Task Synchronisation

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Outline

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   - Threads and Processess Reviewed
2. Concurrency and Synchronisation
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   - Task Synchronisation
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3. Deadlock and Starvation
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Multitasking Review

- Multitasking allows programs to do more than one thing at a time
  - Multiprocessing: multiple CPUs
  - Timesharing: single CPU
- Processes vs. Threads
  - Processes: memory protection, heavyweight
  - Threads: no protection, lightweight
- Scheduling and Dispatching
  - Scheduler: high-level queuing algorithms
  - Dispatcher: low-level CPU assignment

Concurrency Problems

- Two Tasks accessing common resources (e.g. memory)
  → no problem as long as both tasks only read
  - what happens if one task writes while the other task reads?
  - what happens if both tasks try writing?

→ Let's look at some examples!

Concurrency Example (1)

Example (two tasks modifying shared data)

```
int shared = 0;

void task1(void)
{
        shared = 1;
}
```

```
extern int shared;

void task2(void)
{
        shared = 2;
}
```

- No concurrency problem!
  - `shared` is either 0, 1, or 2

→ Both tasks use Atomic Operations

Concurrency Example (2)

Example (two tasks modifying shared data)

```
int shared = 0;

void task1(void)
{
        shared++;
        shared++;
}
```

```
extern int shared;

void task2(void)
{
        shared += 2;

}
```

- Inconsistencies can occur!
  - tasks can interrupt each other at critical points
  - *Read-Modify-Write* operations are not Atomic

  ⇒ `shared` can suddenly end up with an odd value

Avoiding Inconsistencies

- Always use Atomic Actions
  - not always possible for certain operations
  - hard to tell if an operation is atomic

    → depends on compiler and system implementation
- Protect Critical Regions
  - use synchronisation constructs before accessing shared resources

  → transforms operations into atomic actions

Mutual Exclusion, Attempt #1

Example (turn-based mutual exclusion)

```
int turn = 0;
int shared = 0;

void task1(void)
{
        while (turn != 0)
                ; // do nothing

        // critical section
        shared++;
        shared++;

        turn = 1;
}
```

```
extern int turn;
extern int shared;

void task2(void)
{
        while (turn != 1)
                ; // do nothing

        // critical section
        shared += 2;
        // end critical section

        turn = 0;
}
```

Analysis of Attempt #1

- Guarantees Mutual Exclusion
- Drawbacks
  - tasks are forced to strictly alternate their use of the shared resource
    - $\Rightarrow$ pace is dictated by the slower process
  - if one Task fails even outside the critical region, the other Task is stuck forever
  - Waiting Task consumes 100% CPU time
    - $\rightarrow$ Busy Waiting

Attempt #2

Example (flag-based mutual exclusion)

```c
int flag[2] = {FALSE, FALSE};
int shared = 0;

void task1(void)
{
        while (flag[1])
                ; // do nothing

        flag[0] = TRUE;
        // critical section
        shared++;
        shared++;
        flag[0] = FALSE;
}
```

```c
extern int flag[2];
extern int shared;

void task2(void)
{
        while (flag[0])
                ; // do nothing

        flag[1] = TRUE;
        // critical section
        shared += 2;
        // end critical section
        flag[1] = FALSE;
}
```

Analysis of Attempt #2

- Task failing outside Critical Section
  - $\rightarrow$ no longer affects the other task!
- Mutual Exclusion not guaranteed:
  - Task 0 enters and exits `while()` because `flag[1]` is FALSE
  - Task 1 enters and exits `while()` because `flag[0]` is FALSE
  - both set their flags and enter critical section!
    - $\Rightarrow$ flags are set too late!

Attempt #3

Example (setting flags first)

```
int flag[2] = {FALSE, FALSE};
int shared = 0;

void task1(void)
{
        flag[0] = TRUE;
        while (flag[1])
                ; // do nothing

        // critical section
        shared++;
        shared++;
        flag[0] = FALSE;
}
```

```
extern int flag[2];
extern int shared;

void task2(void)
{
        flag[1] = TRUE;
        while (flag[0])
                ; // do nothing

        // critical section
        shared += 2;
        // end critical section
        flag[1] = FALSE;
}
```

Analysis of Attempt #3

- Mutual Exclusion guaranteed
  - only one Task enters critical section at a time
- Deadlock can occur:
  - both tasks set their flags to `TRUE`
  - both tasks enter their `while()` loops and `wait indefinitely` for the other task to clear its flag!
  - no task will ever be able to do anything useful again.

