
do {
    wait(mutex);
    wait(fillCount);
    remove an item from
    buffer to nextc
    signal(emptyCount);
    signal(mutex);
        ...
    consume the item in nextc
        ...
} while (1);
```

Question: Is this solution correct?



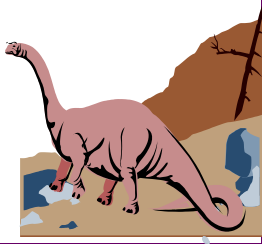
Solution 3 for Producer-Consumer

Producer:

```
do {
        ...
   produce an item in nextp
        ...
    wait(emptyCount);
    wait(mutex);
    add nextp to buffer
    signal(mutex);
    signal(fillCount);
} while (1);
```

Consumer:

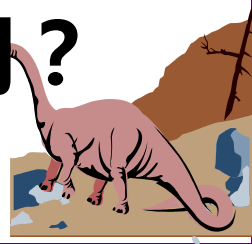
```
do {
    wait(fillCount);
    wait(mutex);
    remove an item from
    buffer to nextc
    signal(mutex);
    signal(emptyCount);
        ...
    consume the item in nextc
        ...
} while (1);
```



A Short Summary

- 结论1：需要用mutex确保对关键共享资源的互斥访问，比如 shared bounded buffer
- 结论2：信号量wait的顺序很重要
  - 例子：如果wait(mutex)错误放在了wait(fillCount)或者wait(emptyCount)之前，会导致死锁

- 问题1：信号量signal的顺序重要吗？
  - 例子：signal(mutex)和signal(fillCount)可以交换吗？
- 问题2：能否把produce an item和consume an item放到wait(mutex)和signal(mutex)之间？



When the buffer size is only one, can we remove the mutex variable?

Initially: **semaphore fillCount = 0, emptyCount = 1**

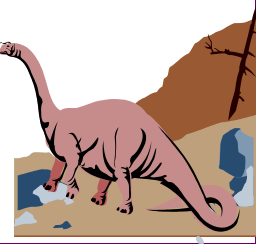
Producer:

```
do {
        ...
   produce an item in nextp
        ...
    wait(emptyCount);
    add nextp to buffer
    signal(fillCount);
} while (1);
```

Consumer:

```
do {
    wait(fillCount);
    remove an item from
    buffer to nextc
    signal(emptyCount);
        ...
    consume the item in nextc
        ...
} while (1);
```

Please give out your reasons.



信号量：生产者消费者习题

- 考虑三个吸烟者进程和一个经销商进程的系统
  - 每个吸烟者连续不断地做烟卷并抽他做好的烟卷，做一支烟卷需要烟草、纸和火柴三种原料。
  - 这三个吸烟者分别掌握有烟草、纸和火柴。
  - 经销商源源不断地提供上述三种原料，但他只随机的将其中的两种原料放在桌上，具有另一种原料的吸烟者就可以做烟卷并抽烟，且在做完后给经销商发信号，然后经销商再拿出两种原料放在桌上，如此反复。
- 基于信号量设计一个同步算法描述他们的活动

信号量：生产者消费者习题

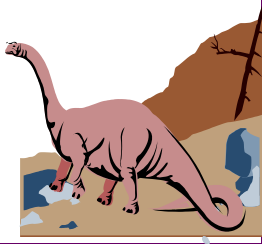
- 可以考虑：设置三个信号量fullA、fullB和fullC，分别代表三种原料组合，初值均为0，即
  - fullA表示烟草和纸的组合，
  - fullB表示纸和火柴的组合，
  - fullC表示烟草和火柴的组合。

- 桌面上一次只能放一种组合，可以看作是只能放一个产品的共享缓冲区，设置信号量empty初值为1，控制经销商往桌子上放原料

信号量：生产者消费者习题

■算法

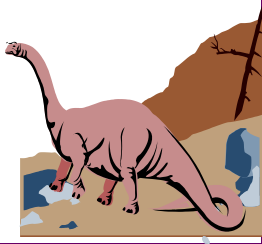
```
Semaphore fullA=fullB=fullC=0, empty=1;

process smokerA() {
    do {
        wait(fullA);
        take tobacco and paper from the table;
        signal(empty);  // signal an empty table event
        make cigarette;
        smoke cigarette;
    } while (1);
}
```



信号量：生产者消费者习题

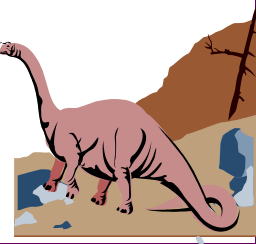
```
process smokerB() {
    do {
        wait(fullB);
        take paper and match
        from the table;
        signal(empty);
        make cigarette;
        smoke cigarette;
    } while (1);
}
```

```
process smokerC() {
    do {
        wait(fullC);
        take tobacco and match
        from the table;
        signal(empty);
        make cigarette;
        smoke cigarette;
    } while (1);
}
```



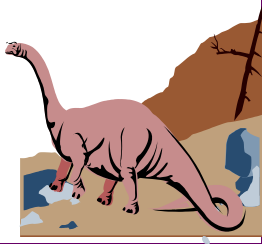
信号量：生产者消费者习题

