Chapter 6: Synchronization Tools

Chapter 6: Outline

- Background
- The Critical-Section Problem
- Peterson's Solution
- Hardware Support for Synchronization
- Mutex Locks
- Semaphores
- Monitors
- Liveness
- Evaluation

Objectives

- Describe the *critical-section problem* and illustrate a *race condition*
- Illustrate *hardware solutions* to the critical-section problem using *memory barriers*, *compare-and-swap operations*, and *atomic variables*
- Demonstrate how *mutex locks*, *semaphores*, *monitors*, and *condition variables* can be used to solve the critical-section problem
- Evaluate *tools* that solve the critical-section problem in *low-*, *moderate-*, and *high-contention scenarios*

Background

- Processes can execute *concurrently* (or *in parallel*)
  - May be interrupted at any time, partially completing execution
- Concurrent access to *shared data* may result in *data inconsistency*
- Maintaining data consistency requires mechanisms to ensure the *orderly execution of cooperating processes*
- Illustration of the problem:
  - Suppose that we wanted to provide a solution to the *consumer-producer problem* that fills *all* the buffers. We can do so by having an integer *counter* that keeps track of the number of full buffers. Initially, *counter* is set to 0. It is *incremented* by the producer after it adds a new item to the buffer and is *decremented* by the consumer after it consumes an item from the buffer

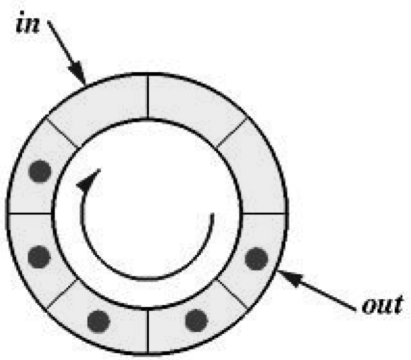
```
#define BUFFER_SIZE 8
        /* 8 buffers */

typedef struct {
        . . .
} item;
item buffer[BUFFER_SIZE];

int in = 0;
int out = 0;
int counter = 0;
```

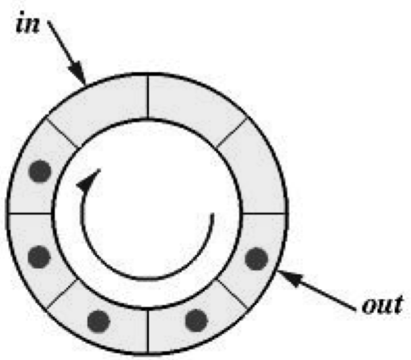
Producer

```
while (true) {
        /* produce an item in next produced */
        while (counter == BUFFER_SIZE)
                ;       /* do nothing */
        buffer[in] = next_produced;
        in = (in + 1) % BUFFER_SIZE; /* pointer in to buffer */
        counter++;
}
```



Consumer

```
while (true) {
        while (counter == 0)
                ;       /* do nothing */
        next_consumed = buffer[out];
        out = (out + 1) % BUFFER_SIZE;/* pointer out from buffer */
         counter--;
        /* consume the item in next_consumed */
}
```



Race Condition

- `counter++;` could be implemented as

```
register1 = counter
register1 = register1 + 1
counter = register1
```

- `counter--;` could be implemented as

```
register2 = counter
register2 = register2 - 1
counter = register2
```

