Chapter 6: Process Synchronization

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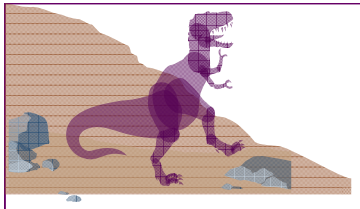
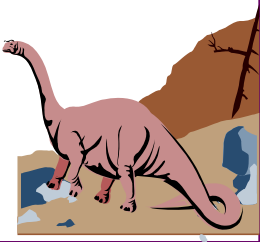
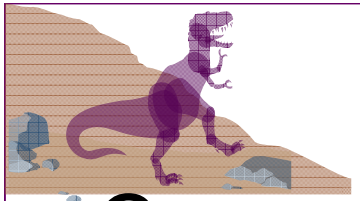


Chapter 6: Process Synchronization

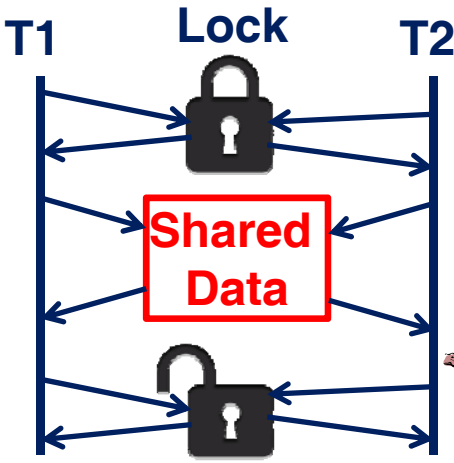
- Background
- The Critical-Section Problem
- Synchronization Hardware
- Semaphores
- Classical Problems of Synchronization
- Monitors
- Synchronization Examples

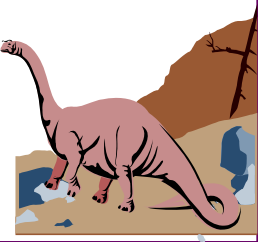


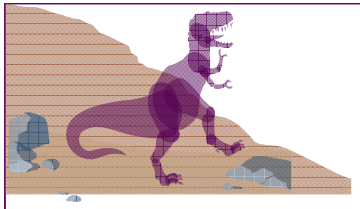


Background

- Concurrent access to shared data may result in data inconsistency.
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes.
- Synchronization primitive for shared memory programming --- Lock
  - Exclusive Lock
  - Shared Lock

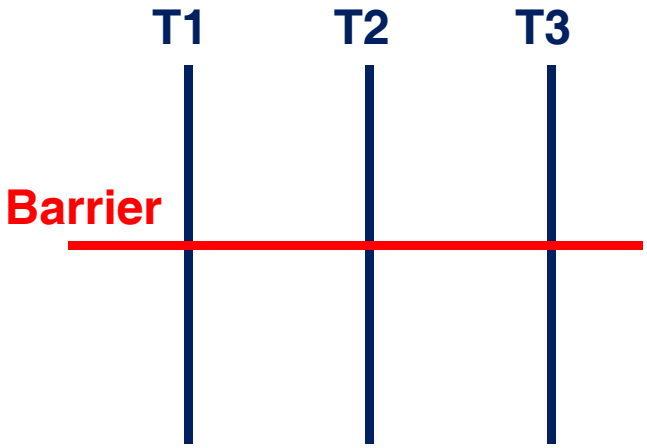




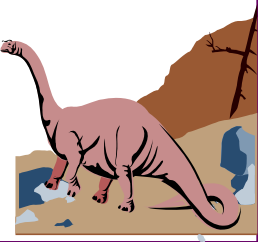


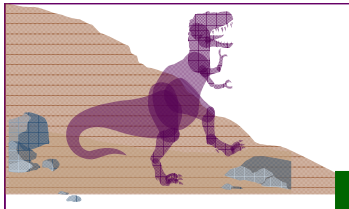
Background (cont.)

- Other synchronization primitive for shared memory programming --- Barrier



- As for this course, we focus primarily on the lock primitive
- Ideas are easy. Implementation is hard.





Revisit the Shared-memory Producer Consumer Problem

- Shared-memory solution to bounded-buffer problem (Chapter 3) allows at most *n* – 1 items in buffer at the same time. A solution, where all *N* buffers are used is not simple.

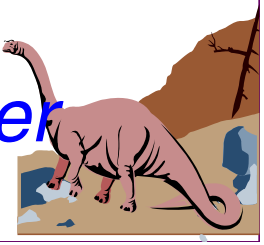
Producer:

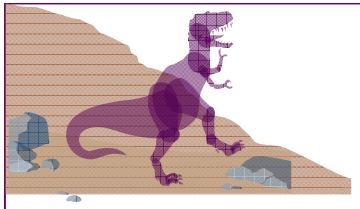
```
while (1) {
  while (((in+1) % BUFFER_SIZE) == out) ;
  ……
  in = (in+1) % BUFFER_SIZE;
}
```

Consumer:

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

- Suppose that we modify the producer-consumer code by adding a variable *counter*

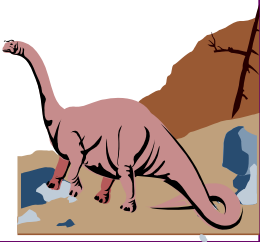


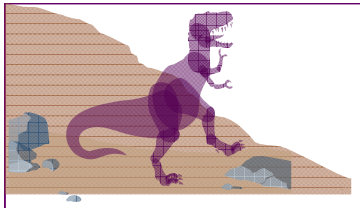


Bounded-Buffer Solution

- Shared data

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



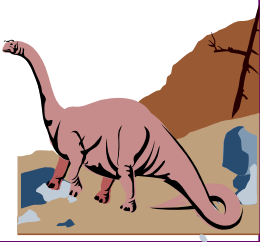


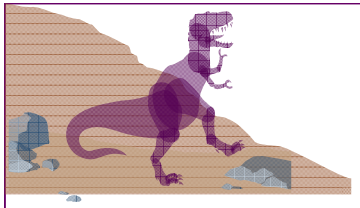
Bounded-Buffer Solution

- Producer process

```
item nextProduced;

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



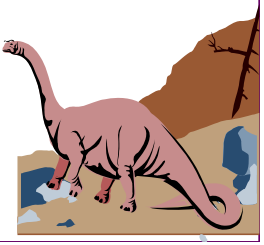


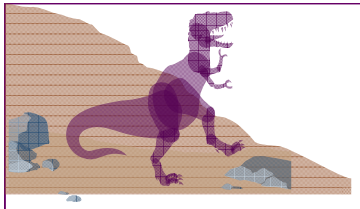
Bounded-Buffer Solution

- Consumer process

```
item nextConsumed;

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





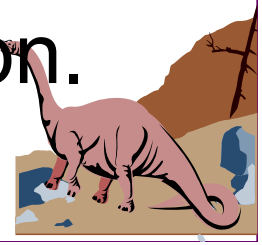
Critical Shred Data

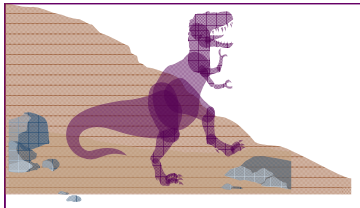
- Counter is a piece of critical shared data
- The statements

  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

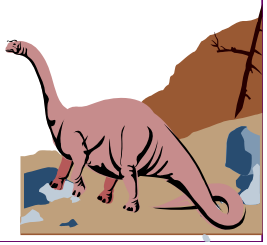
  counter = register1

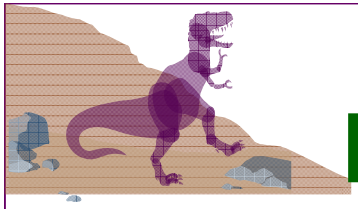
- The statement "**count--**" may be implemented in machine language as:

  register2 = counter

  register2 = register2 – 1

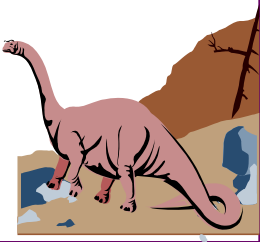
  counter = register2

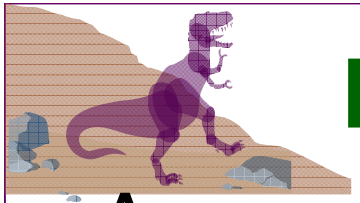




Potential Data Inconsistency

- 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.



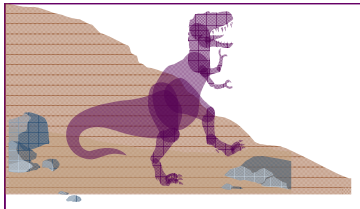


Potential Data Inconsistency

- 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

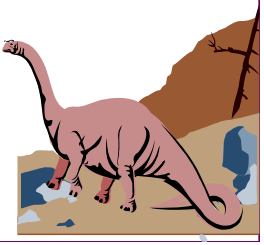
counter = register1

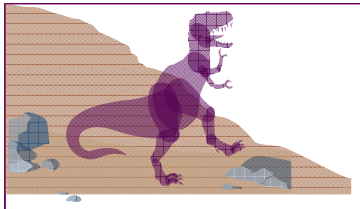
Consumer

register2 = counter

register2 = register2 – 1

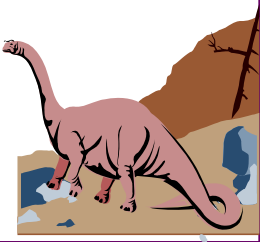
counter = register2

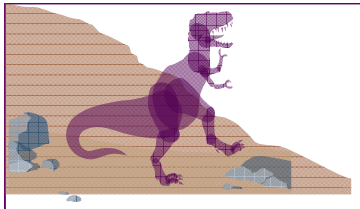




Concept of Race Condition

- **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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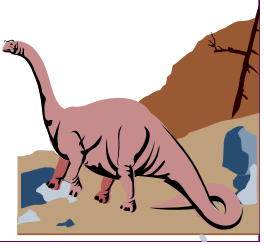
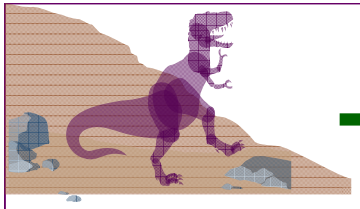
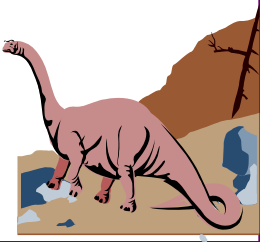
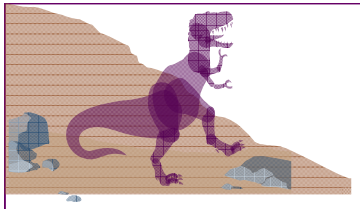




The Critical-Section Problem

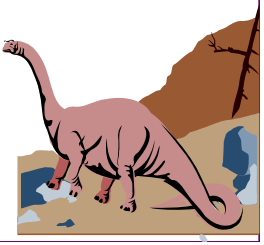
- Multiple processes all competing to use some shared data
- Each process has a code segment, called *critical section*, in which the shared data is accessed.
- Problem – ensure that when one process is executing in its critical section, no other process is allowed to execute in its critical section.