Attempt #4

Example (backing off)

```c
int flag[2] = {FALSE, FALSE};
int shared = 0;

void task1(void)
{
        flag[0] = TRUE;
        while (flag[1]) {
                flag[0] = FALSE;
                // delay a bit
                flag[0] = TRUE;
        }
        // critical section
        shared++;
        shared++;
        flag[0] = FALSE;
}
```

```c
extern int flag[2];
extern int shared;

void task2(void)
{
        flag[1] = TRUE;
        while (flag[0]) {
                flag[1] = FALSE;
                // delay a bit
                flag[1] = TRUE;
        }
        // critical section
        shared += 2;
        // end critical section
        flag[1] = FALSE;
}
```

Analysis of Attempt #4

- Close to a correct solution
  - mutual exclusion guaranteed, no Deadlock
- Livelock can occur:
  - both tasks set their flags to `TRUE`
  - both tasks check the their task's flag (`TRUE`)
  - both tasks release their flag and start again

  → endless loop grabbing and releasing their flag, *consuming 100% of (useless) CPU time*

Peterson's Algorithm

Example (backing off)

```
int flag[2] = {FALSE, FALSE};
int turn = 0;

void task1(void)
{
        flag[0] = TRUE, turn = 1;
        while (flag[1] && turn==0)
                ; // do nothing

        // critical section
        shared++;
        shared++;

        flag[0] = FALSE;
}
```

```
extern int flag[2];
extern int turn;

void task2(void)
{
        flag[1] = TRUE, turn = 0;
        while (flag[0] && turn==1)
                ; // do nothing

        // critical section
        shared += 2;
        // end critical section

        flag[1] = FALSE;
}
```

Peterson's Algorithm (2)

- Correct solution
  - mutual Exclusion, no Dead-/Livelocks
- Not a generic solution
  - works only for two tasks
  - → still uses Busy Waiting
- Solution: Hardware and/or OS-Support
  - atomic Test-And-Set (TAS) CPU instructions
  - blocking a task w/o consuming CPU time

Semaphores

- Simple Signalling Mechanism
  - synchronisation of multiple Tasks
- Shared Integer Variable
  - usually initialised to nonnegative value
  - `Wait()` operation: `P()`
    - block task while semaphore ≤ 0, decrement value
  - `Signal()` operation: `V()`
    - increment value, unblock task(s) on waiting queue

Semaphore Algorithm

Semaphore Operations

```
int semaphore = 1;

P()
{
        while (semaphore <= 0)
                BLOCK;

        semaphore--;
}
```

```
extern int semaphore;

V()
{
        semaphore++;

        WAKEUP;
}
```

- `P()` and `V()` cannot be interrupted!
- `BLOCK` enqueues a Task on the waiting queue
- `WAKEUP` removes the first Task from the waiting queue

Semaphore Advantages

→ Flexibility!

- Multiple tasks
  - more than two tasks can be synchronised
- If initialised to an `n > 1`
  - *n* tasks can enter critical region!
- If initialised to an `n < 1`
  - $-n+1$ `V()` operations are required before first task can enter critical region!

Semaphores in C

- Create and initialise a Semaphore
  - `sem_open()`

  → `sem_t *s = sem_open("mysemaphore", O_CREAT, 0600, 1);`
- `P()`
  - `sem_wait()`
- `V()`
  - `sem_post()`

Task Synchronisation

- Semaphores
  - means for protecting critical regions
  - flexible method, handling more than one task
- `NSLock` Objective-C class
  - simple binary semaphore (0 and 1 values only)
  - → always initialised to 1
  - `-lock`
    - `P()` operation (set semaphore to 0)
  - `-unlock`
    - `V()` operation (set semaphore to 1)
    - → needs to be called by the task that called `lock`
    - → `lock` must have been called before unlock

The Producer/Consumer Problem

- Consider the following scenario:
  - Infinite Array (buffer)
  - Producer: Adds to buffer at position out
  - Consumer: Reads from position in
- Let's look at a simple implementation

Producer/Consumer Code

Example (Producer)

```
for(;;)          // loop forever
{
        produce item v;
        buffer[in++] = v;
}
```

Example (Consumer)

```
for(;;)                         // loop forever
{
        while (out >= in) ;      // wait for buffer data
        consume(buffer[out++]);
}
```

Binary Semaphore Attempt

- Binary Semaphore
  - Protect Critical Region
- Integer `n`
  - `n = in - out`
  - Keeps Track of available buffer positions
- Straightforward Solution?

