Silberschatz and Galvin
Chapter 6

Process Synchronization

Topics discussed

- Process synchronization
- Mutual exclusion--hardware
- Higher-level abstractions
  - Semaphores
  - Monitors
- Classical example problems

Process Synchronization

- Process *coordination*--Multi *processor* considerations caused by interaction of processes on multiple CPUs operating simultaneously
- Shared *state* (e.g., shared memory or shared variables)
- When concurrent processes interact through shared variables, the integrity of the variables' data may be violated if the access is not coordinated
- **What is the problem?**
- **How is coordination achieved?**

Process Synchronization Problem Statement

- Result of parallel computation on shared memory can be nondeterministic
- Example

  A = 1; || A = 2;
- What is result in A? 1, 2, 3, ...?
- *Race condition:* (race to completion)
  - cannot predict what will happen since the result depends on which one goes faster
  - what happens if both go at exactly the same speed?

Process Synchronization Example

Assume that X is a bank account balance

- **Process A: payroll**
- load X, R
  add R, 1000
  store R, X

- Proc B: ATM Withdraw
- load X, R
  add R, -100
  store R, X

If two processes are executed sequentially, e.g.,

load X, R
add R, 1,000
store R, X
…… O.S. context switch
load X, R
add R, -100
store R, X

No problem!

If two processes are interleaved, e.g.,

load X, R
add R, -100
…… O.S. context switch
load X, R
add R, 1,000
store R, X
…… O.S. context switch
store R, X

Problem occurs!

Basic Assumptions for system building

- The order of some operations are irrelevant (some operations are independent)

  A = 1; || B = 2;
- Can identify certain segments where interaction *is* critical
- **Atomic operation**(s) must exist in hardware
  - *Atomic operation*: either happens in its entirety without interruption or not at all
  - Cannot solve critical section problem without atomic operations

Atomic Operations

- Example, consider the possible outcomes of an atomic and a non-atomic `printf`

  `printf("ABC");` || `printf("CBA");`

  but printf is too big to be atomic (hundreds or thousands of instructions executed, I/O waits, etc.)
- Commonly-found atomic operations
  - memory references
  - assigments on simple scalars (e.g., single bytes or words)
  - operations with interrupts disabled on uniprocessor
- Cannot make atomic operations if you do not have them (but *can* use externally supplied operations like disk accesses if they are atomic to build more generally-useful atomic operations)
- More on implementation of atomic operations later

Process Coordination

- Lower-level atomic operations are used to build higher-level ones (more later)
  - e.g., semaphores, monitors, etc.
- Note: in analysis, no assumption on the relative speed of two processes can be made. Process coordination requires explicit control of concurrency.

Process Coordination Problems Producer/Consumer applications

- **Producer**--creates information
- **Consumer**--uses information
- Example--piped applications in Unix
  cat file.t | eqn | tbl | troff | lpr
- **Bounded buffer** between producer and consumer is filled by producer and emptied by consumer

Bounded Buffer

<u>initialize counter, in, out to 0</u>

Producer

```
while (true)  {
    produce an item in nextp;
    while counter == n do noop;
    buffer[in] = nextp;
    in = in + 1 mod n;
    counter = counter + 1;
}
```

Consumer

```
while (true)  {
    while counter == 0 do noop;
    nextc := buffer[out];
    out := out + 1 mod n;
    counter := counter - 1;
    consume item in nextc;
}
```


Bounded Buffer

- Concurrent execution of producer and consumer can cause unexpected results, even if we assume that assignment and memory references are atomic
- For example, interleavings can result in counter value of n, n+1, or n-1 when there are really n values in the buffer

Producer	*Consumer*
load counter	
	load counter
	subtract 1
	store counter
add 1	
store counter	

results in a value of n+1

Controlling interaction

- Similar problems even when we are running the *same* code in the two processes
  - Example: shopping expedition
- Need to manage interaction in areas in which interaction is critical
- **Critical section**: section of code or collection of operations in which only one process may be executing at a given time
  - examples: counter, shopping

Critical Section

initialize counter, in, out to 0

Producer

```
while (true) {
    produce an item in nextp;
    while counter == n do noop;
    buffer[in] = nextp;
    in = in + 1 mod n;
    counter = counter + 1;
}
```

Consumer

```
while (true) {
    while counter == 0 do noop;
    nextc := buffer[out];
    out := out + 1 mod n;
    counter := counter - 1;
    consume item in nextc;
}
```

Critical Sections

Critical Section

- Critical section operations
  - entry: request permission to enter critical section
  - exit: marks the end of the critical section
- **Mutual exclusion**: make sure that only one process is in the critical section at any one time
- **Locking**: prevent others from entering the critical section
- entry then is acquiring the lock
- exit is releasing the lock