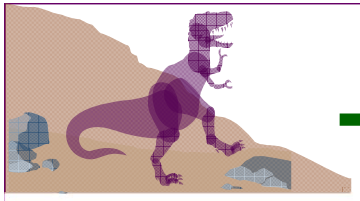




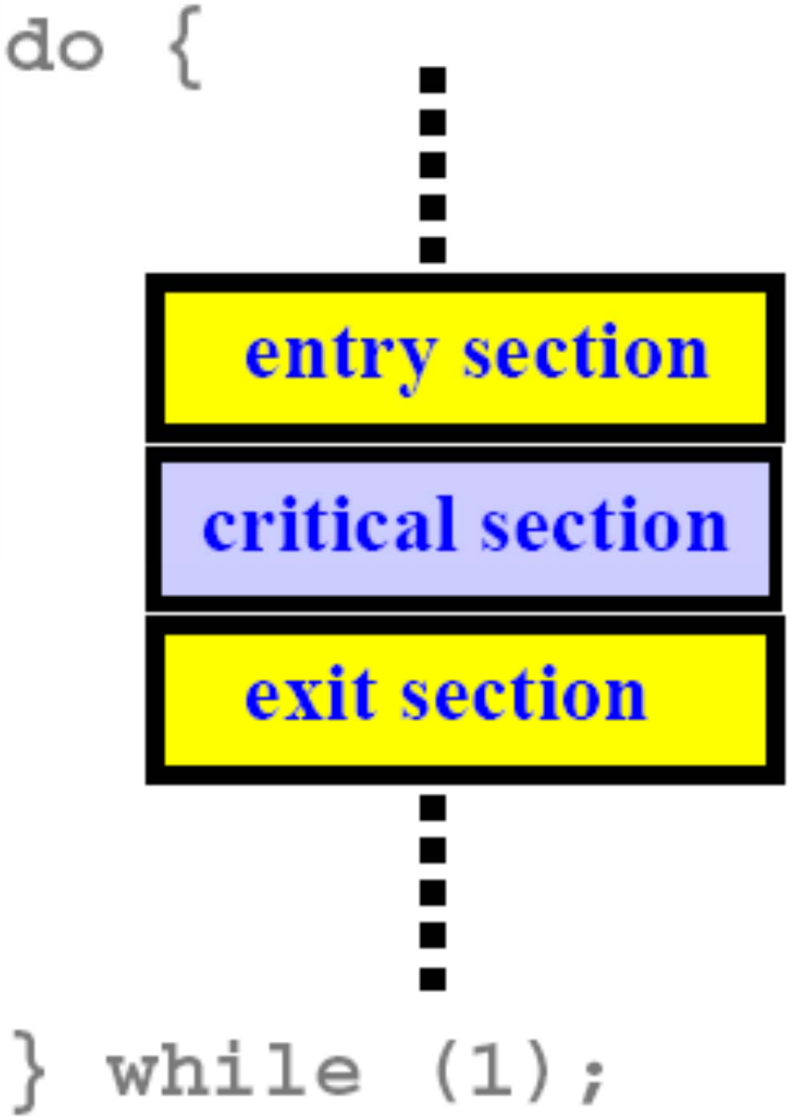
Critical Section and Mutual Exclusion

- 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.

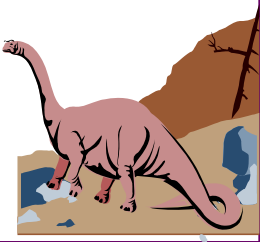


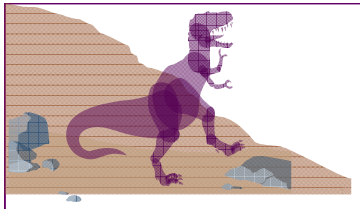


The Critical Section Protocol



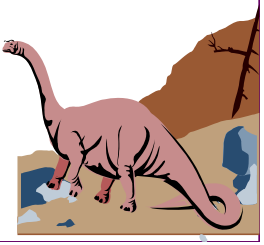
- A critical section protocol consists of two parts: an *entry section (or lock)* and an *exit section (or unlock)*.
- Between them is the critical section that must run in a mutually exclusive way.

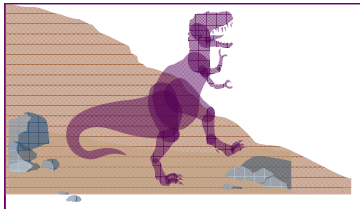




Solution to Critical-Section Problem

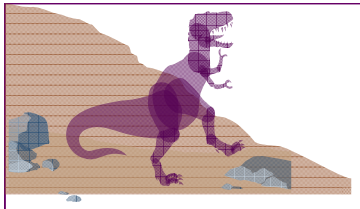
- Any solution to the critical section problem must satisfy the following three conditions:
  - **Mutual Exclusion**
  - **Progress**
  - **Bounded Waiting**
- Moreover, the solution cannot depend on relative speed of processes and scheduling policy.





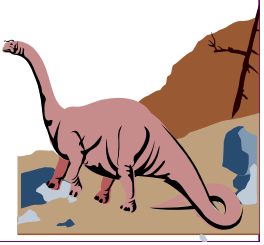
Mutual Exclusion

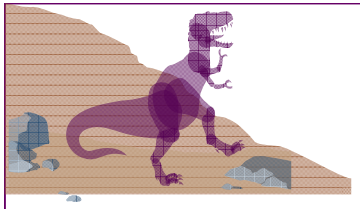
- If a process P is executing in its critical section, then *no* other processes can be executing in their critical sections.
- The entry protocol should be capable of blocking processes that wish to enter but cannot.
- Moreover, when the process that is executing in its critical section exits, the entry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

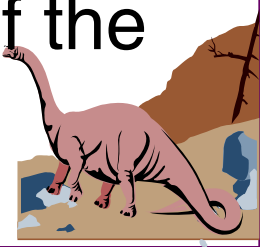


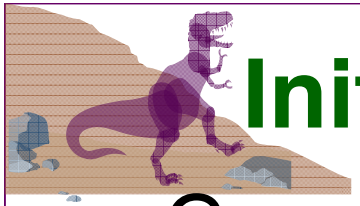


Bounded Waiting

- 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



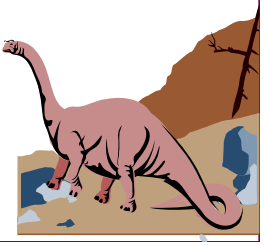


Initial Attempts to Solve Problem

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

```
do {    entry section
            critical section
        exit section
            remainder section
} while (1);
```

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



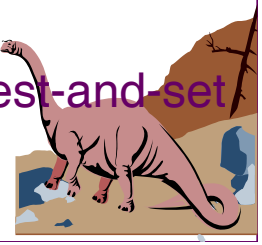
Algorithm 1

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

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

https://en.wikipedia.org/wiki/Test-and-set

- Does not satisfy mutual exclusion



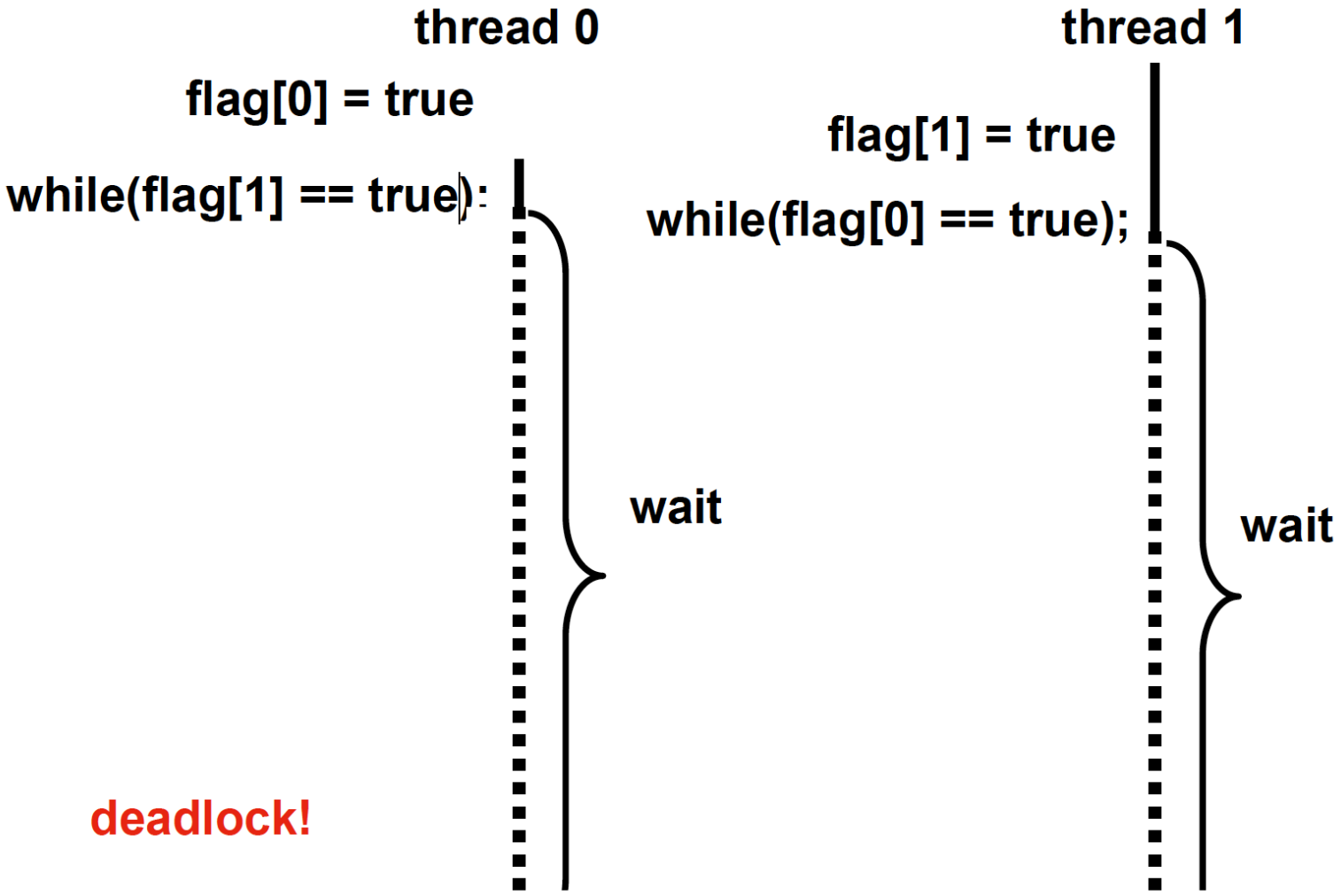
Algorithm 2

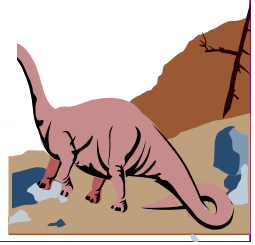
- Shared variables
  - **boolean flag[2];**
    initially **flag[0] = flag[1] = false.**
  - **flag[i] = true** $\Rightarrow$ P_i wants to enter its critical section
- Process P_i

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

- Satisfies mutual exclusion, but not progress requirement

Deadlock Problem of Algorithm 2



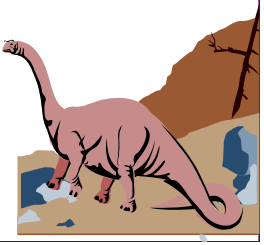


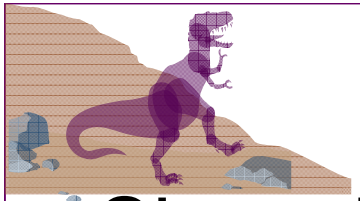
Is the Following Algorithm Correct?

