# V22.0202-001
# Computer Systems Organization II (Honors)
(Introductory Operating Systems)

Lecture 9

Classical Synchronization Problems

Language Support for Synchronization

February 16, 2005

## Outline

- Announcements
  - Lab 2 due today, demos today, tomorrow
  - No class on Monday, February 21st

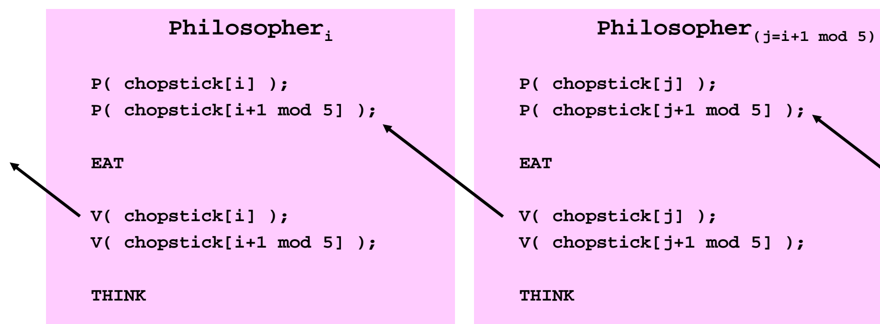
Process Synchronization (cont'd)

- Classical synchronization problems (cont'd)
  - Dining philosophers
  - A larger example
- Language support for synchronization
  - Conditional critical regions
  - Monitors

*[ Silberschatz/Galvin/Gagne: Sections 6.6-6.7 ]*



## Dining Philosophers Using Semaphores



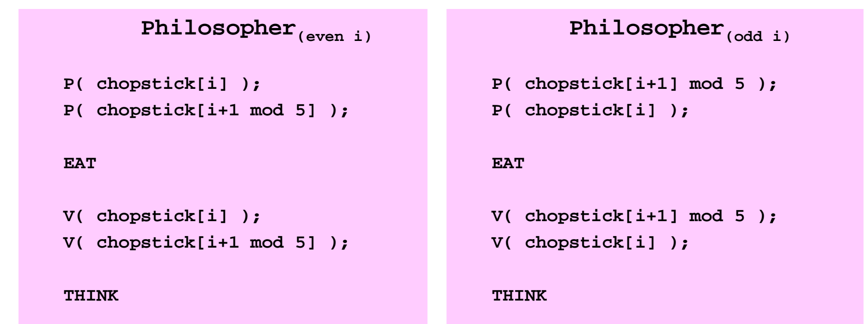

- Deadlock

  *a set of processes is in a deadlock state when every process in the set is waiting for an event that can be caused only by another process in the set*

  - details in Lectures 10 and 11.



## Dining Philosophers Using Semaphores - 2




- Alternate solutions
  - allow at most 4 philosophers to sit simultaneously at the table
  - allow a philosopher to pick up chopsticks only if both are available
- All of these solutions suffer from the possibility of starvation!

# A Larger Example: A Barbershop Problem

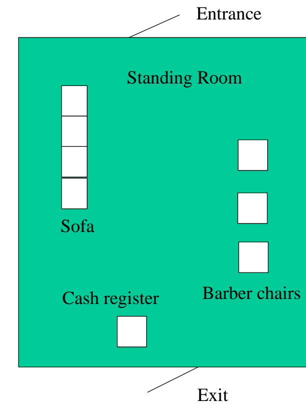
- Example taken from

  Operating Systems: Internals and Design Principles, 3rd Edition
  William Stallings, Prentice Hall, 1998

- The problem: Orchestrating activities in a barbershop
  - 3 chairs, 3 barbers, 1 cash register,
    waiting area: 4 customers on a sofa, plus additional standing room
  - Fire codes limit total number of customers to 20 at a time
  - A customer
    - Will not enter the shop if it is filled to capacity
    - Takes a seat on the sofa, or stands if sofa is filled
    - When a barber is free, the customer waiting longest on sofa is served
      The customer standing the longest takes up seat on the sofa
    - When a customer's haircut is finished, any barber can accept payment but because of the single cash register, only one payment is accepted at a time
    - Barbers divide their time between cutting hair, accepting payment, and sleeping