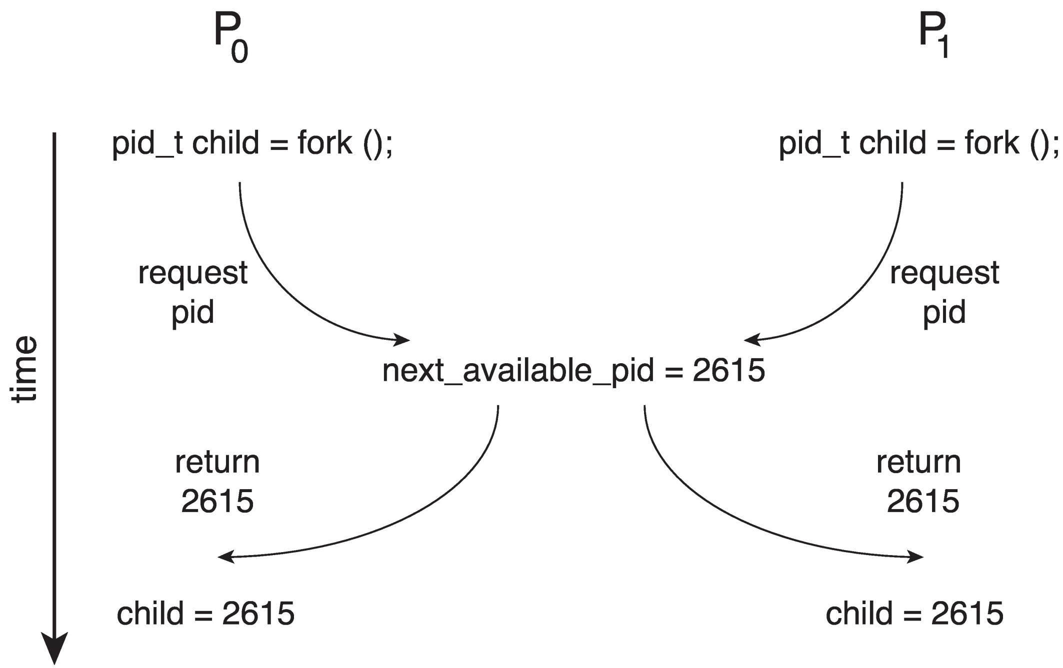
- Consider this execution *interleaving* with "`counter = 5`" initially:

S0: producer execute `register1 = counter` {register1 = 5}
S1: producer execute `register1 = register1 + 1` {register1 = 6}
S2: consumer execute `register2 = counter` {register2 = 5}
S3: consumer execute `register2 = register2 - 1` {register2 = 4}
S4: producer execute `counter = register1` {counter = 6 }
S5: consumer execute `counter = register2` {counter = 4}

=> Data inconsistency

Race Condition (Cont.)

- Processes P_0 and P_1 are creating child processes using the **`fork()`** system call
- Race condition on kernel variable **`next_available_pid`** which represents the next available *process identifier* (**pid**)



- Unless there is mutual exclusion, the same **pid** could be assigned to two different processes!

Critical-Section Problem

- Consider system of *n* processes $\{P_0, P_1, \ldots P_{n-1}\}$
- Each process has *critical section* (i.e., segment of code)
    - Process may be changing common variables, updating table, writing file, etc.
    - When one process in critical section, no other may be in its critical section
- *Critical-section problem* needs to design a protocol to solve this
- Each process must
    - ask permission to enter critical section in *entry section*,
    - may follow critical section with *exit section*,
    - then *remainder section*

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

Critical Section (CS)

- General structure of the process P_i

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

Solution to Critical-Section Problem

1. ***Mutual Exclusion*** – If process P_i is executing in its critical section, then *no other processes* can be executing in their critical sections
2. ***Progress*** – If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of process that will enter the critical section next *cannot be postponed indefinitely*
3. ***Bounded Waiting*** – A bound must exist on the *number of times* that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted
   - Assume that each process executes at a *nonzero speed*
   - No assumption concerning relative speed of the n processes

Critical-Section Handling in OS

- Two approaches depending on if kernel is preemptive or non-preemptive
  - *Preemptive* – allows preemption of process when running in kernel mode
  - *Non-preemptive* – runs until exits kernel mode, blocks, or voluntarily yields CPU
    - Essentially free of *race conditions* in kernel mode

Peterson's Solution

- Not guaranteed to work on modern architectures!
  - (But good algorithmic description of solving the problem)
- *Two-processes* solution
- Assume that the `load` and `store` machine-language instructions are *atomic*; that is, it cannot be interrupted
- The two processes share *two variables*:
  - `int turn;`
  - `boolean flag[i]`
    - The variable `turn` indicates whose turn it is to enter the critical section
    - The `flag[]` array is used to indicate if a process is ready to enter the critical section
      - `flag[i] = true` implies that process P_i is ready!