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

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

- Does not satisfy mutual exclusion





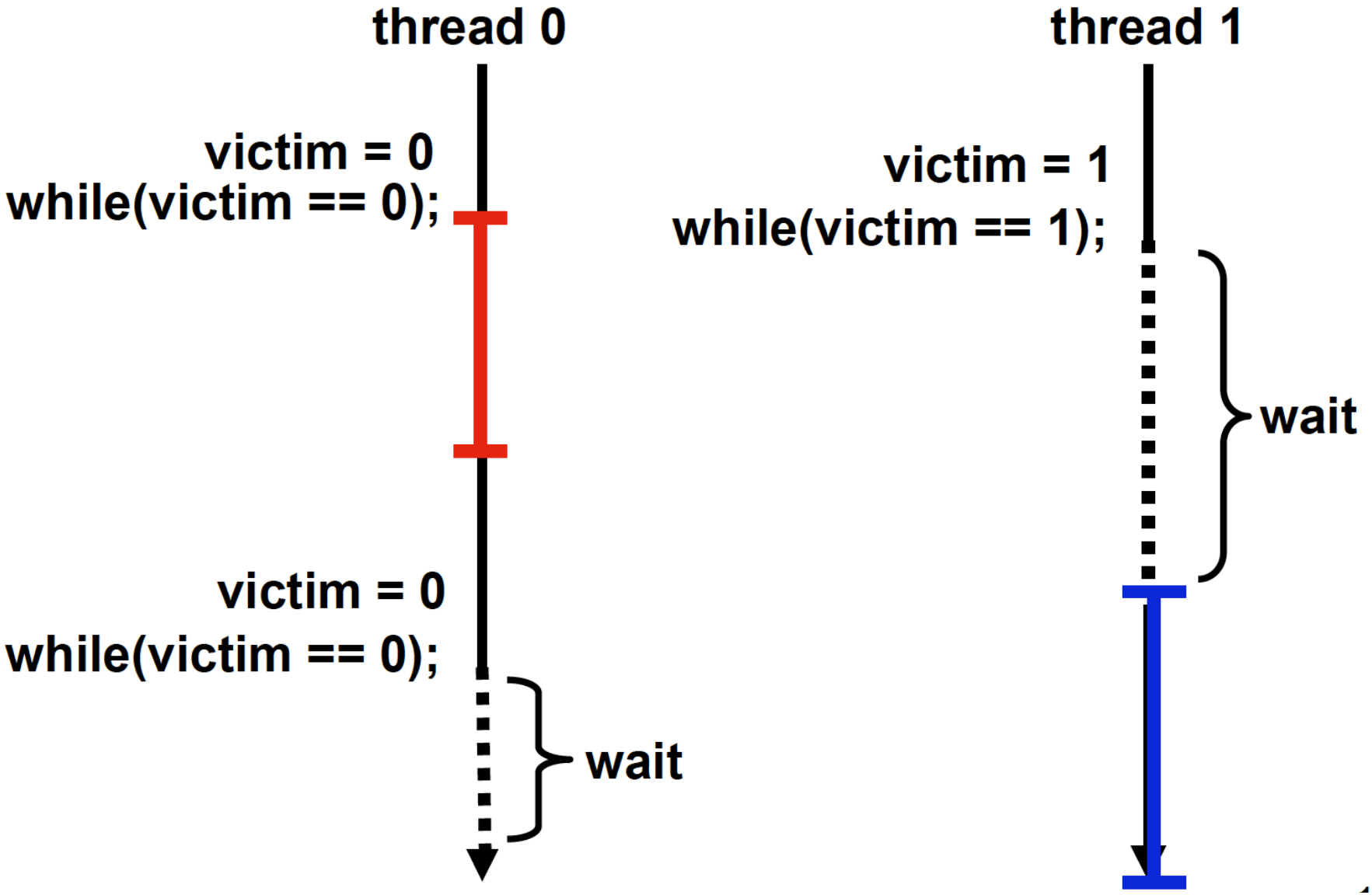
Algorithm 3

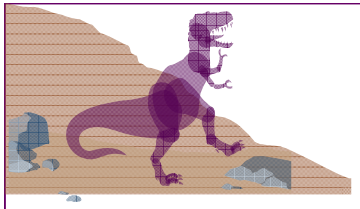
- Shared variables:
  - **int victim**; initially **victim = i (or victim = j)**
- Process P_i:

```
do {    victim = i;
        while (victim == i) ;
          critical section
        // do nothing for CS exit
          remainder section
} while (1);
```

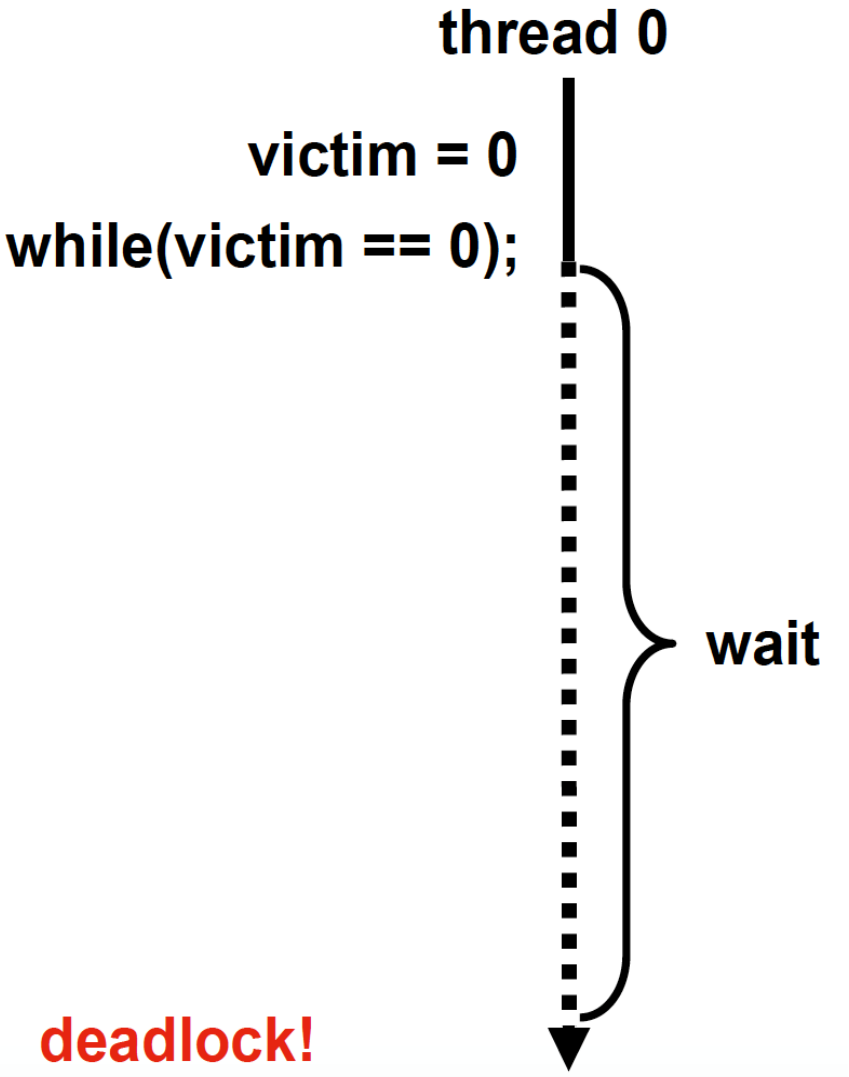
- Processes are forced to run in an alternating way
- Satisfies mutual exclusion, but not progress

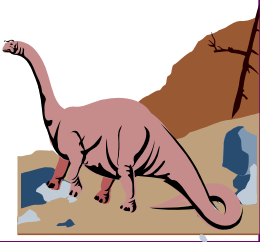
Alternating and Atomic Execution of Algorithm 3

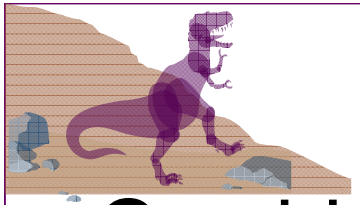




Deadlock of Algorithm 3







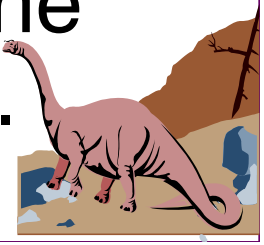
Peterson's Algorithm

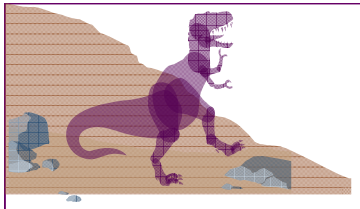
- Combined shared variables of algorithms 2, 3.
- Process P_i

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

          critical section

        flag[i] = false;

          remainder section

} while (1);
```

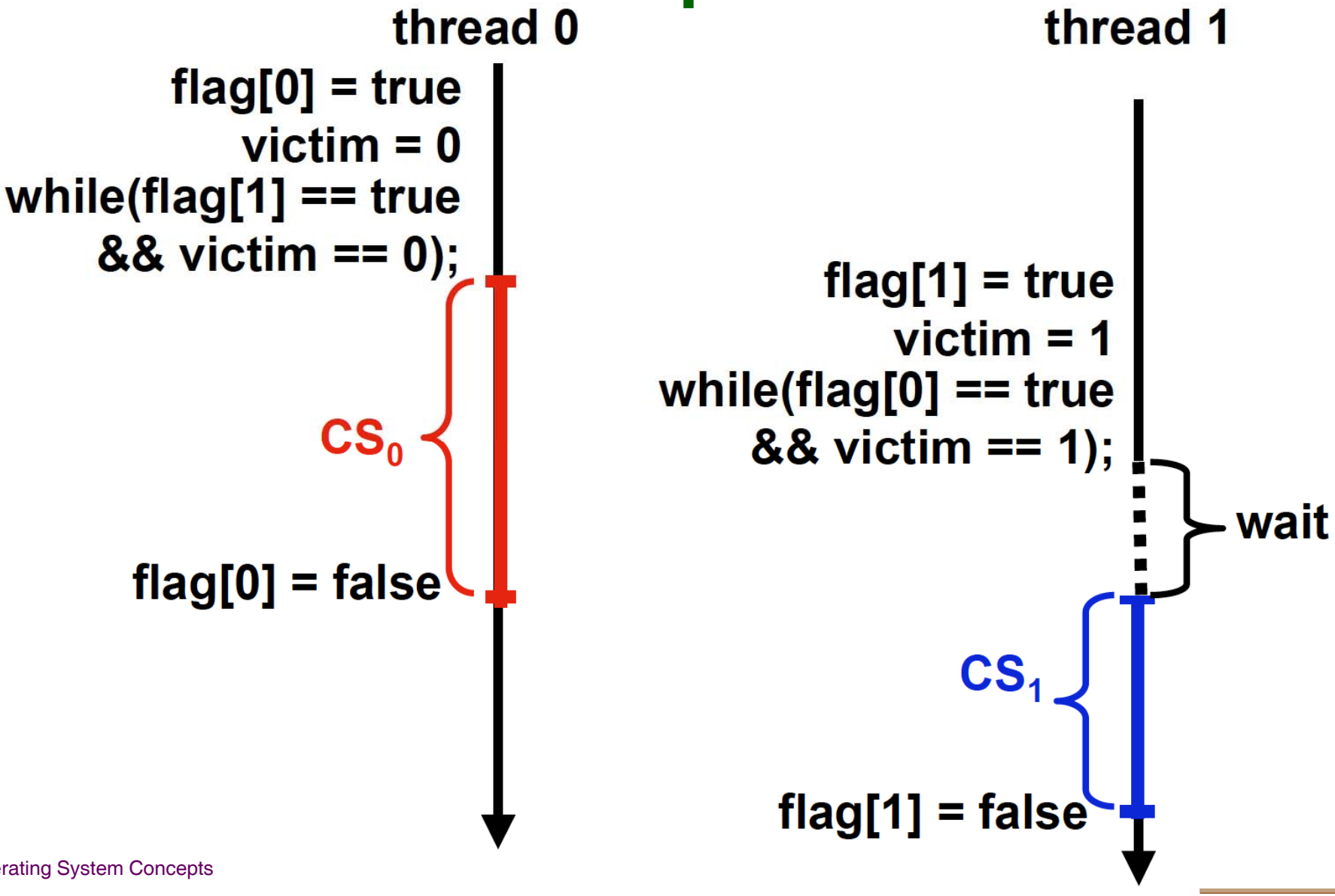
Gary Peterson. Myths about the Mutual Exclusion Problem. Information Processing Letters, 12(3):115-116, 1981.

- Meets all the three requirements; solves the critical-section problem for two processes.

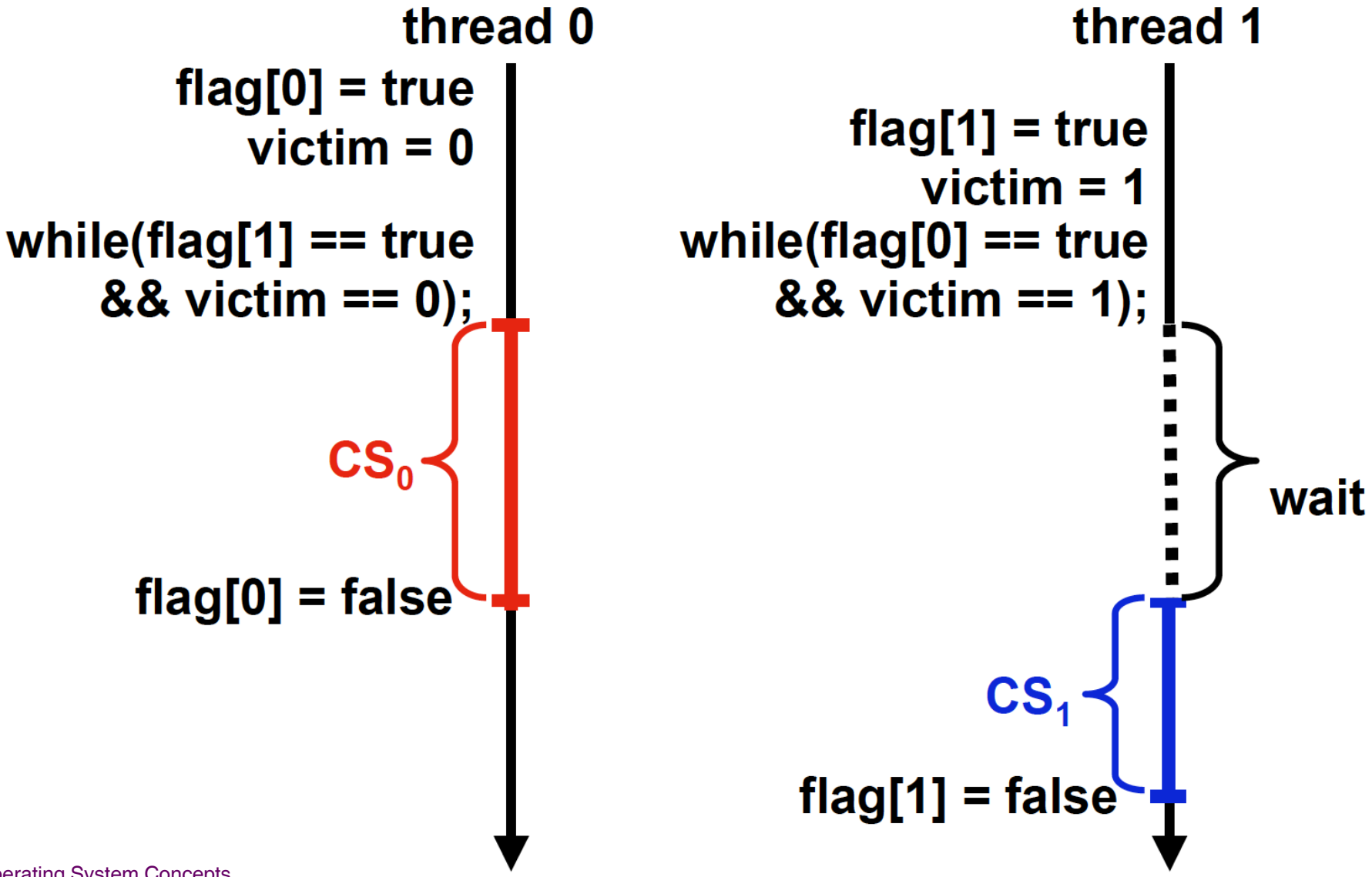


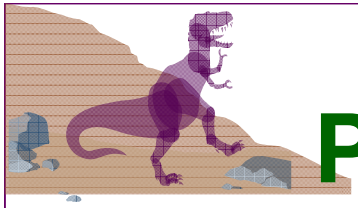


Peterson's Lock: Serialized Acquires



Peterson's Lock: Concurrent Acquires

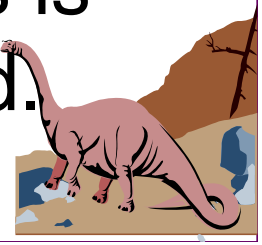


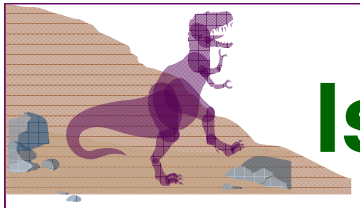


Proof of Peterson's Algorithm

- 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



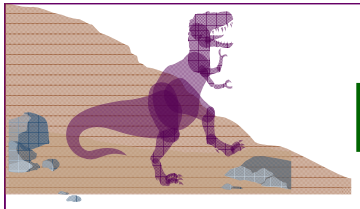


Is the following code correct?

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

