Synchronization

Raju Pandey
Department of Computer Sciences
University of California, Davis
Winter 2005

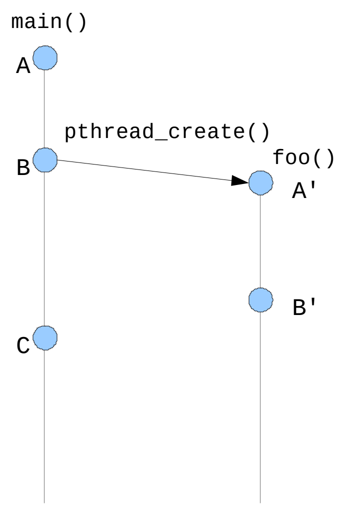
Concurrency

- Reasons for concurrency:
  - Multiple applications
    - Multiprogramming
  - Structured application
    - Application can be a set of concurrent processes
  - Operating-system structure
    - Operating system is a set of processes or threads
- Difficulties due to concurrency:
  - Sharing of global resources
  - Operating system managing the allocation of resources optimally
  - Difficult to locate programming errors

Temporal relations

- Instructions executed by a single thread are totally ordered
  - A < B < C < …
- Absent synchronization, instructions executed by distinct threads must be considered unordered / simultaneous
  - Not A < A’, and not A’ < A

Example



Y-axis is “time.”

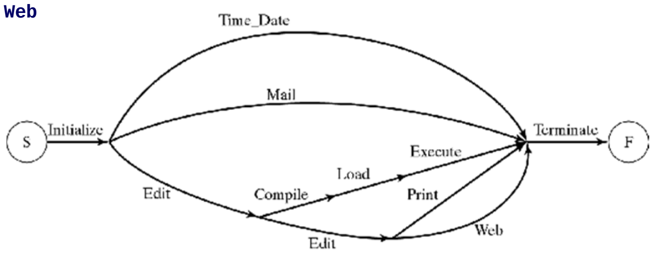
Could be one CPU, could be multiple CPUs (cores).

- A < B < C
- A' < B'
- A < A'
- C == A'
- C == B'

Syntax for Process Creation

- **cobegin / coend**
  - syntax: cobegin C1 // C2 // … // Cn coend
  - meaning:
    - o All Ci may proceed concurrently
    - o When *all* terminate, the statement following cobegin/coend continues

```
cobegin
    Time_Date //
    Mail //
    Edit; cobegin
      (Compile; Load; Execute) //
       Edit; cobegin
          Print // Web
       coend
    coend
coend;
```



Process Interactions

- Competition: The Critical Problem

```
x = 0;
cobegin
p1: …
     x = x + 1;
     …
     //
p2: …
     x = x + 1;
     …
coend
```

- **x** should be 2 after both processes execute
- Interleaved execution (due to parallel processing or context switching):

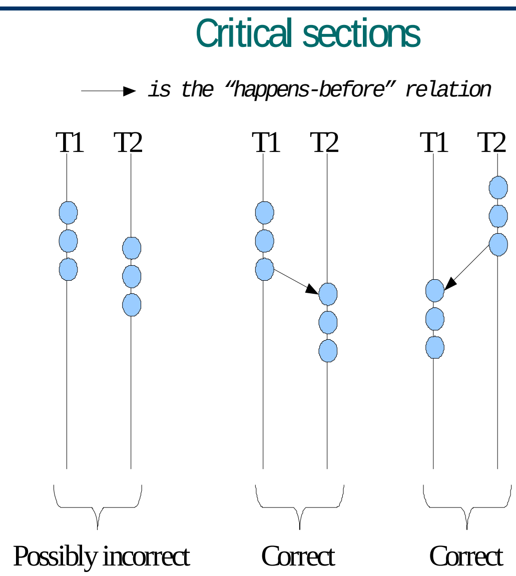
```
p1: R1 = x;           p2: …
    R1 = R1 + 1;          R2 = x;
    x = R1 ;              R2 = R2 + 1;
    …                     x = R2;
```

- **x** has only been incremented once; The first update (**x=R1**) is lost.

