Background

- 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 problem (also called producer consumer problem)

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.

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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

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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.

Race Condition

- **Race condition**: The situation where several processes access – and manipulate shared data concurrently. The final value of the shared data depends upon which process finishes last.

- To prevent race conditions, concurrent processes must be **synchronized**.

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.

Mutual Exclusion: Conditions for Solution

Four conditions to provide mutual exclusion

1. No two processes simultaneously in critical region
2. No assumptions made about speeds or numbers of CPUs
3. No process running outside its critical region may block another process
4. No process must wait forever to enter its critical region

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Initial Attempts to Solve Problem

- Only 2 processes, P_0 and P_1
- General structure of process P_i (other process P_j)

do {
  $\boxed{\textit{entry section}}$
    critical section
  $\boxed{\textit{exit section}}$
    reminder section
} **while (1)**;

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

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Algorithm 1

- Shared variables:
  - **int turn**;
    initially **turn = 0**
  - **turn = i** $\Rightarrow$ P_i can enter its critical section
- Process P_i

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

- Satisfies mutual exclusion, but not progress

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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.

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Algorithm 3

- Combined shared variables of algorithms 1 and 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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Solution to Critical Section Problem

- Peterson’s solution works for two processes
- N-process solution: Bakery algorithm
  - Will discuss in next class
- Both Peterson’s solution and Bakery algorithm are software solutions, i.e. no hardware support needed

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Synchronization Hardware

- Test and modify the content of a word atomically

.

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

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Mutual Exclusion with Test-and-Set

- Shared data:

```
boolean lock = false;
```

- Process P_i

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

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Semaphores

- Synchronization tool that does not require busy waiting.
  - Uses ***blocking synchronization***
- can only be accessed via two indivisible (atomic) operations: wait() and signal()
- Each semaphore has an integer value and a queue associated with it

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**.

Implementation

- Semaphore operations 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);
        }
```

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Critical Section of *n* Processes

- Shared data:

  semaphore mutex; // initially *mutex* = 1

- Process *Pi:*

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

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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
⋮	⋮
code	code
A	*wait*(*flag*)
signal(*flag*)	*B*

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.

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);
```

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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);
```

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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):
```

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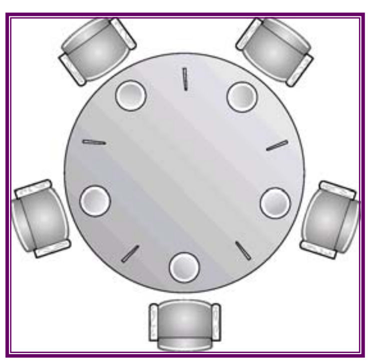
Dining-Philosophers Problem



- Shared data

semaphore chopstick[5];

Initially all values are 1

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Dining-Philosophers Problem: A non-solution

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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High-level synchronization mechanisms

- Semaphores are a very powerful mechanism for process synchronization, but they are a *low-level* mechanism
- Several high-level mechanisms that are easier to use have been proposed
  - Monitors
  - Critical Regions
  - Read/Write Locks
- We will study monitors (Java and Pthreads provide synchronization mechanisms based on monitors)
- NOTE: high-level mechanisms easier to use but equivalent to semaphores in power

