Basic Synchronization Principles

Encourage Concurrency

- No widely-accepted concurrent programming languages
- No concurrent programming paradigm
  - Each problem requires careful consideration
  - There is no common model
  - See SOR example on p 189 for one example
- OS tools to support concurrency are, of necessity, low level

Critical Sections

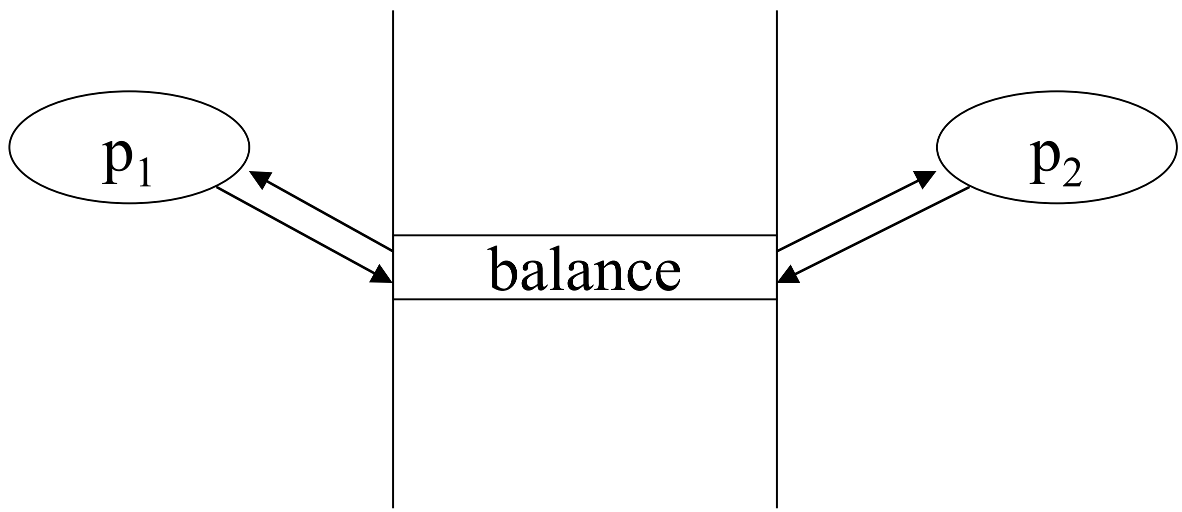
```
shared float balance;
```

Code for p_1

```
 . . .
balance = balance + amount;
 . . .
```

Code for p_2

```
 . . .
balance = balance - amount;
 . . .
```



Critical Sections

```
shared double balance;
```

Code for p_1

```
 . . .
balance = balance + amount;
 . . .
```

Code for p_2

```
 . . .
balance = balance - amount;
 . . .
```

Code for p_1

```
load    R1, balance
load    R2, amount
add     R1, R2
store   R1, balance
```

Code for p_2

```
load    R1, balance
load    R2, amount
sub     R1, R2
store   R1, balance
```

Critical Sections (cont)

- There is a *race* to execute critical sections
- The sections may be different code in different processes
  - Cannot detect with static analysis
- Results of multiple execution are not *determinate*
- Need an OS mechanism to resolve races

Disabling Interrupts

```
shared double balance;
```

Code for p_1

```
disableInterrupts();
balance = balance + amount;
enableInterrupts();
```

Code for p_2

```
disableInterrupts();
balance = balance - amount;
enableInterrupts();
```

Disabling Interrupts

```
shared double balance;
```

Code for p_1

```
disableInterrupts();
balance = balance + amount;
enableInterrupts();
```

Code for p_2

```
disableInterrupts();
balance = balance - amount;
enableInterrupts();
```

- Interrupts could be disabled arbitrarily long
- Really only want to prevent p_1 and p_2 from interfering with one another
- Try using a shared “lock” variable

Using a Lock Variable

```
shared boolean lock = FALSE;
shared double balance;
```

<u>Code for p_1</u>

```
/* Acquire the lock */
  while(lock) ;
  lock = TRUE;
/* Execute critical sect */
  balance = balance + amount;
/* Release lock */
  lock = FALSE;
```

<u>Code for p_2</u>

```
/* Acquire the lock */
  while(lock) ;
  lock = TRUE;
/* Execute critical sect */
  balance = balance - amount;
/* Release lock */
  lock = FALSE;
```

Using a Lock Variable

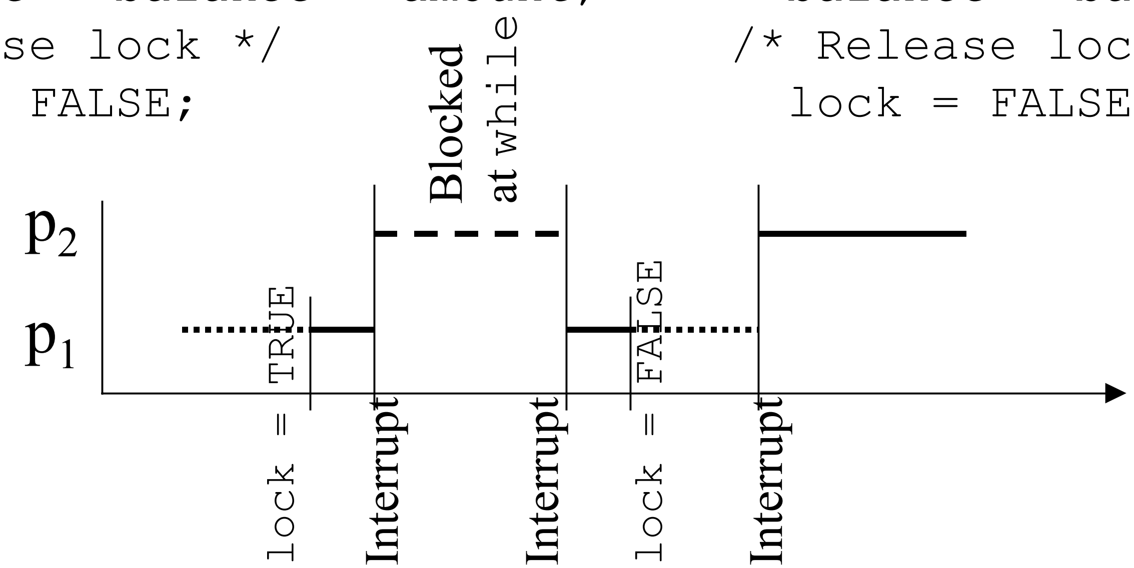
```
shared boolean lock = FALSE;
shared double balance;
```

