Chapter 8

Basic Synchronization Principles

Need for Synchronization

- Multiprogramming
  ➔ Multiple concurrent, independent processes
  ➔ Those processes might want to coordinate activities

```
                shared x, y

Proc A {                        Proc B {
while (true) {                  while (true) {
       <compute A1>                    read(x)
       write(x)                        <compute B1>
       <compute A2>                    write(y)
       read(y)                         <compute B2>
       }                               }
}                               }
```

- Clearly, synchronization is needed if
  - A wants B to read `x` <u>after</u> it writes it & <u>before</u> it re-writes

Barriers to providing synchronization

- What are the barriers to providing good synchronization capabilities ?
  - No widely accepted parallel programming languages
    - CSP
    - Linda
  - No widely use paradigm
    - How do you decompose a problem ?
  - OS only provides minimal support
    - Test and Set
    - Semaphore
    - Monitor

Critical Section Problem

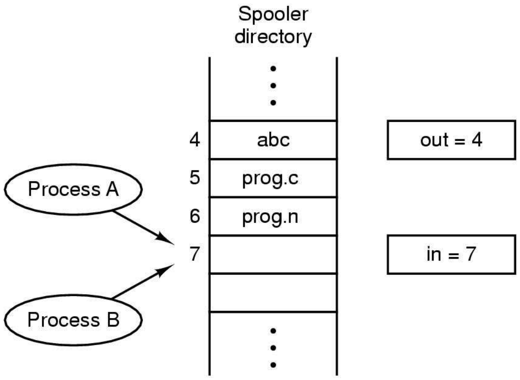
```
                 shared float balance;

/* Code schema for p1 */          /* Code schema for p2 */
..                                ..
balance = balance + amount;       balance = balance - amount;
..                                ..

   /* Schema for p1 */                 /* Schema for p2 */
      load R1, balance                    load R1, balance
      load R2, amount                     load R2, amount
      add R1, R2                          sub R1, R2
      store R1, balance                   store R1, balance
```

Critical Section Problem…

```
   /* Schema for p1 */                    /* Schema for p2 */

     load R1, balance  } 1                load R1, balance  \
                                     4 {                     |
     load R2, amount   }                  load R2, amount    |
 5                                                           > 2
     add R1, R2        } 3                sub R1, R2         |
                                     6 {                     |
     store R1, balance }                  store R1, balance /
```

- Suppose:
  - Execution sequence : 1, 2, 3
    - Lost update : 2
  - Execution sequence : 1, 4, 3 ,6
    - Lost update : 3
- Together => non-determinacy
- Race condition exists

Race Condition Example 2



Taken from Modern Operating Systems, 2nd Ed, Tanenbaum, 2001

Two processes want to access shared memory at same time

Using Shared Global Variables – Ver 1

```
Shared integer processnumber = 1;
```

```
void processone;
{
  while (true)    {
      while (processnumber == 2)
              ;
      criticalsectionone;
      processnumber = 2;
      otherstuffone;
      }
  }
```

Hard wait

```
void processtwo;
{
  while (true)
    {
      while (processnumber == 1)
              ;
      criticalsectiontwo;
      processnumber = 1;
      otherstufftwo;
      }
  }
```

Hard wait

Single global variable forces **lockstep synchronization**

Using Shared Global Variables – Ver 2

```
Shared boolean p1inside = false, p2inside = false;
```

```
void processone;
  {
       while (true)   {
           while (p2inside)
               ;
           p1inside = true;
           criticalsectionone;
           p1inside = false;
           otherstuffone;
         }
  }
```

```
void processtwo;
  {
       while (true) {
           while (p1inside)
               ;
           p2inside = true;
           criticalsectiontwo;
           p2inside = false;
           otherstufftwo;
         }
  }
```

- Process 1 & 2 can both be **in the critical sections at the same time** Because Test & Set operations are **not atomic**

  ==> Move setting of p1inside/p2inside before test

Using Shared Global Variables – Ver 3

```
    Shared boolean: p1wantsin = false, p2wantsin = false;

void processone;                        void processtwo;
  {                                       {
        while (true)  {                         while (true) {
            p1wantsin = true;                       p2wantsin = true;
            while (p2wantsin)                       while (p1wantsin)
                ;                                       ;
            criticalsectionone;                     criticalsectiontwo;
            p1wantsin = false;                      p2wantsin = false;
            otherstuffone;                          otherstufftwo;
          }                                       }
  }                                        }
```

- **Deadlock** can occur if both sets flag at the same time

  ==> Need a way to break out of loops…..

