Chapter 6
Process Synchronization

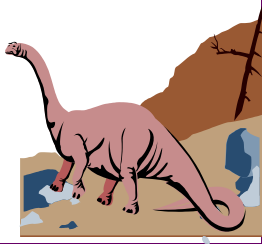
张竞慧

办公室：计算机楼366室

电邮：jhzhang@seu.edu.cn

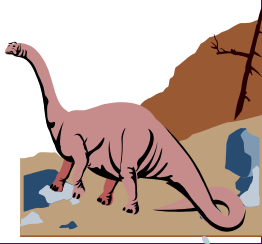
主页：http://cse.seu.edu.cn/PersonalPage/zjh/

电话：025-52091017



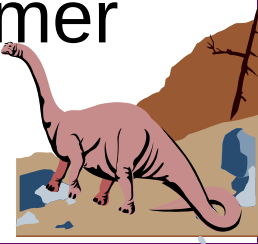
Chapter 6: Process Synchronization

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



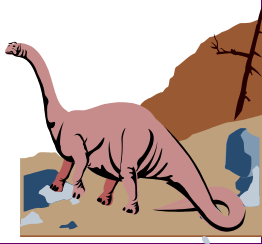
Background

- Concurrent access to shared data may result in data inconsistency.
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes.
- 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.
  - Suppose that we modify the producer-consumer code by adding a variable *counter*



Producer-Consumer Problem (Review)

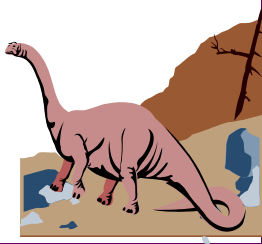
- Paradigm for cooperating processes, *producer* process produces information that is consumed by a *consumer* process.
  - *unbounded-buffer* places no practical limit on the size of the buffer.
  - *bounded-buffer* assumes that there is a fixed buffer size.



Bounded-Buffer – Shared-Memory Solution (Review)

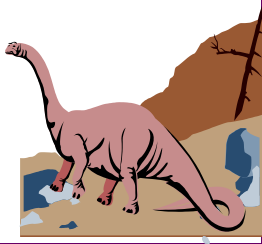
- Shared data

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



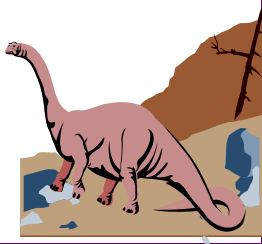
Bounded-Buffer – Producer Process (Review)

```
item nextProduced;

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



Bounded-Buffer – Consumer Process (Review)

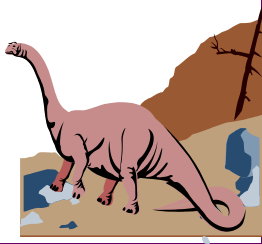
```
item nextConsumed;

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



Bounded-Buffer

- Shared data

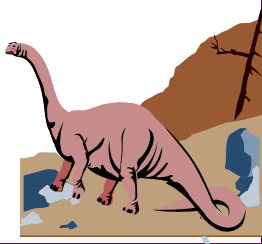
```
#define BUFFER_SIZE 10
typedef struct {
   . . .
} item;
item buffer[BUFFER_SIZE];
int in = 0;
int out = 0;
int counter = 0;
```



Bounded-Buffer

- Producer process

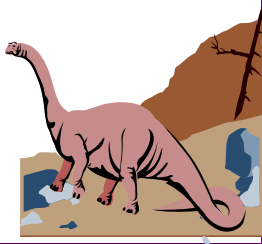
```
item nextProduced;

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



Bounded-Buffer

- Consumer process

```
item nextConsumed;

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



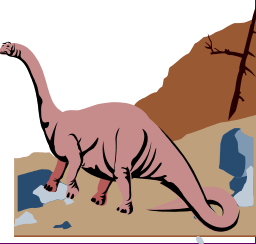
Bounded Buffer

- The statements

  counter++;
  counter--;

  must be performed *atomically*.

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



Bounded Buffer

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

  register1 = counter

  register1 = register1 + 1

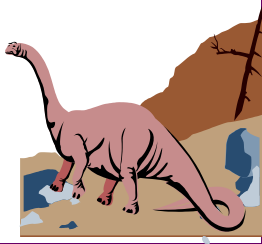
  counter = register1

- The statement "**count--**" may be implemented as:

  register2 = counter

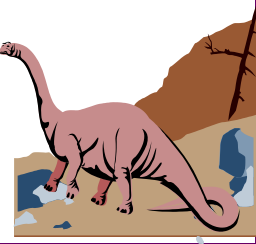
  register2 = register2 – 1

  counter = register2



Bounded Buffer

- 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.



Bounded Buffer

- 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

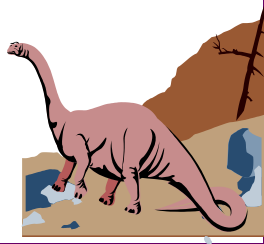
counter = register1

Consumer

register2 = counter

register2 = register2 – 1

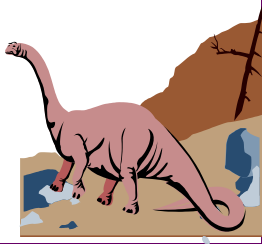
counter = register2



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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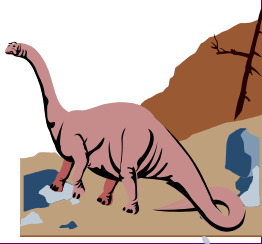
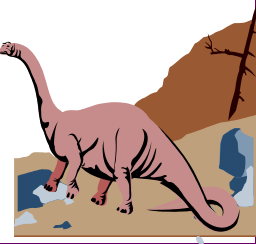


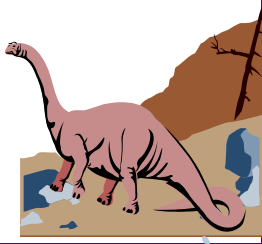
The Critical-Section Problem

- *n* 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.