Critical Section

- Solution must provide
  - Mutual exclusion
  - Progress: if multiple processes are waiting to enter the critical section and there is no process in the critical section, eventually one of the processes will gain entry
  - Bounded waiting: no indefinite postponement
  - Deadlock avoidance
    - deadlock example
      P1 gains resource A; P2 gains resource B;
      P1 waits for resource B; P2 waits for resource A;
- Next, we will consider a number of potential solutions

Critical Section Solution? Using a counter to show turn

turn := 1;

```
while(true) {
    non critical stuff
    while (turn == 2); /* wait */
    critical section
    turn = 2;
    non critical stuff
}
```

```
while(true) {
    non critical stuff
    while (turn == 1); /* wait */
    critical section
    turn = 1;
    non critical stuff
}
```


Critical Section Solution? Check if other process busy

p1busy := false; p2busy := false;

```
while(true) {
    non critical stuff
    while (p2busy); /* wait */
    p1busy = true;
    critical section
    p1busy = false;
    non critical stuff
}
```

```
while(true) {
    non critical stuff
    while (p1busy); /* wait */
    p2busy = true;
    critical section
    p2busy = false;
    non critical stuff
}
```

Critical Section Solution? Set flag <u>before</u> check

p1busy := false; p2busy := false;

```
while(true) {
    non critical stuff
    p1busy = true;
    while (p2busy); /* wait */
    critical section
    p1busy = false;
    non critical stuff
}
```

```
while(true) {
    non critical stuff
    p2busy = true;
    while (p1busy); /* wait */
    critical section
    p2busy = false;
    non critical stuff
}
```


Critical Section Solution? More complicated wait

p1busy := false; p2busy := false;

```
while(true) {
    non critical stuff
    p1busy = true;
    while(p2busy) {
        p1busy = false;
        sleep;
        p1busy = true;
    }
    critical section
    p1busy = false;
    non critical stuff
}
```

```
while(true) {
    non critical stuff
    p2busy = true;
    while(p1busy) {
        p2busy = false;
        sleep;
        p2busy = true;
    }
    critical section
    p2busy = false;
    non critical stuff
}
```

Mutual exclusion solution requirements

- Mutual exclusion is preserved
- The progress requirement is satisfied
- The bounded-waiting requirement is met

Critical Section Solution? Peterson's Algorithm (Alg. 3)

turn = 1; p1busy = false; p2busy = false;

```
while(true) {
    non-critical stuff
    p1busy = true;
    turn = 2;
    while (p2busy and turn == 2)
        ;          /* wait */
    critical section
    p1busy = false;
    non critical stuff
}
```

```
while(true) {
    non-critical stuff
    p2busy = true;
    turn = 1;
    while (p1busy and turn == 1)
        ;          /* wait */
    critical section
    p2busy = false;
    non critical stuff
}
```

Mutual Exclusion Hardware Implementation

- Implementation requires atomic hardware operation
- For example, test-and-set

```
function test-and-set(var target:boolean): boolean;
begin
        test-and-set = target;
        target = true;
end;
```

- Sample use

```
lock = false;
miscellaneous processing...
while(true)  {
        while(test-and-set(lock)) do   ;
        critical section
        lock = false;
}
```


Mutual Exclusion in Hardware

- Can also use other atomic operations (swap, etc.) to implement if test-and-set is not available
- What are the problems?
  - Hardware dependent. Different hardware requires different implementation
  - Hard to generalize to more complex problems
  - Inefficient because of busy wait
- In general, would prefer to use an *abstraction*, which could be implemented *once* for each hardware architecture.
- **Semaphores**: one such abstraction

Semaphores

- Defined by Dijkstra (1965)
- Two operations, P(s) and V(s). s is the **semaphore**, a non-negative integer
- **P**: from the Dutch *probern* (to test) represents a wait
  - P(s)--decrement s by 1 if possible (i.e., without going negative). If s==0 then wait until it is possible to decrement s without going negative.
- **V**: from the Dutch *verhogen* (to increment) represents a signal
  - V(s)--increment s by 1 in a single atomic action

Mutual Exclusion using Semaphores

mutex = 1; /* mutex is the semaphore */

miscellaneous processing...

while (true) {

  P(mutex);

  critical section

  V(mutex);

}

Bounded Buffer with Semaphores

n, the number of buffers, semaphores e, the number of empty buffers, f, the number of full buffers, and b, mutex

e = n; f = 0; b = 1;

Producer

```
while(true) {
    produce next record
    P(e); P(b);
    add to buffer
    V(b); V(f);
}
```

Consumer

```
while(true) {
    P(f); P(b);
    remove from buffer
    V(b); V(e);
    process record
}
```