```
process provider( ) {
    integer i;
    do {
        wait(empty); // wait for an empty table event
        i = random() % 3;
        switch(i) {
            case 0: put T&P on table; signal(fullA); break;
            case 1: put P&M on table; signal(fullB); break;
            case 2: put T&M on table; signal(fullC); break;
        }
    } while(1);
}
```



Reader-Writer Locks

- Imagine a number of concurrent operations, including **reads** and **writes**.
  - Writes change the state of the data
  - Reads do not.
    - ✓Many reads can proceed concurrently, as long as we can guarantee that no write is on-going.

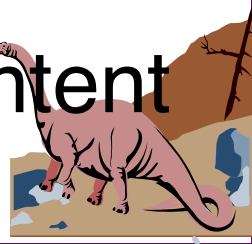


Readers-Writers Problem (or Shared-Lock Problem)

- Shared data

semaphore mutex, wrt;
int readcount;
Initially **mutex = 1, wrt = 1, readcount = 0**

- **readcount**: the number of readers browsing the shared content
- **mutex**: guarantee the mutual exclusive access to the readcount variable
- **wrt**: the right of modifying the shared content



Readers-Writers Problem (solution 1)

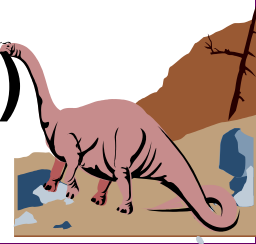
Writer Process

```
wait(wrt);
        ...
    writing is performed
        ...
signal(wrt);
```

Question: Is this solution correct?

Reader Process

```
wait(mutex);
readcount++;
signal(mutex);
if (readcount == 1)
    wait(wrt);
        ...
   reading is performed
        ...
wait(mutex);
readcount--;
signal(mutex);
if (readcount == 0)
   signal(wrt);
```



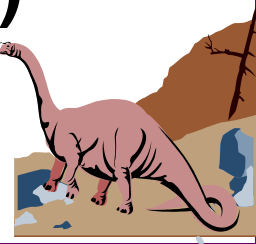
Readers-Writers Problem (solution 2)

Writer Process

```
wait(wrt);
        ...
    writing is performed
        ...
signal(wrt);
```

Reader Process

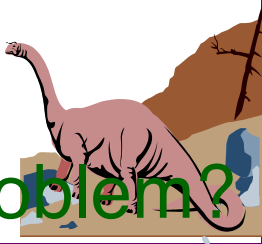
```
wait(mutex);
readcount++;
if (readcount == 1)
     wait(wrt);
signal(mutex);
        ...
   reading is performed
        ...
wait(mutex);
readcount--;
if (readcount == 0)
   signal(wrt);
signal(mutex);
```



```
7   void rwlock_init(rwlock_t *rw) {
8     rw->readers = 0;
9     sem_init(&rw->lock, 0, 1);
10    sem_init(&rw->writelock, 0, 1);
11  }
12
13  void rwlock_acquire_readlock(rwlock_t *rw) {
14    sem_wait(&rw->lock);
15    rw->readers++;
16    if (rw->readers == 1)
17      sem_wait(&rw->writelock); // first reader acquires writelock
18    sem_post(&rw->lock);
19  }
20
21  void rwlock_release_readlock(rwlock_t *rw) {
22    sem_wait(&rw->lock);
23    rw->readers--;
24    if (rw->readers == 0)
25      sem_post(&rw->writelock); // last reader releases writelock
26    sem_post(&rw->lock);
27  }
28
29  void rwlock_acquire_writelock(rwlock_t *rw) {
30    sem_wait(&rw->writelock);
31  }
32
33  void rwlock_release_writelock(rwlock_t *rw) {
34    sem_post(&rw->writelock);
```

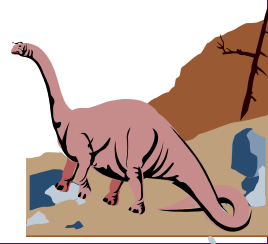
More Info about Reader-Writer Locks

- The first readers–writers problem
  - requires that, no reader be kept waiting unless a writer has already obtained permission to use the shared object.
- The second readers-writers problem
  - requires that, once a writer is ready, that writer perform its write as soon as possible.
- Discussion:
  - Which problem is solved by the previous codes?
  - The first readers-writers problem.
  - How to solve the second readers-writers problem?



Exercise

- 用信号量解决无饥饿的读者－－写者问题。



The (No-starve) Readers-Writers Problem

```
semaphore mutex= 1;
semaphore writemutex=1;
int read_count = 0;
semaphore wfmutex =1;

void write() {
        do {
                wait(wfmutex);
                wait(writemutex);
                /* writing */
                signal(writemutex);
                signal(wfmutex);
    }
    while (1);
}
```

```
void read() {
        do {
                wait(wfmutex);
                signal(wfmutex);
                wait(mutex);
                read_count ++;
                if (read_count == 1)
                        wait(writemutex);
                signal(mutex);
                /* reading */
                wait(mutex);
                read_count --;
                if (read_count == 0)
                        signal(writemutex);
                signal(mutex);
    }
    while (1);
}
```

The (Writer-priority) Readers-Writers Problem

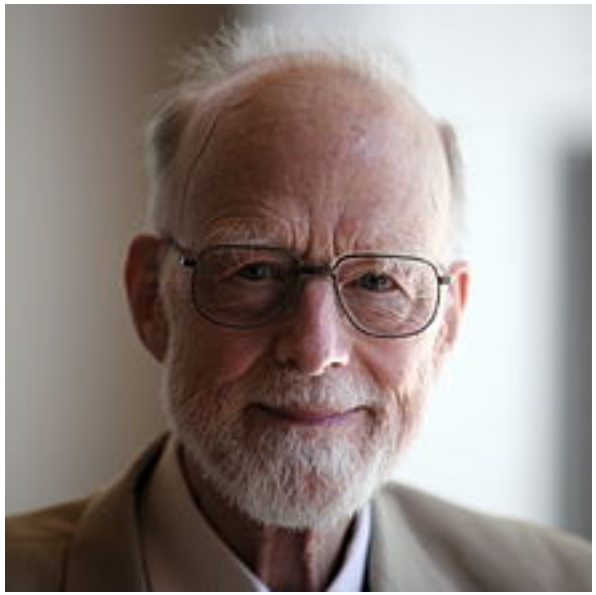
```
semaphore readcount_mutex= 1;
semaphore writemutex=1; //0表示不能写
int write_count = read_count = 0;
semaphore writecount_mutex= 1;
semaphore readmutex=1; //0表示不能读
```

