Process Synchronization – Outline

- Why do processes need synchronization ?
- What is the critical-section problem ?
- Describe solutions to the critical-section problem
  - Peterson's solution
  - using synchronization hardware
  - semaphores
  - monitors
- Classic Problems of Synchronization
- What are atomic transactions ?

Why Process Synchronization ?

- Processes may *cooperate* with each other
  - producer-consumer and service-oriented system models
  - exploit concurrent execution on multiprocessors
- Cooperating processes may share data (globals, files, etc)
  - imperative to maintain data *correctness*
- Why is data correctness in danger ?
  - process run asynchronously, context switches can happen at any time
  - processes may run concurrently
  - different orders of updating shared data may produce different values
- Process synchronization
  - to coordinate updates to shared data
  - order of process execution should not affect shared data
- *Only needed when processes share data !*

Producer-Consumer Data Sharing

Producer

```
while (true){

    /* wait if buffer full */
    while (counter == 10)
     ;  /* do nothing */

    /* produce data */
    buffer[in] = sdata;
    in = (in + 1) % 10;

    /* update number of
        items in buffer */
    counter++;
}
```

Consumer

```
while (true){

    /* wait if buffer empty */
    while (counter == 0)
     ;  /* do nothing */

    /* consume data */
    sdata = buffer[out];
    out = (out + 1) % 10;

    /* update number of
        items in buffer */
    counter--;
}
```

Producer-Consumer Data Sharing

Producer

```
while (true){

    /* wait if buffer full */
    while (counter == 10)
     ;  /* do nothing */

    /* produce data */
    buffer[in] = sdata;
    in = (in + 1) % 10;

    /* update number of
        items in buffer */
    R1 = load (counter);
    R1 = R1 + 1;
    counter = store (R1);
}
```

Consumer

```
while (true){

    /* wait if buffer empty */
    while (counter == 0)
     ;  /* do nothing */

    /* consume data */
    sdata = buffer[out];
    out = (out + 1) % 10;

    /* update number of
        items in buffer */
    R2 = load (counter);
    R2 = R2 – 1;
    counter = store (R2);
}
```

Race Condition

- Suppose *counter = 5*

Incorrect Sequence 1

```
R1 = load (counter);
R1 = R1 + 1;
R2 = load (counter);
R2 = R2 – 1;
counter = store (R1);
counter = store (R2);
```

Final Value in counter = 4!

Incorrect Sequence 2

```
R1 = load (counter);
R1 = R1 + 1;
R2 = load (counter);
R2 = R2 – 1;
counter = store (R2);
counter = store (R1);
```

Final Value in counter = 6!

- Race condition is a situation where
  - several processes concurrently manipulate shared data, and
  - shared data value depends on the order of execution

Critical Section Problem

- Region of code in a process *updating* shared data is called a critical region.
- Concurrent updating of shared data by multiple processes is dangerous.
- Critical section problem
  - how to ensure synchronization between cooperating processes ?
- Solution to the critical section problem
  - only allow a single process to enter its critical section at a time
- Protocol for solving the critical section problem
  - request permission to enter critical section
  - indicate after exit from critical section
  - only permit a single process at a time

Solution to the Critical Section Problem

- Formally states, each solution should ensure
  - *mutual exclusion:* only a single process can execute in *its* critical section at a time
  - *progress:* selection of a process to enter its critical section should be fair, and the decision cannot be postponed indefinitely.
  - *bounded waiting:* there should be a fixed bound on how long it takes for the system to grant a process's request to enter its critical section
- Other than satisfying these requirements, the system should also guard against *deadlocks.*

Preemptive Vs. Non-preemptive Kernels

- Several kernel processes share data
  - structures for maintaining file systems, memory allocation, interrupt handling, etc.
- How to ensure OSes are free from race conditions ?
- Non–preemptive kernels
  - process executing in kernel mode cannot be preempted
  - disable interrupts when process is in kernel mode
  - what about multiprocessor systems ?
- Preemptive kernels
  - process executing in kernel mode can be preempted
  - suitable for real-time programming
  - more responsive

Peterson's Solution to Critical Section Problem

- Software based solution
- Only supports two processes
- The two processes share two variables:
  - int turn;
    - indicates whose turn it is to enter the critical section
  - boolean flag[2]
    - indicates if a process is ready to enter its critical section

