

## Synchronization Principles

CS 256/456

Dept. of Computer Science, University  
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## Synchronization Principles

- Background
  - Concurrent access to shared data may result in data inconsistency.
  - Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes.
- The Critical-Section Problem
  - Pure software solution
  - With help from the hardware
- Synchronization without busy waiting (with the support of process/thread scheduler)
  - Semaphore
  - Mutex lock
  - Condition variables

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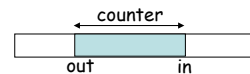
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## Bounded Buffer

### • Shared data

```
typedef struct { ... } item;
item buffer[BUFFER_SIZE];
int in = 0, out = 0;
int counter = 0;
```



### • Producer process

```
item nextProduced;
while (1) {
    while (((in+1)%BUFFER_SIZE==out)
        /* do nothing */
    buffer[in] = nextProduced;
    in = (in+1) % BUFFER_SIZE;
    counter++;
}
```

### • Consumer process

```
item nextConsumed;
while (1) {
    while (in==out)
        /* do nothing */
    nextConsumed = buffer[out];
    out = (out+1) % BUFFER_SIZE;
    counter--;
}
```

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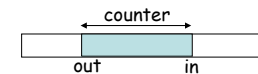
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## Bounded Buffer

### • Shared data

```
typedef struct { ... } item;
item buffer[BUFFER_SIZE];
int in = 0, out = 0;
int counter = 0;
```



### • Producer process

```
item nextProduced;
while (1) {
    while (counter==BUFFER_SIZE)
        /* do nothing */
    buffer[in] = nextProduced;
    in = (in+1) % BUFFER_SIZE;
    counter++;
}
```

### • Consumer process

```
item nextConsumed;
while (1) {
    while (counter==0)
        /* do nothing */
    nextConsumed = buffer[out];
    out = (out+1) % BUFFER_SIZE;
    counter--;
}
```

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## Bounded Buffer

- The following statements must be performed *atomically*:  

```
counter++;
counter--;
```
- Atomic operation means an operation that completes in its entirety without interruption.
- The statement "counter++" may be compiled into the following instruction sequence:  

```
register1 = counter;
register1 = register1 + 1;
counter = register1;
```
- The statement "counter--" may be compiled into:  

```
register2 = counter;
register2 = register2 - 1;
counter = register2;
```

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## Race Condition

- Race condition:**
  - The situation where several processes access and manipulate shared data concurrently.
  - The final value of the shared data and/or effects on the participating processes depends upon the order of process execution - nondeterminism.
- To prevent race conditions, concurrent processes must be **synchronized**.

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## The Critical-Section Problem

- Problem context:
  - $n$  processes all competing to use some shared data
  - Each process has a code segment, called *critical section*, in which the shared data is accessed.
- Find a solution that satisfies the following:
  - Mutual Exclusion.** No two processes simultaneously in the critical section.
  - Progress.** No process running outside its critical section may block other processes.
  - Bounded Waiting/Fairness.** Given the set of concurrent processes, a bound must exist on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted.

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## Eliminating Concurrency

- First idea: eliminating the chance of context switch when a process runs in the critical section.
  - effective as a complete solution only on a single-processor machine
  - only for short critical sections
- How to eliminate context switch?
  - software exceptions
  - hardware interrupts
  - system calls
- Disabling interrupts?
  - not feasible for user programs since they shouldn't be able to disable interrupts
  - feasible for OS kernel programs

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## Critical Section for Two Processes

- Only 2 processes,  $P_0$  and  $P_1$
- General structure of process  $P_i$  (other process  $P_j$ )

```
do {
    entry section
    critical section
    exit section
    remainder section
} while (1);
```

- Processes may share some common variables to synchronize their actions.
- Assumption: instructions are atomic and no re-ordering of instructions.

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## Algorithm 1

- Shared variables:
  - `int turn;`
  - initially `turn = 0;`
  - `turn==i`  $\Rightarrow$   $P_i$  can enter its critical section
- Process  $P_i$ 

```
do {
    while (turn != i) ;
    critical section
    turn = j;
    remainder section
} while (1);
```
- Satisfies mutual exclusion, but not progress

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## Algorithm 2

- Shared variables:
  - `boolean flag[2];`
  - initially `flag[0] = flag[1] = false;`
  - `flag[i]==true`  $\Rightarrow$   $P_i$  ready to enter its critical section
- Process  $P_i$ 

```
do {
    flag[i] = true;
    while (flag[j]) ;
    critical section
    flag[i] = false;
    remainder section
} while (1);
```
- Satisfies mutual exclusion, but not progress requirement.

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## Algorithm 3

- Combine shared variables of algorithms 1 and 2.
- Process  $P_i$ 

```
do {
    flag[i] = true;
    turn = j;
    while (flag[j] && turn==j) ;
    critical section
    flag[i] = false;
    remainder section
} while (1);
```
- Meets all three requirements; solves the critical-section problem for two processes.  $\Rightarrow$  called [Peterson's algorithm](#).