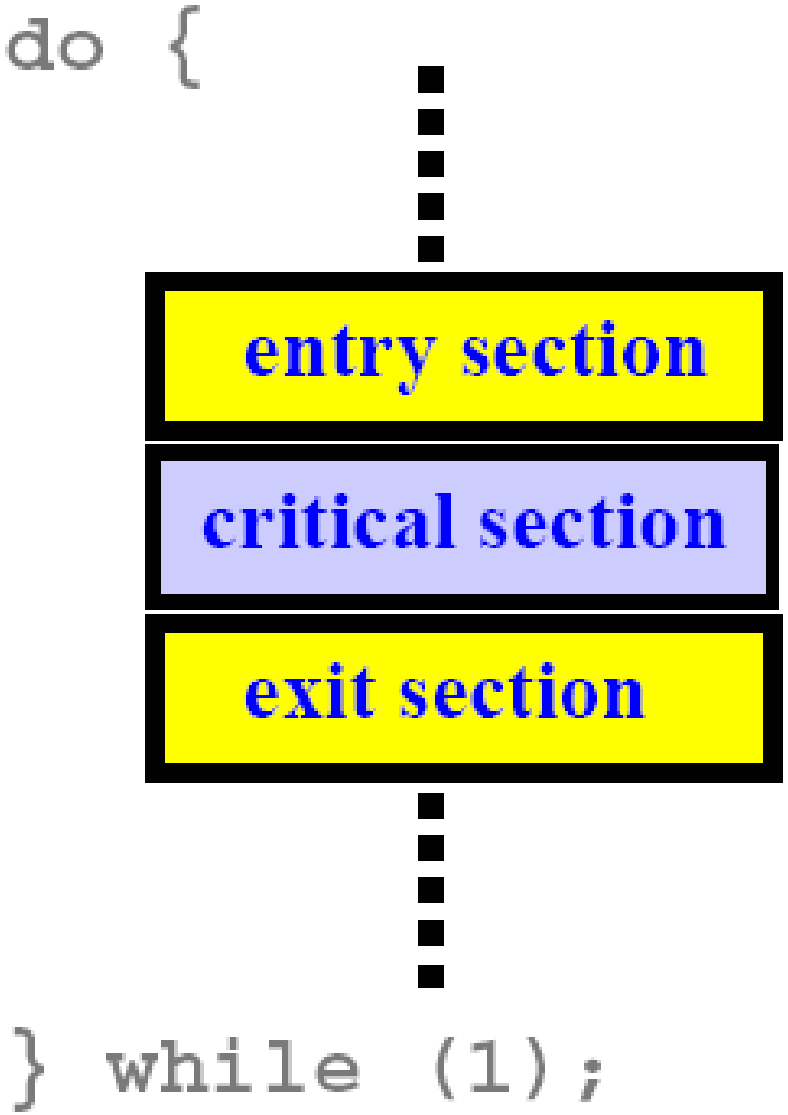


Critical Section and Mutual Exclusion

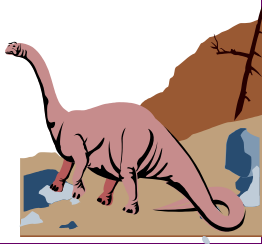
- Thus, the execution of critical sections must be *mutually exclusive* (e.g., at most one process can be in its critical section at any time).
- The *critical-section problem* is to design a protocol that processes can use to cooperate.



The Critical Section Protocol

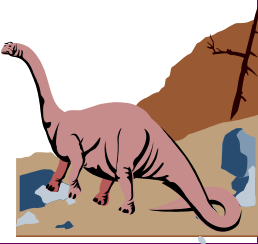


- A critical section protocol consists of **two** parts: an ***entry section*** and an ***exit section***.
- Between them is the critical section that must run in a **mutually exclusive** way.



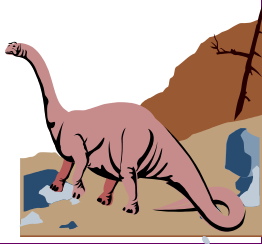
Solution to Critical-Section Problem

- 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.



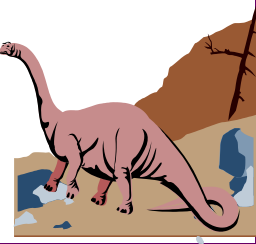
Mutual Exclusion

- 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.



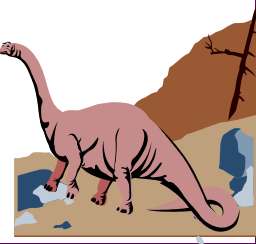
Progress

- 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

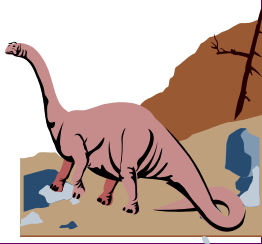


Initial Attempts to Solve Problem

- Only 2 processes, P_0 and P_1
- General structure of process P_i (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.

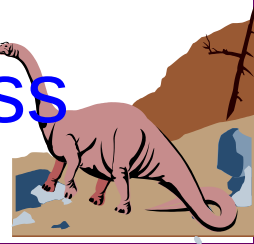


Algorithm 1

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

```
do {    while (turn != i) ;
            critical section
        turn = j;
            remainder section
    } while (1);
```

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



Algorithm 2

- Shared variables
  - **boolean flag[2]**;
    initially **flag [0] = flag [1] = false.**
  - **flag [i] = true** $\Rightarrow$ P_i ready 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.

Consider the following trace:

P_0 sets flag[0] to true

A context-switch occurs

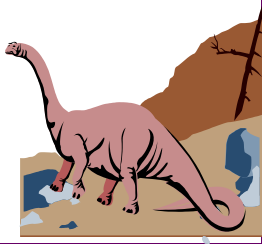
P_1 sets flag[1] to true

P_1 loops in while

A context-switch occurs

P_0 loops in while

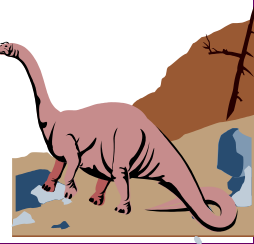
Both P_0 and P_1 loop forever. This is the livelock. No progress.



Is the following algorithm correct?

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

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



Consider the following trace:

P_0 finds (flag[1] == false)

The scheduler forces a context-switch

P_1 (finds flag[0]==false)

P_1 sets (flag[1] = true)

P_1 enters the critical section

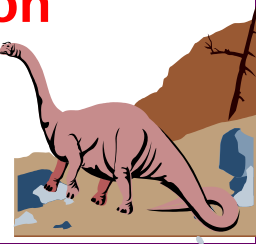
The scheduler forces a context-switch

P_0 sets (flag[0] = true)

P_0 enters the critical section

Both P_0 and P_1 are now in the critical section

With both processes in the critical section, the mutual exclusion criteria has been violated.