```
void write() {
    do {
        wait(writecount_mutex);
        write_count ++;
        if (write_count == 1)
            wait(readmutex);
        signal(writecount_mutex);
        wait(writemutex);

        /* writing */

        signal(writemutex);
        wait(writecount_mutex);
        write_count --;
        if (write_count == 0)
            signal(readmutex);
        signal(writecount_mutex);
    }
    while (1);
}
```

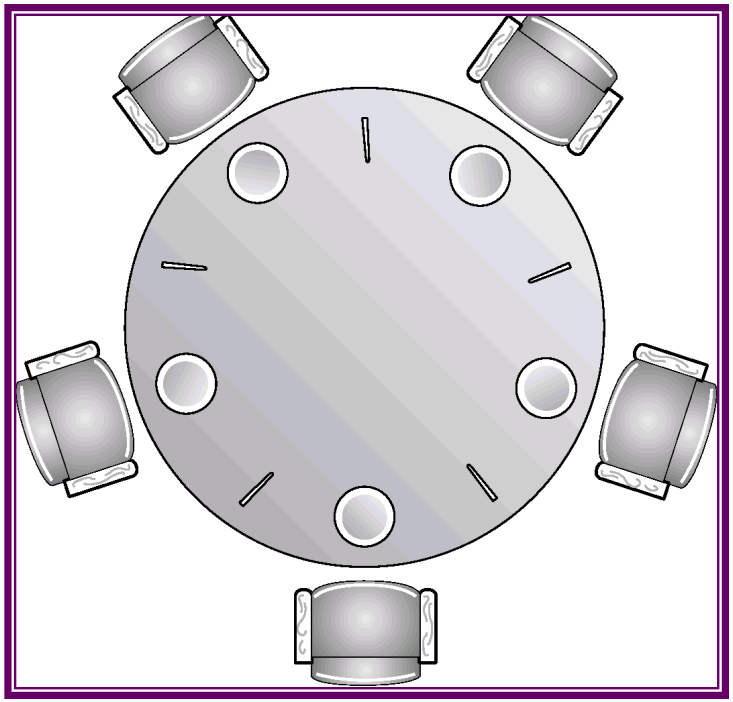
```
void read() {
    do {
        wait(readmutex);
        wait(readcount_mutex);
        read_count ++;
        if (read_count == 1)
            wait(writemutex);
        signal(readcount_mutex);
        signal(readmutex);

        /* reading */

        wait(readcount_mutex);
        read_count --;
        if (read_count == 0)
            signal(writemutex);
        signal(readcount_mutex);
    }
    while (1);
}
```

The Dining Philosophers

- Originally formulated in 1965 by Edsger Dijkstra
- Tony Hoare gave the problem its present formulation



Dining-Philosophers Problem



Here is the basic loop of each philosopher:

```
while (1) {
   think();
   getforks();
   eat();
   putforks();
}
```

- Shared data

  semaphore chopstick[5];

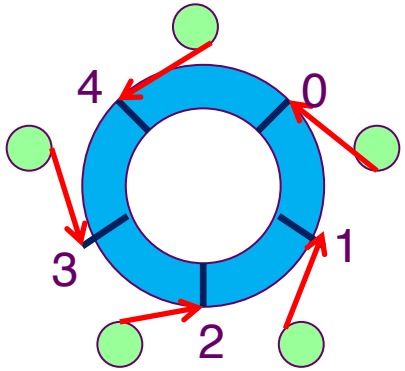
Initial values of all semaphores are set to 1

Dining-Philosophers Problem

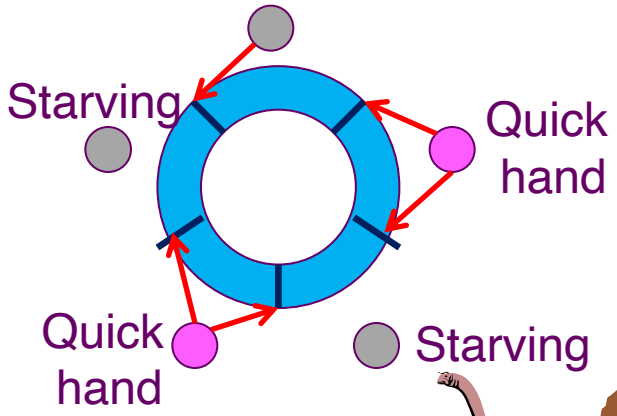
- Philosopher *i*:

```
do {
    wait(chopstick[i]);
    wait(chopstick[(i+1) % 5]);
        ...
        eat
        ...
    signal(chopstick[i]);
    signal(chopstick[(i+1) % 5]);
        ...
        think
        ...
} while (1);
```

- Challenges
  - Deadlock



  - Starvation



  - Lack of Fairness

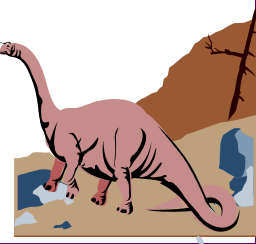
Semaphore 学习的四重境界

1. **理解基础概念**

2. **熟练掌握经典问题（PC, RW, DP）。**

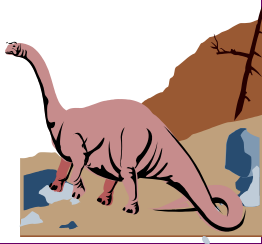
3. **熟悉经典问题的变种，能够将应用题恰当的归约到某个经典问题的变种。**

4. **能够将经典问题灵活组合应用，随心所欲，信手拈来。**



Chapter 6: Process Synchronization

- Background
- The Critical-Section Problem
- Synchronization Hardware
- Semaphores
- Classical Problems of Synchronization
- Condition Variables and Monitors
- Synchronization Examples



Condition Variable

- Semaphore and condition variables are very similar and are used mostly for the same purposes.
  - Semaphore can be easily understood as an in-kernel counter for the units of a type of resource.
  - Condition is an advanced event notification tech.
- However, there are minor differences that could make one preferable.
  - For example, to implement barrier synchronization, you would not be able to use a semaphore. But a condition variable is ideal.

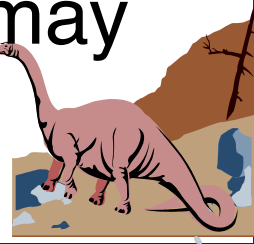
Condition Variable

- The condition variable mechanism allows threads to suspend execution and relinquish the processor until some condition is true.

  Semphore = counter + mutex + waiting list

  Conditional Variable = waiting list

- A problem of semaphore: We cannot read the in-kernel counter hiding inside a semaphore
- A condition variable must be used inside a mutex to avoid a race condition created by one thread preparing to wait and another thread which may signal the condition before the first thread actually waits on it resulting in a deadlock.



Condition Variable vs. Semaphore

Semaphore	Condition Variable
Can be used anywhere	Must be used inside the protection of a mutex
wait() does not always block its caller	wait() always blocks its caller
signal() either releases a process, or increases the semaphore counter	signal() either releases a process, or the signal is lost as if it never occurs
If signal() releases a process, the caller and the released both continue	If signal() releases a process, either the caller or the released continues, but not both

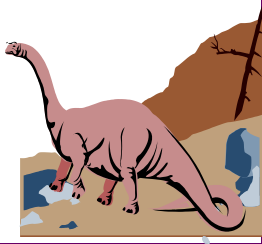
Condition Variable in Pthread Library

- Creating/Destroying:
  - pthread_cond_t cond = THREAD_COND_INITIALIZER;
  - pthread_cond_init
  - pthread_cond_destroy
- Waiting on condition:
  - pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_t *mutex) - unlocks the mutex and waits for the condition variable *cond* to be signaled.
- Waking thread based on condition:
  - pthread_cond_signal(pthread_cond_t *cond) - restarts one of the threads that are waiting on the condition variable *cond*.
  - pthread_cond_broadcast(pthread_cond_t *cond) - wake up all threads blocked by the specified condition variable.

Barrier Problem

- Suppose we wanted to perform a multi-threaded calculation that has two stages, but we don't want to advance to the second stage until the first stage is completed.

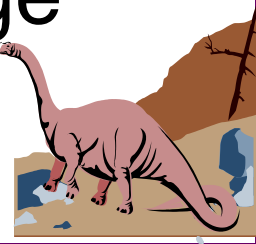
- We could use a synchronization method called a **barrier**. When a thread reaches a barrier, it will wait at the barrier until all the threads reach the barrier, and then they'll all proceed together.



Barrier Problem

- Pthreads has a **pthread_barrier_wait()** function that implements this. You'll need to declare a **pthread_barrier_t** variable and initialize it with **pthread_barrier_init()**.
  - **pthread_barrier_init()** takes the number of threads that will be participating in the barrier as an argument.

- Now let's implement our own barrier and use it to keep all the threads in sync in a large calculation.



Barrier Implementation by Condition Variable

```
#define N (16)
double data[256][8192] ;
pthread_mutex_t m;
pthread_cond_t cv;
int main() {
    int tids[N], i;
    pthread_mutex_init(&m, NULL);
    pthread_cond_init(&cv, NULL);
    for(i = 0; i < N; i++) { tids[i] = i;
       pthread_create(&ids[i], NULL, calc, &(tids[i]));
    }
    for(i = 0; i < N; i++) pthread_join(ids[i], NULL);
```

https://github.com/angrave/SystemProgramming/wiki/Synchronization%2C-Part-6%3A-Implementing-a-barrier

Barrier Implementation by Condition Variable

double data[256][8192]

void *calc(void *ptr) {

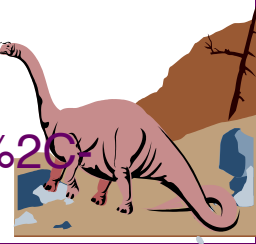
1. Threads do first calculation (use and change values in data)

2. Barrier! Wait for all threads to finish first calculation before continuing

3. Threads do second calculation (use and change values in data)

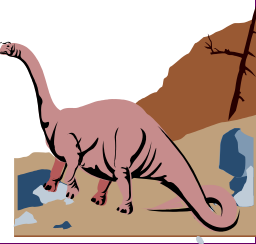
}

https://github.com/angrave/SystemProgramming/wiki/Synchronization%2C-Part-6%3A-Implementing-a-barrier



If using condition variable, the state of counter can be access. But when using semaphore, the state of inner count cannot be accessed.

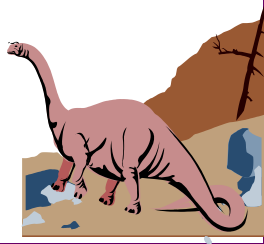
```
#int remain = N;
void *calc(void *ptr) {
 // The thread does first calculation
 pthread_mutex_lock(&m);
 remain--;
 if (remain ==0)  pthread_cond_broadcast(&cv);
 else {
 while(remain != 0) pthread_cond_wait(&cv,&m);
 }
 pthread_mutex_unlock(&m);
 // The thread does second calculation
}
```



Object-Oriented Monitors

- High-level synchronization construct that allows the safe sharing of an abstract data type among concurrent processes.