Code for p_1

```
/* Acquire the lock */
  while(lock) ;
  lock = TRUE;
/* Execute critical sect */
  balance = balance + amount;
/* Release lock */
  lock = FALSE;
```

Code for p_2

```
/* Acquire the lock */
  while(lock) ;
  lock = TRUE;
/* Execute critical sect */
  balance = balance - amount;
/* Release lock */
  lock = FALSE;
```



Using a Lock Variable

```
shared boolean lock = FALSE;
shared double balance;
```

Code for p_1

```
/* Acquire the lock */
  while(lock) ;
  lock = TRUE;
/* Execute critical sect */
  balance = balance + amount;
/* Release lock */
  lock = FALSE;
```

Code for p_2

```
/* Acquire the lock */
  while(lock) ;
  lock = TRUE;
/* Execute critical sect */
  balance = balance - amount;
/* Release lock */
  lock = FALSE;
```

- Worse yet … another race condition …
- Is it possible to solve the problem?

Lock Manipulation

```
enter(lock) {
  disableInterrupts();
/* Loop until lock is TRUE */
  while(lock) {
  /* Let interrupts occur */
    enableInterrupts();
    disableInterrupts();
  }
  lock = TRUE;
  enableInterrupts();
}
```

```
exit(lock) {
  disableInterrupts();
  lock = FALSE;
  enableInterrupts();
}
```

Transactions

- A *transaction* is a list of operations
  - When the system begins to execute the list, it must execute all of them without interruption, or
  - It must not execute any at all
- Example: List manipulator
  - Add or delete an element from a list
  - Adjust the list descriptor, e.g., length

Processing Two Transactions

```
shared boolean lock1 = FALSE;
shared boolean lock2 = FALSE;
shared list L;
```

Code for p_1

```
  . . .
/* Enter CS to delete elt */
  enter(lock1);
  <delete element>;
/* Exit CS */
  exit(lock1);
  <intermediate computation>;
/* Enter CS to update len */
  enter(lock2);
  <update length>;
/* Exit CS */
  exit(lock2);
  . . .
```

Code for p_2

```
  . . .
/* Enter CS to update len */
  enter(lock2);
  <update length>;
/* Exit CS */
  exit(lock2);
  <intermediate computation>
/* Enter CS to add elt */
  enter(lock1);
  <add element>;
/* Exit CS */
  exit(lock1);
  . . .
```

Deadlock

```
shared boolean lock1 = FALSE;
shared boolean lock2 = FALSE;
shared list L;
```

Code for p_1

```
  . . .
/* Enter CS to delete elt */
  enter(lock1);
  <delete element>;
  <intermediate computation>;
/* Enter CS to update len */
  enter(lock2);
  <update length>;
/* Exit both CS */
  exit(lock1);
  exit(lock2);
  . . .
```

Code for p_2

```
  . . .
/* Enter CS to update len */
  enter(lock2);
  <update length>;
  <intermediate computation>
/* Enter CS to add elt */
  enter(lock1);
  <add element>;
       /* Exit both CS */
  exit(lock2);
  exit(lock1);
  . . .
```

Coordinating Processes

- Can synchronize with `FORK`, `JOIN` & `QUIT`
  - Terminate processes with `QUIT` to synchronize
  - Create processes whenever critical section is complete
  - See Figure 8.7
- Alternative is to create OS primitives similar to the `enter`/`exit` primitives

Some Constraints

- Processes p_0 & p_1 enter critical sections
- *Mutual exclusion*: Only one process at a time in the CS
- Only processes competing for a CS are involved in resolving who enters the CS
- Once a process attempts to enter its CS, it cannot be postponed indefinitely
- After requesting entry, only a bounded number of other processes may enter before the requesting process

Some Language

- Let fork(proc, N, arg_1, arg_2, …, arg_N) be a command to create a process, and to have it execute using the given N arguments
- Canonical problem:

```
Proc_0() {
  while(TRUE) {
    <compute section>;
    <critical section>;
  }
}
```

```
proc_1() {
  while(TRUE {
    <compute section>;
    <critical section>;
  }
}
```

```
<shared global declarations>
<initial processing>
fork(proc_0, 0);
fork(proc_1, 0);
```

Assumptions About Solutions

- Memory read/writes are indivisible (simultaneous attempts result in some arbitrary order of access)
- There is no priority among the processes
- Relative speeds of the processes/processors is unknown
- Processes are cyclic and sequential

Dijkstra Semaphore

- Classic paper describes several software attempts to solve the problem (see problem 4, Chapter 8)
- Found a software solution, but then proposed a simpler hardware-based solution
- A *semaphore*, s, is a nonnegative integer variable that can only be changed or tested by these two indivisible functions:

```
V(s): [s = s + 1]
P(s): [while(s == 0) {wait}; s = s - 1]
```