Algorithm for Process P_i

```
while (true){

   flag[i] = true;

   turn = j;

   while (flag[j] && turn == j)

         ;      /* do nothing */

   /* critical section */

   flag[i] = false;

   /* remainder section */


}
```

Peterson's Solution (Cont.)

- Provable that the three CS requirement are met:

1. *Mutual exclusion* is preserved
   - P_i enters CS only if: either **`flag[j] = false`** or **`turn = i`**
2. *Progress* requirement is satisfied
3. *Bounded-waiting* requirement is met

Remarks on Peterson's Solution

- Although useful for demonstrating an algorithm, Peterson's Solution is *not guaranteed to work on modern architectures*
- Understanding why it will not work is also useful for better understanding *race conditions*
- To improve performance, processors and/or compilers may *reorder operations* that have no dependencies
  - For *single-threaded,* this is ok as the result will always be the same.
  - For *multithreaded,* the reordering may produce inconsistent or unexpected results!

Example of Peterson's Solution

- Two threads share the data:

```
boolean flag = false;
int x = 0;
```

- *Thread 1* performs

```
while (!flag)
      ;
print x
```

- *Thread 2* performs

```
x = 100;
flag = true
```

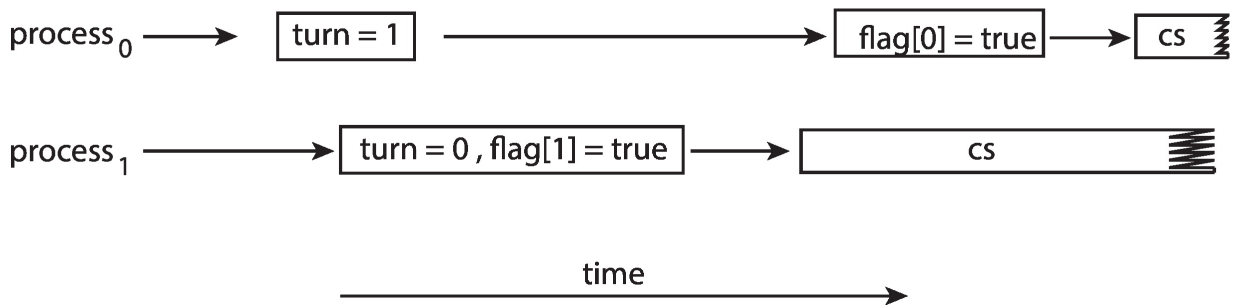
- What is the expected output?

Example of Peterson's Solution

- 100 is the expected output.
- However, the operations for *Thread 2* may be reordered:

```
flag = true;
x = 100;
```

- If this occurs, the output may be 0!
- The effects of *instruction reordering* in Peterson's Solution



- This allows both processes to be in their critical section at the same time!

Synchronization Hardware

- Many systems provide *hardware support* for implementing the critical-section code.
- **Uniprocessors** – could *disable interrupts*
  - Currently running code would execute without preemption
  - Generally too inefficient on multiprocessor systems
    - Operating systems using this are not broadly scalable
- We will look at three forms of hardware support:
  1. *Memory barriers*
  2. *Hardware instructions*
  3. *Atomic variables*

Memory Barriers

- *Memory model* is the memory guarantee that a computer architecture makes to application programs.
- Memory models may be either:
  - *Strongly ordered* – where a memory modification of one processor is immediately visible to all other processors.
  - *Weakly ordered* – where a memory modification of one processor may not be immediately visible to all other processors.
- A *memory barrier* is an instruction that forces any change in memory to be propagated (made visible) to all other processors.