Using Shared Global Variables – Peterson

```
     Shared boolean p1wantsin = false, p2wantsin = false;
     Shared int will_wait;
void processone;                        void processtwo;
  {                                       {
        while (true)  {                         while (true) {
            p1wantsin = true;                       p2wantsin = true;
            will_wait = 1;                          will_wait = 2;
            while (p2wantsin &&                     while (p1wantsin &&
(will_wait == 1))                       (will_wait == 2))
                ;                                       ;
            criticalsectionone;                     criticalsectiontwo;
            p1wantsin = false;                      p2wantsin = false;
            otherstuffone;                          otherstufftwo;
          }                                       }
  }                                        }
```

- **Guarantees mutual exclusion and no blocking**

Wherein Lies the Problem?

- Problem stems from interruption of software-based process while executing critical code (low-level)
- Solution
  - Identify critical section
  - *Disable interrupts* while in Critical Section

```
                    shared double balance;

/* Program for P1 */                  /* Program for P2 */
DisableInterrupts();                  DisableInterrupts();
balance = balance + amount; }CS       Balance = balance – amount; }CS
EnableInterrupts();                   EnableInterrupts();
```

Using Interrupts…

- This works *BUT*…
  - Allows process to disable interrupts for arbitrarily long time
  - What if I/O interrupt needed ?
  - What if one of the processes is in infinite loop inside the Critical Section
- Let's examine the use of Shared Variables again….

Using Shared Variable to Synchronize

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

/* Program for P1 */               /* Program for P2 */
..                                 ..
/* Acquire lock */                 /* Acquire lock */
while(lock) {NULL;}                while(lock) {NULL;}
lock = TRUE;                       lock = TRUE;
/* Execute critical section */     /* Execute critical section */
balance = balance + amount;        balance = balance - amount;
/* Release lock */                 /* Release lock */
lock = FALSE;                      lock = FALSE;
..                                 ..
```

`lock == FALSE` => No process in CS => Any process can enter CS	`lock == TRUE` => One process in CS => No other process admitted to CS

Synchronizing Variable…

- What if P1 interrupted after lock Set to TRUE
  => P2 cannot execute past while does hard wait
  => Wasted CPU time
- What if P1 interrupted after Test, before Set
  => *P1 & P2 can be in the CS at the same time !!!*
- Wasted CPU time is bad, but tolerable…..
  Critical Section Violation **cannot** be tolerated
  ==> Need Un-interruptable "Test & Set" operation

Un-interruptible Test & Set

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

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

Enable interrupts so that the OS, I/O can use them

Re-disable interrupts when ready to test again

Un-interruptible Test & Set…

- Solution

P1

```
   enter(lock);
CS{ balance = balance + amount;
   exit(lock);
```

P2

```
   enter(lock);
CS{ balance = balance - amount;
   exit(lock);
```

- Note
  - CS is totally bounded by enter/exit
  - P2 can still wait (wasted CPU cycles) if P1 is interrupted after setting lock (i.e., entering critical section), but
  - **Mutual exclusion is achieved!!!!!**
- Does not generalize to multi-processing

Protecting Multiple Components

```
        Shared: list L,
                boolean ListLK = False;
                boolean LngthLK = False;

  /* Program for P1 */                   /* Program for P2 */
enter(listLK);                         enter(lngthLK);
   <delete element>;                      <update length>;
exit(listLK);                          exit(lngthLK);
   <intermediate comp.>;               <intermediate comp.>;
enter(lngthLK);                        enter(listLK);
   <update length>;                       <delete element>;
exit(lngthLK);                         exit(listLK);
```

- Use enter/exit to update structure with 2 pieces if information
- ***But* try to *minimize time component locked out***

Protecting Multiple Components: 1st try

```
        Shared: list L,
                boolean ListLK = False;
                boolean LngthLK = False;

  /* Program for P1 */                   /* Program for P2 */
enter(listLK);                         enter(lngthLK);
   <delete element>;                      <update length>;
exit(listLK);                          exit(lngthLK);
☼  <intermediate comp.>;                  <intermediate comp.>;
enter(lngthLK);                        enter(listLK);
   <update length>;                       <delete element>;
exit(lngthLK);                         exit(listLK);
```

Suppose: P1... ☼ ; P2 runs & finishes; P1 ☼ …….

Any access to lngth vble during "intermediate comp." will be incorrect !!!

=> Programming Error: List and variable need to be updated together

Protecting Multiple Components: 2nd try

```
Shared: list L,
        boolean ListLK = False;
        boolean LngthLK = False;
```