Critical Sections / Mutual Exclusion

- Sequences of instructions that may get incorrect results if executed simultaneously are called critical sections
- (We also use the term race condition to refer to a situation in which the results depend on timing)
- Mutual exclusion means "not simultaneous"
  - A < B or B < A
  - We don't care which
- Forcing mutual exclusion between two critical section executions is sufficient to ensure correct execution – guarantees ordering
- One way to guarantee mutually exclusive execution is using locks

Critical sections



When do critical sections arise?

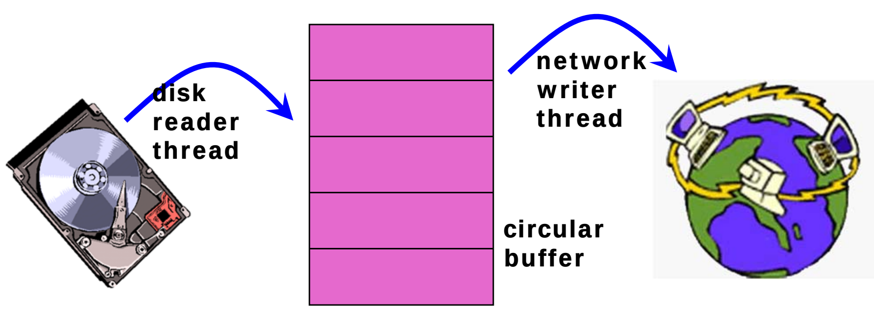
- One common pattern: Read-modify-write of
  - A shared value (variable)
  - In code that can be executed concurrently

    (Note: There may be only one copy of the code (e.g., a procedure), but it can be executed by more than one thread at a time)
- Shared variable:
  - Globals and heap-allocated variables
  - NOT local variables (which are on the stack)

    (Note: Never give a reference to a stack-allocated (local) variable to another thread, unless you're superhumanly careful ...)

Example: buffer management

- Threads cooperate in multithreaded programs
  - to share resources, access shared data structures
    - e.g., threads accessing a memory cache in a web server
  - also, to coordinate their execution
    - e.g., a disk reader thread hands off blocks to a network writer thread through a circular buffer



Example: shared bank account

- Suppose we have to implement a function to withdraw money from a bank account:

```
int withdraw(account, amount) {
  int balance = get_balance(account);     // read
  balance -= amount;                      // modify
  put_balance(account, balance);          // write
  spit out cash;
}
```

- Now suppose that you and your S.O. share a bank account with a balance of $100.00
  - what happens if you both go to separate ATM machines, and simultaneously withdraw $10.00 from the account?

- Assume the bank's application is multi-threaded
- A random thread is assigned a transaction when that transaction is submitted

```
int withdraw(account, amount) {
  int balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  spit out cash;
}
```

```
int withdraw(account, amount) {
  int balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  spit out cash;
}
```

Interleaved schedules

- The problem is that the execution of the two threads can be interleaved, assuming preemptive scheduling:

Execution sequence as seen by CPU

```
balance = get_balance(account);
balance -= amount;
```

context switch

```
balance = get_balance(account);
balance -= amount;
put_balance(account, balance);
spit out cash;
```

context switch

```
put_balance(account, balance);
spit out cash;
```

- What's the account balance after this sequence?
  - who's happy, the bank or you?
- How often is this sequence likely to occur?

