UNIVERSITY of WISCONSIN-MADISON
Computer Sciences Department

CS 537
Intro to Operating Systems

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Lecture 3: Synchronization

- Questions answered in this lecture
  - Why is synchronization necessary?
  - What are race conditions, critical sections, and atomic operations?
  - How to protect critical sections with only atomic loads and stores
  - How to implement locks?
- Readings for this topic
  - See Homepage

Independent vs. Cooperating Processes

- Independent process: Not affected by rest of universe
  - Properties
    - No shared state between process (memory, filesystem)
    - Deterministic: Input alone determines results
    - Stop and restart without adverse effects
  - Example: Isolated program that calculates factorial sequence
- Cooperative: Non-independent (not necessarily “cooperative”)
  - Properties
    - Some shared state with other processes
    - Non-deterministic: May have different results each time
    - May be irreproducible: Difficult to debug and test
    - Timing affects results
  - Example: Two programs sharing single terminal
- Deal with cooperative processes in this course

Why support Cooperative Processes

- Share resources
  - Many users share one computer: Increase throughput and utilization
  - Many users share same data
- Construct system in modular fashion
  - Each process performs simple functions
  - Unix example: Connect output and input with pipes

ps -edaf | grep “java” | wc

- Do things faster
  - Slow device: One process waits for device while other computes
  - Defer work: One process performs non-critical work when idle
  - Parallelism: Divide into smaller jobs and execute on multiprocessor

Cooperating Requires Synchronization

- Two processes share account balance

```
void deposit (int amount) {
   balance += amount;
}
```

balance: $100

- Implemented as sequence of assembly instructions

```
load    R1, balance
add     R1, amount
store   R1, balance
```

- What happens if two processes make deposit at same time?

Time	Process 0: deposit (10)	Time	Process 1: deposit (20)
↓	load R1, balance	↓	load R1, balance
	add R1, amount		add R1, amount
	store R1, balance		store R1, balance

- What is the final balance?
- Race condition: Result depends on ordering of interleaving

Avoiding Race Conditions

- Critical section: Only one process can execute at a time

```
void deposit (int amount) {
    balance += amount;
}
```

balance: $100

- To implement critical sections, need atomic operations
  - Atomic operations: No other instructions can be interleaved
- Examples of atomic operations
  - Loads and stores of words

    load r1, B

    store r1, A
  - Code between interrupts on uniprocessors

    Enable and disable timer interrupts
  - Special instructions

    Test&Set

    Compare&Swap instruction

Critical Sections

- Requirements
  - **Mutual Exclusion:** Only one process in critical section at a time
  - **Progress (Deadlock-free)**

    If several simultaneous requests, must allow one process to proceed

    Must not depend on processes outside critical section
  - **Bounded (Starvation-free)**

    Must eventually allow waiting process to proceed

- Desirable Properties
  - **Efficient:** Don't consume substantial resources while waiting

    Don't busy wait (spin wait)

    Better to relinquish processor and let another process run
  - **Fair:** Don't make some processes wait longer than others
  - **Simple:** Should be easy for programmer to reason about and use

Critical Section: Attempt #1

- Previous example with no mutual exclusion

```
void deposit (int amount) {
    balance += amount;
}
```

balance: $100

- Prevent process from entering when one already executing

```
boolean lock = false;
void deposit (int amount) {
    while (lock) /* wait */;
    lock = true;
    balance += amount;
    lock = false;
}
```

- Why doesn't this work?

Crictical Section: Attempt #2

- Swap order of setting lock and checking lock
  - Use separate locks for each process: lock[pid=0] and lock[pid=1]

```
boolean lock[] = {false, false};

void deposit (int amount) {
    lock [pid] = true;
    while (lock[1-pid]) /* wait */;
    balance += amount;
    lock[pid] = false;
}
```

- Why doesn't this work?

Critical Section: Attempt #3

- Simple test determines which process can enter

```
turn = 0;

void deposit (int amount) {
      while (turn == 1-pid) /* wait */;
      balance += amount;
      turn = 1-pid;
}
```

- Why doesn't this work?