```
/* Program for P1 */

      enter(listLK);                 ⎫
         <delete element>;           ⎪
     ☼   <intermediate comp.>;       ⎬ CS1
CS2 ⎧ enter(lngthLK);                ⎪
    ⎨    <update length>;            ⎪
    ⎪ exit(listLK);                  ⎭
    ⎩ exit(lngthLK);
```

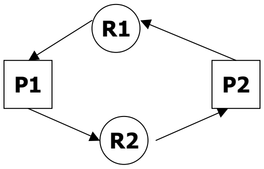
```
/* Program for P2 */

enter(lngthLK);                 ⎫
   <update length>;             ⎪
⊗  <intermediate comp.>;        ⎬ CS2
enter(listLK)          ⎫        ⎪
   <delete element>;   ⎬ CS1    ⎭
exit(lngthLK);         ⎪
exit(listLK);          ⎭
```

- Suppose: P1...☼ ;
  P2 runs to ⊗ and blocks ;
  P1 starts & blocks on “enter”
  => ***DEADLOCK***

Deadlock

- Deadlock
  - When 2 or more processes get into a state whereby each is holding a resource requested by the other

```
P1                          P2
.                           .
Request Resource1           Request Resource2
.                           .
Request Resource2           Request Resource1
.                           .
```



```
P1 requests and gets R1
interrupt
P2 requests and gets R2
interrupt
P1 requests R2 and blocks
P2 requests R1 and blocks
```

Solution to Synchronization

- The previous examples have illustrated 2 methods for synchronizing / coordinating processes
  - Interrupt
  - Shared variable
- Each has its own set of problems
  - Interrupt
    - May be disabled for too long
  - Shared variable
    - Test, then set – interruptible
    - Non-interruptible – gets complex
- Dijkstra introduces a 3rd and much more preferable method
  - Semaphore

Semaphore

- Dijkstra, 1965
- Synchronization primitive with no busy waiting
- It is an integer variable changed or tested by one of the two indivisible operations
- Actually implemented as a protected variable type

```
var x : semaphore
```

Semaphore operations

- **P** operation ("wait")
  - Requests permission to use a critical resource

```
S = S - 1;
if (S < 0) then
      put calling process on queue
```

- **V** operation ("signal")
  - Releases the critical resource

```
S = S + 1;
if (S <= 0) then
      remove one process from queue
```

- Queues are associated with each semaphore variable

Semaphore : Example

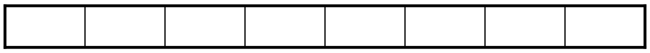
```
Critical resource   T
Semaphore           S ← initial_value
Processes           A,B
```

Process A	Process B
`.`	`.`
`P(S);`	`P(S);`
`<`**CS**`> /* access T */`	`<`**CS**`> /* access T */`
`V(S);`	`V(S);`
`.`	`.`

Semaphore : Example…

```
var S : semaphore ← 1
```

Queue associated with S



Value of S : 1

Process A

```
P(S);
<CS>
V(S);
```

Process B

```
P(S);
<CS>
V(S);
```

Process C

```
P(S);
<CS>
V(S);
```

Types of Semaphores

- Binary Semaphores
  - Maximum value is 1
- Counting Semaphores
  - Maximum value is greater than 1
- Both use same P and V definitions
- Synchronizing code and initialization determines what values are needed, and therefore, what kind of semaphore will be used

Using Semaphores

```
Shared semaphore mutex = 1;
```

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

```
proc_2() {
  while(true) {
    <compute section>;
    P(mutex);
       <critical section>;
    V(mutex);
    }
  }
```

---

(1) P1 => P(mutex)
Decrements; <0 ?; NO (0);
P1 Enters CS;
P1 interrupted

(2) P2 => P(mutex)
Decrements; <0 ?; YES (-1)
P2 **blocks** on **mutex**

Non-Interruptable "Test & Sets"

(3) P1 finishes CS work
P1 => V(mutex);
Increments; <=0 ?; YES (0)
P2 woken & proceeds

Using Semaphores - Example 1

```
Shared semaphore mutex = 1;
```

```
proc_0() {
...
P(mutex);
balance = balance + amount;
V(mutex);
...
}
```

```
proc_1() {
…
P(mutex);
balance = balance – amount;
V(mutex);
...
}
```

Suppose P1 issues P(mutex) first ……
Suppose P2 issues P(mutex) first ……
} No Problem

Note: Could use Interrupts to implement solution,
But (1) with interrupts masked off, what happens if a prior I/O request is satisfied
(2) Interrupt approach would not work on Multiprocessor

Using Semaphores – Example 2

Shared semaphore: s1 = 0, s2 = 0;

Note: values started at 0… ok?