Peterson's Solution

Process 0

```
do {
    flag[0] = TRUE;
    turn = 1;
    while (flag[1]  &&  turn==1)
        ;
    // critical section

    flag[0] = FALSE;

    // remainder section
} while (TRUE)
```

Process 1

```
do {
    flag[1] = TRUE;
    turn = 0;
    while (flag[0]  &&  turn==0)
        ;
    // critical section

    flag[1] = FALSE;

    // remainder section
} while (TRUE)
```

- Solution meets all three requirements
  - P0 and P1 can never be in the critical section at the same time
  - if P0 does not want to enter critical region, P1 does no waiting
  - process waits for at most one turn of the other to progress

Peterson's Solution – Notes

- Only supports two processes
  - generalizing for more than two processes has been achieved
- Assumes that the LOAD and STORE instructions are atomic
- Assumes that memory accesses are not reordered
- May be less efficient than a hardware approach
  - particularly for >2 processes

Lock-Based Solutions

- General solution to the critical section problem
  - critical sections are protected by locks
  - process must acquire lock before entry
  - process releases lock on exit

```
do {
    acquire lock;

        critical section

    release lock;

        remainder section

} while(TRUE);
```

Hardware Support for Lock-Based Solutions – Uniprocessors

- For uniprocessor systems
  - concurrent processes cannot be overlapped, only *interleaved*
  - process runs until it invokes system call, or is *interrupted*
- Disable interrupts !
  - active process will run without preemption

```
do {

    disable interrupts;
        critical section
    enable interrupts;

        remainder section
} while(TRUE);
```

Hardware Support for Lock-Based Solutions – Multiprocessors

- In multiprocessors
  - several processes share memory
  - processors behave independently in a peer manner
- Disabling interrupt based solution will not work
  - too inefficient
  - OS using this not broadly scalable
- Provide hardware support in the form of atomic instructions
  - atomic *test-and-set* instruction
  - atomic *swap* instruction
  - atomic *compare-and-swap* instruction
- Atomic execution of a set of instructions means that instructions are treated as a single step that cannot be interrupted.

TestAndSet Instruction

- Pseudo code definition of *TestAndSet*

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

Mutual Exclusion using *TestAndSet*

```
int mutex;
init_lock (&mutex);

do {

    lock (&mutex);
        critical section
    unlock (&mutex);

        remainder section
} while(TRUE);
```

```
void init_lock (int *mutex)
{
    *mutex = 0;
}

void lock (int *mutex)
{
    while(TestAndSet(mutex))
        ;
}

void unlock (int *mutex)
{
    *mutex = 0;
}
```

Swap Instruction

- Psuedo code definition of swap instruction

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

Mutual Exclusion using *Swap*

```
int mutex;
init_lock (&mutex);

do {

    lock (&mutex);
        critical section
    unlock (&mutex);

        remainder section
} while(TRUE);
```

```
void init_lock (int *mutex) {
    *mutex = 0;
}

void lock (int *mutex) {
    int key = TRUE;
    do {
        Swap(&key, mutex);
    }while(key == TRUE);
}

void unlock (int *mutex) {
    *mutex = 0;
}
```

Fairness not guaranteed by any implementation !

Bounded Waiting Solution

Process i = 0

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != i) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Process i = 1

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != I) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Cycle = 0

lock=FALSE, key=FALSE, waiting[0]=0, waiting[1]=0

Bounded Waiting Solution

Process i = 0

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != i) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Process i = 1

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != I) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Cycle = 1

lock=FALSE, key=FALSE, waiting[0]=1, waiting[1]=1

Bounded Waiting Solution

Process i = 0

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != i) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Process i = 1

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != I) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Cycle = 2

lock=FALSE, key=TRUE, waiting[0]=1, waiting[1]=1

Bounded Waiting Solution

Process i = 0

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != i) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Process i = 1

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != I) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Cycle = 3

lock=FALSE, key=TRUE, waiting[0]=1, waiting[1]=1

Bounded Waiting Solution

Process i = 0

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != i) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Process 0 wins the race

Process i = 1

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != I) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Cycle = 4

lock=TRUE, key=FALSE, waiting[0]=1, waiting[1]=1

Bounded Waiting Solution

Process i = 0

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != i) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Process i = 1