Using Semaphores to Solve the Canonical Problem

```
Proc_0() {
  while(TRUE) {
    <compute section>;
    P(mutex);
      <critical section>;
    V(mutex);
  }
}

semaphore mutex = 1;
fork(proc_0, 0);
fork(proc_1, 0);
```

```
proc_1() {
  while(TRUE {
    <compute section>;
    P(mutex);
      <critical section>;
    V(mutex);
  }
}
```

Shared Account Problem

```
Proc_0() {
  . . .
/* Enter the CS */
  P(mutex);
    balance += amount;
  V(mutex);
  . . .
}
```

```
proc_1() {
  . . .
/* Enter the CS */
  P(mutex);
    balance -= amount;
  V(mutex);
  . . .
}
```

```
semaphore mutex = 1;

fork(proc_0, 0);
fork(proc_1, 0);
```

Two Shared Variables

```
proc_A() {
  while(TRUE) {
    <compute section A1>;
    update(x);
  /* Signal proc_B */
    V(s1);
    <compute section A2>;
  /* Wait for proc_B */
    P(s2);
    retrieve(y);
  }
}
```

```
proc_B() {
  while(TRUE) {
  /* Wait for proc_A */
    P(s1);
    retrieve(x);
    <compute section B1>;
    update(y);
  /* Signal proc_A */
    V(s2);
    <compute section B2>;
  }
}
```

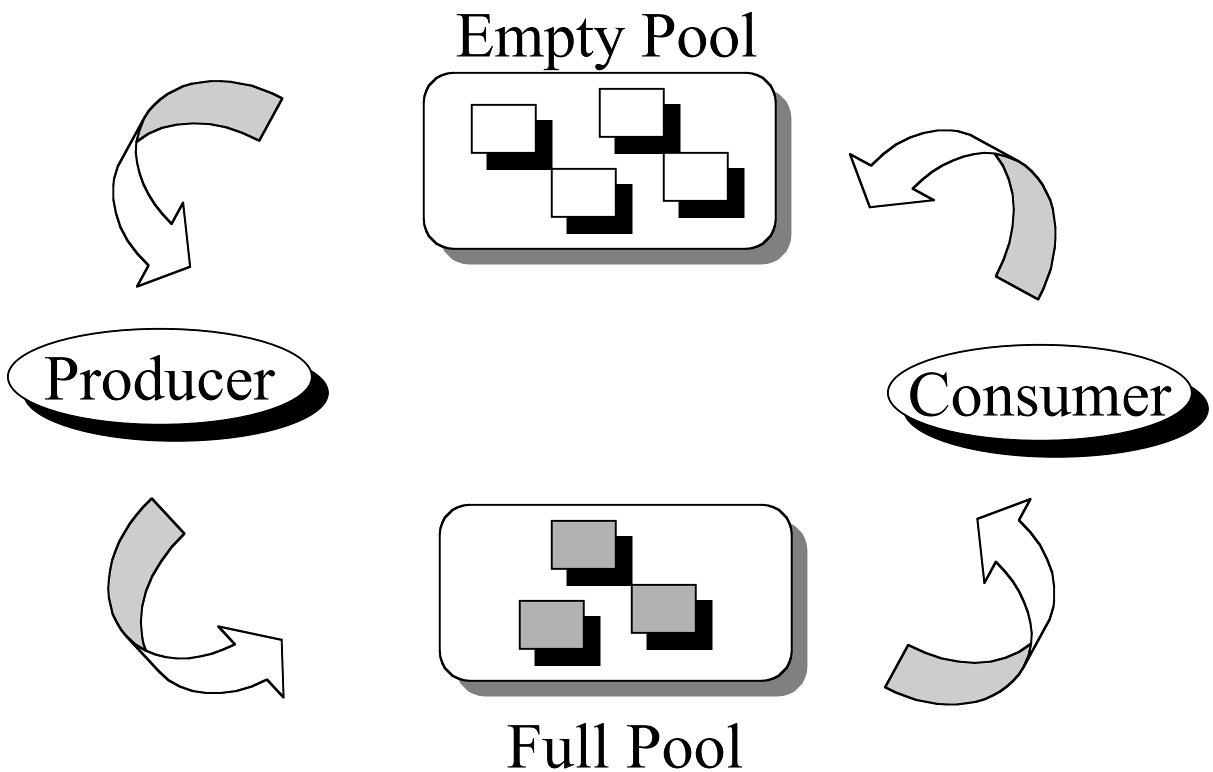
```
semaphore s1 = 0;
semaphore s2 = 0;

fork(proc_A, 0);
fork(proc_B, 0);
```

The Driver-Controller Interface

- The semaphore principle is logically used with the `busy` and `done` flags in a controller
- Driver signals controller with a `V(busy)`, then waits for completion with `P(done)`
- Controller waits for work with `P(busy)`, then announces completion with `V(done)`
- See *In the Cockpit*, page 204

Bounded Buffer



Bounded Buffer

```
producer() {
  buf_type *next, *here;
  while(TRUE) {
    produce_item(next);
  /* Claim an empty */
    P(empty);
    P(mutex);
      here = obtain(empty);
    V(mutex);
    copy_buffer(next, here);
    P(mutex);
      release(here, fullPool);
    V(mutex);
  /* Signal a full buffer */
    V(full);
  }
}
```

```
consumer() {
  buf_type *next, *here;
  while(TRUE) {
  /* Claim full buffer */
    P(mutex);
    P(full);
      here = obtain(full);
    V(mutex);
    copy_buffer(here, next);
    P(mutex);
      release(here, emptyPool);
    V(mutex);
  /* Signal an empty buffer */
    V(empty);
    consume_item(next);
  }
}
```

```
semaphore mutex = 1;
semaphore full = 0;     /* A general (counting) semaphore */
semaphore empty = N;    /* A general (counting) semaphore */
buf_type buffer[N];
fork(producer, 0);
fork(consumer, 0);
```