```
proc_A() {
  while(true) {
    <compute A1>;
    write(x);
    V(s1);
    <compute A2>;
    P(s2);
    read(y);
  }
}
```

A signals B that "write to x" has completed

A blocks until B signals

```
proc_B() {
  while(true) {
    P(s1);
    read(x);
    <compute B1>;
    write(y);
    V(s2);
    <compute B2>;
  }
}
```

B blocks till A signals

B signals A that "write to y" has completed

- Cannot use Interrupt disable/enable here because we have *multiple distinct synchronization points*
- Interrupt disable/enable can only distinguish 1 synchronization event
- **Therefore, 2 Semaphores**

Using Hardware Test & Set [TS(s)] to Implement Binary Semaphore "Semantics"

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

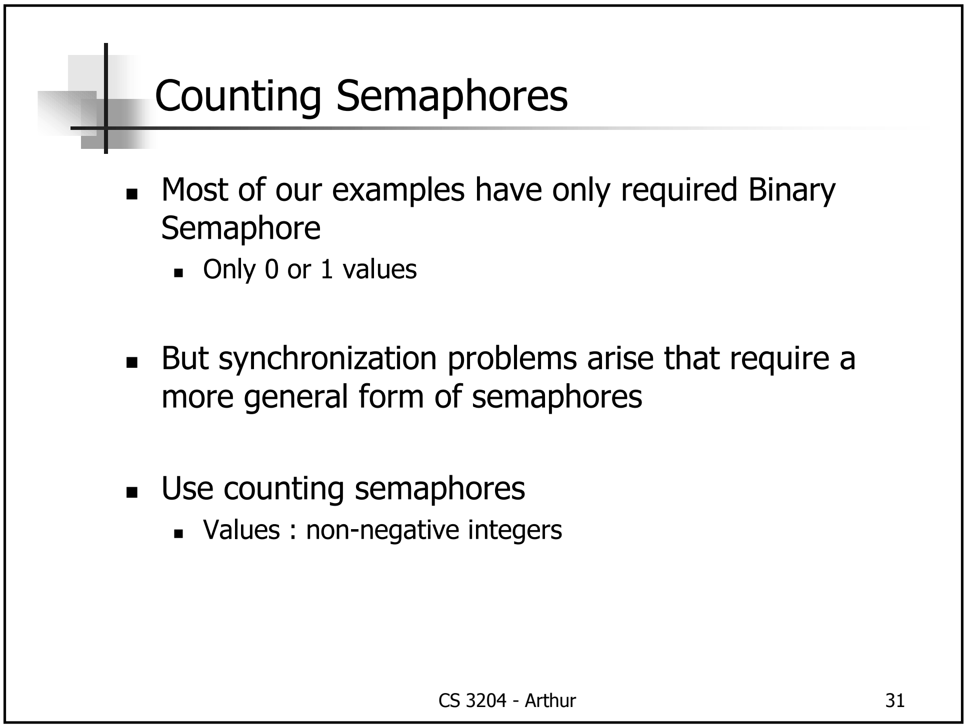
$\overset{?}{\equiv}$

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

- **TS(s)**
  - **Test s**
  - **Set s to True**
  - **Return original value**

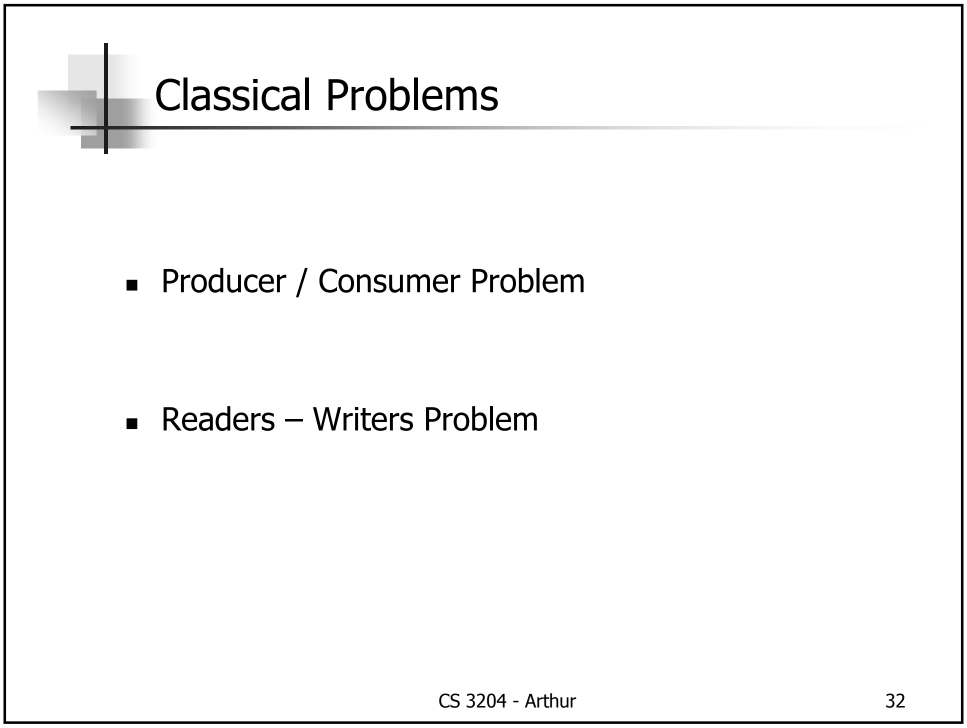
Uninterruptable

Note: No actual queueing, each process just "hard waits"



Counting Semaphores

- Most of our examples have only required Binary Semaphore
  - Only 0 or 1 values
- But synchronization problems arise that require a more general form of semaphores
- Use counting semaphores
  - Values : non-negative integers



Classical Problems

- Producer / Consumer Problem
- Readers – Writers Problem

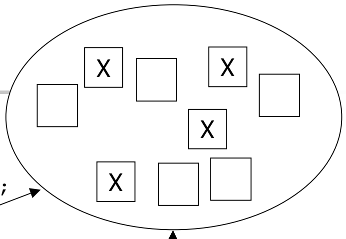
Producer / Consumer Problem (Classic)

- Critical resource
  - Set of message buffers
- 2 Processes
  - Producer : Creates a message and places it in the buffer
  - Consumer : Reads a message and deletes it from the buffer
- Objective
  - Allow the producer and consumer to run concurrently

P/C…

- Constraints
  - Producer must have a non-full buffer to put its message into
  - Consumer must have a non-empty buffer to read
  - Mutually exclusive access to Buffer pool
- Unbounded Buffer problem
  - Infinite buffers
  - Producer never has to wait
  - Not interesting nor practical
- Bounded Buffer Problem
  - Limited set of buffers

P/C - Solution