Semaphores are still low-level

- Semaphores can allow implementation of deadlock

Process one	Process two
P(s);	P(q);
P(q);	P(s);
critical section	*critical section*
V(s);	V(q);
V(q);	V(s);

- Implementation might permit starvation (no guarantees)
- Consequently, even higher-level mechanisms have been developed (to be considered later)

Semaphore Implementation with Hardware atomic actions

- Implementation using test-and-set
- First implement *binary* semaphores
  - Value is either 0 or 1
- Use binary semaphores to implement general semaphores

Implementing binary semaphores

- Binary semaphores Pb(sb) and Vb(sb)
  - sb == false means we can pass
  - sb == true means we must wait
- Pb(sb): while (test-and-set(sb)) do ;
- Vb(sb): sb := false;

Implementing general semaphores

- binary semaphores: mutex and delay
- P(s):

```
Pb(mutex);
s = s - 1;
if(s < 0) then {Vb(mutex); Pb(delay);}
Vb(mutex);
```

- V(s):

```
Pb(mutex);
s = s + 1;
if (s <= 0) then Vb(delay) else Vb(mutex);
```


Semaphore Implementation

- Disadvantage of using test-and-set is busy wait
- However, can implement P and V in more complex ways--for example, block process on P if the resource is busy with the subsequent V unblocking the next process to run (see text section 6.4.2).

Monitor: A Language Construct for Process Synchronization

Syntax of Monitor

type monitor-name = **monitor**
variable declarations

procedure entry P1 (...);
begin
...
end;
......
procedure entry Pn (...);
begin
...
end;

begin
initialization code
end.

Semantic Rules

- Only one process can execute an entry procedure at any time.
- If a process calls an entry procedure while some process is inside the monitor, the caller is put on a waiting queue until the monitor is empty.

Notes about Monitors

- Monitors are a high-level data abstraction tool
- Based on *abstract data types*
  - For any distinct data type there should be a well-defined set of operations through which any instance of the data *must* be manipulated
  - Monitor is implemented as a collection of data (i.e., a resource) and a set of procedures that manipulate the resource
  - Access data *only* through the monitor procedures--outside procedures cannot access monitor's variables
  - Similarly, monitor procedures only access monitor's variables and formal parameters. Scoping rules followed within the monitor.
- Monitor is higher-level than P and V hence is safer and easier to use

Monitor Example

```
type atomic-write = monitor
var count: integer;
procedure entry aputs(s: string)
    begin
        count := count + 1;
        writeln(count,': ', s);
    end;
begin
    count = 0;
end.
```


Monitor condition variables

- At most one procedure can be active in monitor at any time
  - Simplifies synchronization specification!
- What if a procedure has to wait for another procedure to act before continuing (for example: reading from an empty buffer)?
- Add the concept of *condition variables*

Conditional Variables in Monitor

Syntax:

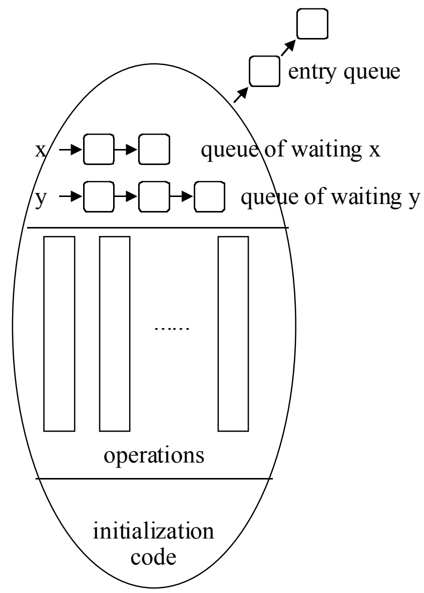
Declaration: **var** x : condition

Use: x.wait and x.signal

Semantics:

A process invoking x.wait is suspended until another process invokes x.signal.

Question?
After x.signal, who should proceed?



Monitor Condition Variables

- P is executing and invokes x.signal; Q is waiting, having invoked x.wait in the past
- Should Q be permitted to resume execution immediately? What about P?
- Continuation options
  - Q remains suspended until P leaves the monitor or P performs a "wait"
  - P suspends and waits until Q either leaves the monitor or Q performs another "wait"
- First choice seems "fairer" since P already is executing
  - Condition Q waiting on may not still hold if P continues executing
- Second choice permits P to invoke multiple signals
- Both have been advocated in practice

Monitor Condition Variables

- Further details
  - if several processes are waiting on a condition, which is resumed?
    - This is a scheduling decision
  - if no process is waiting on a condition, what is the effect of an x.signal?
    - x.signal becomes a nop