Example of Memory Barrier

- We could add a memory barrier to the following instructions to ensure Thread 1 outputs 100:
- *Thread 1* now performs

```
while (!flag)
     memory_barrier();
print x;
```

- *Thread 2* now performs

```
x = 100;
memory_barrier();
flag = true;
```

Hardware Instructions

- *Special hardware instructions* that allow us to either *test-and-modify* the content of a word, or to *swap* the contents of two words atomically (uninterruptedly.)
  - ***`Test-and-Set()`*** instruction
  - ***`Compare-and-Swap()`*** instruction

`test_and_set` Instruction

- Definition:

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

1. Executed atomically
2. Returns the original value of passed parameter (i.e., **`*target`**)
3. Set the new value of passed parameter to **`true`** (i.e., **`*target=true`**)

Solution using *test_and_set()*

- Shared Boolean variable **lock**, initialized to **false**
- Solution:

```
do {
    while (test_and_set(&lock))
        ; /* do nothing */

        /* critical section */

    lock = false;
        /* remainder section */
} while (true);
```

compare_and_swap Instruction

- Definition:

```
int compare_and_swap(int *value, int expected,
                                   int new_value) {
    int temp = *value;
    if (*value == expected)
       *value = new_value;
   return temp;
 }
```

1. Executed atomically
2. Returns the original value of passed parameter **value**
3. Set the variable **value** the value of the passed parameter **new_value** but only if ***value == expected** is true. That is, the swap takes place only under this condition.

Solution using *compare_and_swap*

- Shared integer `lock` initialized to 0;
- Solution:

```
while (true){
   while (compare_and_swap(&lock, 0, 1) != 0)
              ;     /* do nothing */

        /* critical section */

        lock = 0;

        /* remainder section */
}
```

Bounded-waiting Mutual Exclusion with compare-and-swap

```
while (true) {
   waiting[i] = true;
   key = 1;
   while (waiting[i] && key == 1)
      key = compare_and_swap(&lock,0,1);
   waiting[i] = false;
            /* critical section */
   j = (i + 1) % n;
   while ((j != i) && !waiting[j])
      j = (j + 1) % n;
   if (j == i)
      lock = 0;
   else
      waiting[j] = false;
            /* remainder section */
}
```

Atomic Variables

- Typically, instructions such as ***`compare-and-swap`*** are used as building blocks for other synchronization tools.
- One tool is an *atomic variable* that provides *atomic* (uninterruptible) updates on basic data types such as Integers and Booleans.
- For example, the **`increment()`** operation on the atomic variable **`sequence`** ensures **`sequence`** is incremented without interruption:

```
increment(&sequence);
```

Atomic Variables (Cont.)

- The **`increment()`** function can be implemented as follows:

```
void increment(atomic_int *v)
{
        int temp;

        do {
                temp = *v;
        }
        while

(temp != compare_and_swap(v,temp,temp+1));


}
```

Mutex Locks

- *Previous solutions are complicated* and generally inaccessible to application programmers
- OS designers build *software tools* to solve critical section problem
- Simplest is **mutex lock**
- Protect a critical section by first **`acquire()`** a lock then **`release()`** the lock
  - Boolean variable indicating if **`lock`** is available or not
- Calls to **`acquire()`** and **`release()`** must be *atomic*
  - Usually implemented via *hardware atomic instructions* such as *compare-and-swap*
- But this solution requires *busy waiting*
  - This lock therefore called a *spinlock*

Solution to Critical-section Problem using Locks

```
while (true) {
        acquire lock;

        critical section;

        release lock;

        remainder section;
}
```

Mutex Lock Definitions

- ```
  acquire() {
       while (!available)
          ; /* busy wait */
       available = false;;
    }
  ```
- ```
    release() {
       available = true;
    }
  ```

- These two functions must be implemented *atomically*
- Both *test-and-set* and *compare-and-swap* can be used to implement these functions

Semaphore

- *Synchronization tool* that provides more sophisticated ways (than mutex locks) for process to synchronize their activities.
- Semaphore **S** is an integer variable
- Can only be accessed via *two* indivisible (atomic) operations
  - **`wait()`** and **`signal()`**
    - (Originally called **`P()`** and **`V()`**)

- Definition of the **`wait()`** operation

```
wait(S) {
    while (S <= 0)
       ; // busy wait
    S--;
}
```