```
Shared Full: semaphore ← 0;
       Empty semaphore ← MaxBuffers;
       MEPC: semaphore ← 1;
```

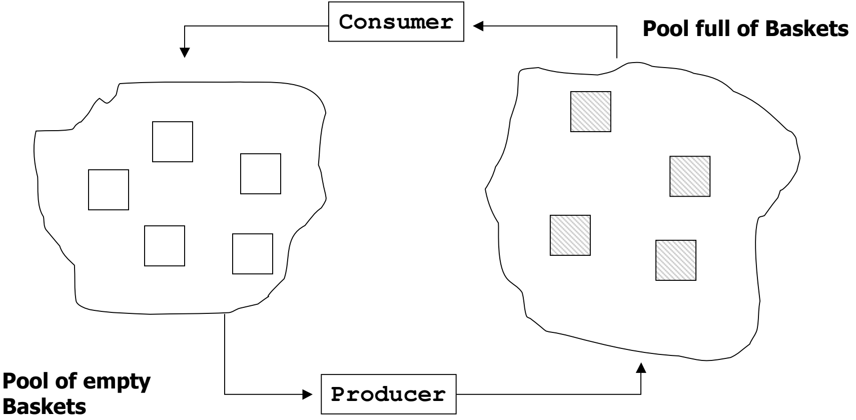
Producer

```
Begin
...
P(Empty);
P(MEPC);
<add item to buffer>
V(MEPC);
V(Full);
...
End;
```

Consumer

```
Begin
...
P(Full);
P(MEPC);
<remove item from buffer>
V(MEPC);
V(Empty);
...
End;
```

P/C – Another Look



Consumer

Pool full of Baskets

Pool of empty Baskets

Producer

P/C – Another Look

- 9 Baskets – Bounded
- Consumer – Empties basket
  - Can *only* remove basket from Full Pool, if one is there => Need “full” count
  - Emptys basket and places it in Empty pool
- Producer – Fills basket
  - Can *only* remove basket from Empty pool, if one is there => Need “empty” count
  - Fills basket and places it in Full pool

P/C - Another Look

```
Shared semaphore: Emutex = 1, Fmutex = 1; full = 0,  empty = 9;
Shared buf_type: buffer[9];
```

```
producer() {
  buf_type *next, *here;
  while(True) {
    produce_item(next);
    P(empty); /*Claim empty buffer*/
    P(Emutex); /*Manipulate the pool*/
    here = obtain(empty);
    V(Emutex);
    copy_buffer(next, here);
    P(Fmutex); /*Manipulate the pool*/
    release(here, fullpool);
    V(Fmutex); /*Signal full buffer*/
    V(full);
  }
}
```