```
monitor monitor-name
{   shared variable declarations
    procedure body P1 (...) {
       . . .}
    procedure body P2 (...) {
       . . .}
    procedure body Pn (...) {
        . . .}
    { initialization code}
}
```



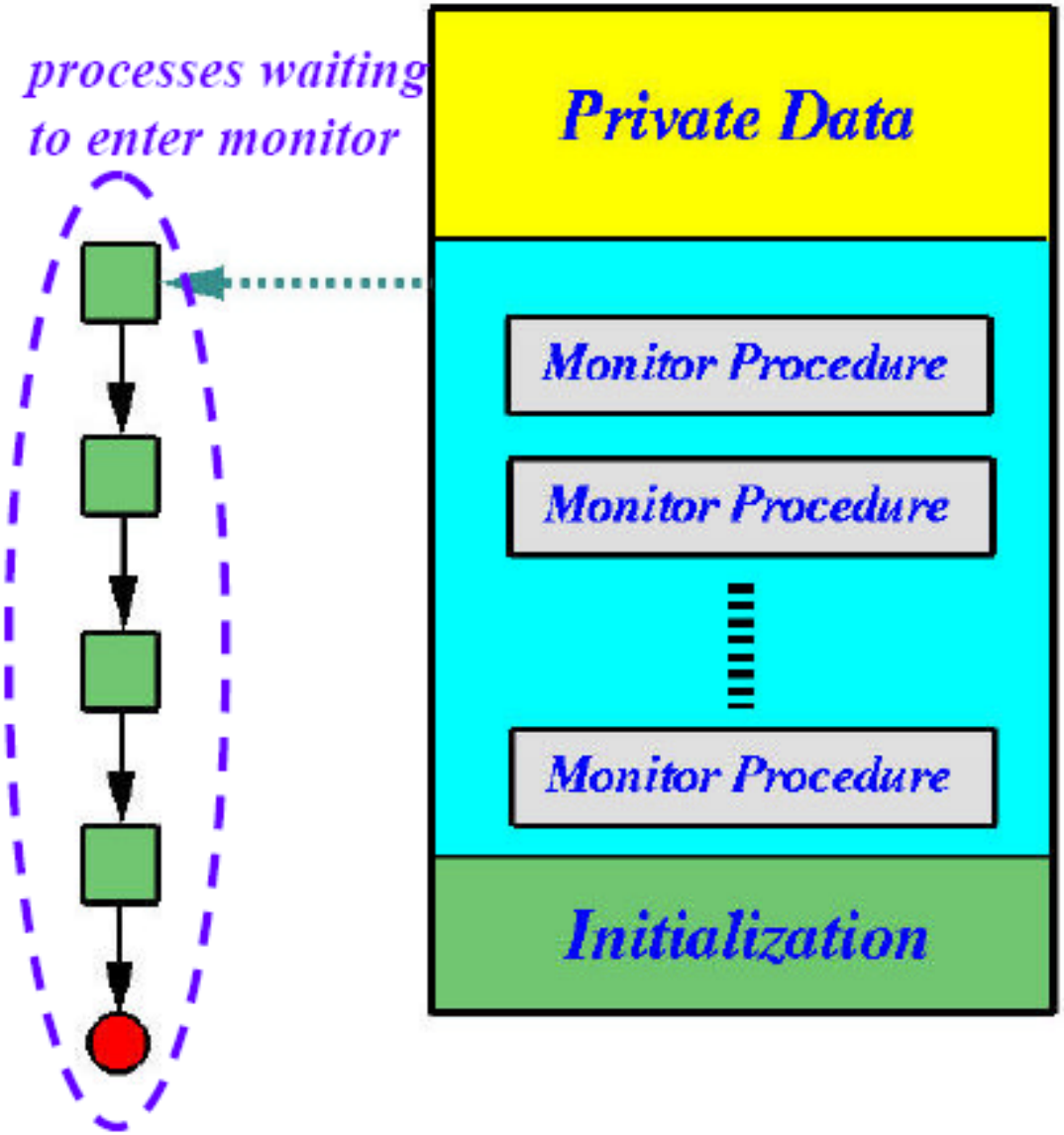
Monitors: Mutual Exclusion

- *No more than one process* can be executing *within* a monitor. Thus, *mutual exclusion* is guaranteed within a monitor.

- When a process calls a monitor procedure and enters the monitor successfully, it is the *only* process executing in the monitor.

- When a process calls a monitor procedure and the monitor has a process running, the caller will be blocked outside of the monitor.

Schematic View of a Monitor



Monitors: Event Notification

- To allow a process to wait within the monitor, a **condition** variable must be declared, as

  condition x, y;

- Condition variable can only be used with the operations **wait** and **signal**.
  - The operation

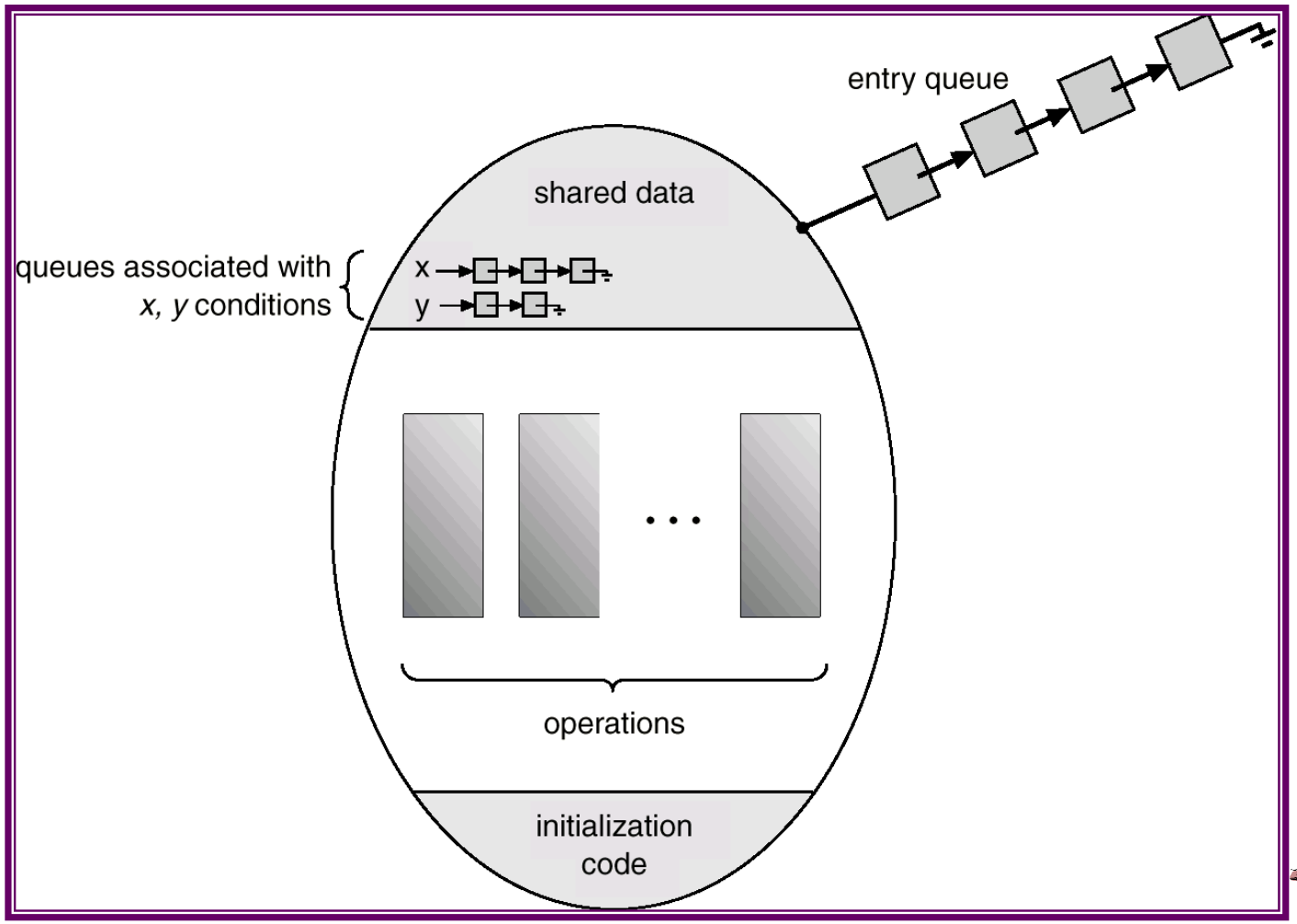
    x.wait();

    means that the process invoking this operation is blocked until another process invokes

    x.signal();

  - The **x.signal** operation wakeup exactly one blocked process. If no process is waiting for the condition, then the **signal** operation has no effect.

Schematic View of a Monitor With Condition Variables



A Subtle Issue of Condition Variable

- **Consider the released process (from the signaled condition) and the process that signals. There are two processes executing in the monitor, and mutual exclusion is violated!**

- There are two common and popular approaches to address this problem:
  - The released process takes over the monitor and the signaling process waits somewhere.
  - The released process waits somewhere and the signaling process continues to use the monitor.

Java's Monitor Supports

- Synchronized methods for mutual exclusion