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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 Pn (…) {
            . . .
        }
        {
            initialization code
        }
}
```


Monitors

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

  condition x, y;

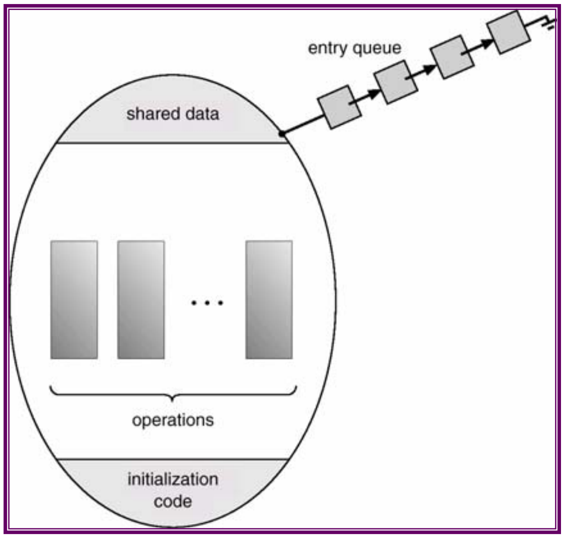
- Condition variable can only be used with the operations **wait** and **signal**.
  - The operation

    x.wait();

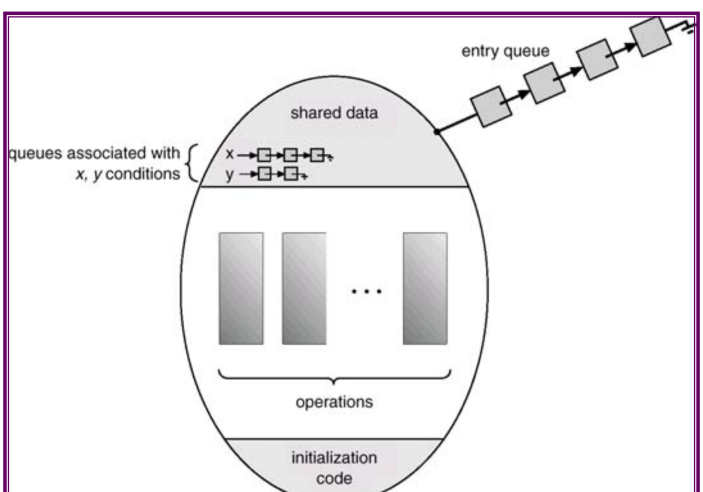
    means that the process invoking this operation is suspended until another process invokes

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

Schematic View of a Monitor



Monitor With Condition Variables



Producer-Consumer using monitors

```
monitor ProducerConsumer
    condition full, empty;
    integer count;
    procedure insert(item: integer);
    begin
        if count = N then wait(full);
        insert_item(item);
        count := count + 1;
        if count = 1 then signal(empty)
    end;
    function remove: integer;
    begin
        if count = 0 then wait(empty);
        remove = remove_item;
        count := count − 1;
        if count = N − 1 then signal(full)
    end;
    count := 0;
end monitor;

procedure producer;
begin
    while true do
    begin
        item = produce_item;
        ProducerConsumer.insert(item)
    end
end;
procedure consumer;
begin
    while true do
    begin
        item = ProducerConsumer.remove;
        consume_item(item)
    end
end;
```


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);
}
```

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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();
      }
}
```

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Cooperating concurrent processes

- Shared Memory
  - Semaphores, mutex locks, condition variables, monitors
  - Mutual exclusion
- Message-passing
  - Pipes, FIFOs (name pipes)
  - Message queues

Synchronization Mechanisms

- Pthreads
  - Semaphores
  - Mutex locks
  - Condition Variables
  - Reader/Writer Locks
- Java
  - Each object has an (implicitly) associated lock and condition variable

Java thread synchronization calls

thread.join(int millisecs)
Blocks the calling thread for up to the specified time until *thread* has terminated.

thread.interrupt()
Interrupts *thread*: causes it to return from a blocking method call such as *sleep()*.

object.wait(long millisecs, int nanosecs)
Blocks the calling thread until a call made to *notify()* or *notifyAll()* on *object* wakes the thread, or the thread is interrupted, or the specified time has elapsed.

object.notify(), object.notifyAll()
Wakes, respectively, one or all of any threads that have called *wait()* on *object*.

Mutual exclusion in Java

```
class Interfere {
   private int data = 0;
   public synchronized void update() {
      data++;
   }
}
```

```
class Interfere {
   private int data = 0;
   public void update() {
         synchronized(this) {
            data++;
         }
   }
}
```

Producer consumer using Java