```
consumer() {
  buf_type *next, *here;
  while(True) {
    P(full); /*Claim full buffer*/
    P(Fmutex); /*Manipulate the pool*/
    here = obtain(full);
    V(Fmutex);
    copy_buffer(here, next);
    P(Emutex); /*Manipulate the pool*/
    release(here, emptypool);
    V(Enmutex); /*Signal empty buffer*/
    V(empty);
    consume_item(next);
  }
}
```

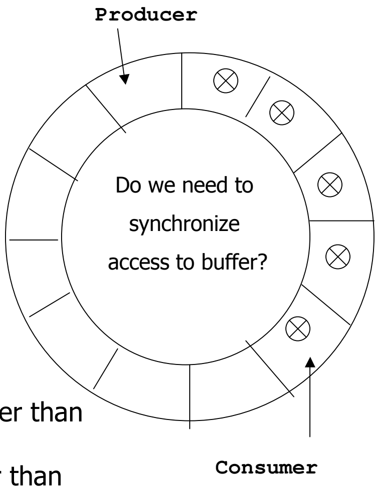
P/C - Example

- How realistic is PCP scenario?
- Consider a circular buffer
  - 12 slots
  - Producer points at next one it will fill
  - Consumer points at next one it will empty
- Don't want :

Producer = Consumer

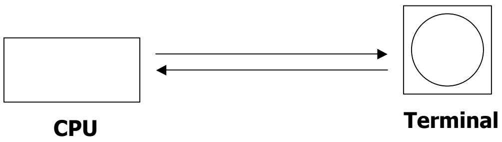
=> (1) Consumer "consumed" faster than producer "produced", or

(2) Producer "produced" faster than consumer "consumed".



P/C – Real World Scenario

- CPU can produce data faster than terminal can accept or viewer can read