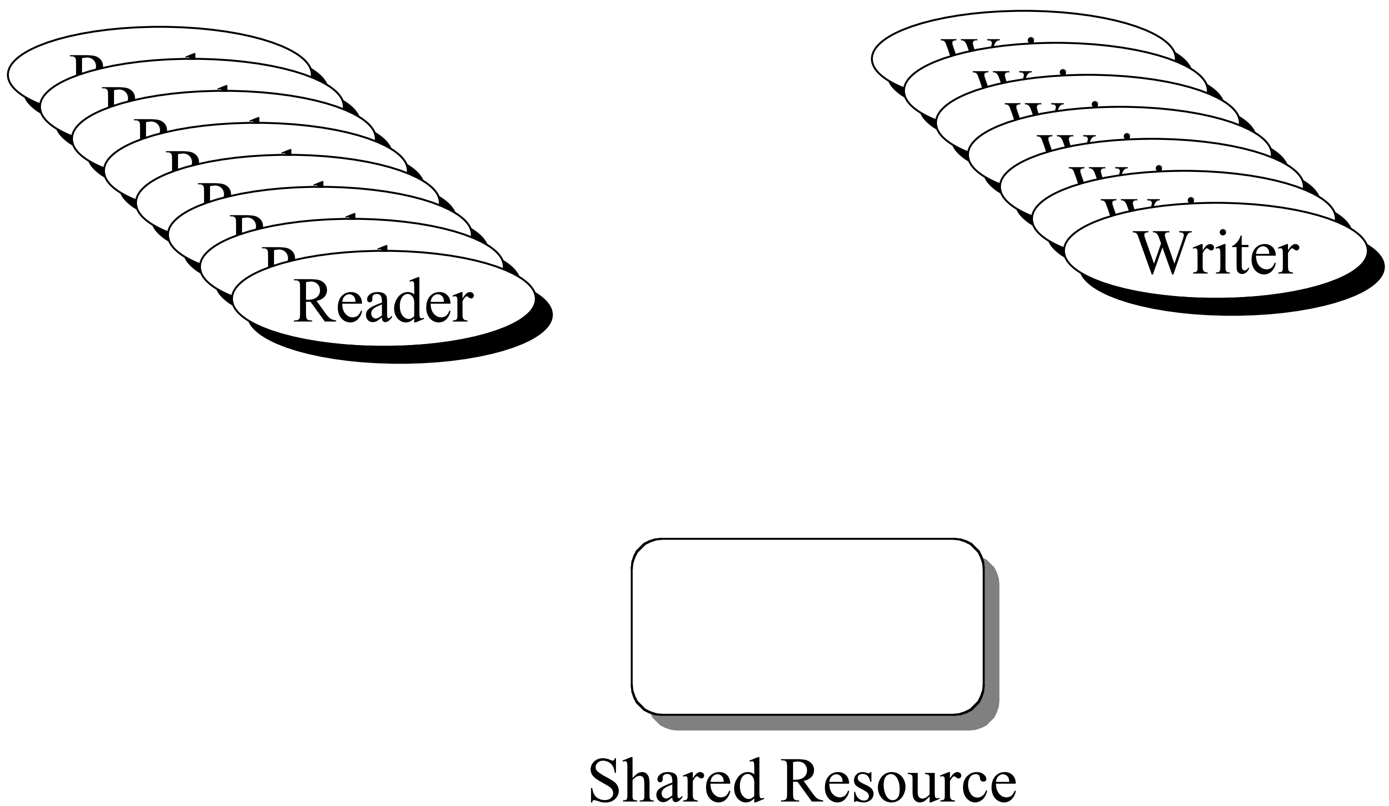
Bounded Buffer

```
producer() {
  buf_type *next, *here;
  while(TRUE) {
    produce_item(next);
  /* Claim an empty */
    P(empty);
    P(mutex);
      here = obtain(empty);
    V(mutex);
    copy_buffer(next, here);
    P(mutex);
      release(here, fullPool);
    V(mutex);
  /* Signal a full buffer */
    V(full);
  }
}
```