Algorithm 3

- Combined shared variables of algorithms 1 , 2.
- Process P_i

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

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

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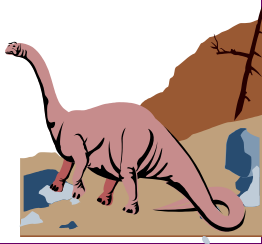
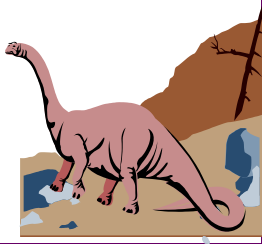
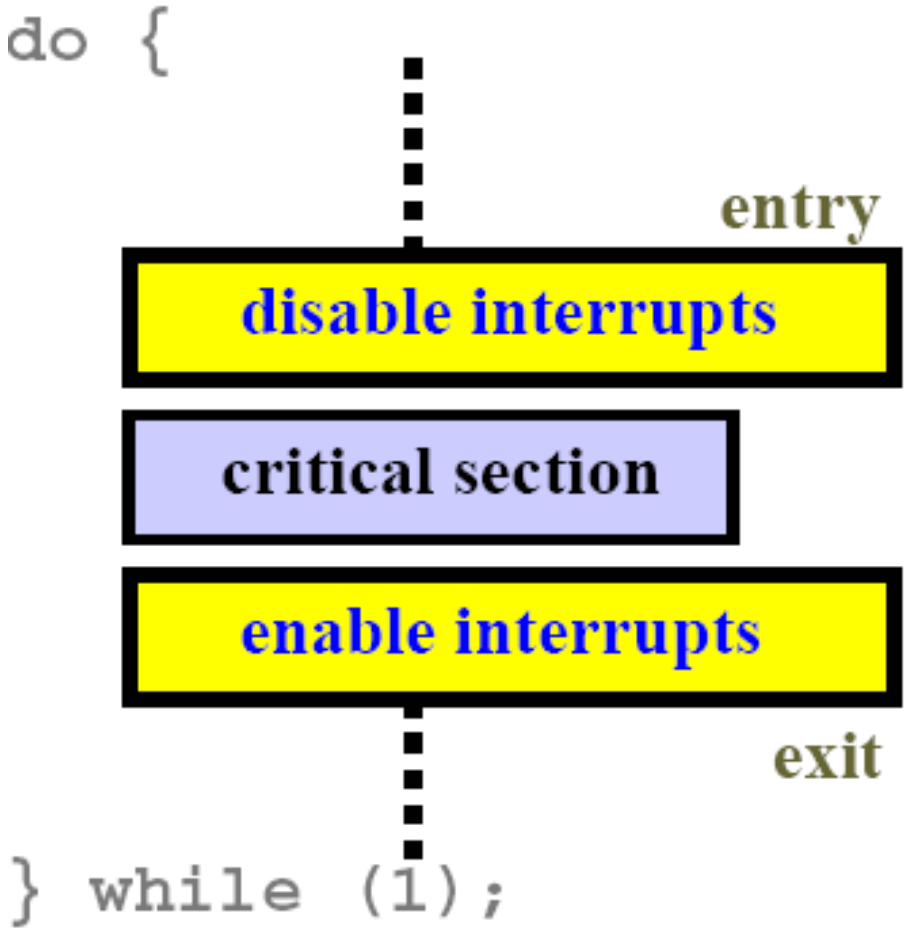


Hardware Support

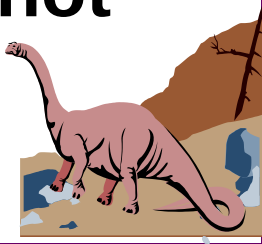
- There are two types of hardware synchronization supports:
  - Disabling/Enabling interrupts: This is slow and difficult to implement on multiprocessor systems.
  - Special machine instructions:
    - ✓Test and set (TS)
    - ✓Swap



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.

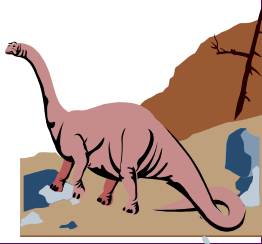


Test-and-Set

- Test and modify the content of a word atomically

.

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



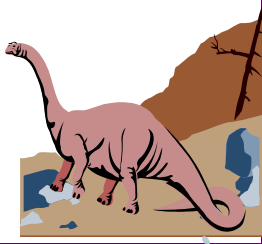
Mutual Exclusion with Test-and-Set

- Shared data:

  boolean lock = false;

- Process P_i

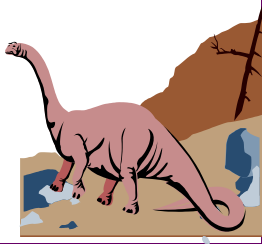
```
do {
   while (TestAndSet(&lock)) ;
      critical section
   lock = false;
      remainder section
}
```



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**):

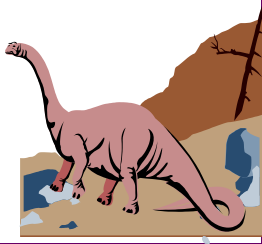
  boolean lock;

- local variable

  boolean key;

- Process P_i

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



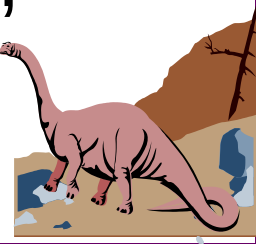
Bounded Waiting Mutual Exclusion with TestAndSet