→ Let's look at the algorithm

Attempt #1

```
BinarySemaphore s = 1, d = 0;
int n = 0;
```

Producer

```
for(;;) {
        P(s);
        append();
        n++;
        if (n == 1)
                V(d);
        V(s);
}
```

Consumer

```
P(d);
for(;;) {
        P(s);
        take();
        n--;
        V(s);
        if (n == 0)
                P(d);
}
```

Analysis of Attempt #1

- Consider the following
  - Consumer has consumed all items: `n = 0` `d = 0`
  - Producer adds another item: `n = 1` `d = 1`
  - Consumer checks if n == 0 `false` `d = 1`
  - Consumer consumes new item `n = 0` `d = 1`
  - Consumer checks if n == 0 `true` `d = 1`
  - Consumer: P(d) returns immediately `n = 0` `d = 0`
  - Consumer reads non-existent item `n = -1`

Problems

- `V(d)` of Producer is not matched by `P(d)` of Consumer!
  - Testing `n` and then waiting is not atomic
  - Moving the test into the critical section
    - Makes it atomic
    - But introduces the possibility of a Deadlock!
- Solution
  - Set auxiliary variable m inside critical region

Attempt #2

```
BinarySemaphore s = 1, d = 0;
int n = 0;
```

Producer

```
for(;;) {
        P(s);
        append();
        n++;
        if (n == 1)
                V(d);
        V(s);
}
```

Consumer

```
P(d);
for(;;) {
        P(s);
        take();
        int m = --n;
        V(s);
        if (m == 0)
                P(d);
}
```

Analysis of Attempt #2

- Correct Solution
  - No deadlocks can occur
  - `m` was modified within the critical section
    - Atomic Action
    - Producer will not modify `m`
    - Test for `m` is safe
- Not very Elegant Solution
  - Easy to mess up, requires a lot of helper variables
- Better: Use Counting Semaphores

Using Counting Semaphores

```
Semaphore s = 1, n = 0;
```

Producer

```
for(;;) {
        P(s);
        append();
        V(s);
        V(n);
}
```

Consumer

```
for(;;) {
        P(n);
        P(s);
        take();
        V(s);
}
```

Counting Semaphores Analysis

- Elegant Solution
  - No extra counters required
- No Deadlocks
  - Principle: grab Semaphores in same order
  - Release in reverse order
  - “Protector” Semaphore is innermost Semaphore
  - Each `P()` must be matched by a `V()`

    → but match can be within another Task!

Counting Extensions

- Arrays are not infinite
  - Add another counting Semaphore
  - Initialise to *capacity* of Array
- Minimum fill level
  - Consumer must wait until reached
  - Initialise counting Semaphore to negative value
    - `-n` is the minimum fill level
  - Beware traditional semaphore implementations!
    - Allow only non-negative values!

Full Extended Example

```
Semaphore s = 1, mini = -1, maxi = 10;
```

Producer

```
for(;;) {
        P(maxi);
        P(s);
        append();
        V(s);
        V(mini);
}
```

Consumer

```
for(;;) {
        P(mini);
        P(s);
        take();
        V(s);
        V(maxi);
}
```

The Reader/Writer Problem

- Shared Data Area
  - Writer(s) write to the area
  - Reader(s) read from the area, but don't consume
- Any number of Readers may simultaneously read
- Only one Writer may write at a time
- While a Writer is writing, no Reader may read

Reader/Writer Attempt #1

```
Semaphore r = 1, w = 1;
int nread = 0;
```

Reader

```
for(;;) {
        P(r);
        if (++nread == 1)
                P(w);
        V(r);
        READ();
        P(r);
        if (--nread == 0)
                V(w);
        V(r);
}
```