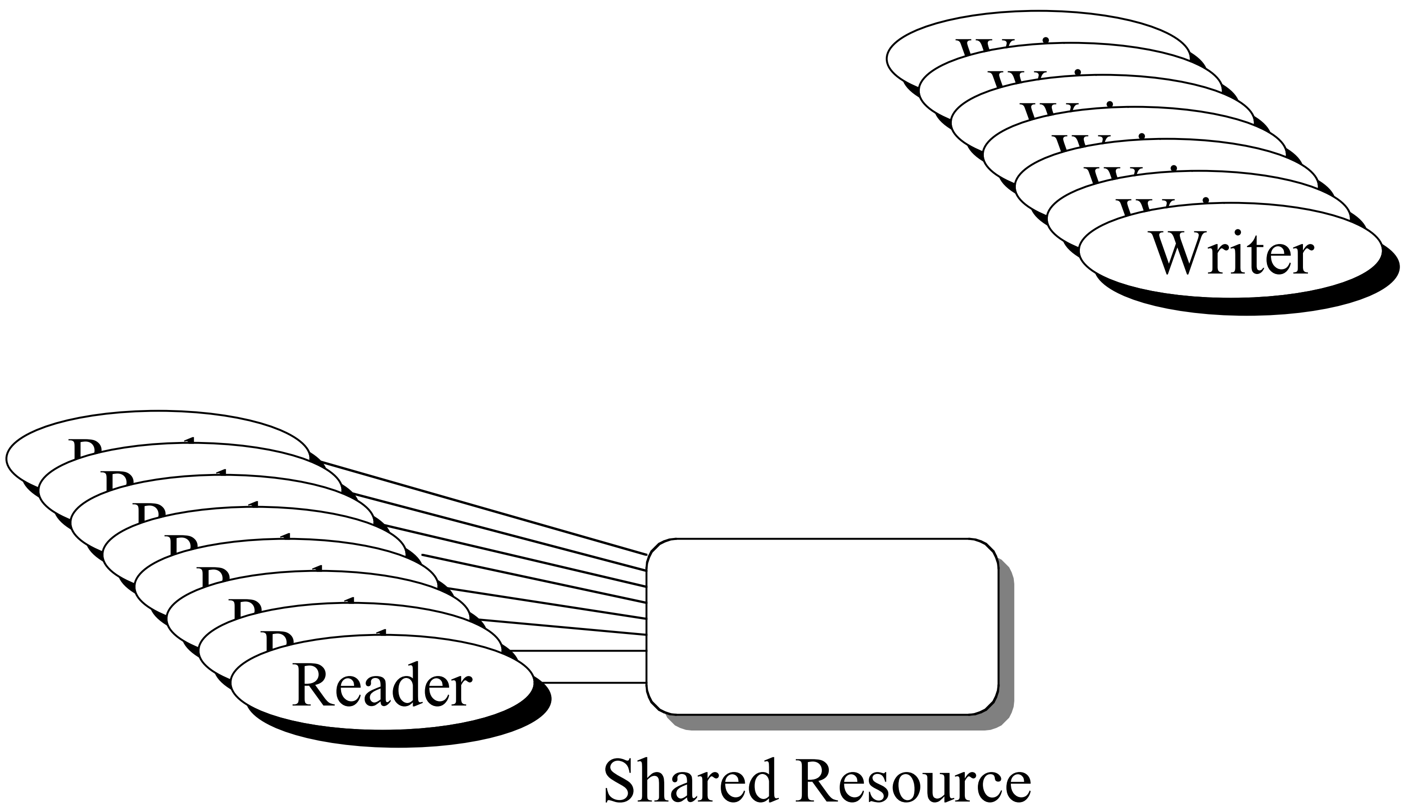
```
consumer() {
  buf_type *next, *here;
  while(TRUE) {
  /* Claim full buffer */
    P(full);
    P(mutex);
      here = obtain(full);
    V(mutex);
    copy_buffer(here, next);
    P(mutex);
      release(here, emptyPool);
    V(mutex);
  /* Signal an empty buffer */
    V(empty);
    consume_item(next);
  }
}
```

```
semaphore mutex = 1;
semaphore full = 0;     /* A general (counting) semaphore */
semaphore empty = N;    /* A general (counting) semaphore */
buf_type buffer[N];
fork(producer, 0);
fork(consumer, 0);
```