# A Barbershop Problem (cont'd)




- Shop and sofa capacity
  - **max_capacity** (initial value = 20)
  - **sofa** (initial value = 4)
- Barber chair capacity
  - **barber_chair** (initial value = 3)
- Ensuring customers are in barber chair
  - **cust_ready** (initial value = 0)
    - barber waits for customer
  - **finished** (initial value = 0)
    - customer waits for haircut to finish
  - **leave_b_chair** (initial value = 0)
    - barber waits for chair to empty
- Paying and receiving
  - **payment** (initial value = 0)
    - cashier waits for customer to pay
  - **receipt** (initial value = 0)
    - customer waits for cashier to ack
- Coordinating barber functions
  - **coord** (initial value = 0)
    - wait for a barber resource to free up



# A Barbershop Problem (cont'd)

- **Shop and sofa capacity**
  - max_capacity (: = 20)
  - sofa (: = 4)
- **Barber chair capacity**
  - barber_chair (: = 3)
- **Ensuring customers are in barber chair**
  - cust_ready (: = 0)
  - finished (: = 0)
  - leave_b_chair (: = 0)
- **Paying and receiving**
  - payment (: = 0)
  - receipt (:= 0)
- **Coordinating barber functions**
  - coord (:= 0)

**Customer**

```
P( max_capacity );
// enter shop
P( sofa );
// sit on sofa
P( barber_chair );
// get up from sofa
V( sofa );
// sit in barber chair
V( cust_ready );
P( finished );
// leave barber chair
V( leave_b_chair );
// pay
V( payment );
P( receipt );
// exit shop
V( max_capacity );
```

**Barber**

```
P( cust_ready );
P( coord );
// cut hair
V( coord );
V( finished );
// wait for customer to leave
P( leave_b_chair );
// tell next customer to hop on
V( barber_chair );
```

**Cashier**

```
P( payment );
P( coord );
// accept payment
V( coord );
V( receipt );
```



# A Barbershop Problem (cont'd): Mutual Exclusion

- **Shop and sofa capacity**
  - max_capacity (: = 20)
  - sofa (: = 4)
- **Barber chair capacity**
  - barber_chair (: = 3)
- **Ensuring customers are in barber chair**
  - cust_ready (: = 0)
  - finished (: = 0)
  - leave_b_chair (: = 0)
- **Paying and receiving**
  - payment (: = 0)
  - receipt (:= 0)
- **Coordinating barber functions**
  - coord (:= 0)

**Customer**

```
P( max_capacity );
// enter shop
P( sofa );
// sit on sofa
P( barber_chair );
// get up from sofa
V( sofa );
// sit in barber chair
V( cust_ready );
P( finished );
// leave barber chair
V( leave_b_chair );
// pay
V( payment );
P( receipt );
// exit shop
V( max_capacity );
```

**Barber**

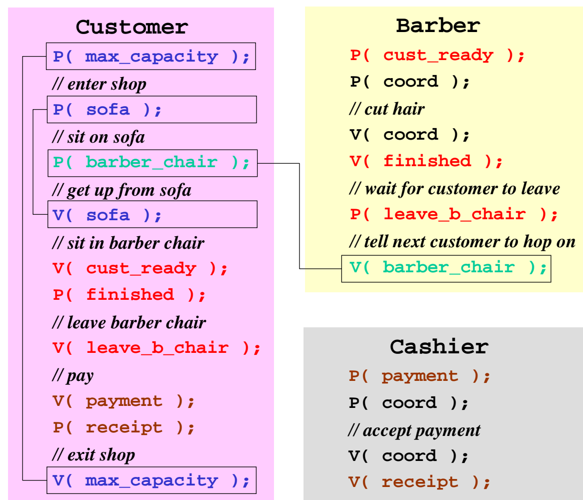
```
P( cust_ready );
P( coord );
// cut hair
V( coord );
V( finished );
// wait for customer to leave
P( leave_b_chair );
// tell next customer to hop on
V( barber_chair );
```