```
class classname {
        synchronized return_type methodname() {……}
}
```

- Coordination support for event notification

Method	Description
void Object.wait();	Enter a monitor's wait set until notified by another thread
void Object.wait(long timeout);	Enter a monitor's wait set until notified by another thread or timeout milliseconds elapses
void Object.notify();	Wake up one thread waiting in the monitor's wait set. (If no threads are waiting, do nothing.)
void Object.notifyAll();	Wake up all threads waiting in the monitor's wait set. (If no threads are waiting, do nothing.)

http://www.ibm.com/developerworks/cn/java/j-lo-synchronized/index.html

http://www.artima.com/insidejvm/ed2/threadsynchP.html

Producer-Consumer Example

```
procedure producer() {
    do {
        item = produceItem();
        PCbuffer.add(item);
    } while (true);
}

procedure consumer() {
    do {
        item = PCbuffer.remove();
        consumeItem(item);
    } while (true);
}
```

```
monitor PCbuffer {
    int itemCount; // <= BUFSIZE
    condition full, empty;
    putItemIntoBuffer(item) {…}
    Item removeItemFromBuffer()
    {…}
    procedure void add(item) {
        ...   // how to implement?
    }
    procedure item remove() {
        …  // how to implement?
    }
}
```

Producer-Consumer Example

```
procedure void add(item) {
    if (itemCount == BUFSIZE)
        full.wait();
    putItemIntoBuffer(item);
    itemCount = itemCount + 1;
    if (itemCount == 1)
        empty.signal();
    return;
}
```

```
procedure item remove() {
    if (itemCount == 0)
        empty.wait();
    item = removeItemFromBuffer();
    itemCount = itemCount - 1;
    if (itemCount == BUFSIZE - 1)
        full.signal();
    return item;
}
```

- Note that **if** statement has been used in the above code, both when testing if the buffer is full or empty.
- With multiple consumers, there is a race condition between the consumer who gets notified that an item has been put into the buffer and another consumer who is waiting on the monitor.

Producer-Consumer Example

```
procedure void add(item) {
    while (itemCount == BUFSIZE)
        full.wait();
    putItemIntoBuffer(item);
    itemCount = itemCount + 1;
    if (itemCount == 1)
        empty.signal();
    return;
}
```