```
do {        flag[i] = true;   // I'm interested
            victim = j;       // I go first
            while (flag[j] and victim == i) ;
                    critical section
             flag[i] = false;
                    remainder section
} while (1);
```

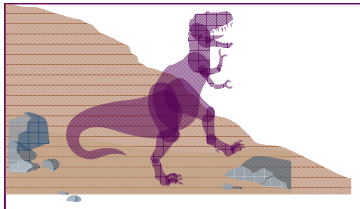
- Does not satisfy mutual exclusion, and not bounded waiting



Lamport's Bakery Algorithm

Critical section for n 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

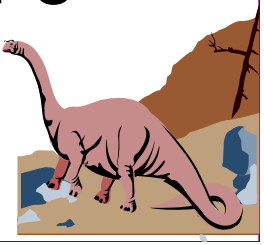
- Notation
  - $(a,b) < (c,d)$ if $a < c$ or if $a = c$ and $b < d$
  - max $(a_0,\ldots, a_{n-1})$ is a number, k, such that $k \geq a_i$ for i - 0, …, $n-1$

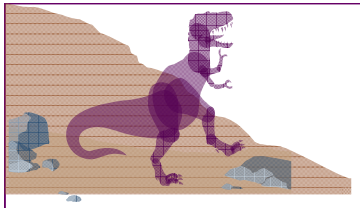
- Shared data

  boolean choosing[n];

  int number[n];

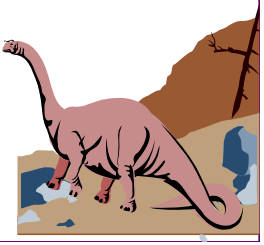
  Data structures are initialized to **false** and **0** respectively

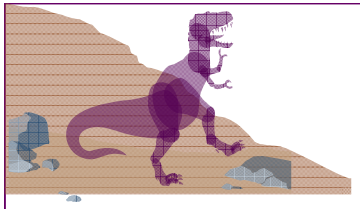




Bakery Algorithm

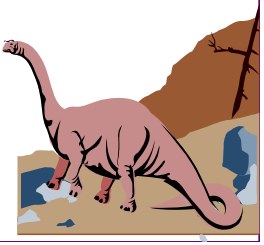
```
do { choosing[i] = true;
     number[i] = max(number[0], number[1], …,
                                number [n – 1]) + 1;
     choosing[i] = false;
     for (j = 0; j < n; j++) {
       while (choosing[j]) ;
       while ( (number[j] != 0) &&
                ((number[j],j) <  (number[i],i)) ) ;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

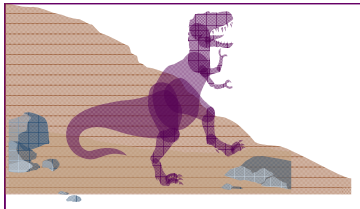




Chapter 6: Process Synchronization

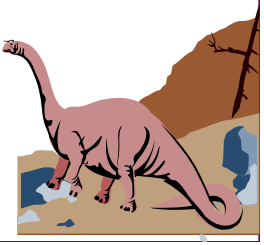
- Background
- The Critical-Section Problem
- Synchronization Hardware
- Semaphores
- Classical Problems of Synchronization
- Monitors
- Synchronization Examples

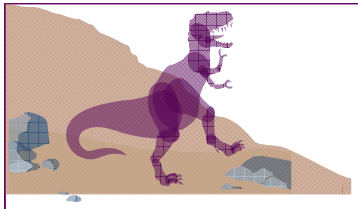




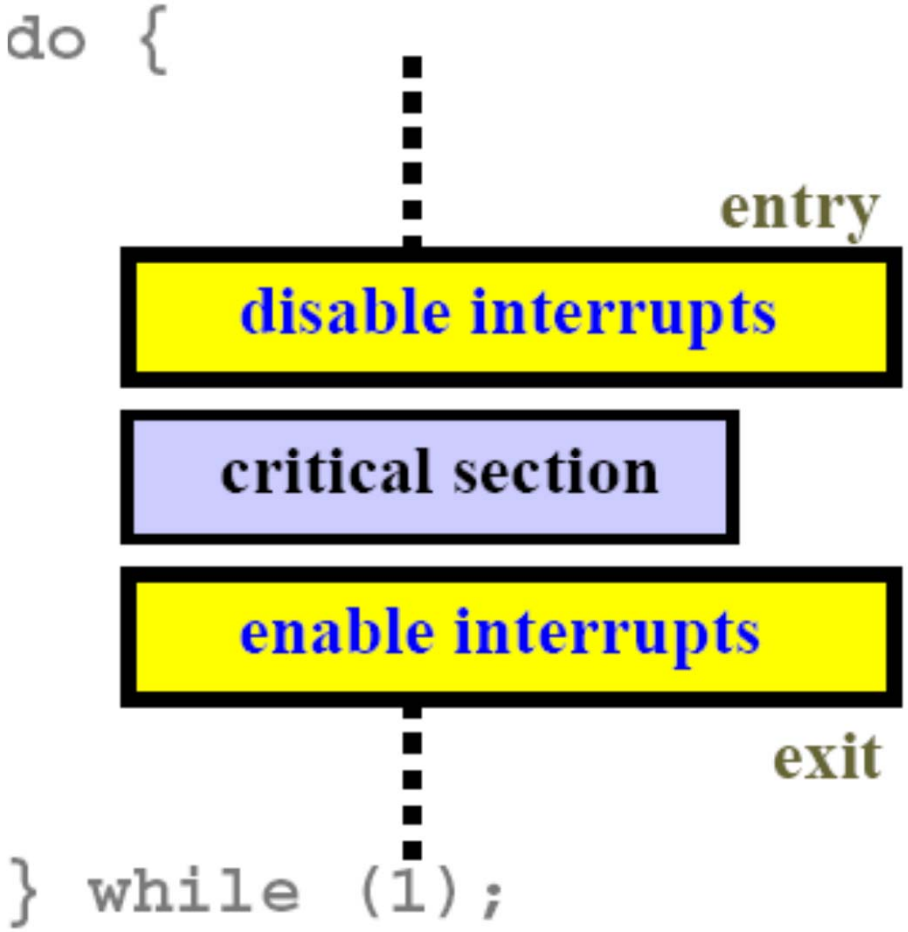
Hardware Support

- 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 (TS)
    - ✓Swap

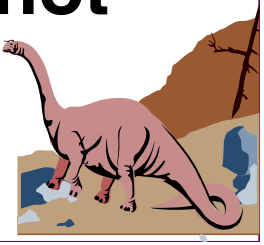


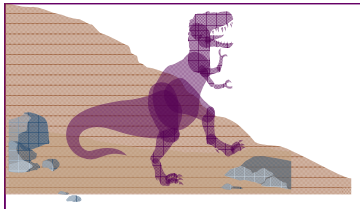


Interrupt Disabling



- 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.