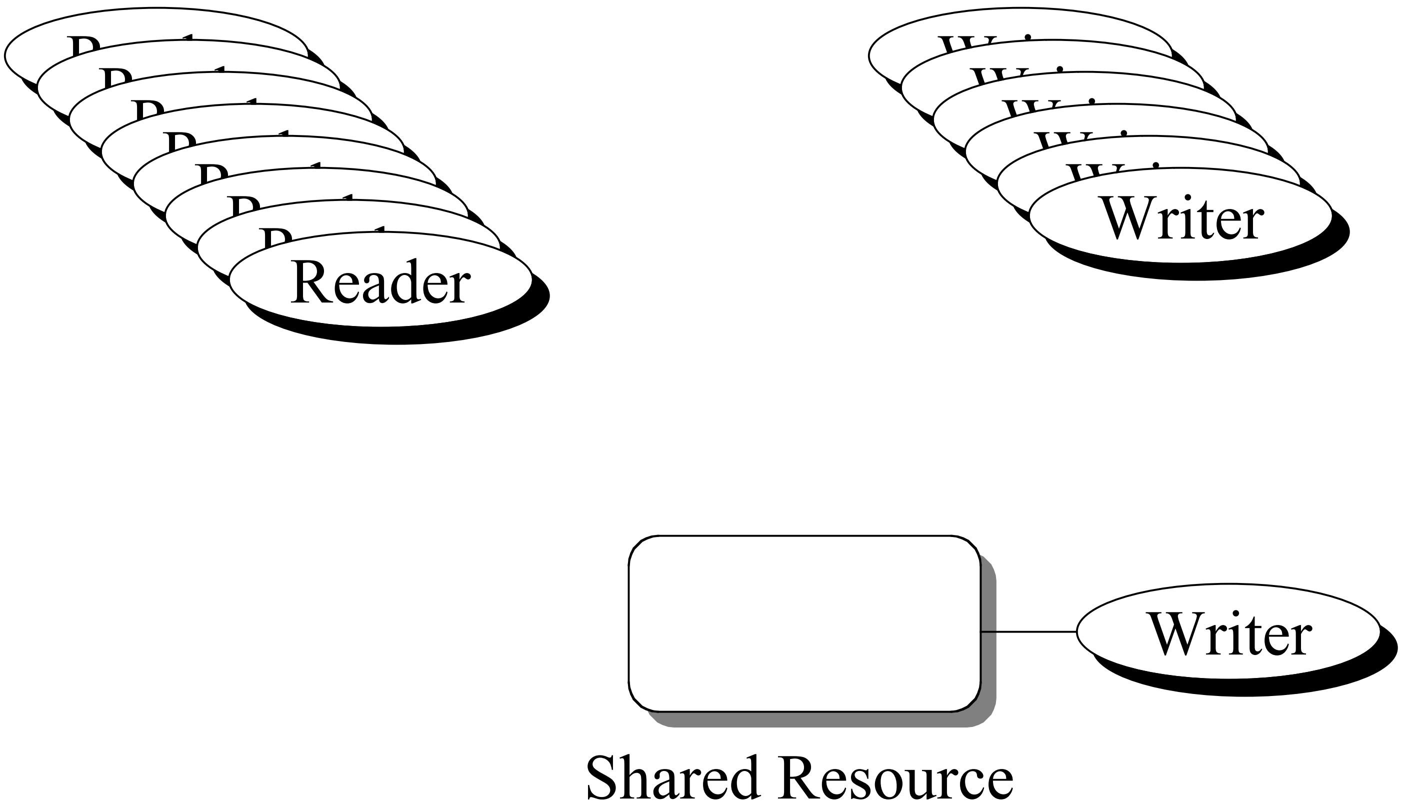
Readers-Writers Problem



Readers-Writers Problem



Readers-Writers Problem



First Solution

```
reader() {
  while(TRUE) {
    <other computing>;
    P(mutex);
      readCount++;
      if(readCount == 1)
        P(writeBlock);
    V(mutex);
  /* Critical section */
    access(resource);
    P(mutex);
      readCount--;
      if(readCount == 0)
        V(writeBlock);
    V(mutex);
  }
}
resourceType *resource;
int readCount = 0;
semaphore mutex = 1;
semaphore writeBlock = 1;
fork(reader, 0);
fork(writer, 0);
```

```
writer() {
  while(TRUE) {
    <other computing>;
    P(writeBlock);
    /* Critical section */
      access(resource);
    V(writeBlock);
  }
}
```

First Solution

```
reader() {
  while(TRUE) {
    <other computing>;
    P(mutex);
      readCount++;
      if(readCount == 1)
        P(writeBlock);
    V(mutex);
  /* Critical section */
    access(resource);
    P(mutex);
      readCount--;
      if(readCount == 0)
        V(writeBlock);
    V(mutex);
  }
}
resourceType *resource;
int readCount = 0;
semaphore mutex = 1;
semaphore writeBlock = 1;
fork(reader, 0);
fork(writer, 0);
```

```
writer() {
  while(TRUE) {
    <other computing>;
    P(writeBlock);
    /* Critical section */
      access(resource);
    V(writeBlock);
  }
}
```

- First reader competes with writers
- Last reader signals writers

First Solution

```
reader() {
  while(TRUE) {
    <other computing>;
    P(mutex);
      readCount++;
      if(readCount == 1)
        P(writeBlock);
    V(mutex);
  /* Critical section */
    access(resource);
    P(mutex);
      readCount--;
      if(readCount == 0)
        V(writeBlock);
    V(mutex);
  }
}
resourceType *resource;
int readCount = 0;
semaphore mutex = 1;
semaphore writeBlock = 1;
fork(reader, 0);
fork(writer, 0);
```

```
writer() {
  while(TRUE) {
    <other computing>;
    P(writeBlock);
    /* Critical section */
      access(resource);
    V(writeBlock);
  }
}
```

- First reader competes with writers
- Last reader signals writers
- Any writer must wait for all readers
- Readers can starve writers
- "Updates" can be delayed forever
- May not be what we want

Writer Takes Precedence

```
reader() {
  while(TRUE) {
    <other computing>;

      P(readBlock);
        P(mutex1);
          readCount++;
          if(readCount == 1)
            P(writeBlock);
        V(mutex1);
      V(readBlock);

      access(resource);
    P(mutex1);
      readCount--;
      if(readCount == 0)
        V(writeBlock);
    V(mutex1);
  }
}
```

```
writer() {
  while(TRUE) {
    <other computing>;
    P(mutex2);
      writeCount++;
      if(writeCount == 1)
        P(readBlock);
    V(mutex2);
    P(writeBlock);
      access(resource);
    V(writeBlock);
    P(mutex2)
      writeCount--;
      if(writeCount == 0)
        V(readBlock);
    V(mutex2);
  }
}
```

```
int readCount = 0, writeCount = 0;
semaphore mutex = 1, mutex2 = 1;
semaphore readBlock = 1, writeBlock = 1, writePending = 1;
fork(reader, 0);
fork(writer, 0);
```

Writer Takes Precedence

```
reader() {
  while(TRUE) {
    <other computing>;

2     P(readBlock);
        P(mutex1);
          readCount++;
          if(readCount == 1)
            P(writeBlock);
        V(mutex1);
      V(readBlock);

1     access(resource);
    P(mutex1);
      readCount--;
      if(readCount == 0)
        V(writeBlock);
    V(mutex1);
  }
}
```

```
writer() {
  while(TRUE) {
    <other computing>;
    P(mutex2);
      writeCount++;
      if(writeCount == 1)
        P(readBlock);
    V(mutex2);
    P(writeBlock);
      access(resource);
    V(writeBlock);
    P(mutex2)
      writeCount--;
      if(writeCount == 0)
        V(readBlock);
    V(mutex2);
  }
}
```

```
int readCount = 0, writeCount = 0;
semaphore mutex = 1, mutex2 = 1;
semaphore readBlock = 1, writeBlock = 1, writePending = 1;
fork(reader, 0);
fork(writer, 0);
```

