CSE 30341
Operating System Principles

Synchronization

Overview

• Background
• The Critical-Section Problem
• Peterson’s Solution
• Synchronization Hardware
• Mutex Locks
• Semaphores
• Classic Problems of Synchronization
• Monitors
• Synchronization Examples
• Alternative Approaches
Objectives

- To introduce the critical-section problem, whose solutions can be used to ensure the consistency of shared data
- To present both software and hardware solutions of the critical-section problem
- To examine several classical process-synchronization problems
- To explore several tools that are used to solve process synchronization problems

Background

- Processes can execute concurrently
  - May be interrupted at any time, partially completing execution
- Concurrent access to shared data may result in data inconsistency
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes
Example

Suppose that we wanted to provide a solution to the consumer-producer problem.

We can do so by having an integer count that keeps track of the slots taken. As we add things, count grows. As we consume things, count shrinks.

Illustration

Main Thread

Global Variable count

Producer Thread (T_p)

Consumer Thread (T_c)

Data gets produced

count = 0  No data, buffer empty

count = 5  Full of data, no room

Data gets consumed
Code

```c
int count = 0;
int in = 0;
int out = 0;

int main (int argc, char * argv[])
{
    pthread_t tC, tP;
    pthread_create (&tP, NULL, thread_Producer, NULL, NULL);
    pthread_create (&tC, NULL, thread_Consumer, NULL, NULL);

    /* Hang around for them to be done (never) */
    pthread_join(tP);
    pthread_join(tC);

    return 1;
}
```

We get two threads that will be executing in addition to our main thread.

Producer

```c
void thread_Producer (void * pData)
{
    while (1)
    {
        /* produce an item in next produced */
        while (count == BUFFER_SIZE) ;
        /* do nothing */

        /* Space in the buffer! */
        buffer[in] = next_produced;
        in = (in+1)%BUFFER_SIZE;
        count++;
    }
}
```

If the buffer is full, hold up.
Consumer

```c
void thread_Consumer (void * pData)
{
    while (1)
    {
        while (count == 0)
            ; /* do nothing */
        next_consumed = buffer[out];
        out = (out+1)%BUFFER_SIZE;
        count--; /* consume the item in next consumed */
    }
}
```

Race Condition

- count++:
  ```
  register1 = count
  register1 = register1 + 1
  count = register1
  ```

- count--:
  ```
  register1 = count
  register1 = register1 - 1
  count = register1
  ```
Race Condition

• Assume count=5
  Step 1: Producer: register1 = count (register1 = ?)
  Step 2: Producer: register1 = register1 + 1 (?
  Step 3: Consumer: register2 = count (register2 = ?)
  Step 4: Consumer: register2 = register2 – 1 (?
  Step 5: Producer: count = register1 (count = ?)
  Step 6: Consumer: count = register2 (count = ?)

Critical Section Problem

• Consider system of \( n \) processes \( \{p_0, p_1, \ldots, p_{n-1}\} \)

• Each process has critical section segment of code
  – Process may be changing common variables, updating table, writing file, etc.
  – When one process in critical section, no other may be in its critical section

  • Critical section: section in code where race conditions can occur!
  • Critical section problem is to design protocol to solve this

  • Each process must ask permission to enter critical section in entry section, may follow critical section with exit section, then remainder section
Critical Section

• General structure of process $p_i$ is

$$
\text{do } \{
\begin{aligned}
&\text{entry section} \\
&\text{critical section} \\
&\text{exit section} \\
&\text{remainder section}
\end{aligned}
\} \text{ while (true);}
$$

Solution to Critical-Section Problem

1. Mutual Exclusion - If process $P_i$ is executing in its critical section, then no other processes can be executing in their critical sections.

2. Progress - If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of the processes that will enter the critical section next cannot be postponed indefinitely.

3. Bounded Waiting - 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.
Peterson’s Solution

- Good algorithmic description of solving the problem
- Two process solution
- Assume that the load and store instructions are atomic; that is, they cannot be interrupted
- The two processes share two variables:
  - int turn;
  - Boolean flag[2]
- The variable turn indicates whose turn it is to enter the critical section
- The flag array is used to indicate if a process is ready to enter the critical section. flag[i] = true implies that process $P_i$ is ready!