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;
```



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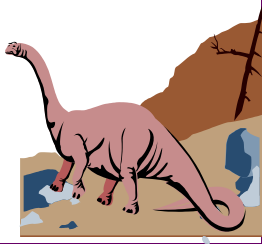


Semaphores

- Semaphore *S* – integer variable
- can only be accessed via two indivisible (atomic) operations

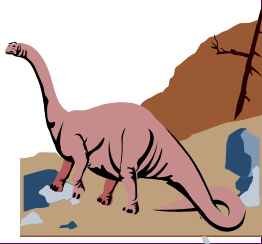
wait (*S*):

while *S*≤ 0 do *no-op*;

S--;

signal (*S*):

S++;



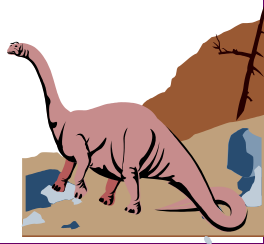
Critical Section of *n* Processes

- Shared data:

  semaphore mutex; ***//***initially *mutex* = 1

- Process P_i:

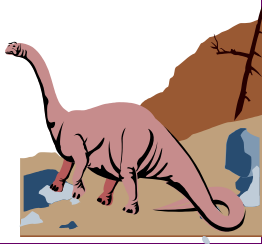
```
do {
    wait(mutex);
        critical section
    signal(mutex);
        remainder section
} while (1);
```



Semaphore as a General Synchronization Tool

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

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

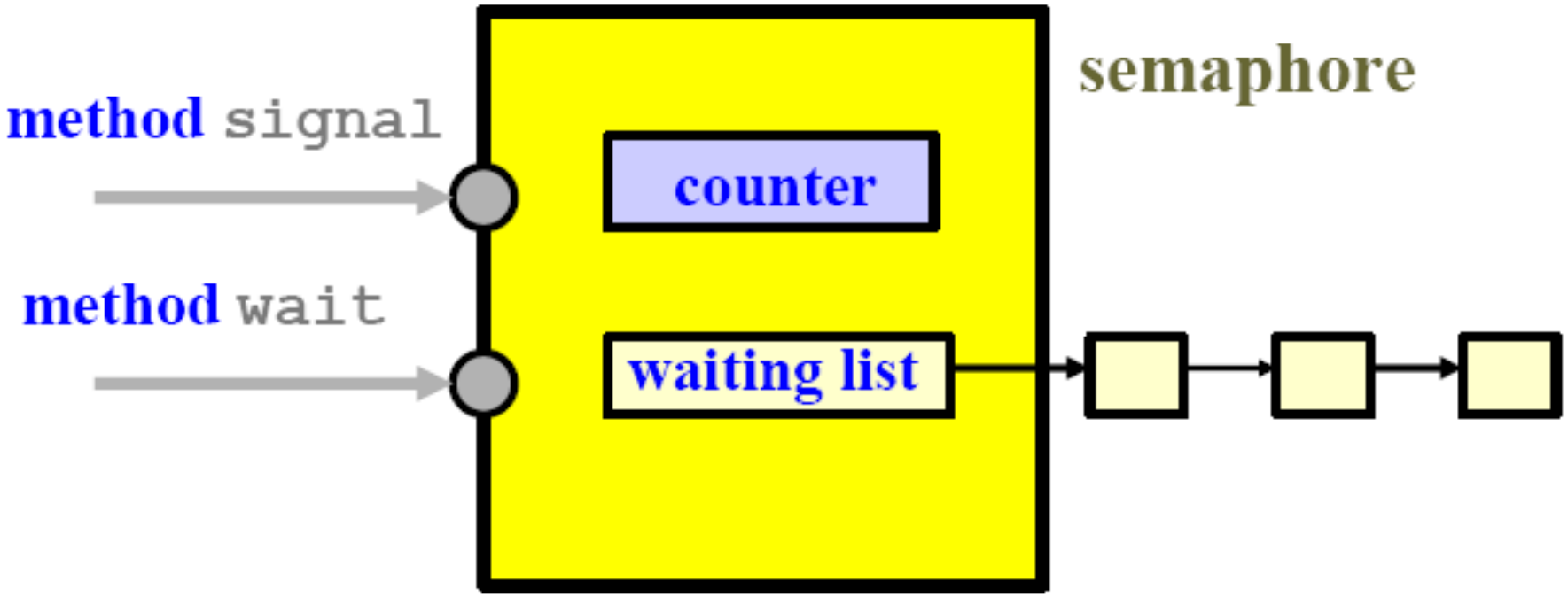


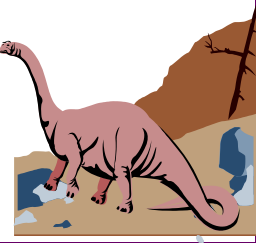
Semaphore Implementation

- Define a semaphore as a record

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

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


semaphore
method signal
method wait
counter
waiting list



Implementation

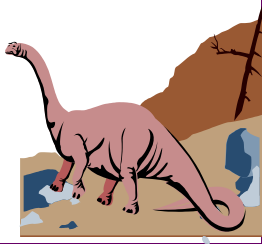
- Semaphore operations now defined as

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);
}
```

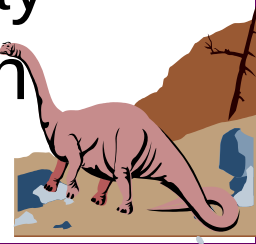


Deadlock and Starvation

- **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

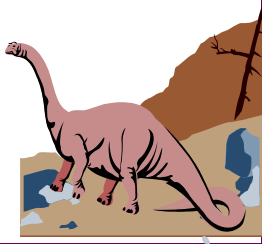
P_0	P_1
wait(*S*);	*wait*(*Q*);
wait(*Q*);	*wait*(*S*);
⋮	⋮
signal(*S*);	*signal*(*Q*);
signal(*Q*)	*signal*(*S*);

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



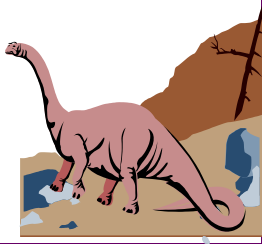
Chapter 6: Process Synchronization

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



Classical Problems of Synchronization

- Bounded-Buffer Problem
- Readers and Writers Problem
- Dining-Philosophers Problem



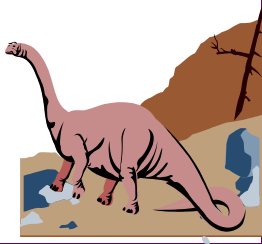
Bounded-Buffer Problem

- Shared data

  semaphore full, empty, mutex;

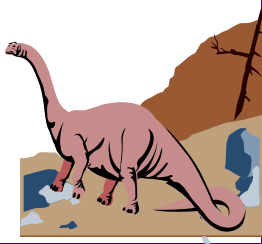
  Initially:

  full = 0, empty = n, mutex = 1



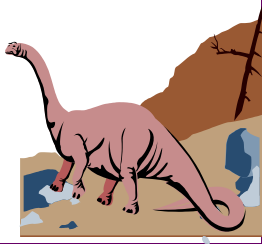
Bounded-Buffer Problem Producer Process

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



Bounded-Buffer Problem Consumer Process

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



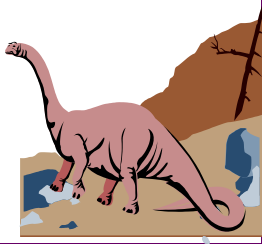
Readers-Writers Problem

- Shared data

  semaphore mutex, wrt;