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != I) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Cycle = 5

lock=TRUE, key=TRUE, waiting[0]=0, waiting[1]=1

Bounded Waiting Solution

Process i = 0

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != i) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Process i = 1

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != I) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Cycle = 6

lock=TRUE, key=TRUE, waiting[0]=0, waiting[1]=1

Bounded Waiting Solution

Process i = 0

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != i) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

j = 1

Process i = 1

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != I) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Cycle = 7

lock=TRUE, key=TRUE, waiting[0]=0, waiting[1]=1

Bounded Waiting Solution

Process i = 0

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != i) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Process i = 1

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != I) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Cycle = 8

lock=TRUE, key=TRUE, waiting[0]=0, waiting[1]=1

Bounded Waiting Solution

Process i = 0

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != i) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Process i = 1

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != I) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Cycle = 9

lock=TRUE, key=TRUE, waiting[0]=0, waiting[1]=1

Bounded Waiting Solution

Process i = 0

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != i) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Process i = 1

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != I) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Cycle = 10

lock=TRUE, key=TRUE, waiting[0]=0, waiting[1]=0

Bounded Waiting Solution

Process i = 0

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != i) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Process i = 1

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != I) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Cycle = 11

lock=TRUE, key=TRUE, waiting[0]=0, waiting[1]=0

Bounded Waiting Solution

Process i = 0

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != i) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Process i = 1

```
do{
    waiting[i] = TRUE;
    key = TRUE;
    while(waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;

    // Critical Section

    j = (i + 1) % n;
    while ((j != I) && !waiting[j])
        j = (j+1) % n;

    if (j == i )
        lock = FALSE;
    else
        waiting[j] = FALSE;
    // Remainder Section
} while (TRUE);
```

Cycle = 12

lock=TRUE, key=TRUE, waiting[0]=0, waiting[1]=0

Semaphores

- Another solution to the critical section problem
  - higher-level than using direct ISA instructions
  - similar to locks, but semantics are different
- Semaphore (simple definition)
  - is an integer variable
  - only accessed via *init( ), wait( ), and signal( )* operations
  - all semaphore operations are atomic
- Binary semaphores
  - value of semaphore can either be 0 or 1
  - used for providing mutual exclusion
- Counting semaphore
  - can have any integer value
  - access control to some finite resource

Mutual Exclusion Using Semaphores

```
int S;
sem_init (&S);

do {

    wait (&S);
        // critical section
    signal (&S);

        // remainder section

} while(TRUE);
```

```
void sem_init (int *S)
{
    *S = 0;
}

void wait (int *S)
{
    while (*S <= 0)
        ;
    *S-- ;
}

void signal (int *S)
{
    *S++;
}
```

Problem With All Earlier Solutions ?

- Busy waiting or spinlocks
  - process may loop *continuously* in the entry code to the critical section
- Disadvantage of busy waiting
  - waiting process holds on to the CPU during its time-slice
  - does no useful work
  - does not let any other process do useful work
- Multiprocessors still do use busy-waiting solutions.

Semaphore with no Busy waiting

- Associate waiting queue with each semaphore
- Semaphore (no busy waiting definition)
  - integer value
  - waiting queue

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

Operations on Semaphore with no Busy waiting (2)

- Wait ( ) operation

```
wait (semaphore *S) {
    S–>value–– ;
    if (S–>value < 0) {
        // add process to
        // S –>list

        block ( );
    }
}
```

block ( ) suspends the process that invokes it.

- Signal ( ) operation

```
signal (semaphore *S) {
    S–>value++ ;
    if (S–>value >= 0) {
        // remove process P
        // from S –>list

        wakeup (P);
    }
}
```

wakeup ( ) resumes execution of the blocked process P.