**Cashier**

```
P( payment );
P( coord );
// accept payment
V( coord );
V( receipt );
```

## A Barbershop Problem (cont'd): Bounded Buffer

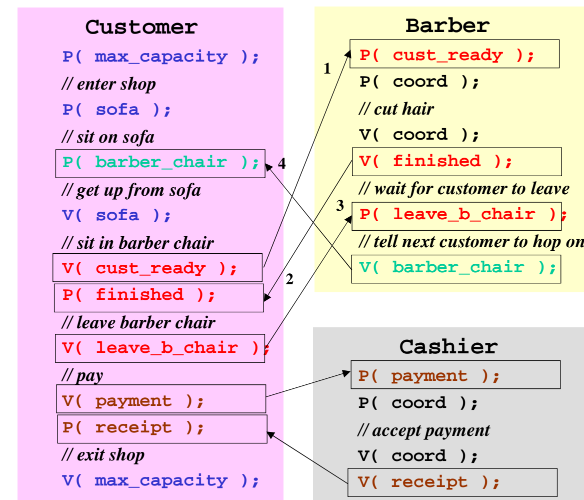
- Shop and sofa capacity
  - max_capacity (: = 20)
  - sofa (: = 4)
- Barber chair capacity
  - barber_chair (: = 3)
- Ensuring customers are in barber chair
  - cust_ready (: = 0)
  - finished (: = 0)
  - leave_b_chair (: = 0)
- Paying and receiving
  - payment (: = 0)
  - receipt (:= 0)
- Coordinating barber functions
  - coord (:= 0)






## A Barbershop Problem (cont'd): Sequencing

- Shop and sofa capacity
  - max_capacity (: = 20)
  - sofa (: = 4)
- Barber chair capacity
  - barber_chair (: = 3)
- Ensuring customers are in barber chair
  - cust_ready (: = 0)
  - finished (: = 0)
  - leave_b_chair (: = 0)
- Paying and receiving
  - payment (: = 0)
  - receipt (:= 0)
- Coordinating barber functions
  - coord (:= 0)






## A Barbershop Problem (cont'd)

- Some problems with the current solution
  - since all customers are waiting on the same semaphore (**finished**), the one who started earliest is released when a barber does **V( finished)**
    - even if the haircut is not done
  - similar problem with the cashier and the **pay** and **receipt** semaphores
    - cashier may accept money from one customer and release another
  - a customer needs to wait on the sofa even if a barber chair is free
- All of these can be solved using additional semaphores



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Process Synchronization (cont'd)

- Classical synchronization problems (cont'd)
  - Dining philosophers
  - A larger example
- Language support for synchronization
  - Conditional critical regions
  - Monitors

*[ Silberschatz/Galvin/Gagne: Sections 6.6-6.7 ]*

## Limitations of Semaphores

- No abstraction and modularity
  - a process that uses a semaphore has to know which other processes use the semaphore, and how these processes use the semaphore
  - a process cannot be written in isolation
- Consider sequencing between three processes
  - $P_1, P_2, P_3, P_1, P_2, P_3, \ldots$

| $P_1$ | $P_2$ | $P_3$ |
|---|---|---|
| `P( sem1 );` | `P( sem2 );` | `P( sem3 );` |
| `// do stuff` | `// do stuff` | `// do stuff` |
| `V( sem2 );` | `V( sem3 );` | `V( sem1 );` |

What happens if there are only two processes?
What happens if you want to use this solution for four processes?



## Limitations of Semaphores (contd.)

- Very easy to write incorrect code
  - changing the order of P and V
    - can violate mutual exclusion requirements

```
V( mutex ); CODE; P( mutex );  instead of
P( mutex ); CODE; V( mutex );
```

    - can cause deadlock

```
P( seq );  instead of
V( seq );
```

  - similar problems with omission
- Extremely difficult to verify programs for correctness
- Need for still higher-level synchronization abstractions!