  Initially

  mutex = 1, wrt = 1, readcount = 0



Readers-Writers Problem Writer Process

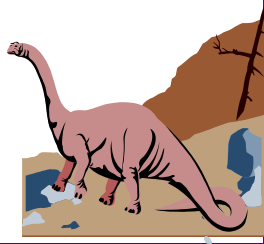
wait(wrt);

...

writing is performed

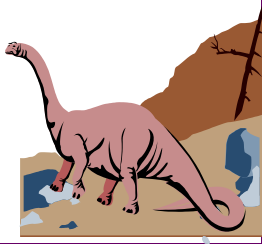
...

signal(wrt);

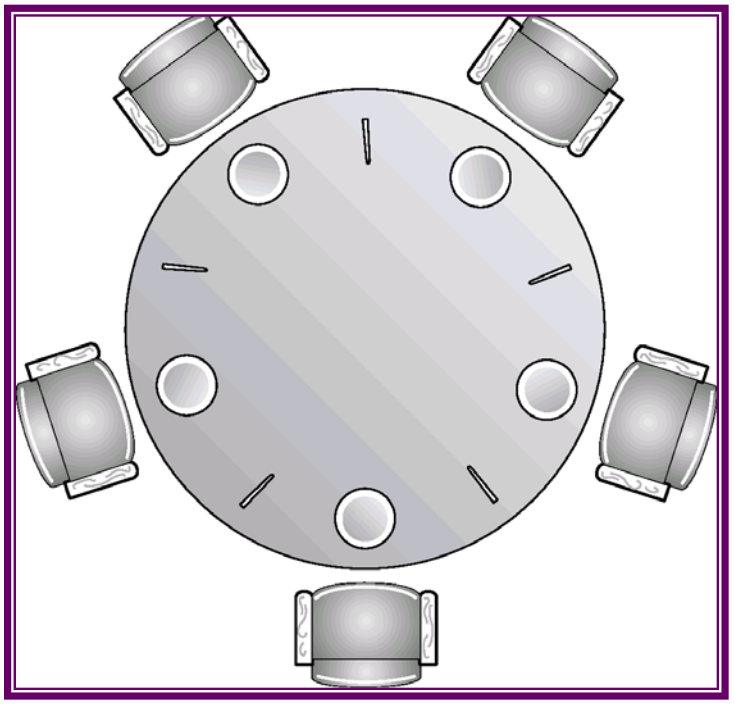


Readers-Writers Problem Reader Process

```
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

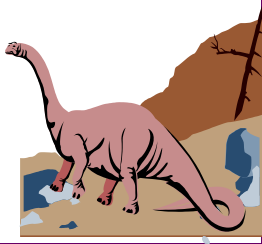
  semaphore chopstick[5];

  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);
```



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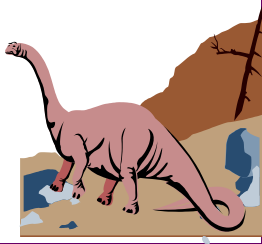
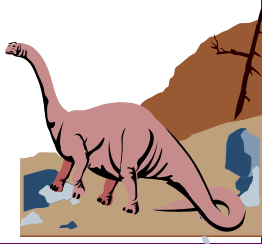


Monitors

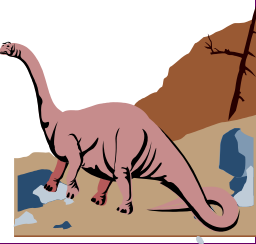
- High-level synchronization construct that allows the safe sharing of an abstract data type among concurrent processes.