- Definition of the **`signal()`** operation

```
signal(S) {
    S++;
}
```

Semaphore Usage

- *Counting semaphore* – integer value can range over an unrestricted domain
- *Binary semaphore* – integer value can range only between 0 and 1
  - Same as a mutex lock
  - Can solve various synchronization problems
- Can implement a counting semaphore S as a binary semaphore
- Consider ***P_1*** and ***P_2*** that require ***S_1*** to happen before ***S_2***
  - Create a semaphore "**synch**" initialized to 0

```
P1:
    S1;
    signal(synch);
P2:
    wait(synch);
    S2;
```

Semaphore Implementation

- Must guarantee that no two processes can execute the **`wait()`** and **`signal()`** on the same semaphore at the same time
- Thus, the implementation becomes the critical-section problem where the **`wait()`** and **`signal()`** code are placed in the critical section
  - Could now have *busy waiting* in critical-section implementation
    - But implementation code is short
    - Little busy waiting if critical section rarely occupied
- Note that applications may spend lots of time in critical sections and therefore this is not a good solution

Semaphore Implementation with no Busy waiting

- With each semaphore there is an *associated waiting queue*
- Each entry in a waiting queue has two data items:
  - **value** (of type integer)
  - **pointer** to next record in the list
- Two operations:
  - *block* – place the process invoking the operation on the appropriate waiting queue
  - *wakeup* – remove one of processes in the waiting queue and place it in the ready queue

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

Implementation with no Busy waiting (Cont.)

```
wait(semaphore *S) {
    S->value--;
    if (S->value < 0) {
        add this process to
S->list;
        block();
    }
}
```

```
signal(semaphore *S) {
    S->value++;
    if (S->value <= 0) {
        remove a process P
from S->list;
        wakeup(P);
    }
}
```

Problems with Semaphores

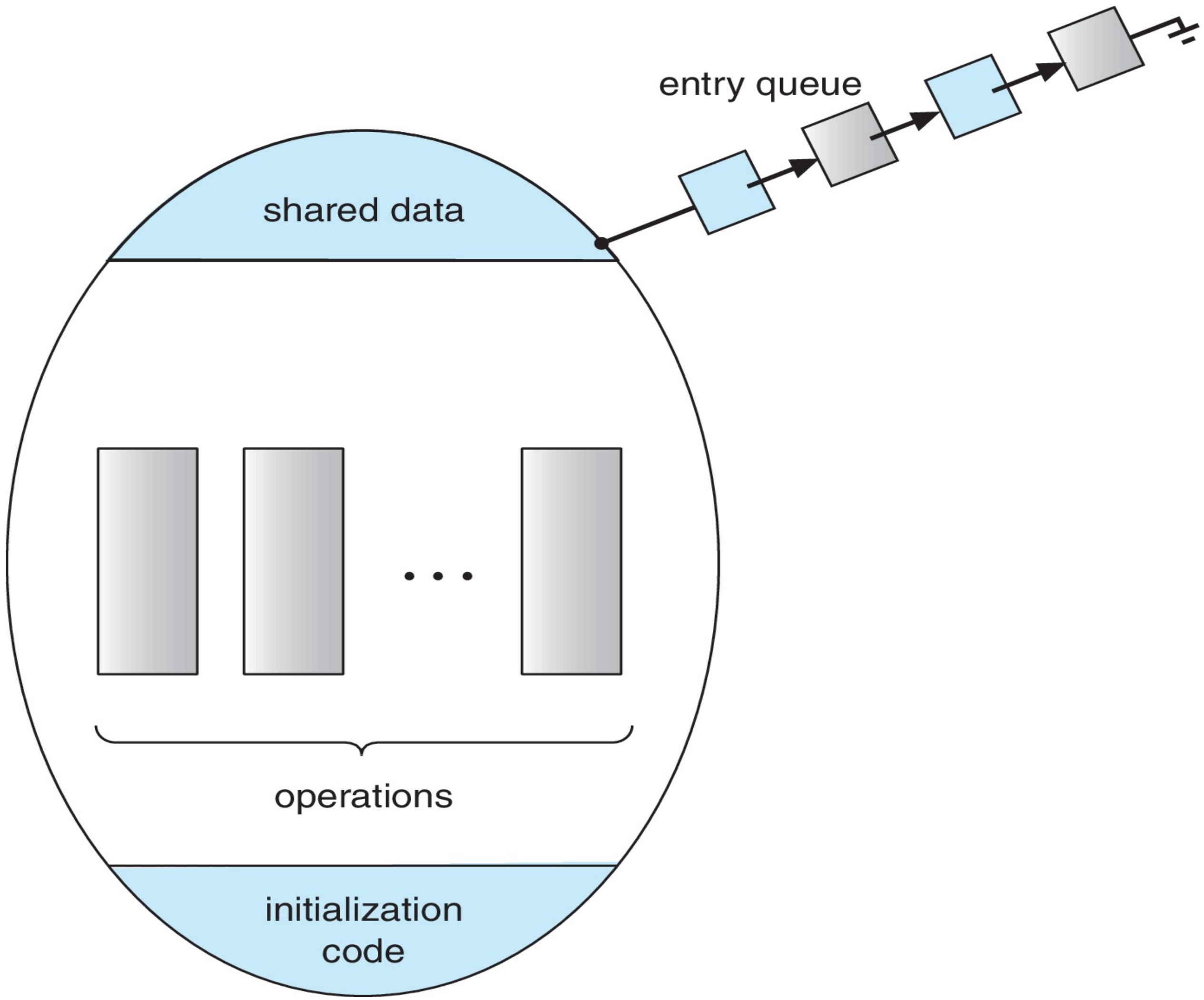
- Incorrect use of **semaphore** operations:
  - `signal(mutex) …. wait(mutex)`
  - `wait(mutex) … signal(mutex)`
  - Omitting of `wait(mutex)` and/or `signal(mutex)`
- These – and others – are examples of what can occur when semaphores and other synchronization tools are used incorrectly.