## Language Support

- Helps simplify expression of synchronization
  - more convenient
  - more secure
  - less buggy
- We shall examine two fundamental constructs
  - conditional critical regions
  - monitors
- These constructs can be found in several concurrent languages
  - Communicating Sequential Processes (CSP) *critical regions*
  - Concurrent Pascal *monitors*
  - object-oriented languages: Modula-2, Concurrent C, Java
  - Ada83, Ada95



## Conditional Critical Regions

- A high-level language declaration
  - informally, it can be used to specify that while a statement *S* is being executed, no more than one process can access a distinguished variable *v*
  - notation

```
var v: shared t;
region v when B do S;
```

    - ***v*** is shared and of type *t*
      - can only be accessed within a region statement
    - ***B*** is a Boolean expression
    - ***S*** is a statement
      - can be a compound statement
- Semantics
  - A process is guaranteed mutually exclusive access to the region *v*
  - Checking of *B* and entry into the region happens atomically

# Conditional Critical Regions: Benefits

Bounded-buffer producer/consumer

```
var buffer : shared record
   pool: array [0..n-1] of item;
   count, in, out: integer;
end;

Producer:
region buffer when count < n
  do begin
     pool[in] := nextp;
     in := (in + 1) mod n;
     count := count + 1;
  end;

Consumer:
region buffer when count > 0
  do begin
     nextc := pool[out];
     out := (out + 1) mod n;
     count := count - 1;
  end;
```

- Guards against simple errors associated with semaphores
  - e.g., changing the order of P and V operations, or forgetting to put one of them
- Division of responsibility
  - the *developer* does not have to program the semaphore or alternate synchronization explicitly
  - the *compiler* ``automatically" plugs in the synchronization code using predefined libraries
  - once done carefully, *reduces* likelihood of mistakes in designing the delicate synchronization code



# Conditional Critical Regions: Implementation

```
var mutex: semaphore;

P( mutex );
while not B
   do begin
      try-and-enter;
   end;
S;
leave-critical-region;
```

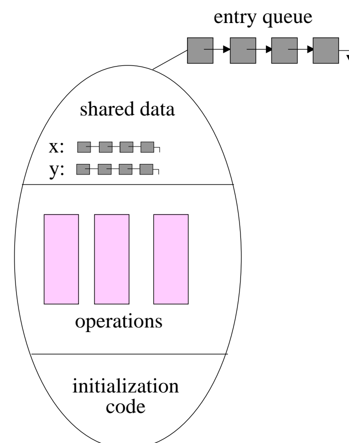
```
var delay: semaphore;
var count: integer;

count++ ;
V( mutex );
P( delay );
// check condition
if ( not B )
  if ( count > 1 )
    // release another
    V( delay );
    P( delay );
  else
    V( mutex );
    P( delay );
else count-- ;

if ( count > 0 )
then V( delay );
else V( mutex );
```

```
var first, second: semaphore;
var fcount, scount: integer;

fcount++ ;
if ( scount > 0 ) V( second );
else V( mutex );
P( first );
fcount-- ;
scount++ ;
if ( fcount > 0 ) V( first );
else V( second );
P( second );
scount-- ;

if ( fcount > 0 ) V( first );
else if ( scount > 0 ) V( second );
else V( mutex );
```



# Language Support (2): Monitors

- An abstract data type
  - private data
  - public procedures
    - only one procedure can be in the monitor at one time
    - each procedure may have
      - local variables
      - formal parameters
  - condition variables
    - queues of processes
    - *wait*: block on a condition variable
    - *signal*: unblock a waiting process
      - no-op if no process is waiting
- Processes can only invoke the public procedures
  - raises the granularity of atomicity to a single user-defined procedure






# Waiting in the Monitor

- Note that the semantics of executing a *wait* in the monitor is that several processes can be waiting “inside” the monitor at any given time but only one is executing
  - wait queues are internal to the monitor
  - there can be multiple wait queues
- Who executes after a signal operation? (say P signals Q)
  - (Hoare semantics) signallee Q continues
    - logically natural since the condition that enabled Q might no longer be true when Q eventually executes
      - P needs to wait for Q to exit the monitor
  - (Mesa semantics) signaller P continues
    - Q is enabled but gets its turn only after P either leaves or executes a *wait*
  - require that the *signal* be the last statement in the procedure
    - advocated by Brinch Hansen (Concurrent Pascal)
    - easy to implement but less powerful than the other two semantics