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

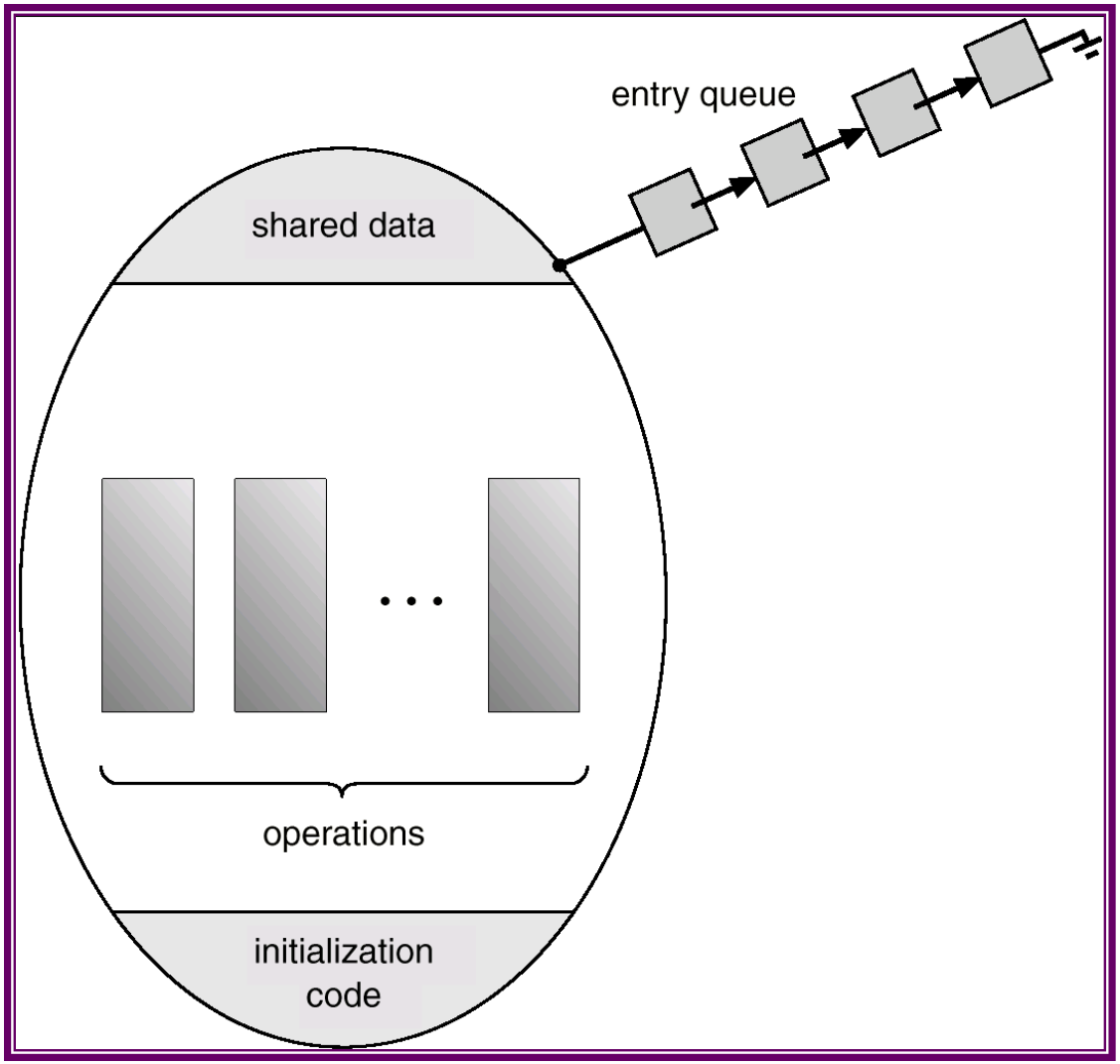


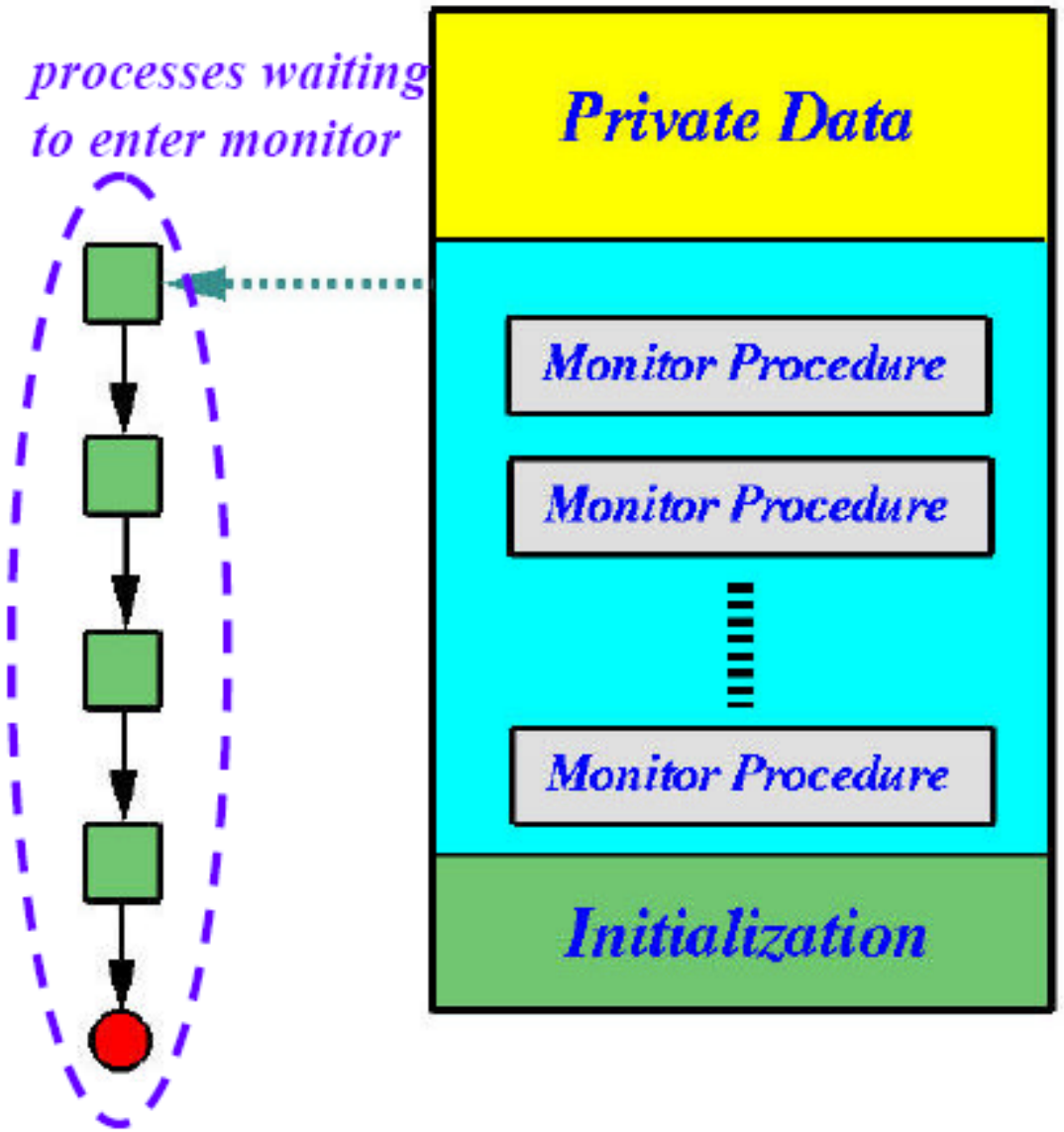
Monitors: Mutual Exclusion

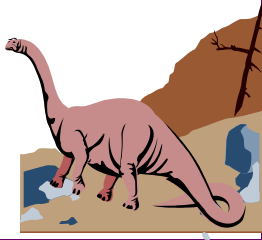
- *No more than one process* can be executing *within* a monitor. Thus, *mutual exclusion* is guaranteed within a monitor.
- When a process calls a monitor procedure and enters the monitor successfully, it is the *only* process executing in the monitor.
- When a process calls a monitor procedure and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

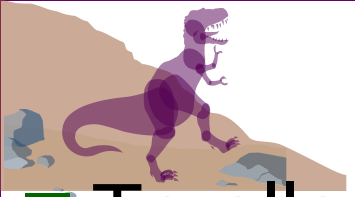


Schematic View of a Monitor




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();

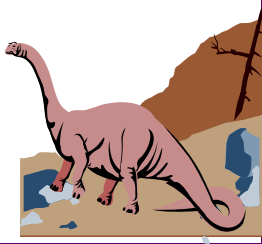
    means that the process invoking this operation is suspended until another process invokes

    x.signal();

  - The **x.signal** operation resumes exactly one suspended process. If no process is suspended, then the **signal** operation has no effect.