Atomic Implementation of Semaphore Operations

- Guarantee that *wait* and *signal* operations are atomic
  - critical section problem again ?
  - how to ensure atomicity of *wait* and *signal* ?
- Ensuring atomicity of *wait* and *signal*
  - implement semaphore operations using hardware solutions
  - uniprocessors – enable/disable interrupts
  - multiprocessors – using spinlocks around *wait* and *signal*
- Did we really solve the busy-waiting problem
  - NO!
  - but we shifted its location, only busy-wait around *wait* and *signal*
  - *wait* and *signal* are small routines

Deadlock

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

P0	*P1*
wait (S);	wait (Q);
wait (Q);	wait (S);
.	.
.	.
.	.
signal (S);	signal (Q);
signal (Q);	signal (S);

Starvation and Priority Inversion

- Indefinite blocking or starvation
  - process is not deadlocked
  - but is never removed from the semaphore queue
- Priority inversion
  - lower-priority process holds a lock needed by higher-priority process !
  - assume three processes L, M, and H
  - priorities in the order L < M < H
  - L holds shared resource R, needed by H
  - M preempts L, H needs to wait for both L and M !!
  - solutions
    - only support at most two priorities
    - *priority inheritance protocol* – lower priority process accessing shared resource inherits higher priority

Problem Solving Using Semaphores

- Bounded-buffer problem
- Readers-Writers problem

Bounded-Buffer Problem

- Problem synopsis
  - a set of resource buffers shared by producer and consumer threads
    - buffers are shared between producer and consumer
  - producer inserts resources into the buffers
    - output, disk blocks, memory pages, processes, etc.
  - consumer removes resources from the buffer set
    - whatever is generated by the producer
  - producer and consumer execute asynchronously
    - no serialization of one behind the other
    - CPU scheduler determines what run when
- *Ensure data (buffer) consistency*
  - consumer should see each produced item *at least* once
  - consumer should see each produced item *at most* once

Bounded Buffer Problem (2)

- Solution employs three semaphores
- *mutex*
  - allow exclusive access to the buffer pools
  - mutex semaphore, initialized to 1
- *empty*
  - count number of empty buffers
  - counting semaphore, initialized to n (the total number of available buffers)
- *full*
  - count number of full buffers
  - counting semaphore, initialized to 0

Bounded Buffer Problem (3)

```
Semaphore bool mutex;

Semaphore int full, empty;
```

Producer

```
do {
    Produce new resource
    wait (empty);
    wait (mutex);
    Add resource to next buffer
    signal (mutex);
    signal (full);
} while (TRUE);
```

Consumer

```
do {
    wait (full);
    wait (mutex);
    Remove resource from buffer
    signal (mutex);
    signal (empty);
    Consume resource
} while (TRUE);
```

Readers – Writers Problem

- Problem synopsis
  - an object shared among several threads
  - some threads only read the object (Readers)
  - some threads only write the object (Writers)
- Problem is to ensure data consistency
  - multiple readers can access the shared resource simultaneously
  - only one writer should update the object at a time
  - readers should not access the object as it is being updated
  - additional constraint
    - readers have priority over writers
    - easier to implement

Readers – Writers Problem (2)

- We use two semaphores
- *mutex*
  - ensure mutual exclusion for the readcount variable
  - mutex semaphore, initialized to 1
- *wrt*
  - ensure mutual exclusion for writers
  - ensure mutual exclusion between readers and writer
  - mutex semaphore, initialized to 1

Readers – Writers Problem (3)

```
semaphore bool mutex, wrt;
int readcount;
```

Writer

```
do {
    wait (wrt);
    . . . .
     write object resource
    . . . .
    signal (wrt);
} while (TRUE);
```

Reader

```
do {
    wait (mutex);
    readcount++;
    if (readcount == 1)
        wait (wrt);
    signal (mutex);
    read from object resource
    wait (mutex);
    readcount––;
    if (readcount == 0)
        signal (wrt);
    signal (mutex);
} while (TRUE);
```