## Use of Monitors: Bounded-buffer

```
type bounded_buffer = monitor

  var buffer: array [0..N] of char;
  var in, out, count: integer;
  var notfull, notempty: condition;

  procedure entry append ...
  procedure entry remove ...

  begin
   in = 0; out = 0; count = 0;
  end;
```

```
procedure entry append(x: char);
  if (count==N) notfull.wait;
  buffer[in] := x;
  in := (in+1) mod N;
  count := count+1;
  notempty.signal;

procedure entry remove(x: char);
  if (count==0) notempty.wait;
  x := buffer[out];
  out := (out+1) mod N;
  count := count-1;
  notfull.signal;
```

Is this solution correct under all monitor semantics? (P signals Q)

Hoare: Q continues, P suspends ................................ YES

Mesa: P continues, Q is put into ready queue ............... NO

Brinch-Hansen: P exits monitor, Q continues ..............YES



## Use of Monitors: Bounded-buffer (Mesa Semantics)

```
type bounded_buffer = monitor

  var buffer: array [0..N] of char;
  var in, out, count: integer;
  var notfull, notempty: condition;

  procedure entry append ...
  procedure entry remove ...

  begin
        in = 0; out = 0; count =
0;
  end;
```

```
procedure entry append(x: char);
  while (count==N) notfull.wait;
  buffer[in] := x;
  in := (in+1) mod N;
  count := count+1;
  notempty.signal;

procedure entry remove(x: char);
  while (count==0) notempty.wait;
  x := buffer[out];
  out := (out+1) mod N;
  count := count-1;
  notfull.signal;
```



## Use of Monitors: Dining Philosophers

- Goal: Solve DP without deadlocks
- Informally:
  - algorithm for Philosopher I

    ```
    dp.pickup(i);
    eat;
    dp.putdown(i);
    ```

  - use array to describe state

    ```
    var state: array [0..4] of
      (thinking, hungry, eating);
    ```

  - use array of condition variables to block on when required resources are unavailable

    ```
    var self: array [0..4] of
      condition;
    ```

- pickup(i)
  - changes state to hungry
  - checks if neighbors are eating
  - if not, grabs chopsticks, and changes state to eating
  - otherwise, waits on self(i)
- putdown(i)
  - checks both neighbors
  - if either is hungry and can proceed, releases him/her



## Dining Philosophers using Monitors - 2

```
type dining_philosophers = monitor

  var state: array [0..4] of
   (thinking, hungry, eating);
  var self: array [0..4] of
   condition;

  procedure entry pickup ...
  procedure entry putdown ...
  procedure test ...

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

```
procedure entry pickup(i: 0..4);
    state[i] := hungry;
    test(i);
    while ( state[i] != eating )
      self[i].wait;

procedure entry putdown(i: 0..4);
    state[i] := thinking;
    test (ln(i));
    test (rn(i));

procedure test(i: 0..4);
    if (state[ln(i)] != eating and
        state[i] == hungry and
        state(rn(i)) != eating)
      state[i] := eating;
      self[i].signal;
```

## Dining Philosophers using Monitors - 3

- What is missing?
  - philosophers cannot deadlock but can starve
    - for example, we can construct timing relationships such that a waiting philosopher will be stuck in the “self” queue forever
  - monitors have to be enhanced with a fair scheduling policy to avoid starvation
    - both at the level of accessing the monitor
    - as well as to regulate “waking-up”' those that are waiting inside
  - how can this be done?
    - use fair enqueue and dequeue policies



## Monitors: Other Issues

- Expressibility: Are monitors more/less powerful than semaphores or conditional critical regions?
  - these three constructs are equivalent
    - the same kinds of synchronization problems can be expressed in each
  - the other two can be implemented using any one of the constructs
    - e.g., critical regions and monitors using semaphores
      - we talked about how critical regions can be implemented
      - in Lab 2: you built condition variables using semaphores
        - » this implementation can be extended to build monitors

- Do monitors have any limitations?
  - absence of concurrency within a monitor
    - workarounds introduce all the problems of semaphores
    - monitor procedures will need to be invoked before and after
    - possibility of improper access, deadlock, etc.