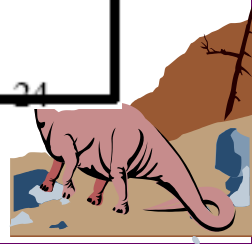
Condition Signal

- **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.

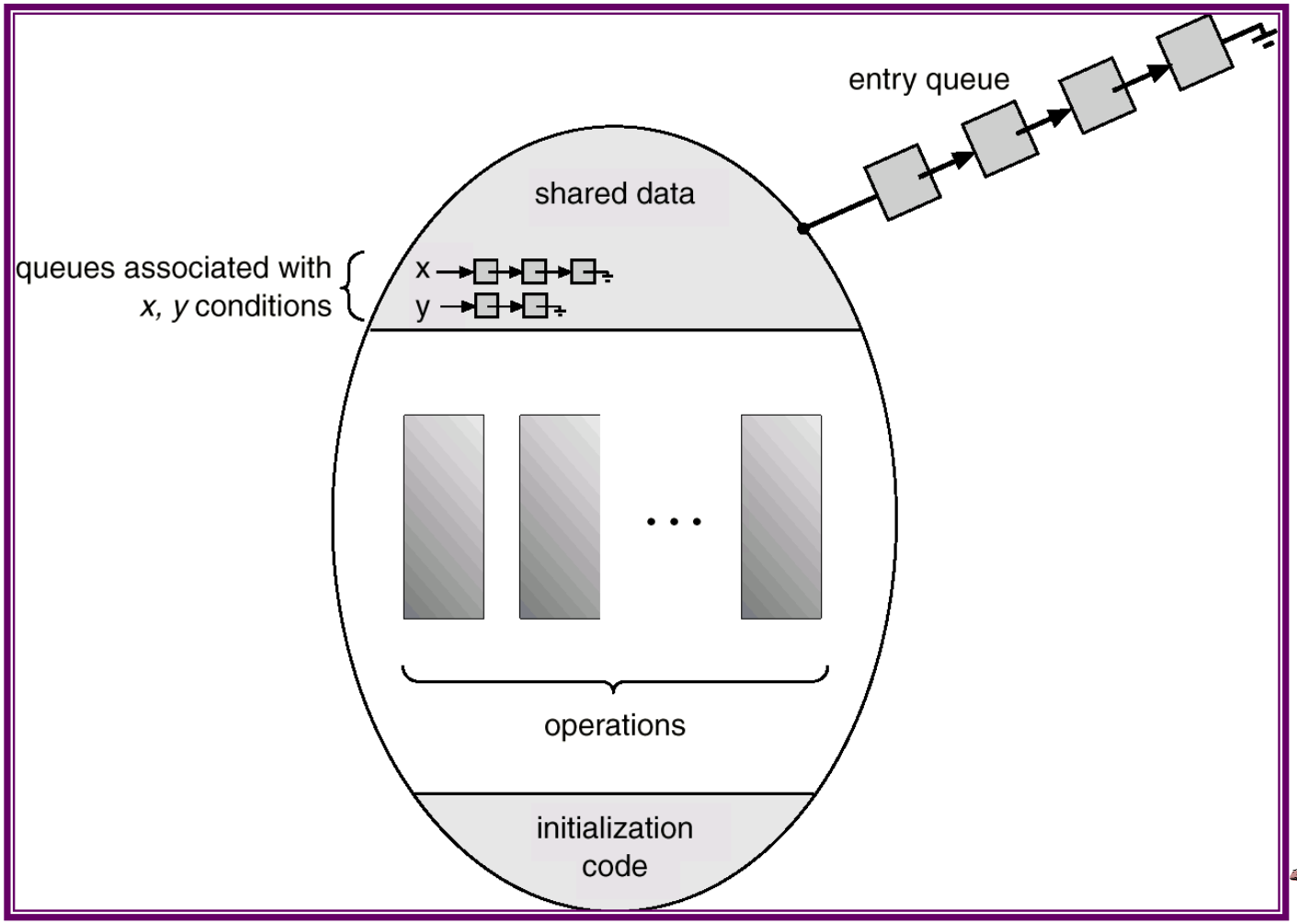


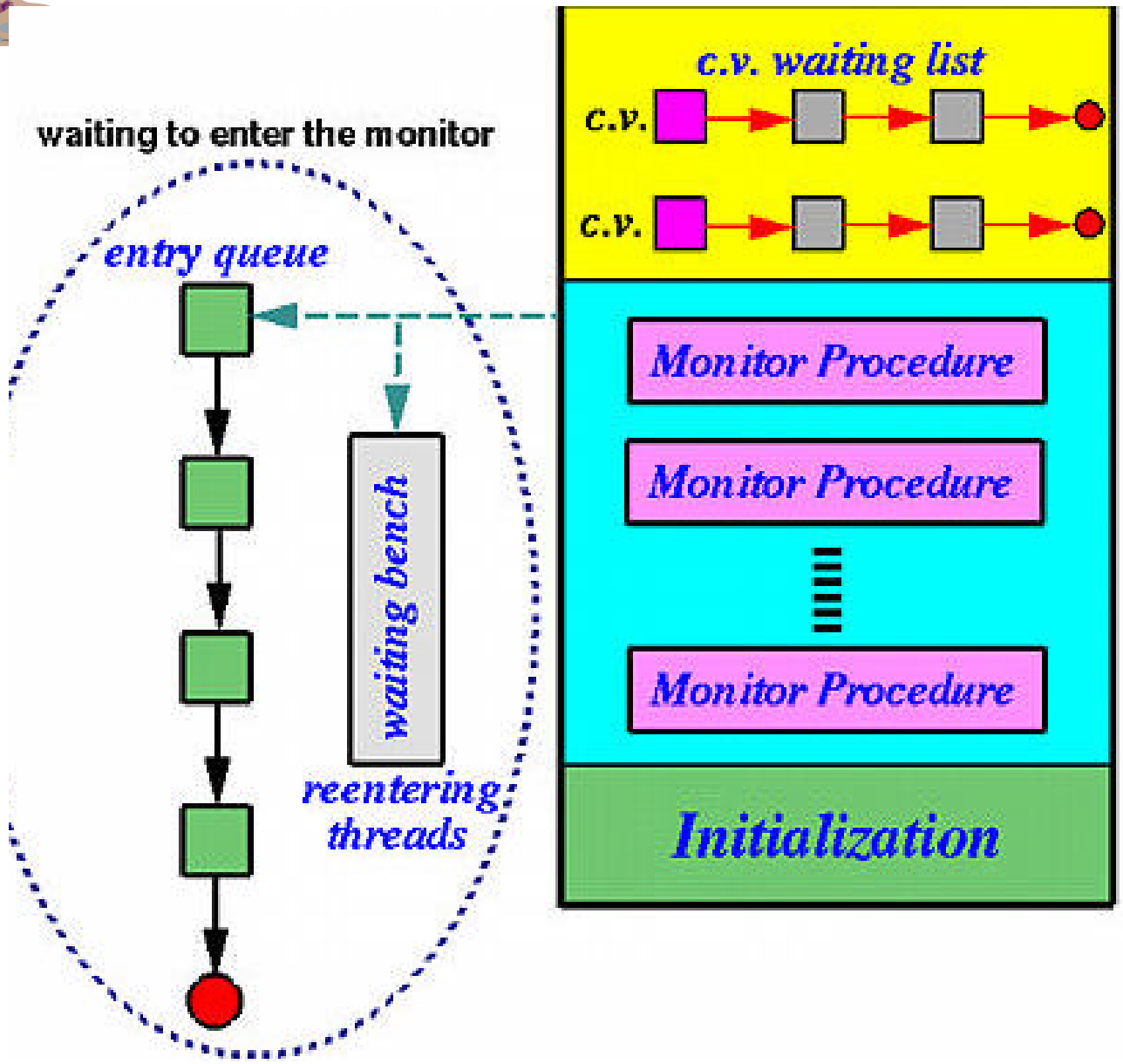
Semaphore vs. Condition

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*



Monitor With Condition Variables




waiting to enter the monitor
entry queue
waiting bench
reentering threads
c.v. waiting list
c.v.
c.v.
Monitor Procedure
Monitor Procedure
Monitor Procedure
Initialization

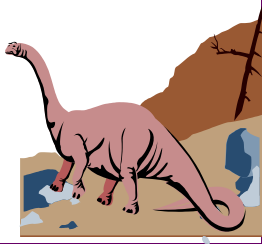
Bounded Buffer Solution Using Monitor

```
/* program producerconsumer */
monitor boundedbuffer;
char buffer [N];                                    /* space for N items */
int nextin, nextout;                                  /* buffer pointers */
int count;                                  /* number of items in buffer */
cond notfull, notempty;          /* condition variables for synchronization */

void append (char x)
{
     if (count == N) cwait(notfull);      /* buffer is full; avoid overflow */
     buffer[nextin] = x;
     nextin = (nextin + 1) % N;
     count++;
     /* one more item in buffer */
     csignal(notempty);                        /* resume any waiting consumer */
}
void take (char x)
{
     if (count == 0) cwait(notempty);   /* buffer is empty; avoid underflow */
     x = buffer[nextout];
     nextout = (nextout + 1) % N;
     count--;                                    /* one fewer item in buffer */
     csignal(notfull);                         /* resume any waiting producer */
}
{                                                          /* monitor body */
     nextin = 0; nextout = 0; count = 0;           /* buffer initially empty */
}
```

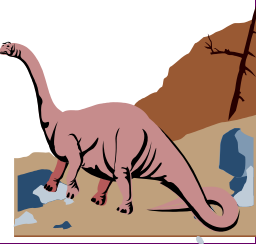
Solution Using Monitor

```
void producer()
{
     char x;
     while (true) {
     produce(x);
     append(x);
     }
}
void consumer()
{
     char x;
     while (true) {
       take(x);