Semaphore – Summary

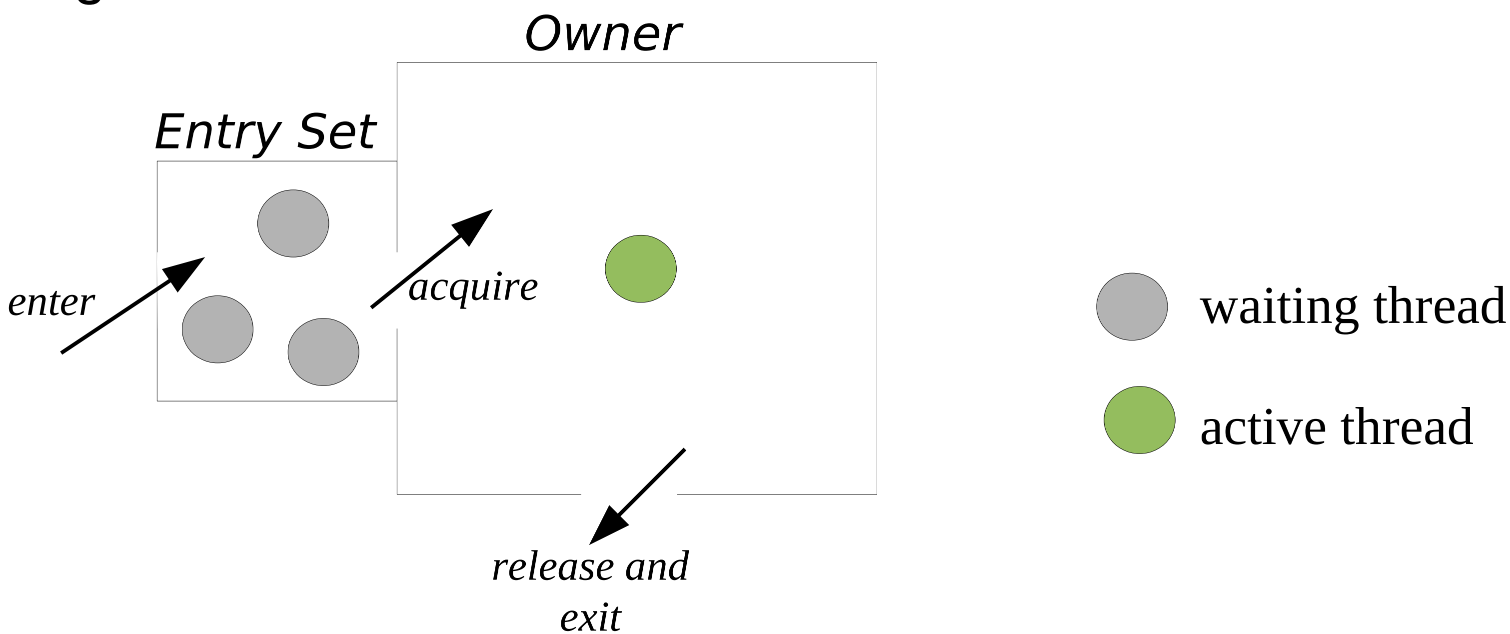
- Semaphores can be used to solve any of the traditional synchronization problems
- Drawbacks of semaphores
  - semaphores are essentially shared global variables
    - can be accessed from anywhere in a program
  - semaphores are very low-level constructs
    - no connection between semaphore and data controlled by a semaphore
    - difficult to use
  - used for both critical section (mutual exclusion) and coordination (scheduling)
  - provides no control of proper usage
    - user may miss a *wait* or *signal*, or replace order of *wait,* and *signal*
- The solution is to use programming-language level support.

Monitors

- Monitor is a programming language construct that controls access to shared data
  - synchronization code added by the compiler
  - synchronization enforced by the runtime
- Monitor is an abstract data type (ADT) that encapsulates
  - shared data structures
  - procedures that operate on the shared data structures
  - synchronization between the concurrent procedure invocations
- Protects the shared data structures inside the monitor from outside access.
- Guarantees that monitor procedures (or operations) can only legitimately update the shared data.

Monitor Semantics for Mutual Exclusion

- Only one thread can execute any monitor procedure at a time.
- Other threads invoking a monitor procedure when one is already executing some monitor procedure must wait.
- When the active thread exits the monitor procedure, one other waiting thread can enter.