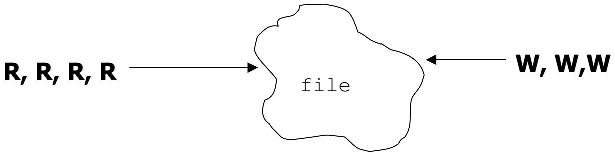


Communication buffers in both

Xon/Xoff Flow Control

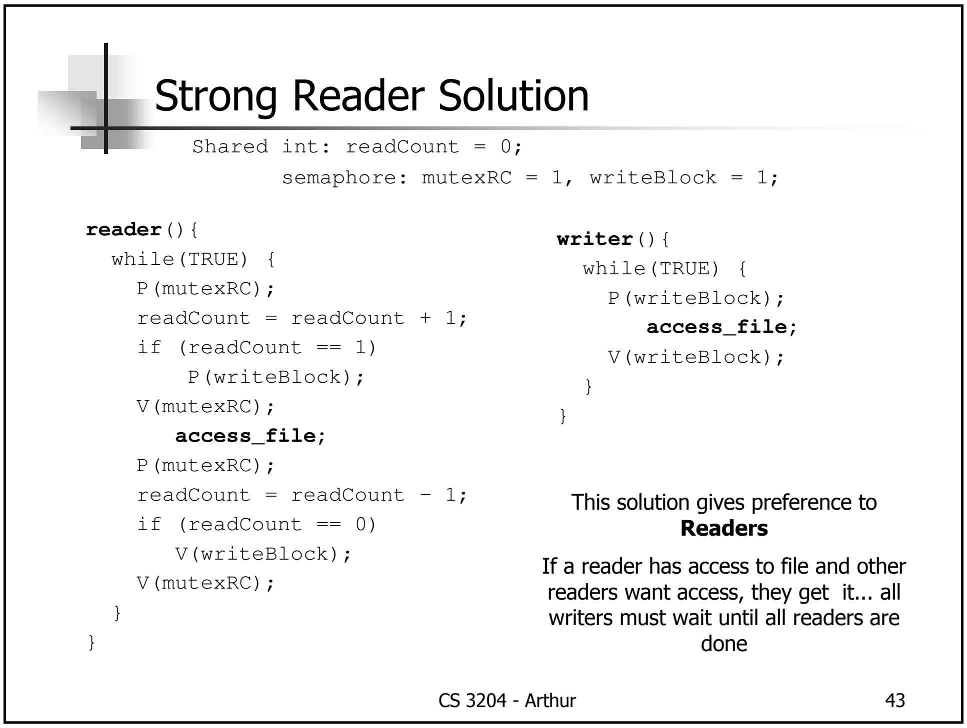
Readers / Writers Problem (Classic)

- Multiple readers of the same file?
  - No problem
- Multiple writers to the same file?
  - Might be a problem writing same record
    => Potentially a "lost update"
- Writing while reading
  - Might be a problem – read might occur while being written
    => Inconsistent data



Readers – Writers Problem

- Critical resource
  - File
- Consider multiple processes which can read or write to the file
- What constraints must be placed on these processes?
  - Many readers may read at one time
  - Mutual exclusion between readers and writers
  - Mutual exclusion between writers



Strong Reader Solution

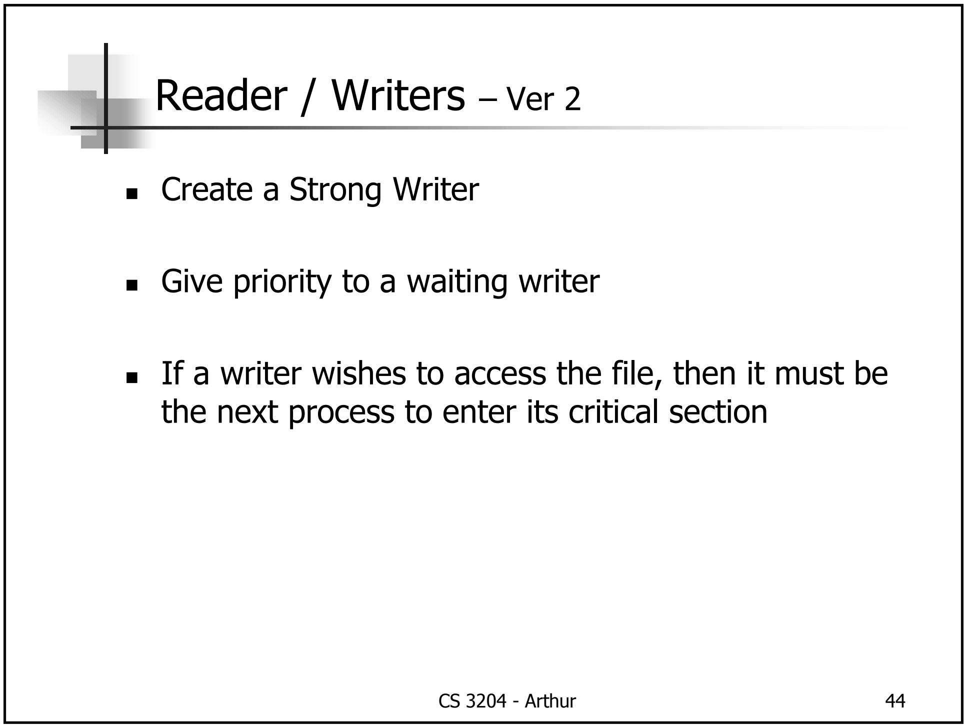
```
Shared int: readCount = 0;
       semaphore: mutexRC = 1, writeBlock = 1;
```