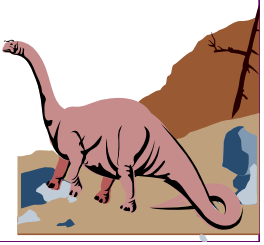


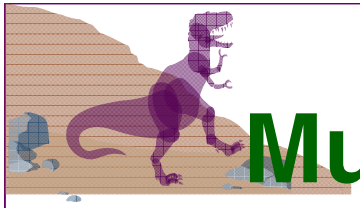


Test-and-Set

- Test and modify the content of a word atomically

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





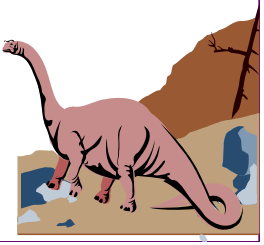
Mutual Exclusion with Test-and-Set

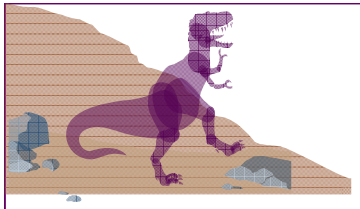
- Shared data:

  boolean lock = false;

- Process P_i

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

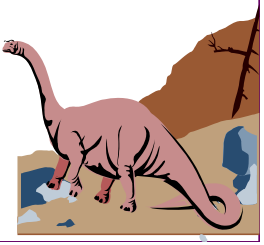


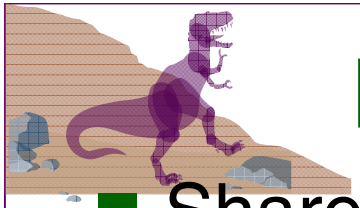


Atomic Swap

- 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**):

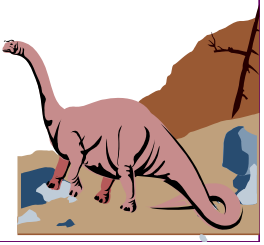
  boolean lock;

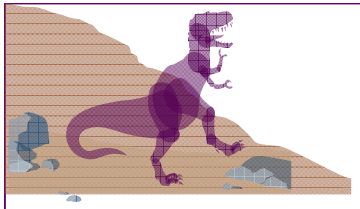
- local variable

  boolean key;

- Process P_i

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





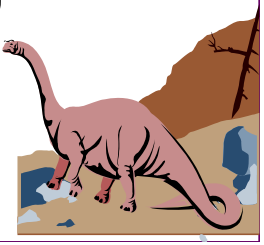
Bounded Waiting Mutual Exclusion with TestAndSet

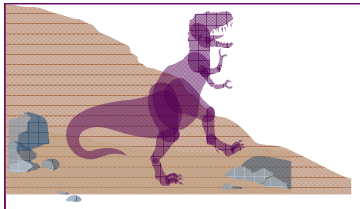
Enter Critical Section

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

Leave Critical Section

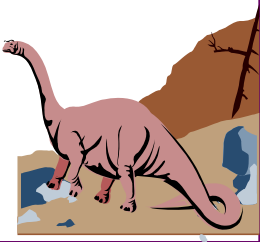
```
j = (i+1)%n
while ((j!=i) && !waiting[j])
   j = (j+1)%n;
if (j == i)
   lock = false;
else
   waiting[j] = false;
```

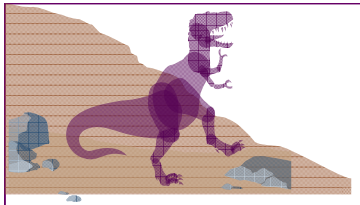




Chapter 6: Process Synchronization

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





Concept of Semaphore

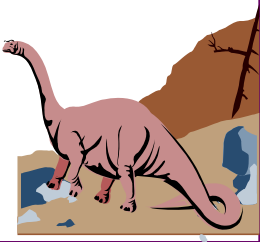
- It is a synchronization tool that does not require busy waiting.
- Semaphore *S* — an integer variable
- It can only be accessed via two indivisible (atomic) operations: **wait** and **signal**
- They are functionally equivalent to the following busy-waiting operations.

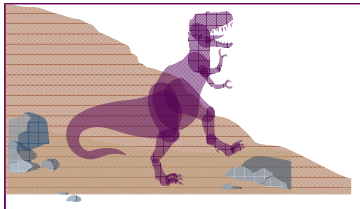
wait **(*S*):**

while *S*≤ 0 do *no-op*;
S--;

signal **(*S*):**

S++;



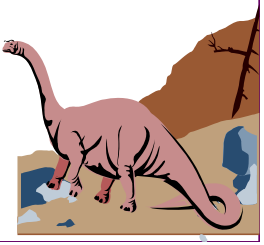


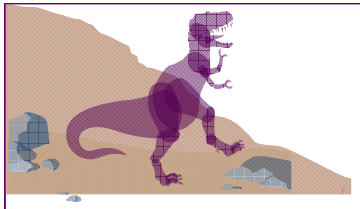
Semaphore Implementation

- Define a semaphore as a record

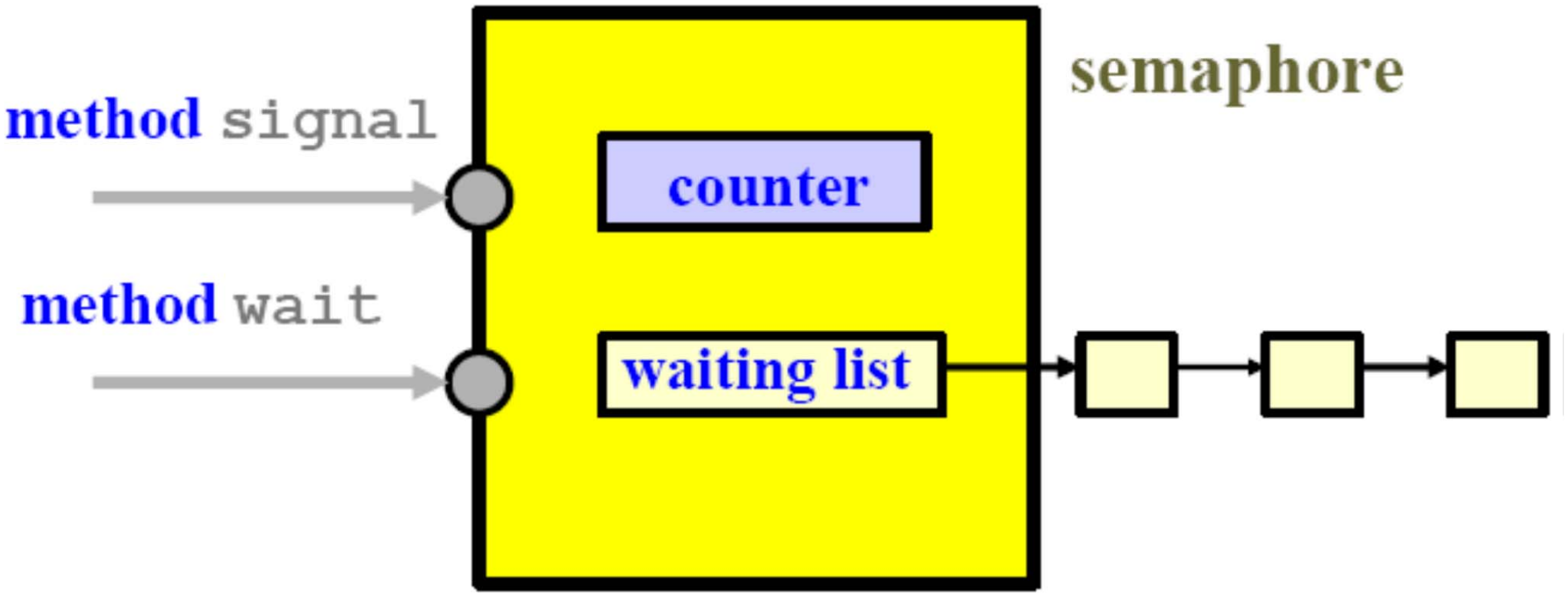
```
typedef struct {
   int value;
   struct process *L;
} semaphore;
```

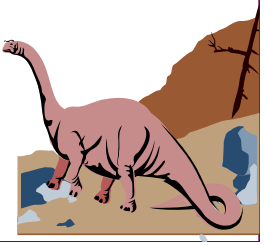
- Assume two simple operations:
  - **block:** block the process that invokes it.
  - **wakeup(*P*):** resumes the execution of a blocked process **P**.

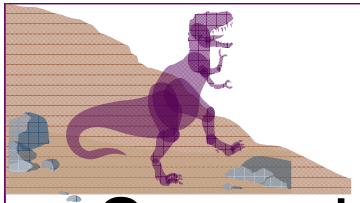




Semaphore Implementation







Semaphore Implementation

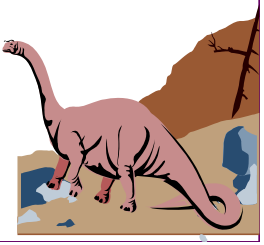
- Semaphore operations now defined as

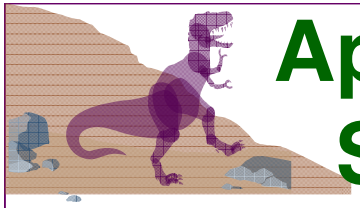
wait(*S*):

```
S.value--;
if (S.value < 0) {
        add this process to S.L;
        block;
}
```

signal(*S*):

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





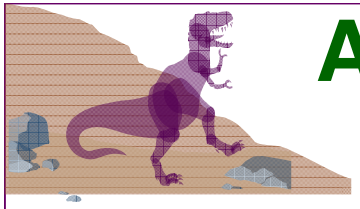
Application 1 of Semaphore: Partially Solve the Critical Section Problem

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

- Process P_i:

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

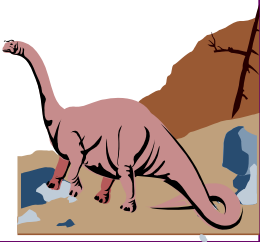
- Does this solution satisfy the three criteria of critical section, i.e., exclusive, progress, bounded waiting?

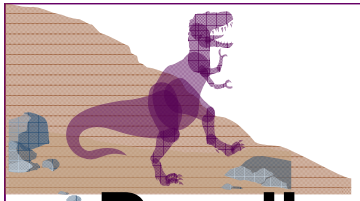


Application 2 of Semaphore: Act as a General Synchronization Tool

- 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*



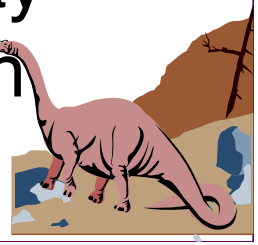


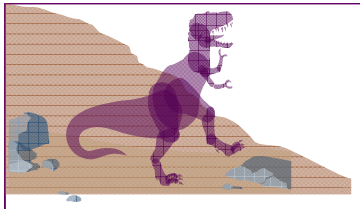
Side Effect of Semaphore: Deadlock and Starvation

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

P_0	P_1
wait(*S*);	*wait*(*Q*);
wait(*Q*);	*wait*(*S*);
⋮	⋮
signal(*S*);	*signal*(*Q*);
signal(*Q*)	*signal*(*S*);

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





Chapter 6: Process Synchronization

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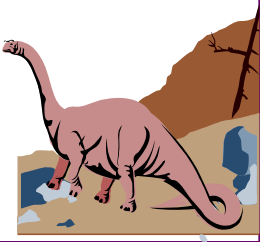
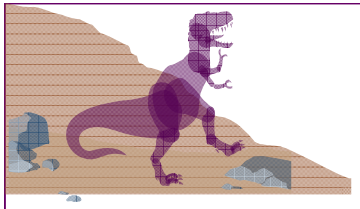
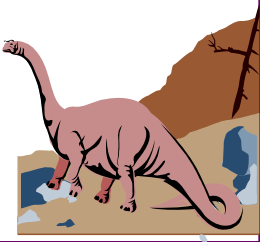
- Monitors
- Synchronization Examples

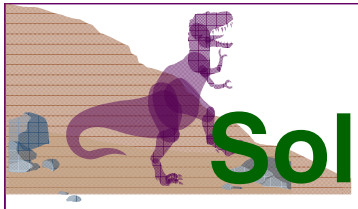




Classical Problems of Synchronization

- Bounded-Buffer Problem (or called Producer-Consumer Problem)
- Readers and Writers 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 spaces in the buffer

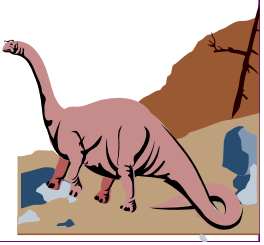
Solution 1 for Producer-Consumer

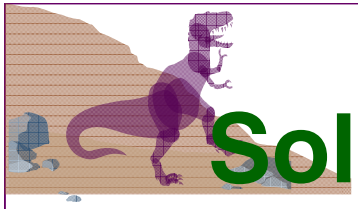
Producer:

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

Consumer:

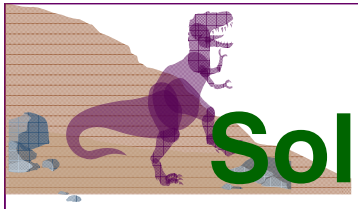
```
do {
    wait(fillCount);
    remove an item from
    buffer to nextc
    signal(emptyCount);
        ...
    consume the item in nextc
        ...
} while (1);
```





Solution 1 for Producer-Consumer

- This solution contains a serious race condition that could 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, imagine how the procedure “add **nextp** to buffer” or “remove an item from buffer” is implemented (*counter++ or counter--*).