```
procedure item remove() {
    while (itemCount == 0)
        empty.wait();
    item = removeItemFromBuffer();
    itemCount = itemCount - 1;
    if (itemCount == BUFSIZE - 1)
        full.signal();
    return item;
}
```

- Note that **while** statement has been used in the above code, both when testing if the buffer is full or empty.
- With multiple consumers, there is a race condition between the consumer who gets notified that an item has been put into the buffer and another consumer who is waiting on the monitor.

Producer-Consumer Example

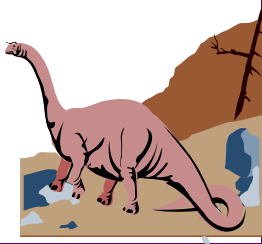
```
procedure void add(item) {
    while (itemCount == BUFSIZE)
        full.wait();
    putItemIntoBuffer(item);
    itemCount = itemCount + 1;
    if (itemCount == 1)
        empty.signal();
    return;
}
```

```
procedure item remove() {
    while (itemCount == 0)
        empty.wait();
    item = removeItemFromBuffer();
    itemCount = itemCount - 1;
    if (itemCount == BUFSIZE - 1)
        full.signal();
    return item;
}
```

- With multiple producers, there is also a race condition between the producer who gets notified that the buffer is no longer full and another producer is already waiting on the monitor.
- If the **while** was instead an **if**, too many items might be put into the buffer or a remove might be attempted on an empty buffer.

Dining Philosophers Example

```
monitor dp
{
    enum {thinking, hungry, eating}   state[5];
    condition self[5];
    void pickup(int i) ;        // pick up chopsticks
    void putdown(int i) ;       // put down chopsticks
    void test(int i) ;          // test if Pi is eligible for eating
    void init() {
        for (int i = 0; i < 5; i++)
            state[i] = thinking;
    }
}
```



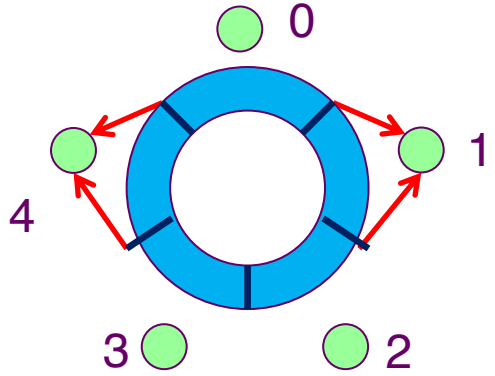
Dining Philosophers Example

```
void pickup(int i) {
    state[i] = hungry;
    test(i);
    while(state[i] != eating)
        self[i].wait();
}
```

```
void putdown(int i) {
    state[i] = thinking;
    test((i+4) % 5); // left
    test((i+1) % 5); // right
}
```

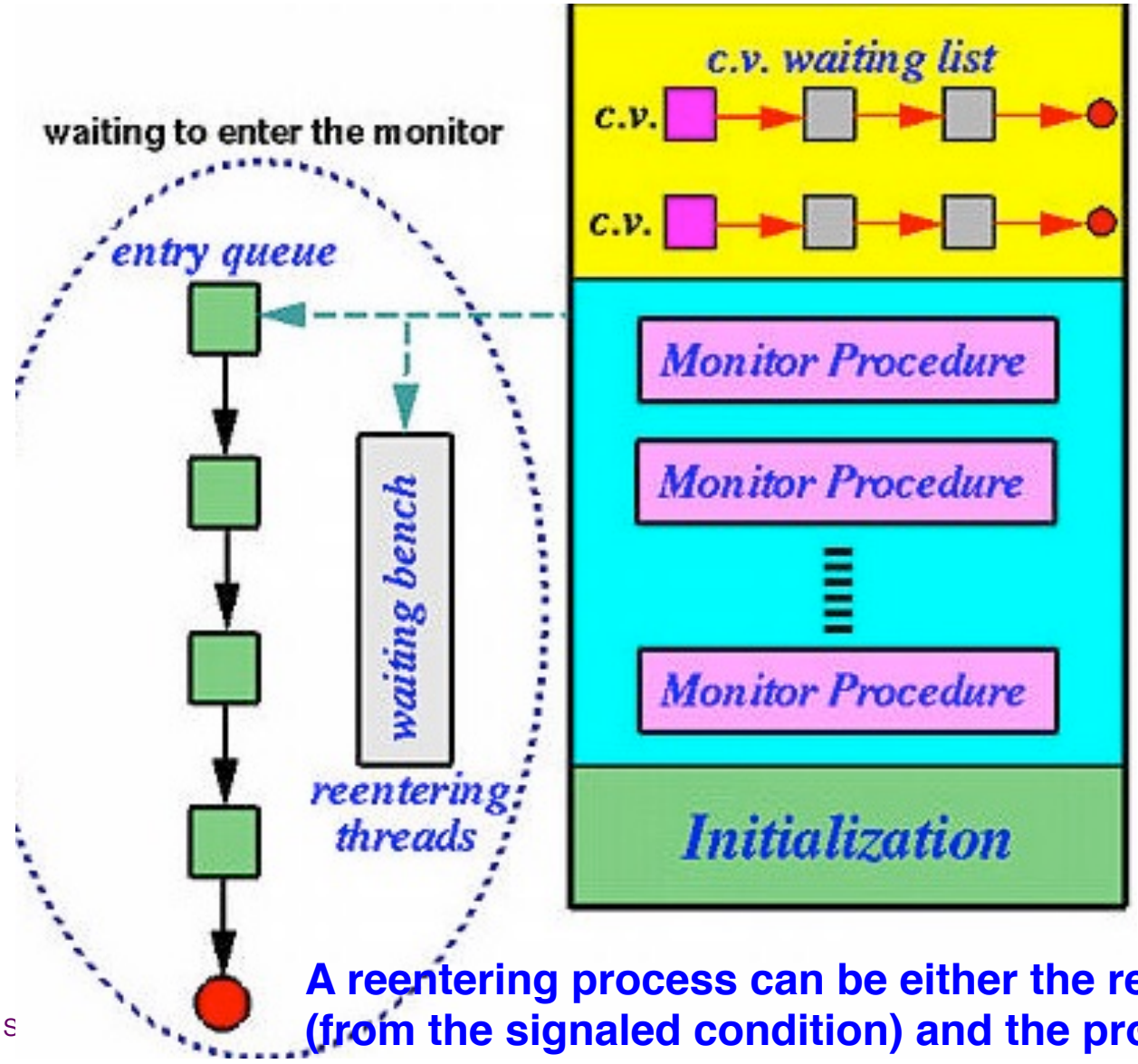
The code has NO deadlock!!! Why?