```
reader(){
  while(TRUE) {
    P(mutexRC);
    readCount = readCount + 1;
    if (readCount == 1)
        P(writeBlock);
    V(mutexRC);
       access_file;
    P(mutexRC);
    readCount = readCount - 1;
    if (readCount == 0)
       V(writeBlock);
    V(mutexRC);
  }
}
```

```
writer(){
  while(TRUE) {
    P(writeBlock);
       access_file;
    V(writeBlock);
  }
}
```

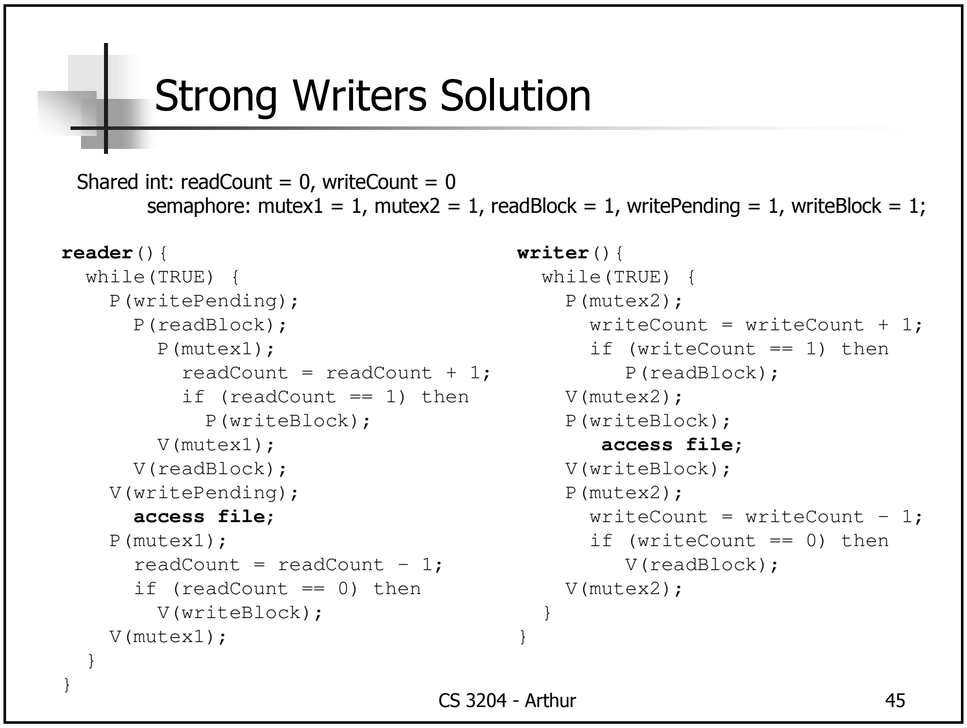
This solution gives preference to **Readers**

If a reader has access to file and other readers want access, they get it... all writers must wait until all readers are done



Reader / Writers – Ver 2

- Create a Strong Writer
- Give priority to a waiting writer
- If a writer wishes to access the file, then it must be the next process to enter its critical section

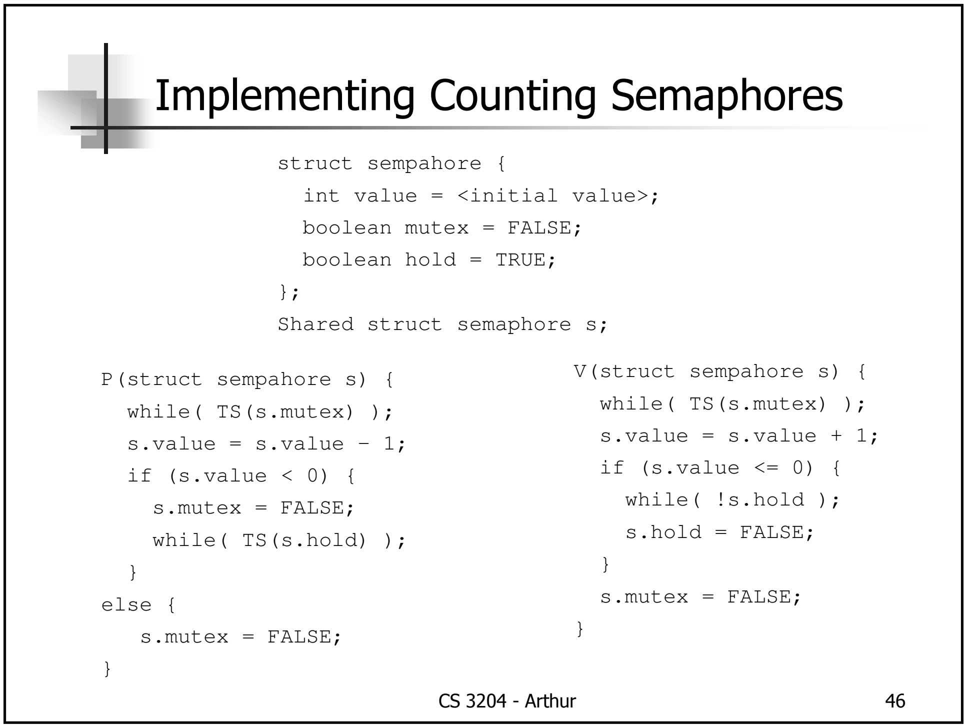


Strong Writers Solution

Shared int: readCount = 0, writeCount = 0
semaphore: mutex1 = 1, mutex2 = 1, readBlock = 1, writePending = 1, writeBlock = 1;

```
reader(){
  while(TRUE) {
    P(writePending);
      P(readBlock);
        P(mutex1);
          readCount = readCount + 1;
          if (readCount == 1) then
            P(writeBlock);
        V(mutex1);
      V(readBlock);
    V(writePending);
      access file;
    P(mutex1);
      readCount = readCount - 1;
      if (readCount == 0) then
        V(writeBlock);
    V(mutex1);
  }
}
```

```
writer(){
  while(TRUE) {
    P(mutex2);
      writeCount = writeCount + 1;
      if (writeCount == 1) then
         P(readBlock);
    V(mutex2);
    P(writeBlock);
       access file;
    V(writeBlock);
    P(mutex2);
      writeCount = writeCount - 1;
      if (writeCount == 0) then
         V(readBlock);
    V(mutex2);
  }
}
```



Implementing Counting Semaphores

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

```
P(struct sempahore s) {
  while( TS(s.mutex) );
  s.value = s.value - 1;
  if (s.value < 0) {
    s.mutex = FALSE;
    while( TS(s.hold) );
  }
else {
   s.mutex = FALSE;
}
```

```
V(struct sempahore s) {
  while( TS(s.mutex) );
  s.value = s.value + 1;
  if (s.value <= 0) {
    while( !s.hold );
    s.hold = FALSE;
  }
  s.mutex = FALSE;
}
```