Solution 2 for Producer-Consumer

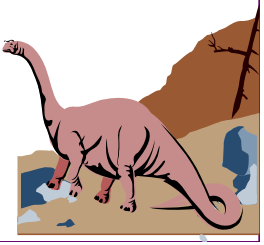
- Shared data

  semaphore fillCount, emptyCount, mutex;

  Initially:

  fillCount = 0, emptyCount = n, mutex = 1

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



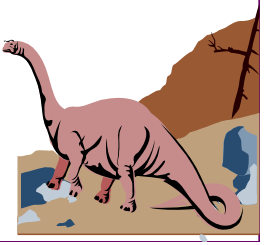
Solution 2 for Producer-Consumer

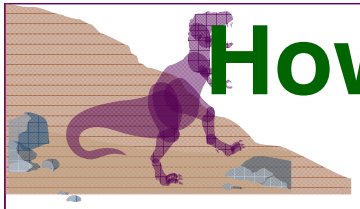
Producer:

```
do {
        ...
   produce an item in nextp
        ...
    wait(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);
```





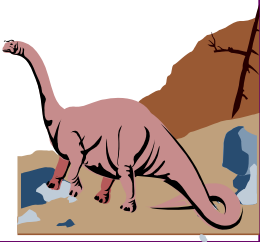
How about we put the emptyCount and fillCount inside mutex?

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);
```



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

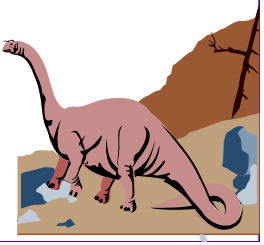
Initially: **semaphore fillCount = 0, emptyCount = 1**

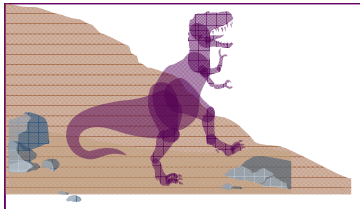
Producer:

```
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);
```





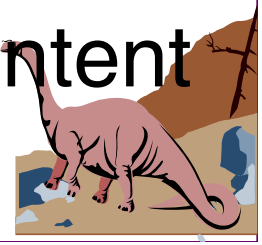
Readers-Writers Problem

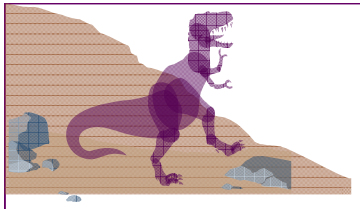
- Shared data

semaphore mutex, wrt;

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





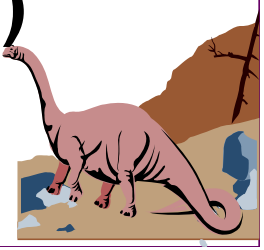
Readers-Writers Problem

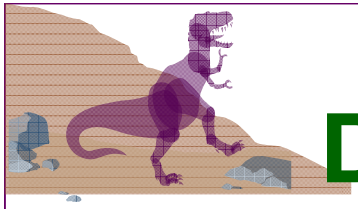
Writer Process

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

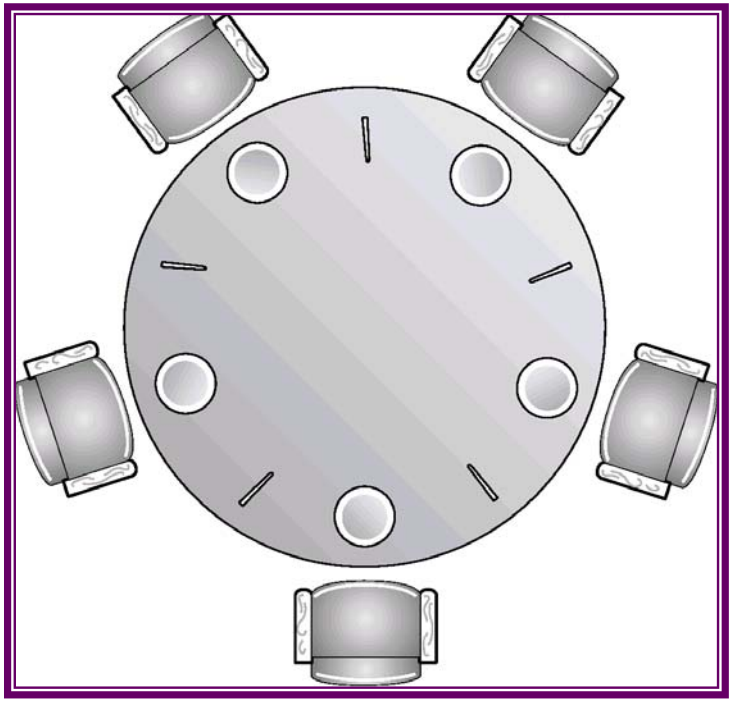
Reader Process

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





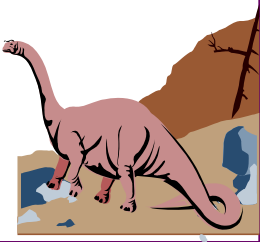
Dining-Philosophers Problem

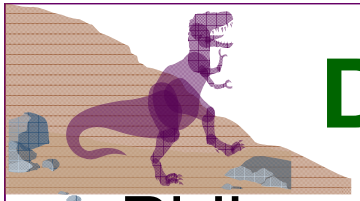


- Shared data

  semaphore chopstick[5];

  Initially all values are 1



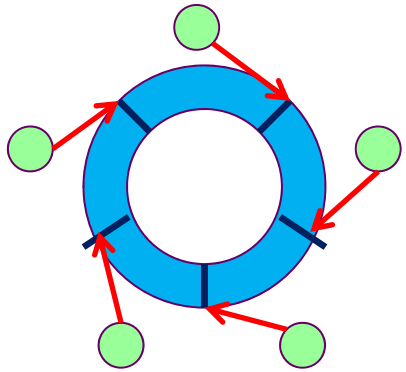


Dining-Philosophers Problem

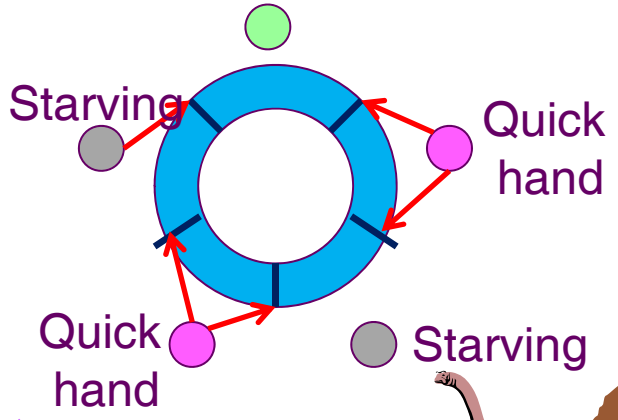
- Philosopher *i*:

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

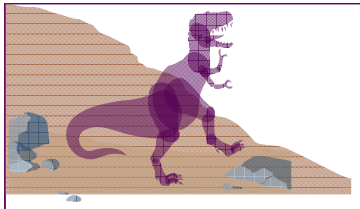
- Challenges
  - Deadlock



  - Starvation

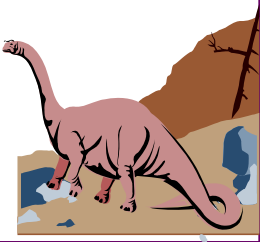


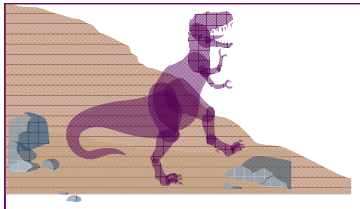
  - Lack of Fairness



Chapter 6: Process Synchronization

- Background
- The Critical-Section Problem
- Synchronization Hardware
- Semaphores
- Classical Problems of Synchronization
- Monitor and Condition Signal
- Synchronization Examples





Semaphore 学习的五重境界

1. 理解基础概念

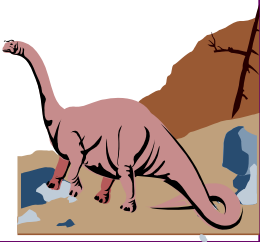
Monitor略讲，
仅推进到阶段2

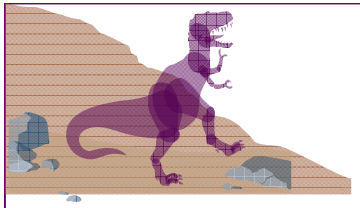
2. 熟练掌握经典问题（PC, RW, DP）。

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。

5. 忘记经典，随心所欲，信手拈来。

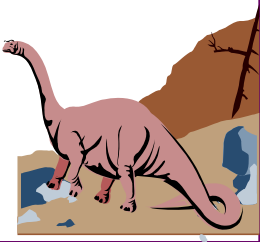


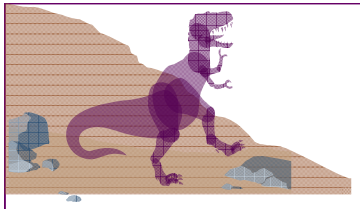


Monitors

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

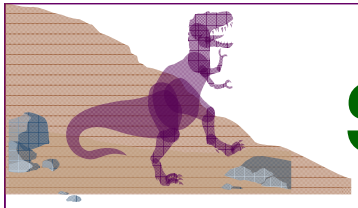
```
monitor monitor-name
{   shared variable declarations
    procedure body P1 (...) {
       . . .}
    procedure body P2 (...) {
       . . .}
    procedure body Pn (...) {
        . . .}
    { initialization code}
}
```



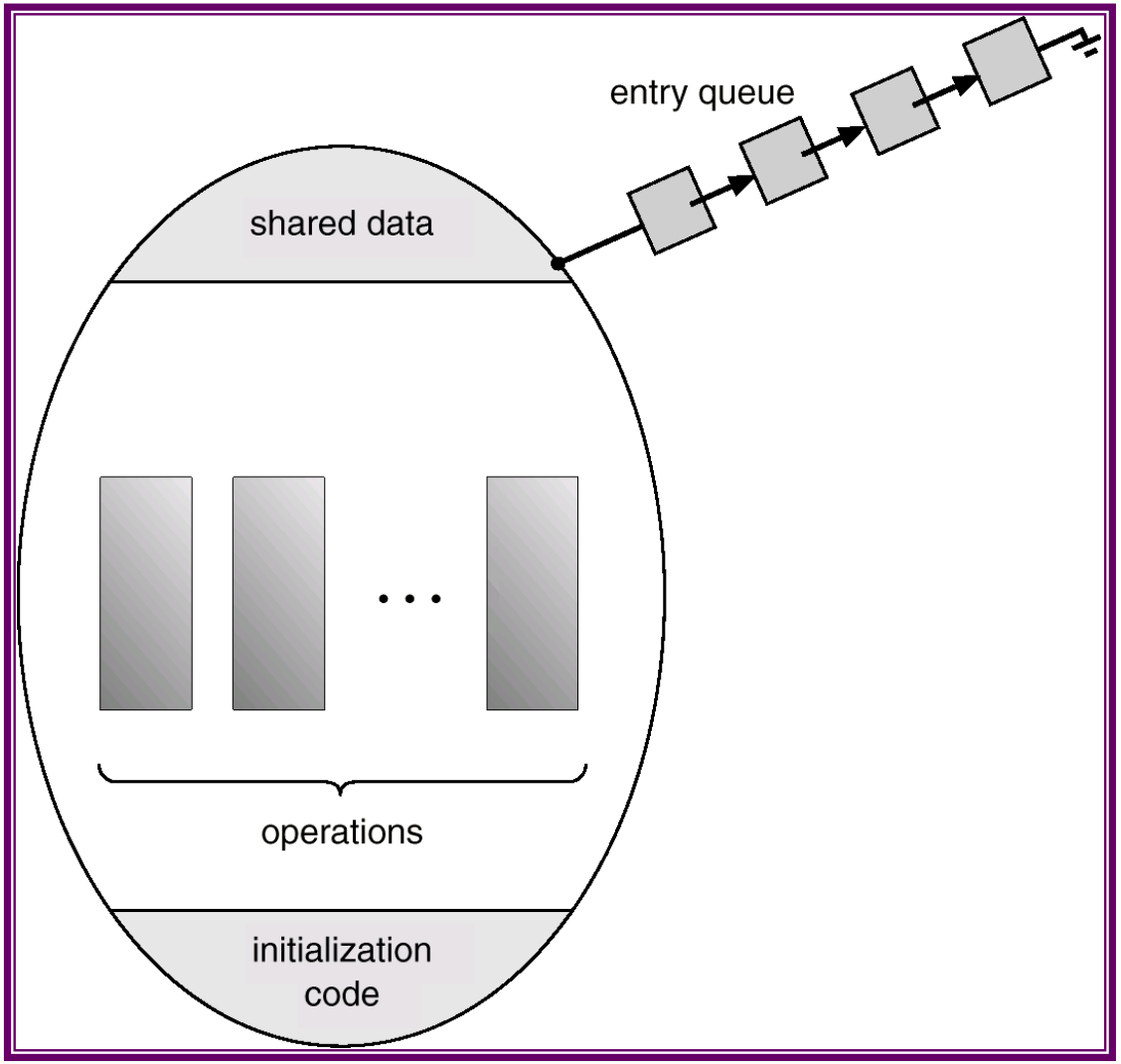


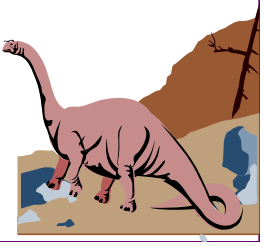
Monitors: Mutual Exclusion

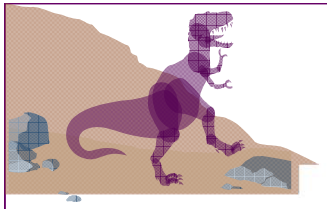
- *No more than one process* can be executing *within* a monitor. Thus, *mutual exclusion* is guaranteed within a monitor.
- When a process calls a monitor procedure and enters the monitor successfully, it is the *only* process executing in the monitor.
- When a process calls a monitor procedure and the monitor has a process running, the caller will be blocked outside of the monitor.

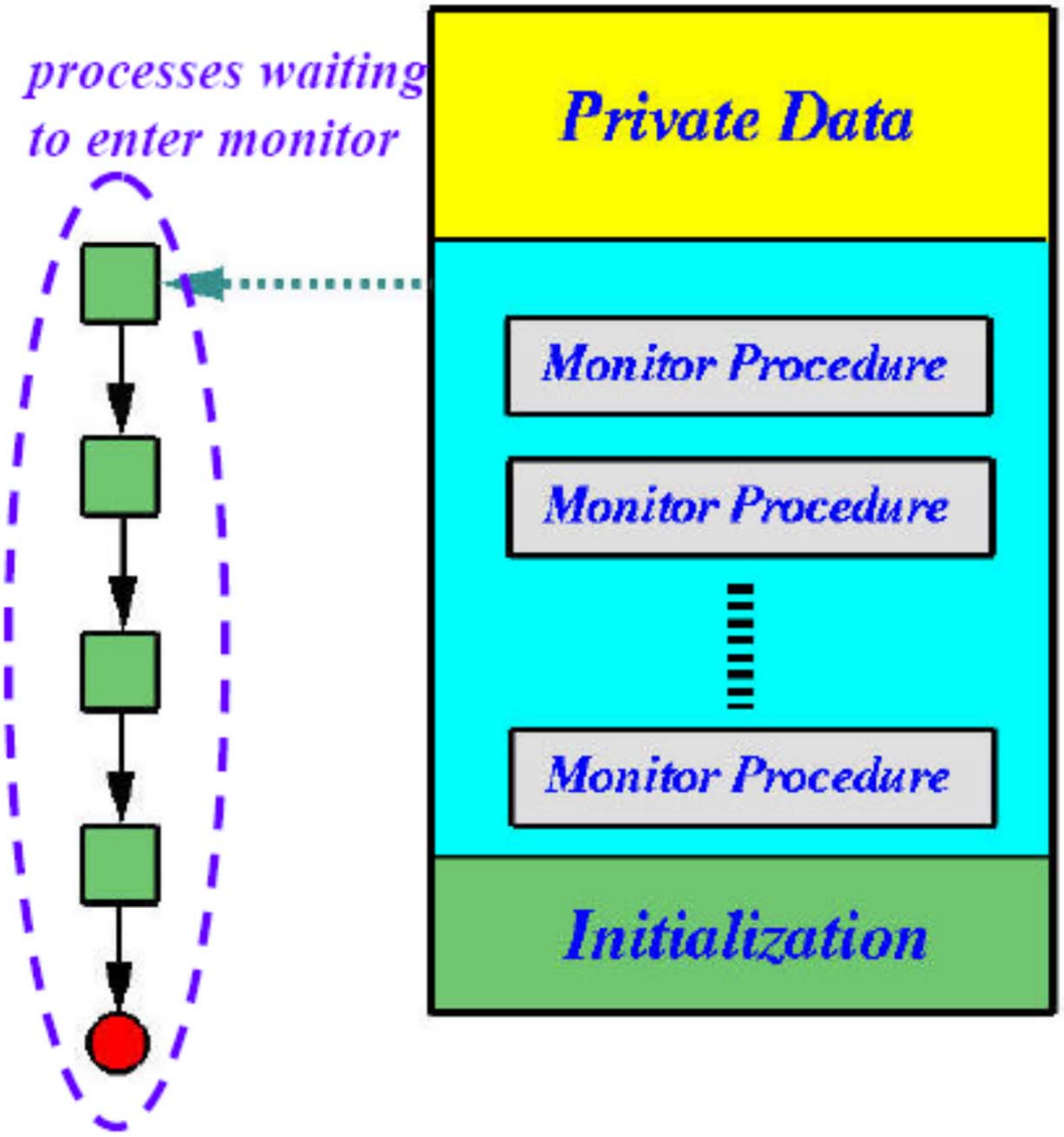


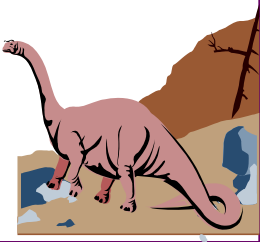
Schematic View of a Monitor

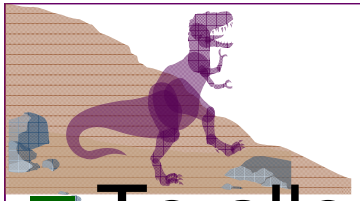







processes waiting
to enter monitor
Private Data
Monitor Procedure
Monitor Procedure
Monitor Procedure
Initialization





Monitors

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

  condition x, y;

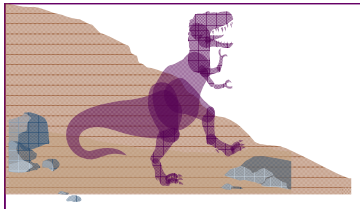
- Condition variable can only be used with the operations **wait** and **signal**.
  - The operation

    x.wait();

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

    x.signal();

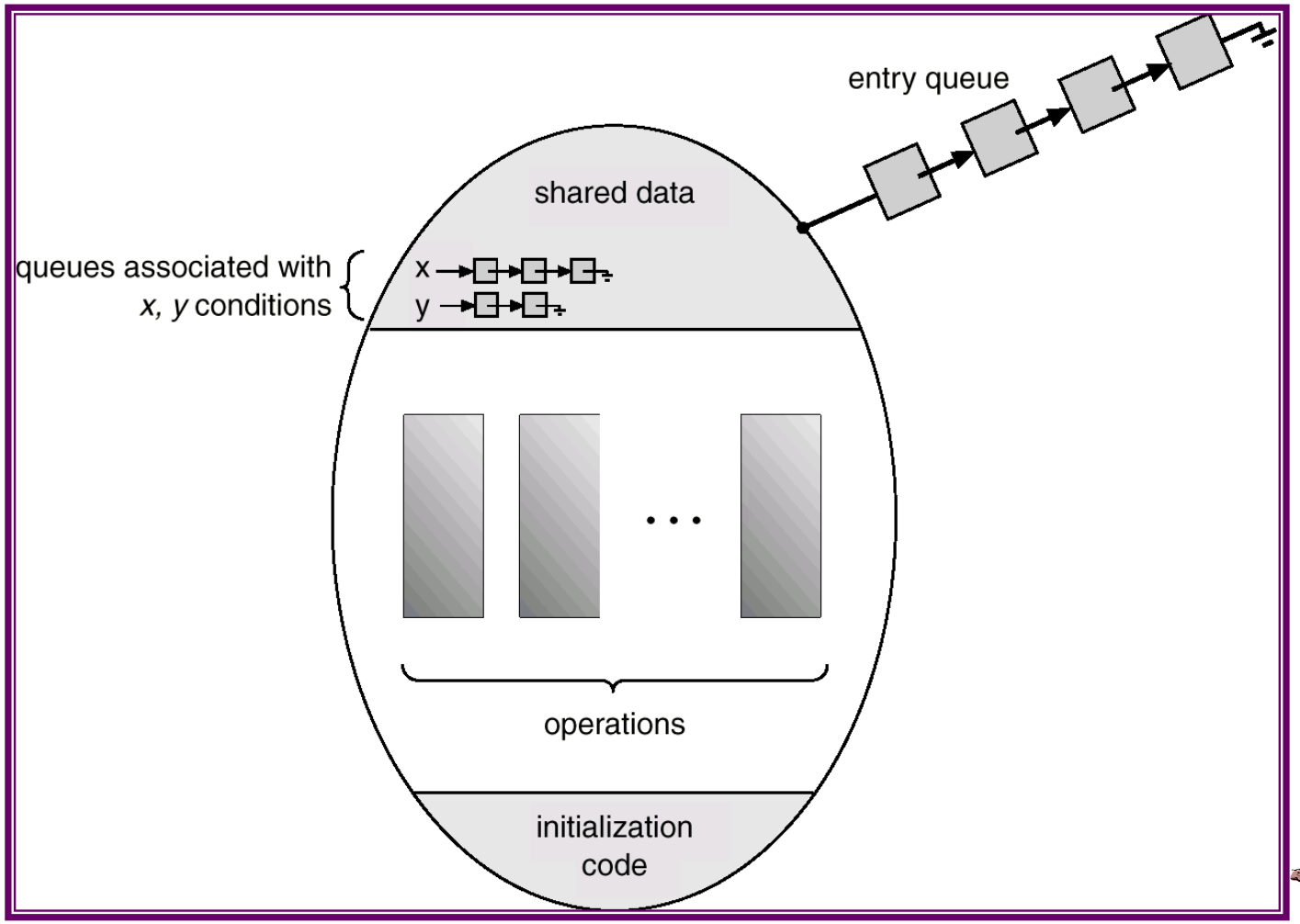
  - The **x.signal** operation wakeup exactly one blocked process. If no process is waiting for the condition, then the **signal** operation has no effect.

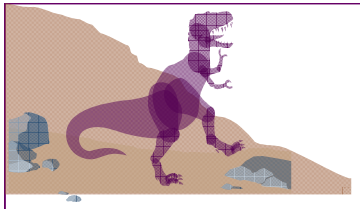


Condition Signal

- **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 the monitor and the signaling process waits somewhere.
  - The released process waits somewhere and the signaling process continues to use the monitor.

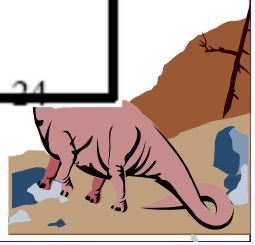
Monitor With Condition Variables

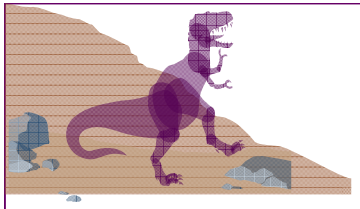




Semaphore vs. Condition

Semaphores	Condition Variables
Can be used anywhere, but not in a monitor	Can only be used in monitors
`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*





Java's Monitor Supports

- Synchronized Method

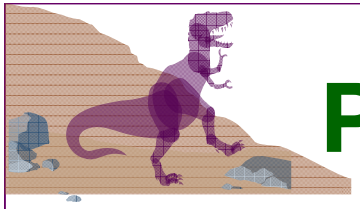
```
class classname {
        synchronized void methodname() {……}
}
```

- Coordination Support

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

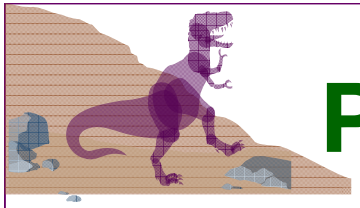


Producer-Consumer Example

```
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?
    }
}
```

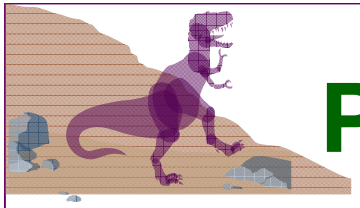


Producer-Consumer Example

```
procedure void add(item) {
    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 the use of **while** statements in the above code, both when testing if the buffer is full or empty.
- With multiple consumers, there is a race condition where one consumer gets notified that an item has been put into the buffer but another consumer is already waiting on the monitor.