Monitors

- A *high-level abstraction* that provides a convenient and effective mechanism for process synchronization
- Abstract *data type*, *internal variables* only accessible by code within the procedure
- *Only one process* may be active within the monitor at a time
- Pseudocode syntax of a **monitor**:

```
monitor monitor-name
{
  // shared variable declarations
  function P1 (…) { …. }
  function P2 (…) { …. }
  function Pn (…) {……}
  initialization code (…) { … }
}
```

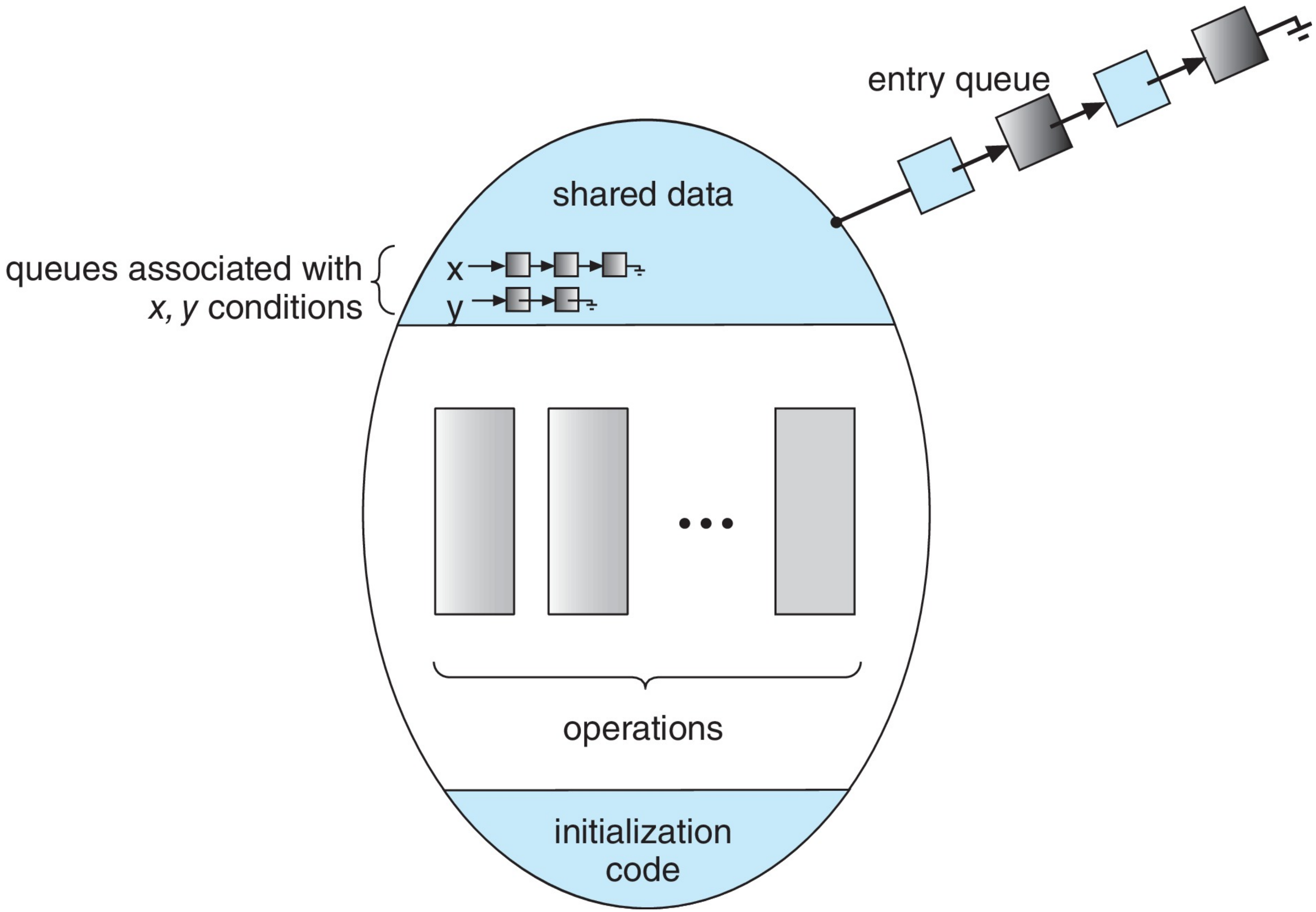
Schematic View of a Monitor



Condition Variables

- `condition x, y;`
- Two operations are allowed on a condition variable:
  - **`x.wait()`** – a process that invokes the operation is suspended until **`x.signal()`**
  - **`x.signal()`** – resumes one of processes (if any) that invoked **`x.wait()`**
    - If no **`x.wait()`** on the variable, then it has no effect on the variable

Monitor with Condition Variables



Condition Variables Choices

- If process **P** invokes **`x.signal()`**, and process **Q** is suspended in **`x.wait()`**, what should happen next?
    - Both **Q** and **P** cann't execute in parallel. If **Q** is resumed, then **P** must wait
- Options include
    - ***Signal and wait*** – **P** waits until **Q** either leaves the monitor or it waits for another condition
    - ***Signal and continue*** – **Q** waits until **P** either leaves the monitor or it waits for another condition
    - Both have pros and cons – language implementer can decide
    - Monitors implemented in **Concurrent Pascal** compromise
        - **P** executing *signal* immediately leaves the monitor, **Q** is resumed
    - Implemented in other languages: **Mesa**, **C#**, **Java**

Monitor Implementation using Semaphores

- Variables

```
semaphore mutex;  /*(initially  = 1)*/
semaphore next;   /*(initially  = 0)*/
int next_count = 0;
```

- Each function ***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 – Condition Variables

- 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 (Cont.)

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

```
if (x_count > 0) {
   next_count++;
   signal(x_sem);
   wait(next);
   next_count--;
}
```

Resuming Processes within a Monitor

- If several processes queued on condition variable **`x`**, and **`x.signal()`** is executed, which process should be resumed?
- FCFS frequently not adequate
- **`conditional-wait`** construct of the form **`x.wait(c)`**
  - Where **`c`** is *priority number*
  - Process with lowest number (highest priority) is scheduled next

Single Resource allocation

- Allocate a single resource among competing processes using priority numbers that specify the maximum time a process plans to use the resource

```
R.acquire(t);

    ...

  access the resurce;

    ...


 R.release;
```