Writer

```
for(;;) {
        P(w);
        WRITE();
        V(w);
}
```

Analysis of Attempt #1

- Mutual Exclusion
  - Writer or first Reader grabs writing semaphore
- Readers can access simultaneously
  - Only first Reader needs to wait on `w`
- Readers have Priority
  - Writers will block until there are no readers

  ⇒ Starvation of Writers

Writer Priority

```
Semaphore x, y, z, w, r;
int nread = 0, nwrite = 0;
```

Reader

```
for(;;) {
        P(z); P(r); P(x);
        if (++nread == 1)
                P(w);
        V(x); V(r); V(z);
        READ();
        P(x);
        if (--nread == 0)
                V(w);
        V(x);
}
```

Writer

```
for(;;) {
        P(y);
        if (++nwrite == 1)
                P(r);
        V(y);
        P(w);
        WRITE();
        V(w);
        P(y);
        if (--nwrite == 0)
                V(r);
        V(y);
}
```

Writer Priority Analysis

- Readers still block writers
  - `P(w)`
- Waiting Writer blocks *new* Readers
  - `P(r)`
  - Outer Semaphore: takes precedence over `P(w)`
- No Starvation

  $\Rightarrow$ Writers take Precedence

Deadlock and Starvation

- Deadlock
  - Permanent (cyclic) blocking of a set of tasks competing for shared resources
- Starvation
  - A condition in which a task gets delayed indefinitely (or for a significant period of time) because other tasks are always given preference

Deadlock Conditions

1. Mutual Exclusion
   - Only one task may enter a critical section
2. Hold and Wait
   - A task holds allocated resources while awaiting assignment of other resources
3. No Preemption
   - No resource can be forcibly removed from a task
4. Circular Wait
   - Closed chain of tasks, such that each task holds at least one resource needed by the next task in the chain

Deadlock Occurrence

- A Deadlock Occurs . . .
  - . . . if all four conditions are met at the same time

$\Rightarrow$ Strategies need to tackle at least one of these conditions

  - Deadlock Prevention
  - Deadlock Avoidance
  - Deadlock Detection

Deadlock Prevention

- Excludes Deadlock Possibility
- Mutual Exclusion
  - cannot be disallowed!
- Hold and Wait
  - task must request all resources at once
- No Preemption
  - forcefully take away resources
- Circular Wait
  - Define a *linear ordering* of resource types

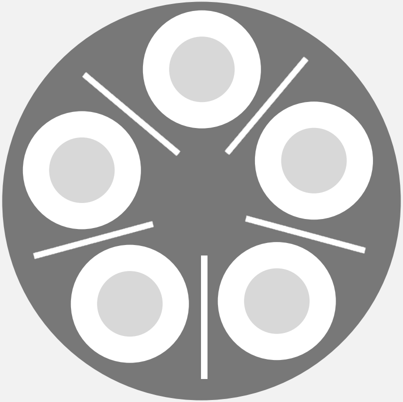
Deadlock Avoidance

- Task Initiation Denial
  - Do not start a task if its resource requirements do not meet available resources (and thus may cause a deadlock)
- Resource Allocation Denial
  - Banker’s Algorithm
- Allows more Concurrency than Deadlock Prevention
  - Dynamic Avoidance vs. static Prevention

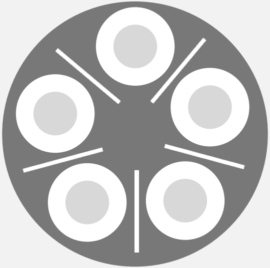
Deadlock Detection

- Check for Deadlocks
  - At each resource allocation
- Less Conservative
  - better Resource Utilisation
  - after-the-fact detection of deadlocks
- Requires Recovery Strategy
  - abort all or some deadlocked tasks
  - checkpointing
  - preempt resources until Deadlock goes away

Dining Philosophers



Dining Philosophers (2)



- Each Philosopher needs two chopsticks to eat
- Deadlock:
  - Everybody picks up one chopstick and waits for the other
- Solution: Deadlock Prevention
  - Number the chopsticks (linear ordering)
  - Pick up chopstick with lower number first