Writer Takes Precedence

```
reader() {
  while(TRUE) {
    <other computing>;

      P(readBlock);
2       P(mutex1);
          readCount++;
          if(readCount == 1)
            P(writeBlock);
        V(mutex1);
      V(readBlock);

1     access(resource);
    P(mutex1);
      readCount--;
      if(readCount == 0)
        V(writeBlock);
    V(mutex1);
  }
}
```

```
writer() {
  while(TRUE) {
    <other computing>;
    P(mutex2);
      writeCount++;
      if(writeCount == 1)
3       P(readBlock);
    V(mutex2);
    P(writeBlock);
      access(resource);
    V(writeBlock);
    P(mutex2)
      writeCount--;
      if(writeCount == 0)
        V(readBlock);
    V(mutex2);
  }
}
```

```
int readCount = 0, writeCount = 0;
semaphore mutex = 1, mutex2 = 1;
semaphore readBlock = 1, writeBlock = 1, writePending = 1;
fork(reader, 0);
fork(writer, 0);
```

Writer Takes Precedence

```
reader() {
  while(TRUE) {
    <other computing>;

      P(readBlock);                    // 4
        P(mutex1);
          readCount++;                 // 2
          if(readCount == 1)
            P(writeBlock);
        V(mutex1);
      V(readBlock);

      access(resource);                // 1
    P(mutex1);
      readCount--;
      if(readCount == 0)
        V(writeBlock);
    V(mutex1);
  }
}
```

```
writer() {
  while(TRUE) {
    <other computing>;
    P(mutex2);
      writeCount++;
      if(writeCount == 1)
        P(readBlock);                  // 3
    V(mutex2);
    P(writeBlock);
      access(resource);
    V(writeBlock);
    P(mutex2)
      writeCount--;
      if(writeCount == 0)
        V(readBlock);
    V(mutex2);
  }
}
```

```
int readCount = 0, writeCount = 0;
semaphore mutex = 1, mutex2 = 1;
semaphore readBlock = 1, writeBlock = 1, writePending = 1;
fork(reader, 0);
fork(writer, 0);
```

Writer Takes Precedence

```
reader() {
  while(TRUE) {
    <other computing>;

4     P(readBlock);
        P(mutex1);
          readCount++;
          if(readCount == 1)
            P(writeBlock);
        V(mutex1);
2     V(readBlock);

1     access(resource);
    P(mutex1);
      readCount--;
      if(readCount == 0)
        V(writeBlock);
    V(mutex1);
  }
}
```

```
writer() {
  while(TRUE) {
    <other computing>;
    P(mutex2);
      writeCount++;
      if(writeCount == 1)
3       P(readBlock);
    V(mutex2);
    P(writeBlock);
      access(resource);
    V(writeBlock);
    P(mutex2)
      writeCount--;
      if(writeCount == 0)
        V(readBlock);
    V(mutex2);
  }
}
```

```
int readCount = 0, writeCount = 0;
semaphore mutex = 1, mutex2 = 1;
semaphore readBlock = 1, writeBlock = 1, writePending = 1;
fork(reader, 0);
fork(writer, 0);
```

Readers-Writers

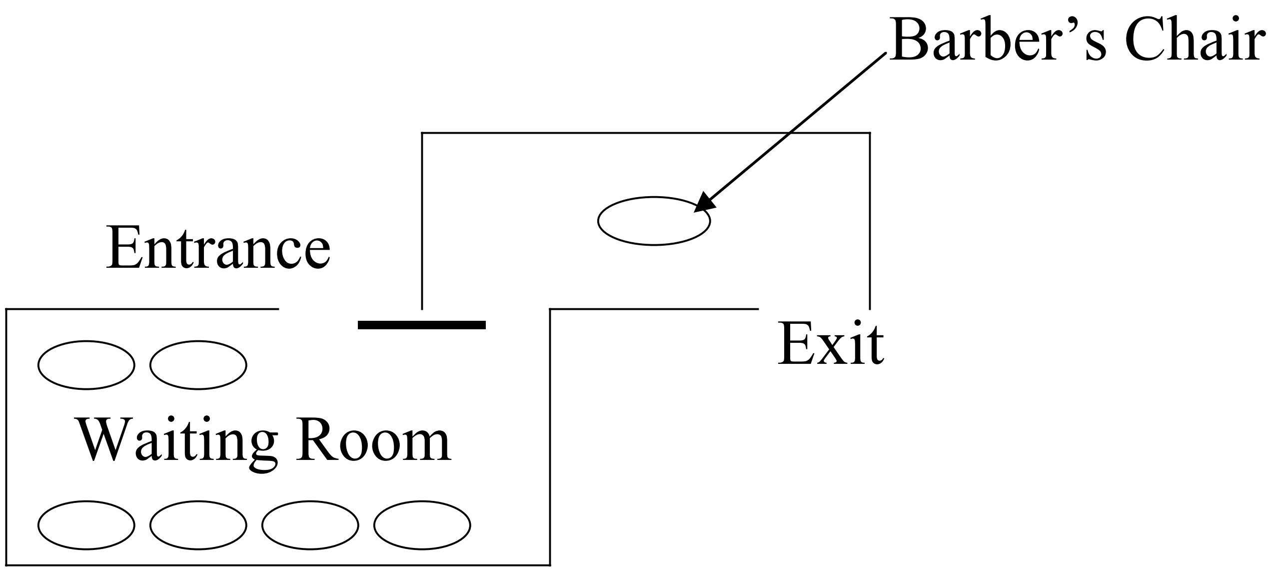
```
  reader() {
    while(TRUE) {
      <other computing>;
4     P(writePending);
        P(readBlock);
          P(mutex1);
            readCount++;
            if(readCount == 1)
              P(writeBlock);
          V(mutex1);
2       V(readBlock);
      V(writePending);
1       access(resource);
      P(mutex1);
        readCount--;
        if(readCount == 0)
          V(writeBlock);
      V(mutex1);
    }
  }
```

```
  writer() {
    while(TRUE) {
      <other computing>;
      P(mutex2);
        writeCount++;
        if(writeCount == 1)
3         P(readBlock);
      V(mutex2);
      P(writeBlock);
        access(resource);
      V(writeBlock);
      P(mutex2)
        writeCount--;
        if(writeCount == 0)
          V(readBlock);
      V(mutex2);
    }
  }
```

```
int readCount = 0, writeCount = 0;
semaphore mutex = 1, mutex2 = 1;
semaphore readBlock = 1, writeBlock = 1, writePending = 1;
fork(reader, 0);
fork(writer, 0);
```