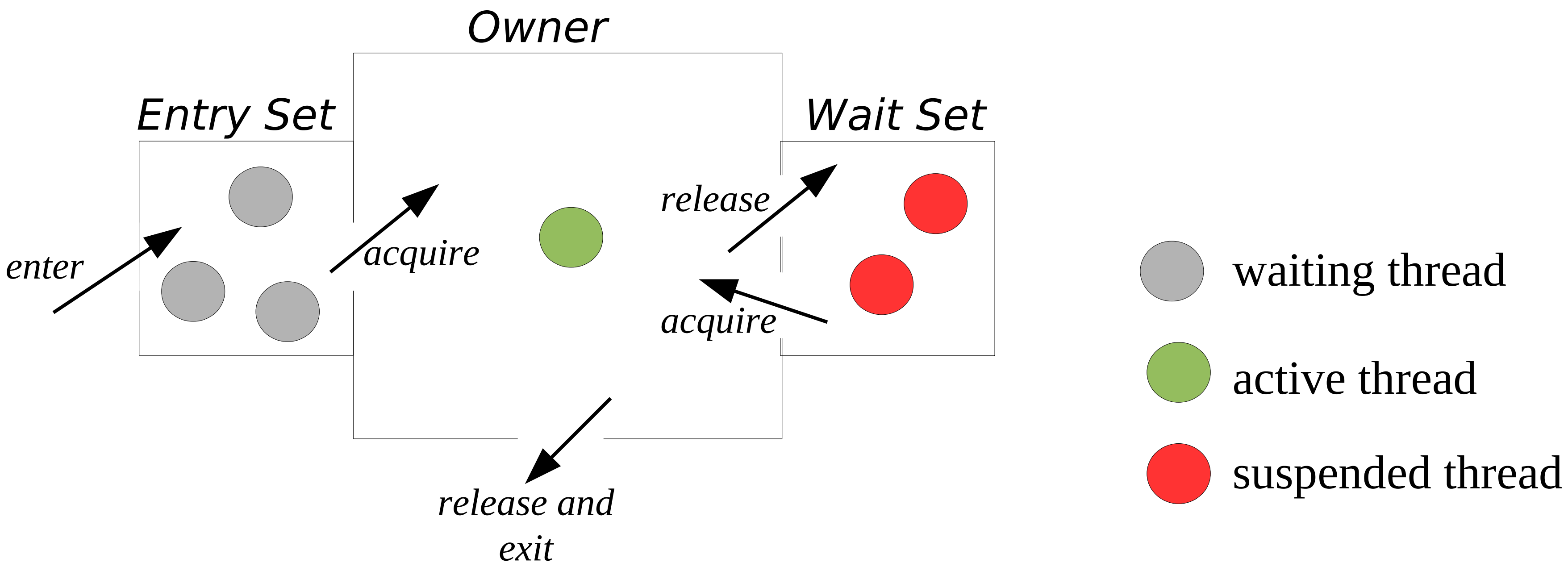
Monitor for Mutual Exclusion

```
Monitor Account {
    double balance;

    double withdraw (amount) {
        balance = balance –
                      amount ;
        return balance;
    }
}
```

1	withdraw (amount) { balance = balance – amount;
2	withdraw (amount)
3	withdraw (amount)
1	return balance; } (*release lock and exit)*
3	balance = balance – amount; return balance; } (*release lock and exit)*
2	balance = balance – amount; return balance; } (*release lock and exit)*

Monitor for Coordination

- What if a thread needs to wait inside a monitor
  - waiting for some resource, like in producer-consumer relationship
  - monitor with condition variables.
- Condition variables provide mechanism to wait for events
  - resource available, no more writers, etc.



Condition Variable Semantics

- Condition variables support two operations
  - wait – release monitor lock, and suspend thread
    - condition variables have wait queues
  - signal – wakeup one waiting thread
    - if no process is suspended, then *signal* has no affect
- Signal semantics
  - Hoare monitors (original)
    - *signal* immediately switches from the caller to the waiting thread
    - waiter's condition is guaranteed to hold when it continues execution
  - Mesa monitors
    - waiter placed on ready queue, signaler continues
    - waiter's condition may no longer be true when it runs
  - Compromise - signaler immediately leaves monitor, waiter resumes operation