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## Basic Hardware Mechanisms for Synchronization

- Test-and-set – atomic exchange
- Fetch-and-op (e.g., increment) – returns value and atomically performs op (e.g., increments it)
- Compare-and-swap – compares the contents of two locations and swaps if identical
- Load-locked/store conditional – pair of instructions – deduce atomicity if second instruction returns correct value

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## Synchronization Using Special Instruction: TSL (test-and-set)

```

entry_section:
    TSL R1, LOCK      | copy lock to R1 and set lock to 1
    CMP R1, #0        | was lock zero?
    JNE entry_section | if it wasn't zero, lock was set, so loop
    RET               | return; critical section entered

exit_section:
    MOV LOCK, #0      | store 0 into lock
    RET               | return; out of critical section
  
```

- Does it solve the synchronization problem?
- Does it work for multiple (>2) processes?

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## Implementing Locks Using Test&Set

- On the SPARC ldstub moves an unsigned byte into the destination register and rewrites the same byte in memory to all 1s

```

_Lock_acquire:
    ldstub [%o0], %o1
    addcc %g0, %o1, %g0
    bne _Lock
    nop
fin:
    jmpl %r15+8, %g0
    nop
_Lock_release:
    st %g0, [%o0]
    jmpl %r15+8, %g0
  
```

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## Using ll/sc for Atomic Exchange

- Swap the contents of R4 with the memory location specified by R1

```

try: mov R3, R4      ; mov exchange value
     ll  R2, 0(R1)   ; load linked
     sc R3, 0(R1)    ; store conditional
     beqz R3, try    ; branch if store fails
     mov R4, R2      ; put load value in R4
  
```

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## Solving the Critical Section Problem with Busy Waiting

- In all our solutions, a process enters a loop until the entry is granted  $\Rightarrow$  busy waiting.
- Problems with busy waiting:
  - Waste of CPU time
  - If a process is switched out of CPU during critical section
    - other processes may have to waste a whole CPU quantum
    - may even deadlock with strictly prioritized scheduling (priority inversion problem)
- Solution
  - Avoid busy wait as much as possible (yield the processor instead).
  - If you can't avoid busy wait, you must prevent context switch during critical section (disable interrupts while in the kernel)

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## Recap

- Concurrent access to shared data may result in data inconsistency - race condition.
- The Critical-Section problem
  - Pure software solution
  - With help from the hardware
- Problems with busy-waiting-based synchronization
  - Waste CPU, particularly when context switch occurs while a process is inside critical section
- Solution
  - Avoid busy wait as much as possible (yield the processor instead).
  - If you can't avoid busy wait, you must prevent context switch during critical section (disable interrupts while in the kernel)

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## Semaphore

- Synchronization tool that does not require busy waiting.
- Semaphore  $S$  - integer variable which can only be accessed via two atomic operations
- Semantics (roughly) of the two operations:
 

```
wait(S) or P(S):
  wait until S>0;
  S--;

signal(S) or V(S):
  S++;
```
- Solving the critical section problem:
 

```
Shared data:
  semaphore mutex=1;

Process Pi:
  wait(mutex);
  critical section
  signal(mutex);
  remainder section
```

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## Semaphore Implementation

- Define a semaphore as a record
 

```
typedef struct {
  int value;
  proc_list *L;
} semaphore;
```
- Semaphore operations now defined as (both are atomic):
 

```
wait(S):
  value = (S.value--);
  if (value < 0) {
    add this process to S.L;
    block;
  }

signal(S):
  value = (S.value++);
  if (value <= 0) {
    remove a process P from S.L;
    wakeup(P);
  }
```
- Assume two simple operations:
  - block suspends the process that invokes it.
  - wakeup(P) resumes the execution of a blocked process P.

How do we make sure wait(S) and signal(S) are atomic?  
So have we truly removed busy waiting?

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## Mutex Lock (Binary Semaphore)

- Mutex lock - a semaphore with only two state: locked/unlocked

- Semantics of the two (atomic) operations:

lock(mutex) :

```
wait until mutex==unlocked;
mutex=locked;
```

unlock(mutex) :

```
mutex=unlocked;
```

- Can you implement mutex lock using semaphore?
- How about the opposite?

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## Implement Semaphore Using Mutex Lock

- Data structures:

```
mutex_lock L1, L2;
int C;
```

- Initialization:

```
L1 = unlocked;
L2 = locked;
C = initial value of semaphore;
```

- wait operation:

```
lock(L1);
C--;
if (C < 0) {
    unlock(L1);
    lock(L2);
}
```

- signal operation:

```
lock(L1);
C++;
if (C <= 0)
    unlock(L2);
else
    unlock(L1);
```

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## Classical Problems of Synchronization

- Bounded-Buffer Problem
- Dining-Philosophers Problem

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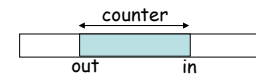
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## Bounded Buffer

- Shared data

```
typedef struct { ... } item;
item buffer[BUFFER_SIZE];
int in = 0, out = 0;
int counter = 0;
```



- Producer process

```
item nextProduced;
while (1) {
    while (counter==BUFFER_SIZE)
        ; /* do nothing */
    buffer[in] = nextProduced;
    in = (in+1) % BUFFER_SIZE;
    counter++;
}
```

- Consumer process

```
item nextConsumed;
while (1) {
    while (counter==0)
        ; /* do nothing */
    nextConsumed = buffer[out];
    out = (out+1) % BUFFER_SIZE;
    counter--;
}
```

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## Bounded Buffer Problem

- Shared data

```
buffer;
```

- Producer process

```
while (1) {
    ...
    produce an item in nextp;
    ...
    add nextp to buffer;
    ...
}
```

- Consumer process

```
while (1) {
    ...
    remove an item from buffer to nextc;
    ...
    consume nextc;
    ...
}
```

- Protecting the critical section for safe concurrent execution.
- Synchronizing producer and consumer when buffer is empty/full.