Sleepy Barber Problem

- Barber can cut one person's hair at a time
- Other customers wait in a waiting room



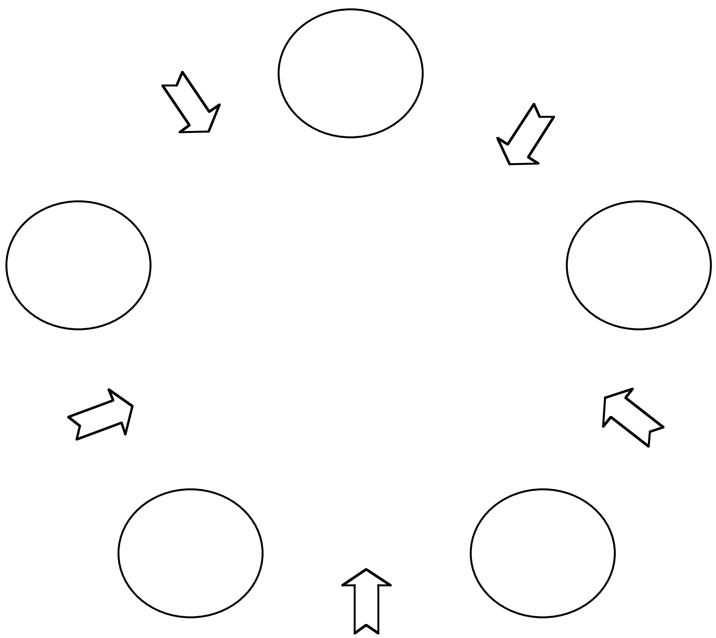
Sleepy Barber Problem (Bounded Buffer Problem)

```
customer() {
  while(TRUE) {
    customer = nextCustomer();
    if(emptyChairs == 0)
      continue;
    P(chair);
      P(mutex);
        emptyChairs--;
        takeChair(customer);
      V(mutex);
    V(waitingCustomer);
  }
}
```

```
barber() {
  while(TRUE) {
    P(waitingCustomer);
      P(mutex);
        emptyChairs++;
        takeCustomer();
      V(mutex);
    V(chair);
  }
}
```

```
semaphore mutex = 1, chair = N, waitingCustomer = 0;
int emptyChairs = N;
fork(customer, 0);
fork(barber, 0);
```

Dining Philosophers



```
while(TRUE) {
  think();
  eat();
}
```

Cigarette Smokers' Problem

- Three smokers (processes)
- Each wish to use tobacco, papers, & matches
  - Only need the three resources periodically
  - Must have all at once
- 3 processes sharing 3 resources
  - Solvable, but difficult

Implementing Semaphores

- Minimize effect on the I/O system
- Processes are only blocked on their own critical sections (not critical sections that they should not care about)
- If disabling interrupts, be sure to bound the time they are disabled

Implementing Semaphores: Disabling Interrupts

```
class semaphore {
  int value;
public:
  semaphore(int v = 1) { value = v;};
  P(){
    disableInterrupts();
    while(value == 0) {
      enableInterrupts();
      disableInterrupts();
    }
    value--;
    enableInterrupts();
  };
  V(){
    disableInterrupts();
    value++;
    enableInterrupts();
  };
};
```

Implementing Semaphores: Test and Set Instruction

- TS(m): [Reg_i = memory[m]; memory[m] = TRUE;]

```
boolean s = FALSE;
  . . .
  while(TS(s)) ;
  <critical section>
  s = FALSE;
  . . .
```

```
semaphore s = 1;
  . . .
  P(s) ;
  <critical section>
  V(s);
  . . .
```

General Semaphore

```
struct semaphore {
  int value = <initial value>;
  boolean mutex = FALSE;
  boolean hold = TRUE;
};

shared struct semaphore s;
```

```
P(struct semaphore s) {
  while(TS(s.mutex)) ;
  s.value--;
  if(s.value < 0) (
    s.mutex = FALSE;
    while(TS(s.hold)) ;
  }
  else
    s.mutex = FALSE;
}
```

```
V(struct semaphore s) {
  while(TS(s.mutex)) ;
  s.value++;
  if(s.value <= 0) (
    while(!s.hold) ;
    s.hold = FALSE;
  }
  s.mutex = FALSE;
}
```

General Semaphore

- Block at arrow
- Busy wait

```
struct semaphore {
  int value = <initial value>;
  boolean mutex = FALSE;
  boolean hold = TRUE;
};

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General Semaphore

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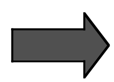

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  s.value++;
  if(s.value <= 0) (
    while(!s.hold) ;
    s.hold = FALSE;
  }
  s.mutex = FALSE;
}
```

- Block at arrow
- Busy wait
- Quiz: Why is this statement necessary?

Active vs Passive Semaphores

- A process can dominate the semaphore
  - Performs V operation, but continues to execute
  - Performs another P operation before releasing the CPU
  - Called a *passive* implementation of V
- *Active* implementation calls scheduler as part of the V operation.
  - Changes semantics of semaphore!
  - Cause people to rethink solutions