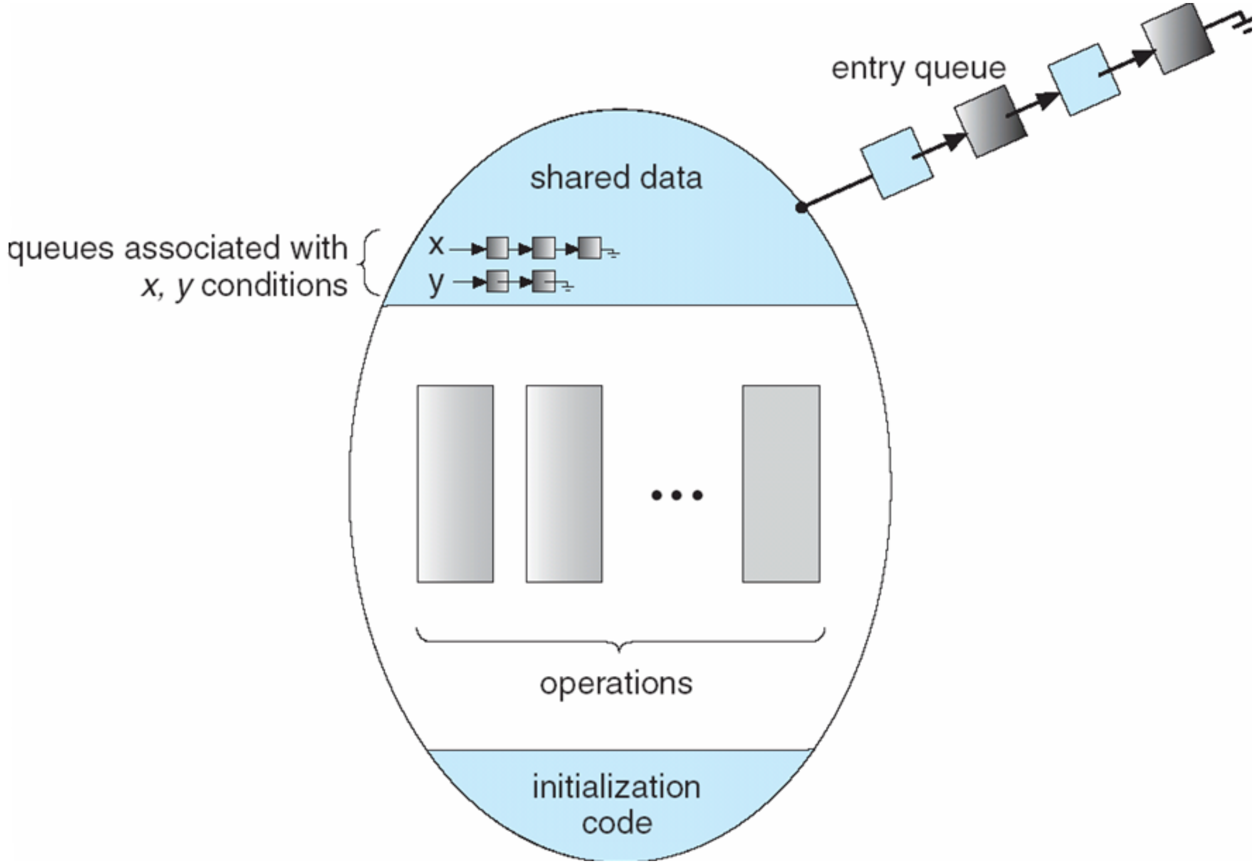
Bounded Buffer Using Monitors

```
Monitor bounded_buffer {
    Resource buffer[N];
    // condition variables
    Condition empty, full;

    void producer (Resource R) {
        while (buffer full)
            empty.wait( );
        // add R to buffer array
        full.signal( );
    }

    Resource consumer ( ) {
        while (buffer empty)
            full.wait( );
        // get Resource from buffer
        empty.signal( );
        return R;
    }
} // end monitor
```

Condition Variables

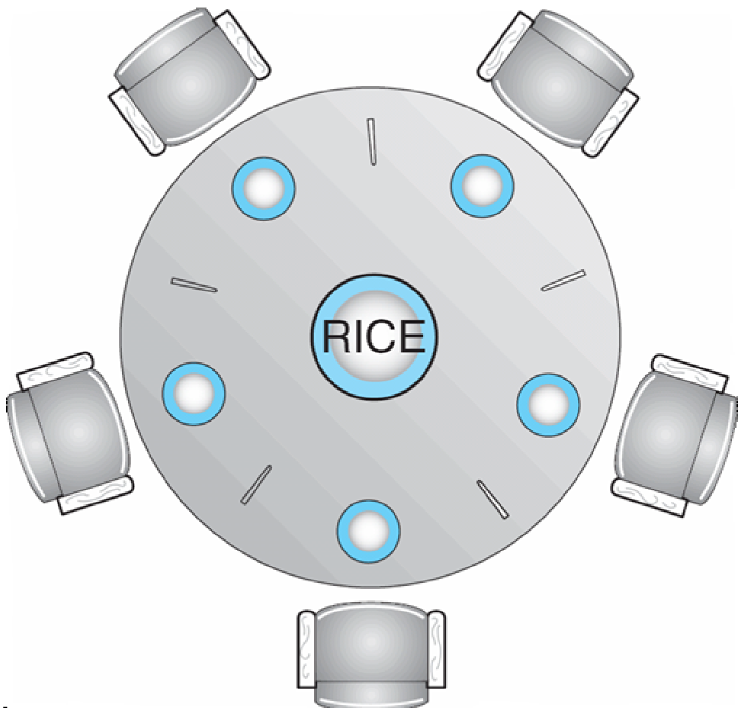
- Condition variables are not booleans
  - "if (condition_variable) then … " is not logically correct
  - wait( ) and signal( ) are the only operations that are correct
- Condition variable != Semaphores
  - they have very different semantics
  - each can be used to implement the other
- *Wait ( )* semantics
  - wait blocks the calling thread, and gives up the lock
  - Semaphore::wait just blocks the calling thread
  - only monitor operations can call wait ( ) and signal ( )
- *Signal ( )* semantics
  - if there are no waiting threads, then the signal is lost
  - Semaphore::signal just increases global variable count, allowing entry to future thread