- Where **R** is an instance of type `ResourceAllocator`

A Monitor to Allocate Single Resource

```
monitor ResourceAllocator {
        boolean busy;
        condition x;
        void acquire(int time) {
                if (busy)
                        x.wait(time);
                busy = true;
        }
        void release() {
                busy = FALSE;
                x.signal();
        }
   initialization code() {
         busy = false;
        }
}
```

Liveness

- Processes may have to wait indefinitely while trying to acquire a synchronization tool such as a *mutex lock* or *semaphore*
- Waiting indefinitely violates the *progress* and *bounded-waiting* criteria discussed at the beginning of this chapter
- **Liveness** refers to a *set of properties* that a system must satisfy to ensure processes make progress
- Indefinite waiting is an example of a liveness failure

Liveness (Cont.)

- *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);`

- Consider if P_0 executes `wait(S)` and P_1 `wait(Q)`. When P_0 executes `wait(Q)`, it must wait until P_1 executes `signal(Q)`
- However, P_1 is waiting until P_0 execute `signal(S)`
- Since these `signal()` operations will never be executed, P_0 and P_1 are *deadlocked*

Liveness (Cont.)

Other forms of deadlock:

- **Starvation** – indefinite blocking
  - A process may never be removed from the semaphore queue in which it is suspended
- **Priority Inversion** – Scheduling problem when lower-priority process holds a lock needed by higher-priority process
  - Solved via **priority-inheritance protocol**

Priority Inheritance Protocol

- Consider the scenario with three processes ***P_1***, ***P_2***, and ***P_3***.
  - ***P_1*** has the highest priority, ***P_2*** the next highest, and ***P_3*** the lowest.
  - Assume a resource ***P_3*** is assigned a resource ***R*** that ***P_1*** wants. Thus, ***P_1*** must wait for ***P_3*** to finish using the resource.
  - However, ***P_2*** becomes runnable and preempts ***P_3***.
  - What has happened is that ***P_2*** - a process with a lower priority than ***P_1*** - has indirectly prevented ***P_3*** from gaining access to the resource.
- To prevent this from occurring, a *priority inheritance protocol* is used.
  - This simply allows the priority of the highest thread waiting to access a shared resource to be assigned to the thread currently using the resource.
  - Thus, the current owner of the resource is assigned the priority of the highest priority thread wishing to acquire the resource.

Summary

- A *race condition* occurs when processes have concurrent access to shared data and the final result depends on the particular order in which concurrent accesses occur. Race conditions can result in corrupted values of shared data.

- A *critical section* is a section of code where shared data may be manipulated and a possible race condition may occur. The critical-section problem is to design a protocol whereby processes can synchronize their activity to cooperatively share data.

- A *solution to the critical-section problem* must satisfy the following three requirements: (1) *mutual exclusion*, (2) *progress*, and (3) *bounded waiting*. Mutual exclusion ensures that only one process at a time is active in its critical section. Progress ensures that programs will cooperatively determine what process will next enter its critical section. Bounded waiting limits how much time a program will wait before it can enter its critical section.

Summary (Cont.)

- Software solutions to the critical-section problem, such as *Peterson's solution*, do not work well on modern computer architectures.
- *Hardware support* for the critical-section problem includes memory barriers; hardware instructions, such as the compare-and-swap instruction; and atomic variables.
- A *mutex lock* provides mutual exclusion by requiring that a process acquire a lock before entering a critical section and release the lock on exiting the critical section.
- *Semaphores*, like mutex locks, can be used to provide mutual exclusion. However, whereas a mutex lock has a binary value that indicates if the lock is available or not, a semaphore has an integer value and can therefore be used to solve a variety of synchronization problems.

Summary (Cont.)

- A *monitor* is an abstract data type that provides a high-level form of process synchronization. A monitor uses condition variables that allow processes to wait for certain conditions to become true and to signal one another when conditions have been set to true.
- Solutions to the critical-section problem may suffer from *liveness problems*, including *deadlock*.
- The *various tools* that can be used to solve the critical-section problem as well as to synchronize the activity of processes can be evaluated under varying levels of contention. Some tools work better under certain contention loads than others.

End of Chapter 6