Synchronization

The Issue...

- Concurrent access to shared data may result in data inconsistency.
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes.

Bounded Buffer Revisited

- Previous, unsynchronized, solution always left one entry empty.
  - Only the producer could access that entry, so no need for synchronization.
- What if we want to use every entry?
- Introduce a `count` variable that tracks the number of full entries.

Producer Code

```
while (true) {
     /*  produce an item and put in nextProduced  */
     while (count == BUFFER_SIZE)
          ; // do nothing
     buffer [in] = nextProduced;
     in = (in + 1) % BUFFER_SIZE;
     count++;
}
```

Consumer Code

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

Race Condition

- In hardware:
  - `count++` could be implemented as:

```
register1 = count
register1 = register1 + 1
count = register1
```

  - `count--` could be implemented as:

```
register2 = count
register2 = register2 - 1
count = register2
```

Race Condition

- Consider this execution interleaving with "count = 5" initially:

S0: producer execute register1 = count {register1 = 5}

S1: producer execute register1 = register1 + 1 {register1 = 6}

S2: consumer execute register2 = count {register2 = 5}

S3: consumer execute register2 = register2 - 1 {register2 = 4}

S4: producer execute count = register1 {count = 6 }

S5: consumer execute count = register2 {count = 4}

Critical Sections

- A region of code in which a process could access or change shared data.
- The critical section problem:
  - Design a protocol that allows a set of processes to cooperate safely.
- Structure of cooperating code:

```
{
   ENTRY SECTION     //Request access to critical section.
   CRITICAL SECTION
   EXIT SECTION      //Protocol code to exit critical section.
   REMAINDER SECTION //Do the other work this process does.
}
```

Solution Requirements

- Mutual exclusion – At most one process in a critical section.
- Progress – No process in a remainder section can block another process.
- Bounded Waiting – It should not be possible for a process to wait forever in its entry section.
  - I.e. there is a limit on the number of times other processes can enter their critical sections after a process has requested access to its own.
  - Assume that all processes execute at non-zero speed.
  - No assumption about relative speed of processes.

Foolproof Solution

- On a single processor system just turn off interrupts before entering critical section.
- Turn them back on when exiting.
- This approach is not acceptable for user level code.
  - Why not?
- It is often used for kernel code.

Naive Proposal: Lock Variable

```
while (lock == 1) {;}
lock = 1;
CRITICAL SECTION
lock = 0;
```

- Does it work?

(Note, some of this discussion is based on
Tenenbaum's Modern Operating Systems, 2001)

Another Naive Proposal: Strict Alteration

<u>Process 0</u>

```
while (turn != 1) {;}
CRITICAL SECTION
turn = 1;
REMAINDER SECTION
```

<u>Process 1</u>

```
while (turn != 0) {;}
CRITICAL SECTION
turn = 0;
REMAINDER SECTION
```

- `turn` is initialized to 0.
- Guarantees mutual exclusion!
- Any problems?

Another Naive Proposal: Strict Alteration

Process 0

```
while (turn == 1) {;}
CRITICAL SECTION
turn = 1;
REMAINDER SECTION
```

Process 1

```
while (turn == 0) {;}
CRITICAL SECTION
turn = 0;
REMAINDER SECTION
```

- Any problems?
  - Imagine the situation...
  - Both processes are in their remainder section.
  - It is 0's turn.
  - 1 exits its remainder section, and is ready to run.
  - Violates the progress requirement.

Peterson's Solution (1981)

- Two shared data items:

```
int turn; //Who's turn is it?

boolean flag[2]; //Readiness state for each process.
```

```
{
   flag[i] = true;
   turn = j;
   while (flag[j] == true && turn == j){;}

   CRITICAL SECTION

   flag[i] = false;

   REMAINDER SECTION
}
```

Synchronization Hardware

- Modern machines provide special atomic hardware instructions.
    - Atomic = non-interruptable
  - Either test memory word and set value.
  - Or swap contents of two memory words.

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

```
void Swap (bool *a, bool *b) {
      bool tmp = *a;
      *a = *b;
      *b = tmp;
}
```

Test and Set Mutual Exclusion

```
{
        while ( TestAndSet (&lock )) {;}
        CRITICAL SECTION
        lock = FALSE
        REMAINDER SECTION
}
```

- `lock` is initialized to false.
- Guarantees mutual exclusion.
- Where does it fail?

Test and Set Mutual Exclusion

```
{
        while ( TestAndSet (&lock )) {;}
        CRITICAL SECTION
        lock = FALSE
        REMAINDER SECTION
}
```

- Where does it fail?
  - Bounded waiting.
- The book presents a solution that meets all three conditions.
- It's complicated.