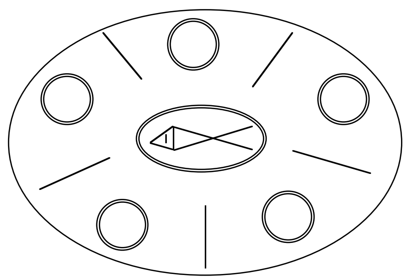
Monitor Example

```
type bounded buffer = monitor
    var buffer: array [0..n-1] of item;
            counter, in, out: integer;
            notempty, notfull: condition;
procedure entry add(item);
    begin
            if (counter == n) then
                        notfull.wait;
            buffer[in] := item;
            in := (in + 1) mod n;
            counter := counter + 1;
            notempty.signal;
    end;
```

```
procedure entry remove(var item);
    begin
            if (counter == 0) then
                        notempty.wait;
            item := buffer[out];
            out := (out + 1) mod n;
            counter := counter - 1;
            notfull.signal;
    end;
begin
    counter := 0;  in := 0; out := 0;
end.
```

Dining Philosophers Problems

- n philosophers spend their lives thinking and eating.
- From time to time, a philosopher gets hungry and tries to pick up the two chopsticks and eat.
- A philosopher may pick up one chopstick at a time. He needs two to eat. When he finishes, he releases the two chopsticks and starts thinking again.



Dining Philosophers Semaphore Solution

- Possible solution: each chopstick is a semaphore
  - **var** chopstick: **array** [0..4] **of** *semaphore*;
  - **while**(true) {
    P(chopstick[i]);
    P(chopstick[i+1 **mod** 5]);
    ... eat ...
    V(chopstick[i]);
    V(chopstick[i+1 **mod** 5]);
    ... think ...
    }
  - possibility of deadlock (e.g., each philosopher grabs left chopstick simultaneously)

DiningPhilosophers Semaphore Solution

- So, simple solution is not adequate. Try some more complex solutions:
  - Pick up left, see if right available. If not, release left.
  - Odd philosophers pick up left first; even ones pick up right first
  - Philosopher picks up chopsticks only if both are available (an additional critical section)
    - Solution hint: add notion of state (HUNGRY, THINKING, EATING). Check state of neighbors.
- Goals
  - no starvation
  - maximal concurrency (n-1 philosophers can eat at the same time)

Dining Philosophers Semaphore Solution

semaphores: mutex (initially == 1) for for fork acquisition and return

phil(N), one per philosopher, to indicate that the philosopher is blocked awaiting fork release (initially == 0)

```
get_forks(i) {
    P(mutex);
    state[i] := HUNGRY;
    test(i);  /* to be defined---test that forks are
              available and acquire if so */
    V(mutex);
    P(phil[i]);         /* block if forks not
              available---see test() */
}
```

```
put_forks(i) {
    P(mutex);
    state[i] = THINKING;
    test((i-1) mod N);
    test((i+1) mod N);
    V(mutex);
}
test(i) {
    if((state[i] == HUNGRY) &&
            (state[(i-1) mod N] != EATING) &&
            (state[(i+1) mod N] != EATING) &&
    {
                    state[i] := EATING;
                    V(phil[i]);
    }
}
```

Dining Philosophers Monitor Solution

```
type dining-philosophers = monitor
var state: array[0..4] of (thinking, hungry, eating);
    self: array[0..4] of condition;

procedure entry test(k: 0..4);
   begin
     if state[k+4 mod 5] <> eating and
       state[k] = hungry and
         state[k+1 mod 5] <> eating
       then begin
            state[k] := eating;
            self[k].signal;
       end;
   end;
```



```
procedure entry pickup(i: 0..4);
begin
   state[i] := hungry;
   test(i);
   if state[i] <> eating then
     self[i].wait;
end;

procedure entry putdown(i: 0..4);
begin
  state[i] := thinking;
  test(i+4 mod 5);
  test(i+1 mod 5);
end;

begin
  for i := 0 to 4
    do state[i] := thinking;
end.
```

```
Process Philosopher i

begin

  repeat

    pickup(i);

    eating;

    putdown(i);

    thinking

  until false;

end.
```

Classical Problems Readers/Writers (summary only)

- Two categories of processes accessing a data object
  - Readers (examine object)
  - Writers (modify object)
- Multiple *readers* can access object simultaneously without conflict
- *Writer* must have exclusive access to object, otherwise inconsistencies may arise
  - two writers modifying object simultaneously
  - reader getting inconsistent information because of access during write

Readers/Writers Summary

- Writers have exclusive access to object
- Reader behavior depends on definition of problem chosen
  - *First* readers-writers problem: no reader is kept waiting unless a writer has already obtained permission to use the shared object (i.e., readers don't have to wait merely because a writer is waiting).
  - *Second* readers-writers problem: writer performs write as soon as possible once ready (i.e., no new readers can enter once a writer is waiting).
- See text figures 6.12 and 6.13 for one solution (pp. 183 and 184).