```
void test(int i) {
    if ( (state[(i + 4) % 5] != eating) &&
        (state[i] == hungry) &&
        (state[(i + 1) % 5] != eating)) {
        state[i] = eating;
        self[i].signal();
    }
}
```

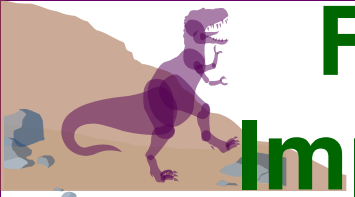


When P_1 and P_4 finish eating at the same time, will P_2 and P_3 compete for their common chopstick after their wakeup?

Another Subtle Issue of Monitor: Queue of Reentering Threads/Proc



A reentering process can be either the released process (from the signaled condition) and the process that signals



For Better Understanding, Let's Implement Monitor by Semaphores

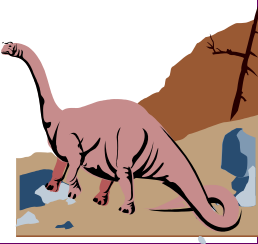
- Variables

```
semaphore mutex;  // (initially  = 1)
semaphore next;   // (initially  = 0)
int next-count = 0;
```

- Each external procedure ***F*** will be replaced by

```
wait(mutex);
    …  //  body of F;
if (next-count > 0)
   signal(next);
else
   signal(mutex);
```

- Mutual exclusion within a monitor is ensured.



Monitor Implementation Using Semaphores

- For each condition variable ***x***, we have:

  semaphore x-sem; // (initially = 0)

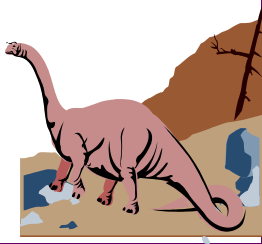
  int x-count = 0;

- The operation **x.wait** can be implemented as:

```
x-count++;
if (next-count > 0)
    signal(next);
else
    signal(mutex);
wait(x-sem);
x-count--;
```

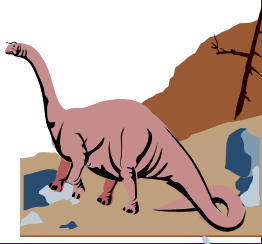
- The operation **x.signal** can be implemented as:

```
if (x-count > 0) {
    next-count++;
    signal(x-sem);
    wait(next);
    next-count--;
}
```



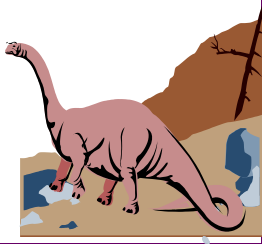
Monitor Implementation (Cont.)

- Check two conditions to establish correctness of system:
  - User processes must always make their calls on the monitor in a correct sequence.
  - Must ensure that an uncooperative process does not ignore the mutual-exclusion gateway provided by the monitor, and try to access the shared resource directly, without using the access protocols.



Condition Enhanced with a Priority Number

- *Conditional-wait* construct: **x.wait(c);**
  - **c** – integer expression evaluated when the **wait** operation is executed.
  - value of **c** (a *priority number*) stored with the name of the process that is suspended.
  - when **x.signal** is executed, process with smallest associated priority number is resumed next.



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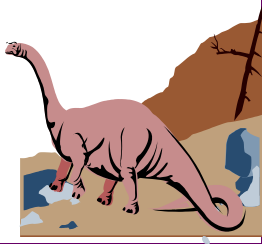


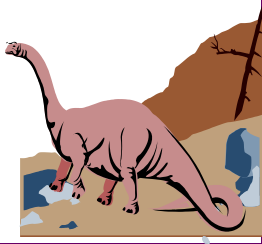
Solaris 2 Synchronization

- Implements a variety of locks to support multitasking, multithreading (including real-time threads), and multiprocessing.
- Uses *adaptive mutexes* for efficiency when protecting data from short code segments.
- Uses *condition variables* , *semaphore*, and *readers-writers* locks when longer sections of code need access to data.
- Uses *turnstiles* to order the list of threads waiting to acquire either an adaptive mutex or reader-writer lock.

Adaptive Mutex

- Most operating systems (including Solaris, Mac OS X and FreeBSD) use a hybrid approach called "adaptive mutex". The idea is to use a spinlock when trying to access a resource locked by a currently-running thread, but to sleep if the thread is not currently running. (The latter is *always* the case on single-processor systems.)

https://en.wikipedia.org/wiki/Spinlock#Alternatives



Windows XP Synchronization

- Uses interrupt masks to protect access to global resources on uniprocessor systems.
- Uses *spinlocks* on multiprocessor systems.
- Also provides *dispatcher objects* which may act as mutexes and semaphores.
- Dispatcher objects may also provide *events*. An event acts much like a condition variable.