Other Execution Orders

- Which interleavings are ok? Which are not?

```
int withdraw(account, amount) {
  int balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  spit out cash;
}
```

```
int withdraw(account, amount) {
  int balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  spit out cash;
}
```

How About Now?

```
int xfer(from, to, amt) {
  withdraw( from, amt );
  deposit( to, amt );
}
```

```
int xfer(from, to, amt) {
  withdraw( from, amt );
  deposit( to, amt );
}
```

- Morals:
  - Interleavings are hard to reason about
    - We make lots of mistakes
    - Control-flow analysis is hard for tools to get right
  - Identifying critical sections and ensuring mutually exclusive access is … "easier"

Terms related to concurrency

- **Critical section**: Section of code within a program/process that requires access to shared resource and which cannot be accessed while another process is in a corresponding section of code
- **Mutual Exclusion**: Requirement that when a process is in a critical section that accesses a shared resource, no other process may be in a critical section that access any of those resources
- **Race conditions**: A situation in which multiple threads or processes read or write a shared data item and the final result depends on the relative timing of their execution
- **Deadlock**: Situation where two or more processes are unable to proceed because each is waiting for other to do something
- **Livelock**: Situation where 2 or more processes continuously change their state in response to changes in others without doing any useful work
- **Starvation**: A situation in which a runnable process is overlooked indefinitely by the sceduler; although it is able to proceed, it is never chosen.
- **Fairness**: A constraint that ensures every process gets to run

Process Interaction

Degree of Awareness	Relationship	Influence the one process has on another	Potential control problem
Process unaware of each other	Competition	•Results of one process independent of the action of others •Timing of process may be affected	• Mutual exclusion •Deadlock (renewable resources) •Starvation
Process indirectly unaware of each other	Cooperation by sharing	•Results of one process may depend on information obtained from others •Timing of process may be affected	•Mutual exclusion •Deadlock(renewable resources) •Starvation •Data coherence
Processes directly aware of each other	Cooperation by communication	•Results of one process may depend on information obtained from others •Timing of process may be affected	•Deadlock(consumable resources) •Starvation

Requirements for Mutual Exclusion

- mutual exclusion
  - at most one thread is in the critical section
- progress
  - if thread T is outside the critical section, then T cannot prevent thread S from entering the critical section
- bounded waiting (no starvation)
  - if thread T is waiting on the critical section, then T will eventually enter the critical section
    - o assumes threads eventually leave critical sections
- performance
  - the overhead of entering and exiting the critical section is small with respect to the work being done within it

Mutual Exclusion: Hardware Support

- Interrupt Disabling
  - Disabling interrupts guarantees mutual exclusion
  - Processor is limited in its ability to interleave programs
  - Disadvantages:
    - o Responsiveness of system reduced
    - o May loose some important interrupts
    - o Does not work on multi-processing systems
      - disabling interrupts on one processor will not guarantee mutual exclusion

```
While (true) {
   disable interrupts
   critical section
   enable interrupts
   remainder
}
```


Mutual Exclusion: Hardware Support

- Special Machine Instructions
  - Performed in a single instruction cycle
  - Access to the memory location is blocked for any other instructions

Test and Set

```
boolean testset (int i) {

   if (i == 0) {
      i = 1;
      return true;
   } else return false;
}
```

Exchange Instruction

```
void exchange (int register,
                int memory) {
    int temp;
    temp = memory;
    memory = register;
    register = temp;
}
```

Mutual Exclusion (Test and Set)

```
const int n = /* number of processes */
int bolt;
void P(int i) {
        while (true) {
                while (! test_and_set (bolt))
                        /* do nothing */
                /* Critical Section */
                bolt = 0;
                /* Reminder */
        }
}
void main ()
{
        bolt = 0;
        cobegin
                P(1); P(2); ...; P(n);
        coend
}
```


Mutual Exclusion (Exchange)

```
const int n = /* number of processes */
int bolt;
void P(int i) {
        int keyi;
        while (true) {
                keyi = 1;
                while (keyi != 0)
                        exchange(keyi, bolt);
                /* Critical Section */
                exchange(keyi, bolt);
                /* Reminder */
        }
}
void main ()
{
        bolt = 0;
        cobegin P(1); P(2); ...; P(n); coend
}
```

Mutual Exclusion Machine Instructions

- Advantages
  - Applicable to any number of processes on either a single processor or multiple processors sharing main memory
  - It is simple and therefore easy to verify
  - It can be used to support multiple critical sections
- Disadvantages
  - Busy-waiting consumes processor time
  - Starvation is possible when a process leaves a critical section and more than one process is waiting.
  - Deadlock
    - o If a low priority process has the critical region and a higher priority process needs, the higher priority process will obtain the processor to wait for the critical region