Algorithm for Process $P_i$

do {
  flag[i] = true;
  turn = j;
  while (flag[j] && turn == j);
  critical section
  flag[i] = false;
  remainder section
} while (true);

1. Mutual exclusion is preserved
2. Progress requirement is satisfied
3. Bounded-waiting requirement is met
Synchronization Hardware

- Many systems provide hardware support for critical section code

- All solutions below based on idea of locking
  - Protecting critical regions via locks

- Uniprocessors – could disable interrupts
  - Currently running code would execute without preemption
  - Generally too inefficient on multiprocessor systems
    - Operating systems using this not broadly scalable

- Modern machines provide special atomic hardware instructions
  - Atomic = non-interruptible
    - Either test memory word and set value (TestAndSet())
    - Or swap contents of two memory words (Swap())

Solution to Critical-section Problem Using Locks

```c
  do {
    acquire lock
    critical section
    release lock
    remainder section
  } while (TRUE);
```
TestAndSet Instruction

• Definition:

```c
boolean TestAndSet (boolean *target) {
    boolean rv = *target;
    *target = TRUE;
    return rv;
}
```

Solution using test_and_set()

• Shared boolean variable `lock`, initialized to FALSE
• Solution:

```c
do {
    while (TestAndSet(&lock))
        /* do nothing */
        /* critical section */
        lock = FALSE;
        /* remainder section */
} while (TRUE);
```
Swap Instruction

• Definition:

```c
void Swap(boolean *a, boolean *b) {
    boolean temp = *a;
    *a = *b
    *b = temp;
}
```

Solution using Swap

• Shared Boolean variable lock initialized to FALSE; each process has a local Boolean variable key
• Solution:

```c
do {
    key = TRUE;
    while (key == TRUE) {
        Swap(&lock, &key);
        /* critical section */
        lock = FALSE;
        /* remainder section */
    } while (TRUE);
```
Bounded-waiting Mutual Exclusion with TestAndSet

do {
    waiting[i] = true;
    key = true;
    while (waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = false;
    /* critical section */
    j = (i + 1) % n;
    while ((j != i) && !waiting[j])
        j = (j + 1) % n;
    if (j == i)
        lock = false;
    else
        waiting[j] = false;
    /* remainder section */
} while (true);

Mutex Locks

• Previous solutions are complicated and generally inaccessible to application programmers!
• OS designers build software tools to solve critical section problem
• Simplest is mutex lock
• Protect critical regions with it by first acquire() a lock then release() it
  — Boolean variable indicating if lock is available or not
• Calls to acquire() and release() must be atomic
  — Usually implemented via hardware atomic instructions
• But this solution requires busy waiting
  • This lock therefore called a spinlock
acquire() and release()

```c
acquire() {
    while (!available)
        ; /* busy wait */
    available = false;;
}
release() {
    available = true;
}

do {
    acquire lock
    critical section
    release lock
    remainder section
} while (true);
```

Semaphore

- Synchronization tool that does not require busy waiting
- Semaphore S – integer variable
- Two standard operations modify S: `wait()` and `signal()`
  - Originally called `P()` and `V()`
- Less complicated
- Can only be accessed via two indivisible (atomic) operations

```c
wait (S) {
    while (S <= 0)
        ; // busy wait
    S--;
}
signal (S) {
    S++;
}
```
### Semaphore Usage

- **Counting semaphore** – integer value can range over an unrestricted domain
- **Binary semaphore** – integer value can range only between 0 and 1
  - Then a *mutex lock*
- Consider $P_1$ and $P_2$ that require $S_1$ to happen before $S_2$
  
  ```
  P1:
  S_1;
  signal(synch);
  P2:
  wait(synch);
  S_2;
  ```

### Semaphore Implementation

- Must guarantee that no two processes can execute `wait()` and `signal()` on the same semaphore at the same time

- Thus, implementation becomes the critical section problem where the wait and signal code are placed in the critical section
  - Could now have **busy waiting** in critical section implementation
    - But implementation code is short
    - Little busy waiting if critical section rarely occupied

- Note that applications may spend lots of time in critical sections and therefore this is not a good solution
Semaphore Implementation with no Busy Waiting

• With each semaphore there is an associated waiting queue.
• Each entry in a waiting queue has two data items:
  – value (of type integer)
  – pointer to next record in the list

• Two operations:
  – **block** – place the process invoking the operation on the appropriate waiting queue
  – **wakeup** – remove one of processes in the waiting queue and place it in the ready queue

```c
wait(semaphore *S) {
    S->value--;
    if (S->value < 0) {
        add this process to S->list;
        block();
    }
}

signal(semaphore *S) {
    S->value++;
    if (S->value <= 0) {
        remove a process from S->list;
        wakeup(P);
    }
}
```
Deadlock and Starvation

- **Deadlock** – two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes
- Let $s$ and $q$ be two semaphores initialized to 1

```c
P_0 : 
    wait(S);
    wait(Q);
    signal(Q);
    signal(S);

P_1 : 
    wait(Q);
    wait(Q);
    wait(S);
    signal(Q);
    signal(Q);

```

- **Starvation** – indefinite blocking
  - A process may never be removed from the semaphore queue in which it is suspended

- **Priority Inversion** – Scheduling problem when lower-priority process holds a lock needed by higher-priority process

Classical Problems of Synchronization

- Classical problems used to test newly-proposed synchronization schemes
  - Bounded-Buffer Problem
  - Readers and Writers Problem
  - Dining-Philosophers Problem
Bounded-Buffer Problem

- \( n \) buffers, each can hold one item
- Semaphore \texttt{mutex} initialized to the value 1
- Semaphore \texttt{full} initialized to the value 0
- Semaphore \texttt{empty} initialized to the value \( n \)

Bounded Buffer Problem (Cont.)

