Synchronization Principles

CS 256/456

Dept. of Computer Science, University of Rochester

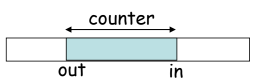
Synchronization Principles

- 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

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++;
}
```

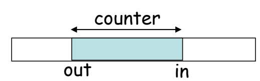
- Consumer process

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


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--;
}
```

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:
  1. **Mutual Exclusion**. No two processes simultaneously in the critical section.
  2. **Progress**. No process running outside its critical section may block other processes.
  3. **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** ⇒ 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** ⇒ 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. ⇒ 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

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?

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
    nop
```


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
```

Solving the Critical Section Problem with Busy Waiting

- In all our solutions, a process enters a loop until the entry is granted ⇒ 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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Scheduler-Based Synchronization

- In all our solutions so far, a process enters a loop until the entry is granted ⇒ 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) – scheduler-based synchronization
  - 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;
```

- Assume two simple operations:
  - **block** suspends the process that invokes it.
  - **wakeup(P)** resumes the execution of a blocked process **P**.

- 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);
    }
```

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);
}
unlock(L1);
```

- *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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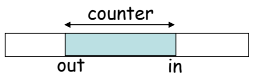
Bounded Buffer

- 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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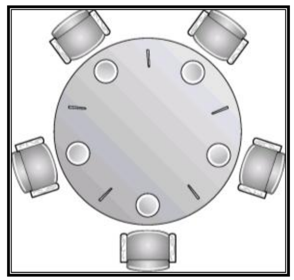
Dining-Philosophers Problem



- Philosopher i (1 ≤ i ≤ 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 P1 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 P1 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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