       consume(x);
     }
}
void main()
{
     parbegin (producer, consumer);
}
```



Dining Philosophers Example

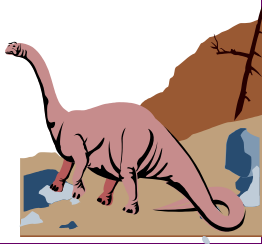
```
monitor dp
{
  enum {thinking, hungry, eating} state[5];
  condition self[5];
  void pickup(int i)              // following slides
  void putdown(int i)    // following slides
  void test(int i)               // following slides
  void init() { for (int i = 0; i < 5; i++)
                      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



Dining Philosophers

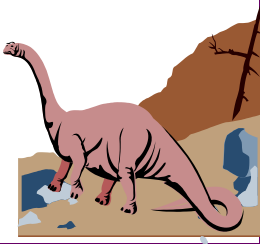
```
void pickup(int i) {
        state[i] = hungry;
        test[i];
        if (state[i] != eating)
                self[i].wait();
}

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



Dining Philosophers

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



Monitor Implementation Using Semaphores

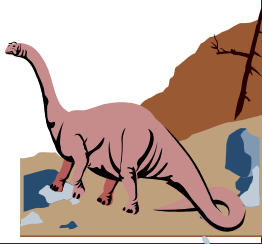
- Variables

```
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

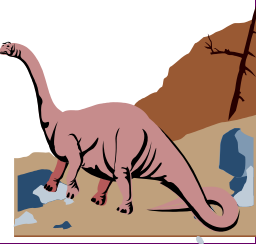
- For each condition variable ***x***, we have:

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

  int x-count = 0;

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

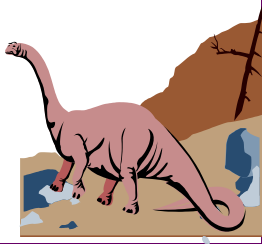
```
x-count++;
if (next-count > 0)
    signal(next);
else
    signal(mutex);
wait(x-sem);
x-count--;
```



Monitor Implementation

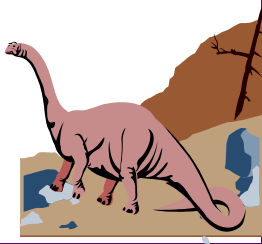
- The operation **x.signal** can be implemented as:

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



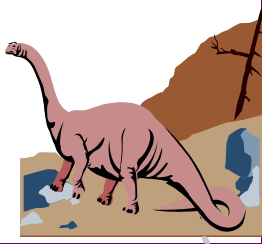
Monitor Implementation

- *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.



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.



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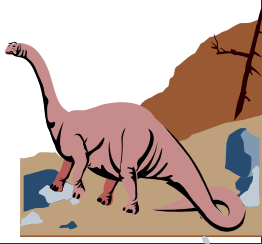

Solaris 2 Synchronization

- 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.

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.