Busy Waiting

- All of the solutions so far have included tight while loops.
  - Busy waiting, spin locks.
  - Why is that a problem?
- The solutions so far have also been complicated for the programmer.
- What is the solution?

Semaphores!

- A semaphore is a counter.
- Two operations can be applied:
  - `wait(S)` – if S is less than or equal to zero, wait.
    - When done waiting decrement S.
  - Otherwise, just keep going.
    - Immediately decrement S.
  - `signal(S)` – Increment S. Give waiting processes a chance to wake up.
- Invented by Dijkstra in '65.
- Wait was called P, signal was called V.

Semaphore Applications: Mutual Exclusion

- Let at most three processes enter a critical region:
  - Initialize `S = 3`.

```
{
    wait(S)
    CRITICAL SECTION
    signal(S)
}
```

- A mutex is a binary semaphore.
  - Sufficient for mutual exclusion.

Semaphore Applications: Guaranteed Ordering

- Make sure that S_1 takes place before S_2:
  - Initialize `SEM = 0`

```
{
    S1
    signal(SEM)
}
```

```
{
    wait(SEM)
    S2
}
```

Semaphore Implementation

A semaphore may be implemented as a counter and a list of waiting processes:

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

```
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 to S->list
    wakeup(P);
  }
}
```

- Is this implementation OK?

Semaphore Implementation

- No. Modifying and checking the semaphore data needs to be atomic.
- Two possibilities:
  - Turn off interrupts.
  - Spin locks.
- Is there anything special we need to do to ensure bounded waiting?

Semaphore Deadlock

- 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)`

Producer Consumer Solution Using Semaphores

- N entries, each can hold one item.
- Semaphore `mutex` initialized to the value 1.
- Semaphore `full` initialized to the value 0.
- Semaphore `empty` initialized to the value N.

Producer Consumer Solution Using Semaphores

Producer

```
while (true)  {
     // produce an item
     wait (empty);
     wait (mutex);
     // add item to the buffer
     signal (mutex);
     signal (full);
}
```

Consumer

```
while (true)  {
     wait (full);
     wait (mutex);
     // remove item from the buffer
     signal (mutex);
     signal (empty);
     // consume the item
}
```

- Why not just use the mutex?

Readers Writers Problem

- A data set is shared among a number of concurrent processes.
  - Readers – only read the data set; they do not perform any updates.
  - Writers – can both read and write.
- Problem – allow multiple readers to read at the same time. Only one writer at a time.

Readers-Writers Solution

- Shared Data
  - Data set
  - Semaphore `mutex` initialized to 1.
  - Semaphore `wrt` initialized to 1.
  - Integer `readcount` initialized to 0.

Readers-Writers Solution

<u>Writer</u>

```
while (true) {
     wait (wrt);
     // writing is performed
     signal (wrt);
}
```

- Any possibility of starvation?
  - (Violations of bounded waiting.)

<u>Reader</u>

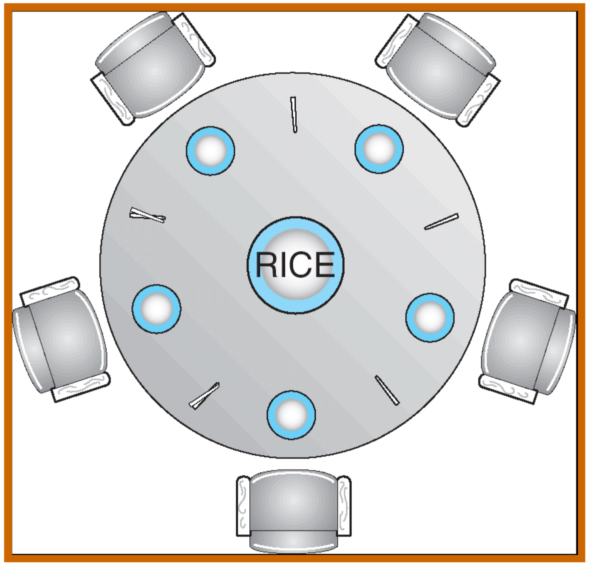
```
while (true) {
     wait (mutex) ;
     readcount++ ;
     if (readcount == 1)  wait (wrt) ;
     signal (mutex)

     // reading is performed

     wait (mutex) ;
     readcount-- ;
     if (readcount  == 0)  signal (wrt) ;
     signal (mutex) ;
}
```

Readers-Writers Solution

- This is a solution to the *first* readers-writers problem.
  - No reader will be kept waiting unless a writer has already been granted access.
- The *second* readers-writers problem requires that no new readers may be granted access if a writer is waiting.
- Some system provide built in reader-writer locks.
  - Parameter determines what sort of lock is obtained.
  - Linux kernel has these.