Critical Section: Solution

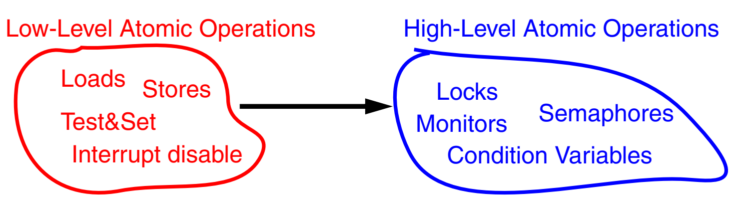
- Combine approaches: Separate locks and turn variable

```
boolean lock[] = {false, false}
void deposit (int amount) {
      lock[pid] = true;
      turn = 1 - pid;
      while (lock[1-pid] && turn == 1 - pid) /* wait */;
      balance += amount;
      lock[pid] = false;
}
```

- Mutual exclusion: Enter critical section if and only if
  - Other process does not want to enter
  - Other process wants to enter, but your turn
- Progress: All processes cannot wait forever at while() loop
  - Complete if other process does not want to enter
  - One process (matching turn) will complete
- Bounded Waiting: Process waits at most one critical section

Synchronization Layering

- Build higher-level synchronization operations in OS
  - Operations that ensure correct ordering of instructions in processes



- Build them once and get them right

Locks

- lock.acquire()
  - Acquire exclusive access to lock
  - Wait if lock is not available
- lock.release()
  - Release exclusive access to lock
- Modify previous example to use locks

Lock lock = new Lock();

Time

```
lock.acquire().
balance += amount;
lock.release();
```

```
lock.acquire().
balance += amount;
lock.release();
```

Implementing Locks: Version 1

- Build locks from atomic loads and stores
  - Use previous solution

```
class Lock {
    private boolean lock[] = {false, false};
    private int turn = 0;

    public void acquire() {
        lock[pid] = true;
        turn = 1 - pid;
        while (lock[1-pid] && turn == 1 - pid) /* wait */;
    }

    public void release() {
        lock[pid] = false;
    }
}
```

- Disadvantages?

Implementing Locks: Version 2

- Turn off interrupts for critical section
  - Prevent dispatcher from running another process
  - Code executes atomically

```
lock.aquire () <--> disableInterrupts();
balance += amount;
lock.release() <--> enableInterrupts();
```

- Disadvantages?

- OS should carefully manage when interrupts are disabled

Implementing Locks: Version 3

- Problem with Attempt 1: Testing of lock and setting not atomic

```
boolean lock = false;
    while (lock) /* wait */;
    lock = true;}
```

- Special instruction: TestAndSet address
  - Returns previous value of address
  - Sets value at address

atomic

- New solution

```
private boolean lock = false; // true if process in CS

public void acquire() {
    while (TestAndSet(lock, true));
}

public void release() {
    lock = false;
}
```

- Disadvantages?

Spin-Wait or Block (Sleep)

- Uniprocessor
  - Waiting process is scheduled --> process holding lock isn't
  - **Conclusion:** Waiting process should relinquish processor
  - Block: Associate queue with each lock --> Helps fairness
- Multiprocessor
  - Waiting process is scheduled --> ???
  - Correct action depends on how long before lock is released
    - Lock released "quickly" --> Spin-Wait
    - Lock released "slowly" --> Block
  - "Quick" or "Slow" is relative to **context-switch cost**
- Theoretical result: Two-Phase Waiting
  - Spin for length of context-switch
  - If lock not available, then block
  - Performance always within factor of two of optimal

Implementing Locks: Version 4

- Add process to list when cannot obtain lock

```
class Lock {
    private boolean lock = false; // true if process in CS
    private boolean guard = false;
    private queue q = new queue();

    public void acquire() {
        while (TestAndSet(guard, true));
        if (lock == true) {
            Add self to q;
            guard = false;
            Call dispatcher;
        } else {
            lock = true;
            guard = false;
        }
    }
    public void release() {
        while (TestAndSet(guard, true));
        if (q == empty) lock = false;
        else Remove and wake first process on q;
    }
```