```
public class ProducerConsumer {
    static final int N = 100;                     // constant giving the buffer size
    static producer p = new producer( );          // instantiate a new producer thread
    static consumer c = new consumer( );// instantiate a new consumer thread
    static our_monitor mon = new our_monitor( );  // instantiate a new monitor
    public static void main(String args[ ]) {
        p.start( );                               // start the producer thread
        c.start( );                               // start the consumer thread
    }
    static class producer extends Thread {
        public void run( ) {                      // run method contains the thread code
            int item;
            while (true) {                        // producer loop
                item = produce_item( );
                mon.insert(item);
            }
        }
        private int produce_item( ) { ... }       // actually produce
    }
    static class consumer extends Thread {
        public void run( ) {                      run method contains the thread code
            int item;
            while (true) {                        // consumer loop
                item = mon.remove( );
                consume_item (item);
            }
        }
        private void consume_item(int item) { ... }    // actually consume
    }
```

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Producer consumer using Java cont'd

```
    static class our_monitor {                    // this is a monitor
        private int buffer[ ] = new int[N];
        private int count = 0, lo = 0, hi = 0; // counters and indices
        public synchronized void insert(int val) {
            if (count == N) go_to_sleep( );       // if the buffer is full, go to sleep
            buffer [hi] = val;                    // insert an item into the buffer
            hi = (hi + 1) % N;                    // slot to place next item in
            count = count + 1;                    // one more item in the buffer now
            if (count == 1) notify( );            // if consumer was sleeping, wake it up
        }
        public synchronized int remove( ) {
            int val;
            if (count == 0) go_to_sleep( );       // if the buffer is empty, go to sleep
            val = buffer [lo];                    // fetch an item from the buffer
            lo = (lo + 1) % N;                    // slot to fetch next item from
            count = count – 1;                    // one few items in the buffer
            if (count == N – 1) notify( );        // if producer was sleeping, wake it up
            return val;
        }
        private void go_to_sleep( ) { try{wait( );} catch(InterruptedException exc) {};}
    }
}
```

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The Reader/Writer Problem

```
class RWbasic {                 // basic read or write (no synch)
  protected int data = 0;  // the "database“
  protected void read() {
          System.out.println("read:  " + data);
    }
  protected void write() {
      data++;
      System.out.println("wrote:  " + data);
    }
}
```

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```
class ReadersWriters extends RWbasic {  // Readers/Writers
    int nr = 0;

    private synchronized void startRead() {
         nr++;
    }

    private synchronized void endRead()  {
          nr--;
          if (nr==0)  notify();  // awaken waiting Writers
    }

   public void read() {
       startRead();
       System.out.println("read:  " + data);
       endRead();
  }
```

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```
   public synchronized void write() {
      while (nr>0)
          try { wait(); }
             catch (InterruptedException ex  {return;}
      data++;
      System.out.println("wrote:  " + data);
      notify();              // awaken another waiting Writer
    }
  }
 class Reader extends Thread {
   int rounds;
   ReadersWriters RW;
   public Reader(int rounds, ReadersWriters RW) {
     this.rounds = rounds;
     this.RW = RW;
  }
  public void run() {
    for (int i = 0; i<rounds; i++) {
       RW.read();
   } } }
```

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```
class Writer extends Thread {
  int rounds;
  ReadersWriters RW;
  public Writer(int rounds, ReadersWriters RW) {
          this.rounds = rounds;    this.RW = RW;
  }
  public void run() {
          for (int i = 0; i<rounds; i++) {
              RW.write();    }
  }
}
class Main {          // driver program -- two readers and one writer
   static ReadersWriters RW = new ReadersWriters();
   public static void main(String[] arg) {
       int rounds = Integer.parseInt(arg[0],10);
       new Reader(rounds, RW).start();
       new Reader(rounds, RW).start();
       new Writer(rounds, RW).start();
    }
}
```

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