Software: Algorithm 1

- Use a single "**turn**" variable:

```
int turn = 1;
cobegin
  p1: while (1) {
      while (turn==2); /*wait*/
          CS1; turn = 2; program1;
      }
  p2: while (1) {
      while (turn==1); /*wait*/
          CS1; turn = 1; program1;
      }
 // ...
```

- Violates blocking requirement;
- p1 can block p2 even if it is not inside critical section

Software Solutions: Algorithm 2

- Use two variables to indicate intent:

```
int c1 = 0, c2 = 0;
cobegin
p1: while (1) {
        c1 = 1;
        while (c2); /*wait*/
            CS1; c1 = 0; program1;
    }

p2: while (1) {
        c2 = 1;
        while (c2); /*wait*/
            CS1; c2 = 0; program2;
    }
```

- What if they access c1 and c2 at the same time?
  - Violates blocking requirement: deadlock. Processes wait forever.

Software Solutions: Algorithm 3

- Similar to #2, but reset intent variable each time:

```
int c1 = 0, c2 = 0;
cobegin
  p1: while (1) {
      c1 = 1;
      if (c2) c1 = 0;
      else {CS1; c1 = 0; program1}
      }
  p2: while (1) {
      c2 = 1;
      if (c1) c2 = 0;
      else {CS1; c2 = 0; program1}
   }
```

- What if p1 and p2 operate at same speed: livelock
- What if p2 always checks c1 after c2 has been set to 1: fairness

Software Solutions: Algorithm 4 (Peterson)

- Like #2 but use a "**turn**" variable to break a tie:

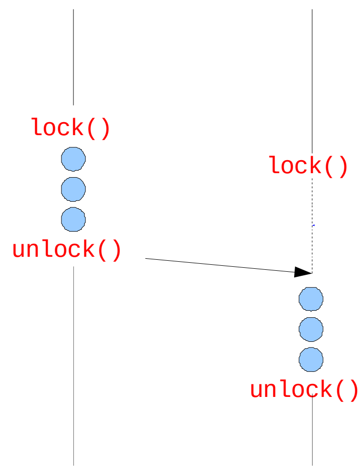
```
int c1 = 0, c2 = 0, WillWait;
cobegin
  p1: while (1) {
      c1 = 1;
      willWait = 1;
      while (c2 && (WillWait==1)); /*wait*/
      CS1; c1 = 0; program1;
    }
  p2: while (1) {
      c2 = 1;
      willWait = 2;
      while (c1 && (WillWait==2)); /*wait*/
      CS1; c2 = 0; program2;
    }
```

- Does it guarantee mutual exclusion?
- What about deadlock? What about livelock? Fairness?

Locks

- A lock is a memory object with two operations:
  - `acquire()`: obtain the right to enter the critical section
  - `release()`: give up the right to be in the critical section
- acquire() prevents progress of the thread until the lock can be acquired
- (Note: terminology varies: acquire/release, lock/unlock)

Locks: Example



Acquire/Release

- Threads pair up calls to `acquire()` and `release()`
  - between `acquire()`and `release()`, the thread holds the lock
  - `acquire()` does not return until the caller “owns” (holds) the lock
    - at most one thread can hold a lock at a time
  - What happens if the calls aren’t paired?
  - What happens if the two threads acquire different locks?
    - (granularity of locking)

Using locks

```
int withdraw(account, amount) {
  acquire(lock);
  balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  release(lock);
  spit out cash;
}
```

critical section

```
acquire(lock)
balance = get_balance(account);
balance -= amount;
```

```
acquire(lock)
```

```
put_balance(account, balance);
release(lock);
```

```
balance = get_balance(account);
balance -= amount;
put_balance(account, balance);
release(lock);
spit out cash;
```

```
spit out cash;
```

- What happens when green tries to acquire the lock?