- The structure of the producer process
  
  \[
  \text{do } \{ \\
  \quad \ldots \\
  \quad /* \text{produce an item in next\_produced} */ \\
  \quad \ldots \\
  \quad \text{wait(empty);} \\
  \quad \text{wait(mutex);} \\
  \quad \ldots \\
  \quad /* \text{add next produced to the buffer} */ \\
  \quad \ldots \\
  \quad \text{signal(mutex);} \\
  \quad \text{signal(full);} \\
  \} \text{while (true);} 
  \]
Bounded Buffer Problem (Cont.)

- The structure of the consumer process

```c
do {
    wait(full);
    wait(mutex);
    ...
    /* remove an item from buffer to next_consumed */
    ...
    signal(mutex);
    signal(empty);
    ...
    /* consume the item in next consumed */
    ...
} while (true);
```

Readers-Writers Problem

- A data set is shared among a number of concurrent processes
  - Readers – only read the data set; they do not perform any updates
  - Writers – can both read and write

- Problem – allow multiple readers to read at the same time
  - Only one single writer can access the shared data at the same time

- Shared Data
  - Data set
  - Semaphore `wrt` initialized to 1
  - Semaphore `mutex` initialized to 1
  - Integer `read_count` initialized to 0
Readers-Writers Problem (Cont.)

• The structure of a writer process

```c
do {
    wait(wrt);
    ...
    /* writing is performed */
    ...
    signal(wrt);
} while (true);
```

Readers-Writers Problem (Cont.)

• The structure of a reader process

```c
do {
    wait(mutex);
    read_count++;
    if (read_count == 1)
        wait(wrt);
    signal(mutex);
    ...
    /* reading is performed */
    ...
    wait(mutex);
    read_count--;
    if (read_count == 0)
        signal(wrt);
    signal(mutex);
} while (true);
```
Dining-Philosophers Problem

- Philosophers spend their lives thinking and eating
- Don’t interact with their neighbors, occasionally try to pick up 2 chopsticks (one at a time) to eat from bowl
  - Need both to eat, then release both when done
- In the case of 5 philosophers
  - Shared data
    - Bowl of rice (data set)
    - Semaphore chopstick [5] initialized to 1

Dining-Philosophers Problem Algorithm

- The structure of Philosopher $i$:

```c
do {
  wait (chopstick[i]);
  wait (chopstick[(i + 1) % 5]);
  // eat
  signal (chopstick[i]);
  signal (chopstick[(i + 1) % 5]);
  // think
} while (TRUE);
```

- What is the problem with this algorithm?
Monitors

- A high-level abstraction that provides a convenient and effective mechanism for process synchronization
- Abstract data type, internal variables only accessible by code within the procedure
- Only one process may be active within the monitor at a time
- But not powerful enough to model some synchronization schemes

```plaintext
monitor monitor-name
{
    // shared variable declarations
    procedure P1 (...) { .... }

    procedure Pn (...) {......}

    Initialization code (...) { ... }
}
}
```

Schematic View of a Monitor

![Diagram showing the schematic view of a monitor](image)
Condition Variables

- condition \( x, y \);

Two operations on a condition variable:
- \( x.\text{wait}() \) – a process that invokes the operation is suspended until \( x.\text{signal}() \)
- \( x.\text{signal}() \) – resumes one of processes (if any) that invoked \( x.\text{wait}() \)
  - If no \( x.\text{wait}() \) on the variable, then it has no effect on the variable

Monitor with Condition Variables
Solution to Dining Philosophers

```c
monitor DiningPhilosophers
{
    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 left and right neighbors
        test((i + 4) % 5);
        test((i + 1) % 5);
    }
}
```

Solution to Dining Philosophers (Cont.)

```c
void test (int i) {
    if (state[(i + 4) % 5] != EATING) &&
    (state[i] == HUNGRY) &&
    (state[(i + 1) % 5] != EATING) ) {
        state[i] = EATING;
        self[i].signal ();
    }
}

initialization_code() {
    for (int i = 0; i < 5; i++)
        state[i] = THINKING;
}
```
Dining Philosophers

- Each philosopher \( i \) invokes the operations `pickup()` and `putdown()` in the following sequence:
  
  ```
  DiningPhilosophers.pickup (i);
  EAT
  DiningPhilosophers.putdown (i);
  ```

- No deadlock, but starvation is possible!