Dining Philosophers Problem

- Five philosophers, five chopsticks
- Each philosopher:
  - Picks up one chopstick.
  - Picks up another.
  - Eats a while.
  - Puts down a chopstick.
  - Puts down the other.
  - Thinks for a while.
  - Repeats.



- The problem: how to avoid starvation and deadlock.

Naive Solution

- One semaphore for each chopstick.

```
while (true) {
    wait(chopstick[i]);
    wait(chopstick[ (i+1) % 5]);
    //EAT
    signal(chopstick[i]);
    signal(chopstick[ (i+1) % 5]);
    //THINK
}
```

- What is the problem?
- Any better ideas?

General Problems With Semaphores

- Coding with semaphores is error prone.
  - `signal (mutex) ...  wait (mutex)`
  - `wait (mutex)  ...  wait (mutex)`
  - Omitting of `wait(mutex)` or `signal(mutex)` (or both)
- The errors are extremely hard to catch.
- Not easily reproducible.

Monitors

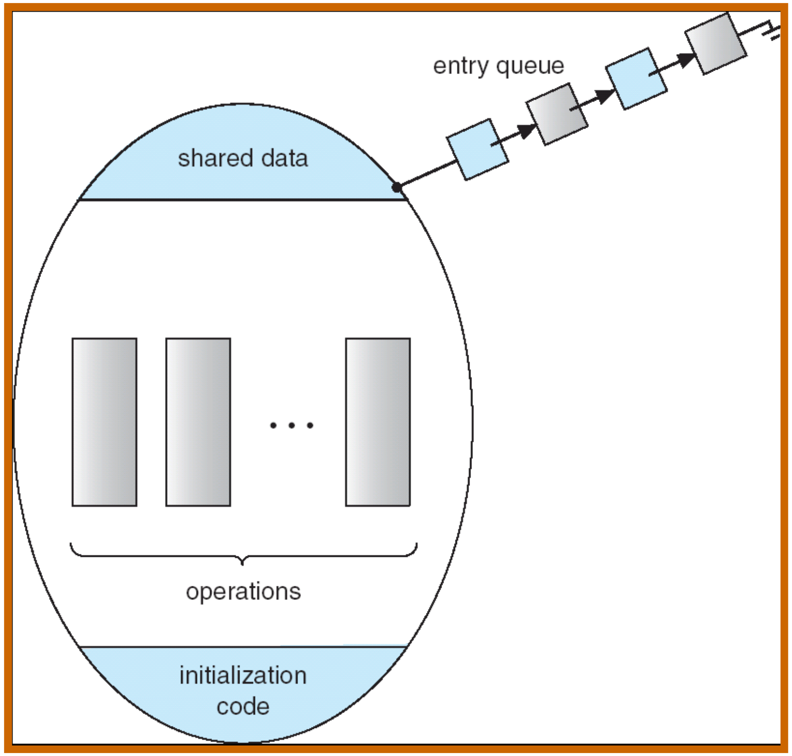
- A programming language construct designed to make synchronization easier.
- Implemented in C#, Java.
- Only one process at a time can be executing monitor code.
- Only monitor code can access local monitor data.
- Very object orientedish.

Monitors

"Syntax"

```
monitor monitor-name
{
    // shared variable declarations
    procedure P1 (...) { ... }
    procedure Pn (...) { ... }
    initializationCode(...) {...}
}
```

Schematic



A Problem

- Monitors are easy to use, but there is a problem...
- Imagine that in the producer consumer problem, we have a monitor procedure for add.
- What does the procedure do when it finds that the buffer is full?