Spinlocks

- How do we implement locks? Here’s one attempt:

```
struct lock_t {
  int held = 0;
}
void acquire(lock) {
   while (lock->held);
   lock->held = 1;
}
void release(lock) {
  lock->held = 0;
}
```

the caller “busy-waits”, or spins, for lock to be released ⇒ hence spinlock

- Why doesn’t this work?
  - where is the race condition?

Implementing locks (cont.)

- Problem is that implementation of locks has critical sections, too!
  - the acquire/release must be **atomic**
    - atomic == executes as though it could not be interrupted
    - code that executes "all or nothing"
- Need help from the hardware
  - atomic instructions
    - test-and-set, compare-and-swap, ...
  - disable/reenable interrupts
    - to prevent context switches

Spinlocks redux: Hardware Test-and-Set

- CPU provides the following as one atomic instruction:

```
bool test_and_set(bool *flag) {
  bool old = *flag;
  *flag = True;
  return old;
}
```

- Remember, this is a single atomic instruction ...

Implementing locks using Test-and-Set

- So, to fix our broken spinlocks:

```
struct lock {
  int held = 0;
}
void acquire(lock) {
   while(test_and_set(&lock->held));
}
void release(lock) {
  lock->held = 0;
}
```

  - mutual exclusion? (at most one thread in the critical section)
  - progress? (T outside cannot prevent S from entering)
  - bounded waiting? (waiting T will eventually enter)
  - performance? (low overhead)

Reminder of use …

```
int withdraw(account, amount) {
  acquire(lock);
  balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  release(lock);
  spit out cash;
}
```

critical section

```
acquire(lock)
balance = get_balance(account);
balance -= amount;
acquire(lock)
put_balance(account, balance);
release(lock);
balance = get_balance(account);
balance -= amount;
put_balance(account, balance);
release(lock);
spit out cash;
spit out cash;
```

- How does a thread blocked on an “acquire” (that is, stuck in a test-and-set loop) yield the CPU?
  - calls yield( ) *(spin-then-block)*
  - there’s an involuntary context switch

Problems with spinlocks

- Spinlocks work, but are horribly wasteful!
  - if a thread is spinning on a lock, the thread holding the lock cannot make progress
    - o You'll spin for a scheduling quantum
  - `(pthread_spin_t)`

- Only want spinlocks as primitives to build higher-level synchronization constructs
  - Why is this okay?

- We'll see later how to build blocking locks
  - But there is overhead – can be cheaper to spin
  - `(pthread_mutex_t)`

Another approach: Disabling interrupts

```
struct lock {
}
void acquire(lock) {
   cli();   // disable interrupts
}
void release(lock) {
  sti();    // reenable interrupts
}
```

Problems with disabling interrupts

- Only available to the kernel
  - Can't allow user-level to disable interrupts!
- Insufficient on a multiprocessor
  - Each processor has its own interrupt mechanism
- "Long" periods with interrupts disabled can wreak havoc with devices

- Just as with spinlocks, you only want to use disabling of interrupts to build higher-level synchronization constructs

Problems with suggested solution

- Difficult to understand and verify
- Solution is applicable only in cases when processes are competing for resources
- Busy waiting
  - Slows down overall system
- Fairness is not guaranteed or enforced

- Solution: Language/System primitives
  - Semaphores
  - Event synchronization
  - Monitors and others

Dijkstra's Semaphores

A **Semaphore** is a *non-negative integer*, **s** (how many tasks can proceed simultaneously), and *two indivisible operations*:

- **P(s)**, often written **Wait(s)**; think "Pause": "P" from "*passaren*" ("pass" in Dutch) or from "*prolagan*," combining "*proberen*" ("try") and "*verlagen*" ("decrease").
  - o **while (s<1)/*wait*/; s=s-1**
- **V(s)**, often written **Signal(s)**; think of the "V for Victory" 2-finger salute: "V" from "*vrigeven*" ("release") or "verhogen" ("*increase*").
  - o **s=s+1;**