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## Bounded Buffer Solution

- Shared data

```
buffer;
semaphore full=0;
semaphore empty=n;
semaphore mutex=1;
```

- Producer process

```
while (1) {
    ...
    produce an item in nextp;
    ...
    wait(empty);
    wait(mutex);
    add nextp to buffer;
    signal(mutex);
    signal(full);
    ...
}
```

- Consumer process

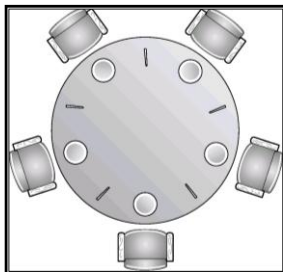
```
while (1) {
    ...
    wait(full);
    wait(mutex);
    remove an item from buffer to nextc;
    signal(mutex);
    signal(empty);
    ...
    consume nextc;
    ...
}
```

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## Dining-Philosophers Problem



- Philosopher  $i$  ( $1 \leq i \leq 5$ ):

```
while (1) {
    ...
    eat;
    ...
    think;
    ...
}
```

- eating needs both chopsticks (the left and the right one).

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## Dining-Philosophers: Possible Solution

- Shared data:

```
semaphore chopstick[5];
Initially all values are 1;
```

- Philosopher  $i$ :

```
while(1) {
    ...
    wait(chopstick[i]);
    wait(chopstick[(i+1) % 5]);
    eat;
    signal(chopstick[i]);
    signal(chopstick[(i+1) % 5]);
    ...
    think;
    ...
};
```

Deadlock?

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## Monitors

- High-level synchronization construct that allows the safe sharing of an abstract data type among concurrent processes.
- Native support for mutual exclusion.

```

monitor monitor-name
{
    shared variable declarations
    procedure body P1 (...) {
        . . .
    }
    procedure body Pn (...) {
        . . .
    }
    {
        initialization code
    }
}

```

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## Condition Variables in Monitors

- To allow a process to wait within the monitor, a **condition variable** must be declared, as
 

```
condition x, y;
```
- Condition variable can only be used with the operations **wait** and **signal**.
  - The operation
 

```
x.wait();
```

 means that the process invoking this operation is suspended until another process invokes
 

```
x.signal();
```
  - The **x.signal** operation resumes exactly one suspended process. If no process is suspended, then the signal operation has no effect.
- Unlike semaphore, there is no counting in condition variables

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## Two Semantics of Condition Variables

- Hoare semantics:
  - $p_0$  executes signal while  $p_1$  is waiting  $\Rightarrow p_0$  immediately yields the monitor to  $p_1$
  - The logical condition holds when  $P_1$  gets to run

```

if (resourceNotAvailable()) Condition.wait();
/* now available ... continue ... */
. . .

```

- Alternative semantics:
  - $p_0$  executes signal while  $p_1$  is waiting  $\Rightarrow p_0$  continues to execute, then when  $p_0$  exits the monitor  $p_1$  can receive the signal
  - The logical condition may not hold when  $P_1$  gets to run
  - Brinch Hansen ("Mesa") semantics:  $p_0$  must exit the monitor after a signal

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## Dining Philosophers Solution

```

monitor dp {
    enum {THINKING, HUNGRY, EATING} state[5];
    condition self[5];
    void pickup(int i) {
        state[i] = HUNGRY;
        test(i);
        if (state[i] != EATING)
            self[i].wait();
    }
    void putdown (int i) {
        state[i] = THINKING;
        test((i+4)%5);
        test((i+1)%5);
    }
    void test (int i) {
        if (state[(i+4)%5] != EATING && state[(i+1)%5] != EATING && state[i] == HUNGRY) {
            state[i] = EATING;
            self[i].signal();
        }
    }
    void init() {
        for (int i=0; i<5; i++)
            state[i] = THINKING;
    }
}

```

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## Dining Philosophers Alternative

### Solution

```
monitor dp {
  enum {thinking, eating} state[5];
  condition cond[5];

  void pickup(int i) {
    while (state[(i+4)%5]==eating || state[(i+1)%5]==eating)
      cond[i].wait();
    state[i] = eating;
  }

  void putdown(int i) {
    state[i] = thinking;
    cond[(i+4)%5].signal();
    cond[(i+1)%5].signal();
  }

  void init() {
    for (int i=0; i<5; i++)
      state[i] = thinking;
  }
}
```

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