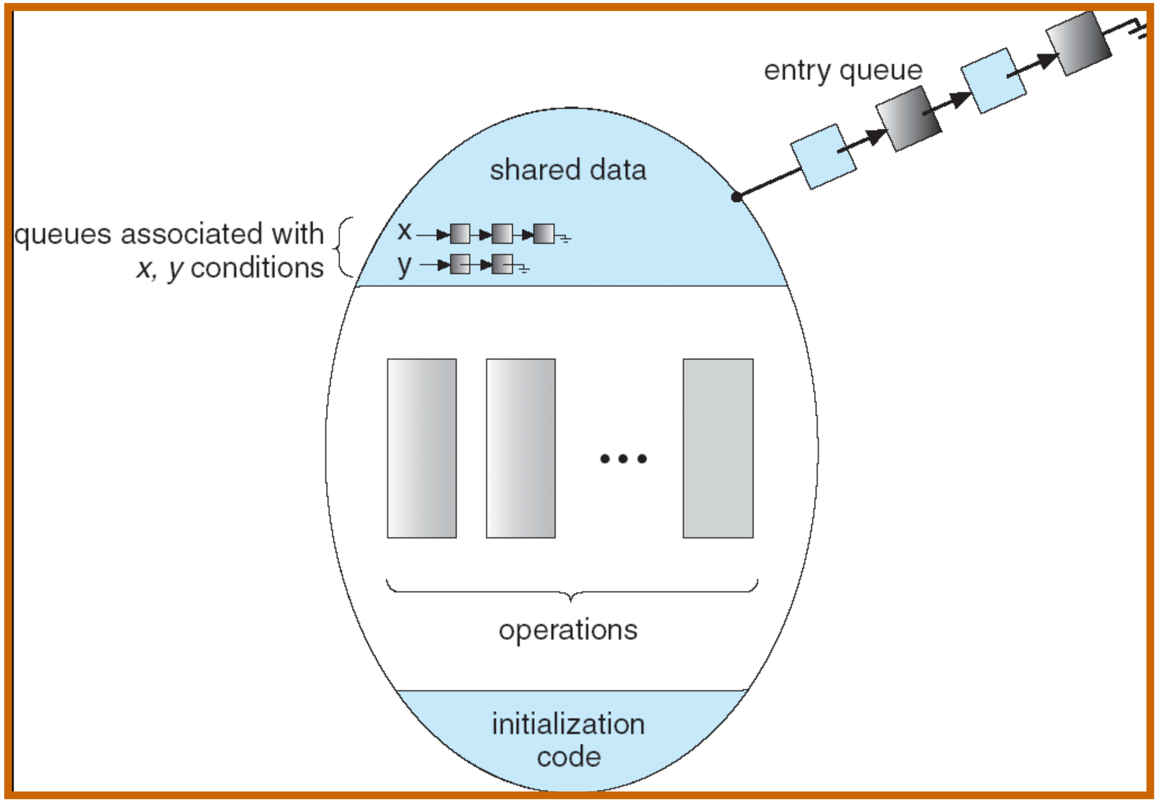
Condition Variables

- Condition variables: `condition x, y;`
- Two operations on a condition variable:
  - `x.wait()` – a process that invokes the operation is suspended.
  - `x.signal()` – resumes one of processes (if any) that invoked `x.wait()`.
- Something like a non-counting semaphore.

Producer Consumer With Monitors

```
monitor producer-consumer {
    condition empty, full;
    int count=0;

    void insert(item) {
        if (count == MAX) wait(empty);
        insert_item(item);
        count = count+1;
        signal(full);
    }

    int remove() {
        int ret_val;
        if (count == 0) wait(full);
        ret_val = remove_item();
        count = count-1
        signal(empty);
        return ret_val;
    }
}
```

Schematic


entry queue
shared data
queues associated with
x, y conditions
x
y
operations
initialization
code

What Exactly Should Wait/Signal Do?

- Only one process can be in a monitor at a time.
- When a signal occurs and a process is waiting, who gets to stay?
- Simplest solution is to require a signal to be the final instruction in a procedure.

Dining Philosophers Solution

```
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 left and right neighbors
      test((i + 4) % 5);
      test((i + 1) % 5);
   }
```

Dining Philosophers Solution

```
    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;
        }
    }
}
```

Dining Philosophers Solution

- Philosopher i does the following:

```
DP.pickup(i);

EAT

DP.putdown(i);
```

Java Monitors

- Any method can be declared “synchronized”.
- Every object has a single lock.
- Every call to a synchronized method must wait for the lock.

Synchronization Examples

- The book talks about the synchronization mechanisms provided by:
  - Solaris
  - Windows XP
  - Linux
  - pthreads
- Check it out.

Atomic Transactions

- Assures that operations happen as a single logical unit of work, in its entirety, or not at all.
- Related to field of database systems.
- Challenge is assuring atomicity despite computer system failures.
- We might take a closer look at this material when we get to file systems...

Atomic Transactions

- Transaction - collection of instructions or operations that performs single logical function.
  - Here we are concerned with changes to stable storage – disk
  - Transaction is series of read and write operations
  - Terminated by commit (transaction successful) or abort (transaction failed) operation.
  - Aborted transaction must be rolled back to undo any changes it performed.

Acknowledgments

- Portions of these slides are taken from Power Point presentations made available along with:
  - Silberschatz, Galvin, and Gagne. Operating System Concepts, Seventh Edition.
- Original versions of those presentations can be found at:
  - http://os-book.com/