Semaphore Primitives

```
struct semaphore {
        int count;
        queueType queue;
}
void semWait(semaphore s) {
        s.count --;
        if (s.count < 0) {
                place this process in s.queue;
                block this process;
        }
}
void semSignal(semphore s) {
        s.count++;
        if (s.count <= 0) {
                remove process P from s.queue;
                place process P on ready list;
        }
}
```

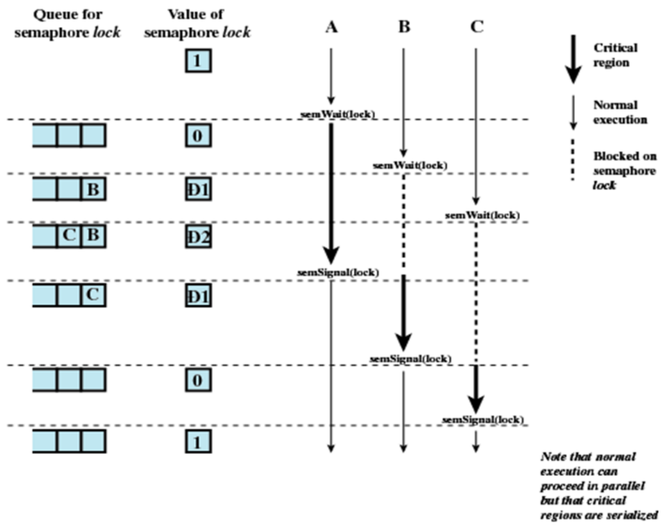
Binary Semaphore Primitives

```
struct binary_semaphore {
        enum {zero, one} value;
        queueType queue;
}
void semWaitB(binary_semaphore s) {
        if (s.value == one) s.value == zero;
        else {
                place this process in s.queue;
                block this process;
        }
}
void semSignal(binary_semphore s) {
        if (s.queue.is_empty())
                s.value = one;
        else {
                remove process P from s.queue;
                place process P on ready list;
        }
}
```


Mutual Exclusion with Semaphores

```
semaphore s;
const int n = /* number of processes
void P(int i) {
   while (true) {
        semWait(s);
        /* critical section */
        semSignal(s);
        /* remainder */
   }
}
void main() {
   s.count = 1; /* initialize the semaphore */
   cobegin P(1); P(2); ...; P(n); coend
}
```

Example



Producer/Consumer Problem

- Processes: producer and consumer
  - One or more producers are generating data and placing these in a buffer
  - A single consumer is taking items out of the buffer one at time
- Sharing:
  - A common buffer
- Synchronization problem:
  - Only one producer or consumer may access the buffer at any one time

Producer
```
while (true) {
        /* produce item v */
        b[in] = v;
        in++;
}
```

Consumer
```
while (true) {
        while (in <= out)
                /*do  nothing */;
        w = b[out];
        out++;
        /* consume item w */
}
```

Solution 1

int n; binary_semaphore s = 1; binary_semaphore delay = 0;

```
void producer() {
    while (true) {
      produce();
      semWaitB(s);
      append();
       n++;
       if (n == 1)
          semSignalB(delay);
       semSignalB(s);
    }
}
```

```
void consumer() {
     semWaitB(delay):
     while (true) {
       semWaitB(s);
       take();
       n--;
       semSignalB(s);
       consume();
       if (n == 0)
          semWaitB(delay);
     }
}
```

```
void main() {
        n = 0; cobegin producer(); consumer(); coend
}
```


Solution 2

int n; binary_semaphore s = 1; binary_semaphore delay = 0;

```
void producer() {
    while (true) {
      produce();
      semWaitB(s);
      append();
       n++;
       if (n == 1)
          semSignalB(delay);
       semSignalB(s);
    }
}
```

```
void consumer() {
    int m;
     semWaitB(delay):
     while (true) {
       semWaitB(s);
       take();
       n--;
       m = n;
       semSignalB(s);
       consume();
       if (m == 0)
          semWaitB(delay);
     }
}
```

```
void main() {
        n = 0; cobegin producer(); consumer(); coend
}
```