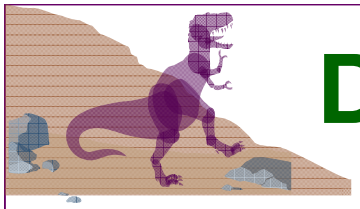


Producer-Consumer Example

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

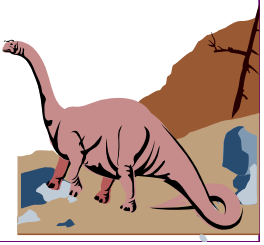
```
procedure item remove() {
    while (itemCount == 0)
        empty.wait();
    item = removeItemFromBuffer();
    itemCount = itemCount - 1;
    if (itemCount == BUFSIZE - 1)
        full.signal();
    return item;
}
```

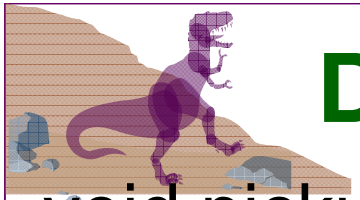
- With multiple producers, there is also a race condition where one producer gets notified that the buffer is no longer full but another producer is already waiting on the monitor.
- If the **while** was instead an **if**, too many items might be put into the buffer or a remove might be attempted on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



Dining Philosophers Example

```
monitor dp
{
    enum {thinking, hungry, eating}   state[5];
    condition self[5];
    void pickup(int i) ;          // see the next slide
    void putdown(int i) ;         // see the next slide
    void test(int i) ;            // see the next slide
    void init() {
        for (int i = 0; i < 5; i++)
            state[i] = thinking;
    }
}
```



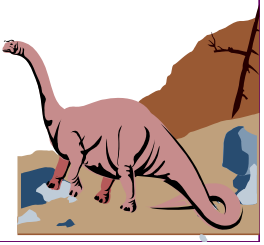


Dining Philosophers Example

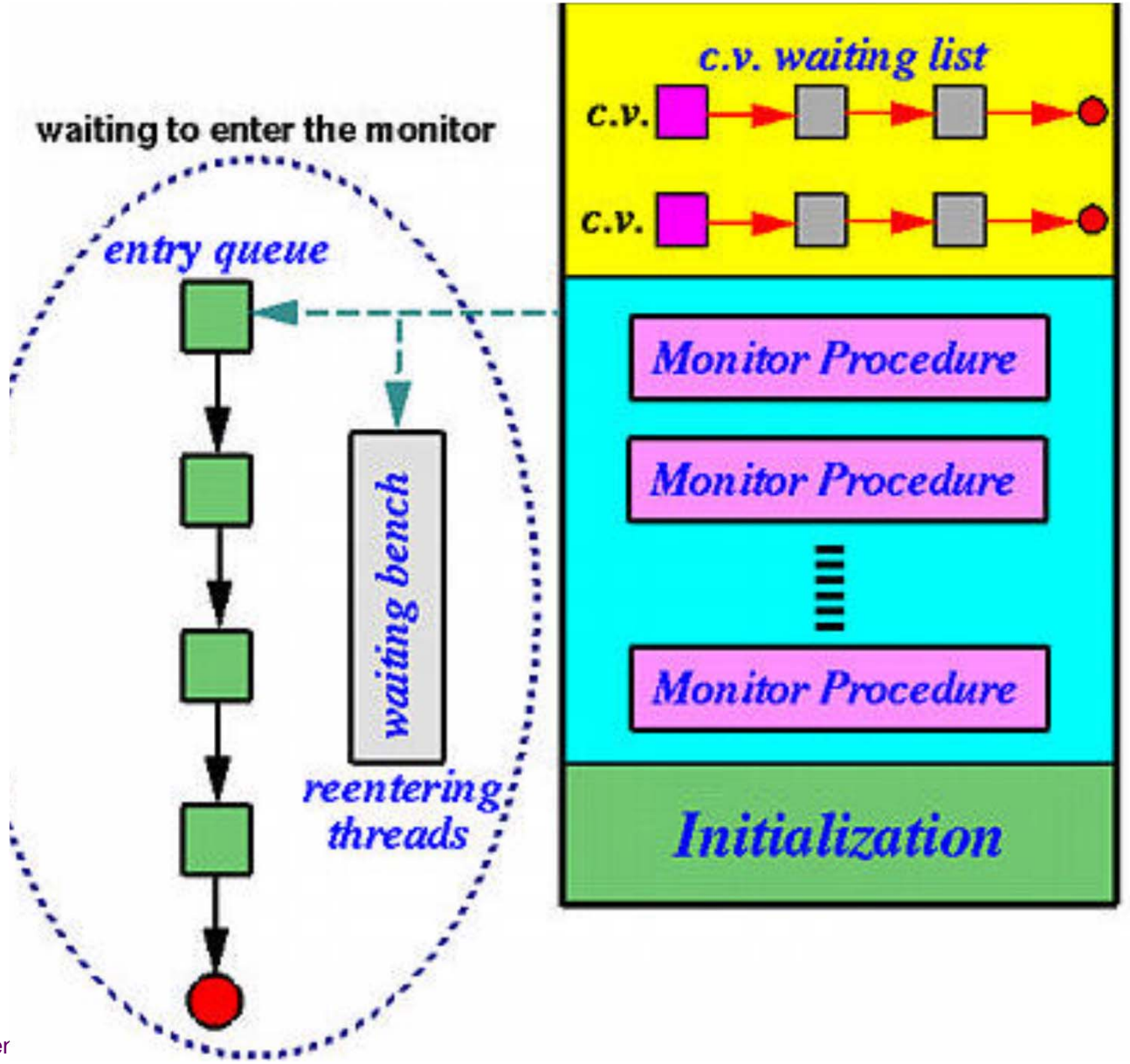
```
void pickup(int i) {
      state[i] = hungry;
      test(i);
      if (state[i] != eating)
           self[i].wait();
}
void test(int i) {
      if ( (state[(i + 4) % 5] != eating) &&
           (state[i] == hungry) &&
           (state[(i + 1) % 5] != eating)) {
            state[i] = eating;
 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

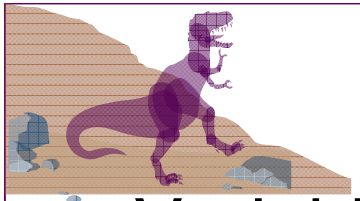
```
void putdown(int i) {
      state[i] = thinking;
      test((i+4) % 5); // left
      test((i+1) % 5); // right
}
```

NO Deadlock!!! Why?



Queue of Reentering Threads/Proc





Monitor Implementation Using Semaphores

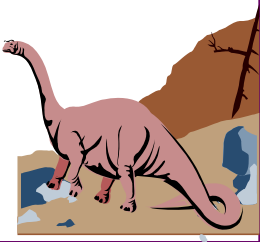
- Variables

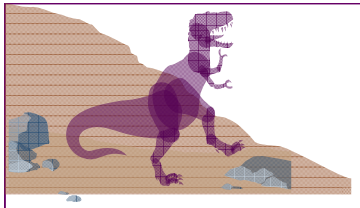
```
semaphore mutex;  // (initially  = 1)
semaphore next;   // (initially  = 0)
int next-count = 0;
```

- 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)

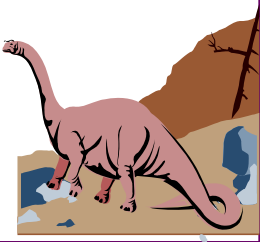
  int x-count = 0;

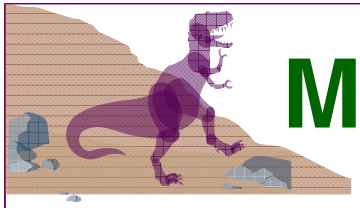
- The operation **x.wait** can be implemented as:

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

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

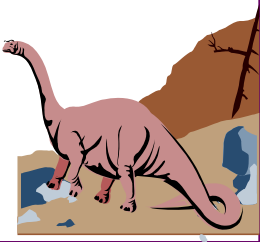
```
if (x-count > 0) {
    next-count++;
    signal(x-sem);
    wait(next);
    next-count--;
}
```

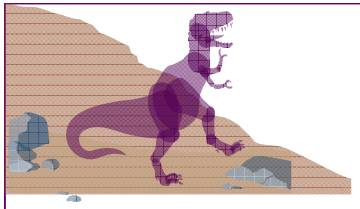




Monitor Implementation (Cont.)

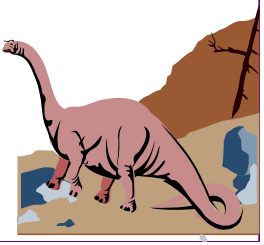
- Check two conditions to establish correctness of system:
  - User processes must always make their calls on the monitor in a correct sequence.
  - Must ensure that an uncooperative process does not ignore the mutual-exclusion gateway provided by the monitor, and try to access the shared resource directly,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

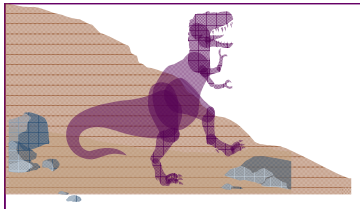




Condition Enhanced with a Priority Number

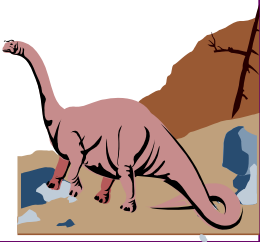
- *Conditional-wait* construct: **x.wait(c);**
  - **c** – integer expression evaluated when the **wait** operation is executed.
  - value of **c** (a *priority number*) stored with the name of the process that is suspended.
  - when **x.signal** is executed, process with smallest associated priority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

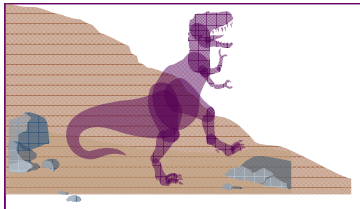




Chapter 6: Process Synchronization

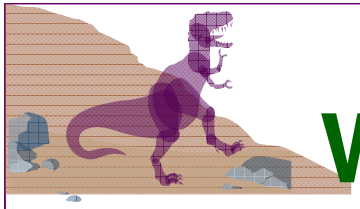
- Background
- The Critical-Section Problem
- Synchronization Hardware
- Semaphores
- Classical Problems of Synchronization
- Monitors and Condition Signal
- Synchronization Examples





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.



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.