Monitor with Condition Variables



Dining Philosophers Problem

- Represents need to allocate several resources among several processes in a deadlock-free and starvation-free manner.
- Problem synopsis
  - 5 philosophers, circular table
  - 2 states, *hungry* and *thinking*
  - 5 single chopsticks
  - *hungry,* pick up two chopsticks
    - right and left
  - may only pick up one stick at a time
  - eat when have both sticks
- Problem definition
  - allow each philosopher to eat and think without deadlocks and starvation



Dining Philosophers Problem (2)

- Restriction on the problem
  - only pick chopsticks if both are available
- Problem solution
  - use three states, *thinking, hungry, eating*
  - condition variable for each philosopher
    - delay if hungry but waiting for chopsticks
  - invoke monitor operations in the following sequence

```
DiningPhilosophers.pickup (i);
    ......
     // eat
    .......
DiningPhilosophers.putdown (i);
```

Solution to Dining Philosophers

```
Monitor DP
{
   enum { THINKING; HUNGRY,
 EATING) state [5] ;
   condition self [5];

   void pickup (int i)
   {
      state[i] = HUNGRY;
      test(i);
      if (state[i] != EATING)
         self [i].wait;
   }

   void putdown (int i)
   {
      state[i] = THINKING;
      // test neighbors
      test((i + 4) % 5);
      test((i + 1) % 5);
   }

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

   initialization_code() {
      for (int i = 0; i < 5; i++)
         state[i] = THINKING;
   }

} // end monitor
```

OS Implementation Issues

- How to wait on a lock held by another thread ?
  - sleeping or spin-waiting
- Overhead of spin-waiting
  - a spinning thread occupies the CPU; slows progress of all other threads, including the one holding the lock
- Overhead of sleeping
  - issue a wait and sleep; send signal to sleeping thread; wakeup thread; multiple context switches
- Spin-waiting is used on
  - multiprocessor systems
  - when the thread holding the lock is the one running
  - locked data is only accessed by short code segments

OS Implementation Issues (2)

- Reader-writer locks
  - used when shared data is read more often
  - more expensive to set up than mutual exclusion locks
- Non-preemptive kernel
  - process in kernel mode cannot be preempted
  - used in Linux on single processor machines
  - uses `preempt_disable()` and `preempt_enable()`system calls
  - spin-locks, semaphores used on multiprocessor machines

Atomic Transactions

- Transaction – collection of instructions that perform a single logical function
- Atomicity – execute transaction as one uninterruptible unit
- Mutual exclusion – execute critical sections atomically
  - what happens if system fails during a transaction ?
  - how to preserve atomicity in the possibility of system failures ?
- Committed – transaction has completed successfully
- Aborted – transaction has failed
  - rollback the transaction to previous consistent state, called recovery
- Strategies
  - log-based recovery
  - checkpoints

Concurrent Atomic Transactions

- Serializability – execution of multiple concurrent transactions is equivalent to their execution in an arbitrary order

T_0	T_1
read(A)	
write(A)	
read(B)	
write(B)	
	read(A)
	write(A)
	read(B)
	write(B)

T_0	T_1
read(A)	
write(A)	
	read(A)
	write(A)
read(B)	
write(B)	
	read(B)
	write(B)