Solution 3

semaphore n = 0; semaphore s= 1;

```
void producer() {
    while (true) {
      produce();
      semWait(s);
      append();
      semSignal(s);
      semSignal(n);
    }
}
```

```
void consumer() {
    while (true) {
      semWait(n);
      semWait(s);
      take();
      semSignal(s);
      consume();
    }
}
```

```
void main() {
        cobegin producer(); consumer(); coend
}
```


Solution to bounded buffer problem

const int sizeofbuffer = /* buffers size */
semaphore n = 0; semaphore s= 1;
semaphore e = sizeofbuffer;

```
void producer() {
    while (true) {
      produce();
      semWait(e);
      semWait(s);
      append();
      semSignal(s);
      semSignal(n);
    }
}
```

```
void consumer() {
    while (true) {
      semWait(n);
      semWait(s);
      take();
      semSignal(s);
      semSignal(e);
      consume();
    }
}
```

```
void main() {
        cobegin producer(); consumer(); coend
}
```

Motivation

- Semaphores are:
  - Powerful but low-level abstractions
    - o Programming with them is highly error prone
    - o Such programs are difficult to design, debug, and maintain
  - Not usable in distributed memory systems
- Need higher-level primitives: Based on semaphores or messages
- Monitors (Hoare, 1974)
  - Follow principles of abstract data type (object-oriented) programming:
    - o A data type is manipulated only by a set of predefined operations
  - A monitor is
    1. A *collection of data* representing the state of the resource controlled by the monitor, and
    2. *Procedures* to manipulate that resource data

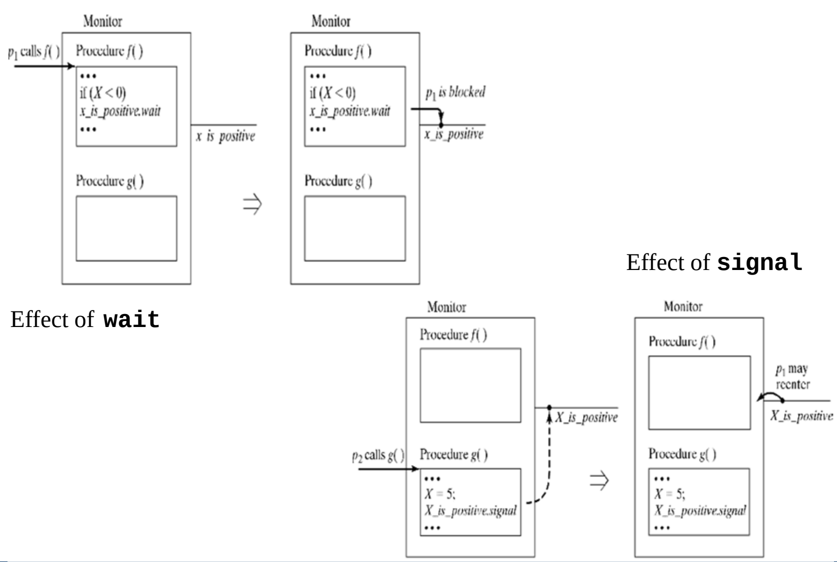
Monitors

- Implementation must guarantee:
  1. Resource accessible *only* by monitor procedures
  2. Monitor procedures are mutually exclusive
- For coordination, monitors provide:
  - **`c.wait:`** Calling process is blocked and placed on waiting queue associated with condition variable **c**
  - **`c.signal:`** Calling process wakes up first process on **c** queue
  - “condition variable” **c** is *not a conventional variable*
    - o **c** has no value
    - o **c** is an arbitrary name chosen by programmer to designate an event, state, or condition
    - o Each **c** has a waiting queue associated
    - o A process may “block” itself on **c** -- it *waits* until another process issues a *signal* on **c**

Hoare Monitors

- After **`c.signal`**, there are 2 ready processes:
  - The calling process which did the **`c.signal`**
  - The process which the **`c.signal`** “woke up”
- Which should continue?
  (Only one can be executing inside the monitor!)
- Hoare monitor:
  - Woken-up process continues
  - Calling process is placed on high-priority queue

Hoare Monitors



Monitor-based solution for Bounded buffers

```
monitor boundedbuffer;
char buffer[N]; int nextin, nextout; int count;
cond notfull, notempty;
void append(char x) {
   if (count == N) notfull.wait(); /* buffer is full*/
   buffer[nextin] = x; nextin = (nextin+1) mod N;
   count++;
   notempty.signal();
}
Void take(char x)
{
   if (count == 0) notempty.wait(); /* emptt buffer */
   x = buffer[nextout];
   nextout = (nextout+1) mod N;
   count--;
   notfull.signal();
}
void init() {
        nextin = 0; nextout = 0; count = 0;
}
```


Monitor-based solutin for Bounded buffers

```
void producer() {
    char x;
    while (true) {
      produce(x);
      append(x);
    }
}
```

```
void consumer() {
    char x;
    while (true) {
      take(x);
      consume(x);
    }
}
```

```
void main() {
        cobegin producer(); consumer(); coend
}
```

Readers/Writers Problem

- Processes: reader and writers
  - Readers: read file
  - Writers: write to file
- Sharing: common file
- Synchronization constraints:
  - Any number of readers may simultaneously read the file
  - Only one writer at a time may write to the file
  - If a writer is writing to the file, no reader may read it
  - Prevent starvation of either process type (variation 1)
    - o If Rs are in CS, a new R must not enter if W is waiting
    - o If W is in CS, once it leaves, all Rs waiting should enter (even if they arrived after new Ws

Reader/Writer Solution

```
int readcount; semaphore x = 1, wsem  = 1;
void reader() {
    while (true) {
      semWait(x);
      readcount++;
      if (readcount == 1)
         semWait(wsem);
      semSignal(x);
      READUNIT();
      semWait(x);
      readcount--;
      if (readcount == 0)
          semSignal(wsem);
      semSignal(x);
    }
}
```

```
void writer() {
   while (true) {
      semWait(wsem);
      WRITEUNIT();
      semSignal(wsem);
}
```

Readers have priority

```
void main() {
    readcount = 0;cobegin producer(); consumer(); coend
}
```

Reader/Writer Solution

Writers have priority

```
int readcount, writecount;
semaphore x = 1, y=1, z=1, wsem  = 1, rsem=1;
```

```
void reader() {
    while (true) {
      semWait(z);
        semWait(rsem);
          semWait(x);
              readcount++;
              if (readcount == 1)
                semWait(wsem);
          semSignal(x);
        semSignal(rsem);
      semSignal(z);
      READUNIT();
      semWait(x);
          readcount--;
          if (readcount == 0)
            semSignal(wsem);
      semSignal(x);
    }
}
```

```
void writer() {
    while (true) {
      semWait(y);
        writecount++;
        if(writecount == 1)
          semWait(rsem);
      semSignal(y);
      semWait(wsem);
      WRITEUNIT();
      semSignal(wsem);
      semWait(y);
        writecount--;
        if (writecount == 0)
          semSignal(rsem);
      semSignal(y);
    }
}
```

```
void main() {
    readcount = writecount = 0;cobegin producer(); consumer(); coend
}
```


Solution using monitor

```
monitor Readers_Writers {
   int readCount=0, writing=0;
   condition OK_R, OK_W;
   start_read() {
      if (writing || !empty(OK_W)) OK_R.wait;
      readCount = readCount + 1;
      OK_R.signal;
   }
   end_read() {
      readCount = readCount - 1;
      if (readCount == 0) OK_W.signal;
   }
   start_write() {
      if ((readCount != 0)||writing) OK_W.wait;
      writing = 1;
   }
   end_write() {
      writing = 0;
      if (!empty(OK_R)) OK_R.signal;
      else OK_W.signal;
   }
}
```