EECS 482
Introduction to Operating Systems

Winter 2018

Harsha V. Madhyastha

Recap: Processes

- Hardware interface:

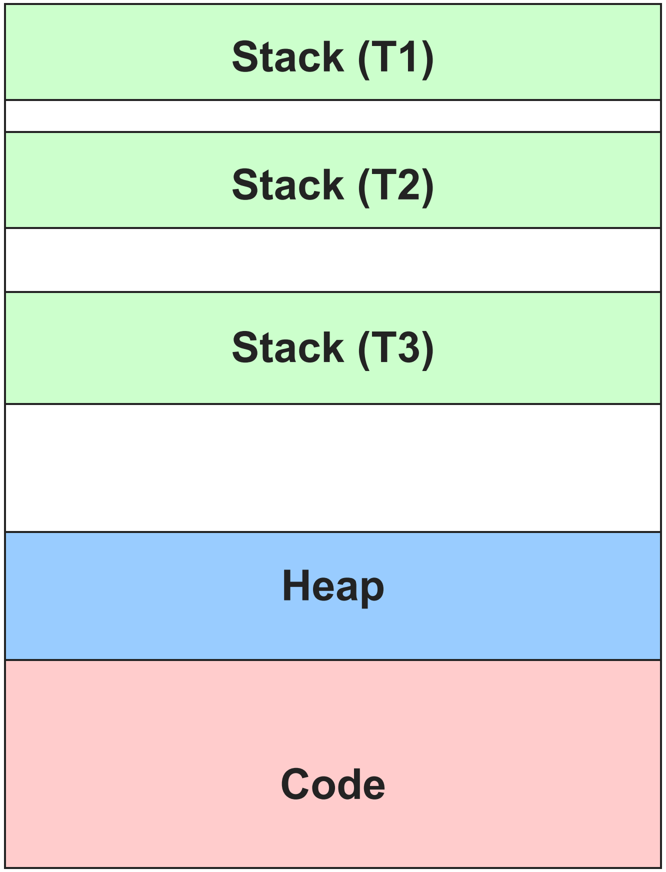
$$\frac{\texttt{app1+app2+app3}}{\texttt{CPU + memory}}$$

- OS interface:

$$\frac{\texttt{app1}}{\texttt{CPU + memory}} \qquad \frac{\texttt{app2}}{\texttt{CPU + memory}} \qquad \frac{\texttt{app3}}{\texttt{CPU + memory}}$$

Recap: Threads

- Benefits:
  - Simplify concurrent programming
  - Useful when there is a slow resource
- Challenge:
  - Share parts of address space
  - How to prevent undesired outcomes?



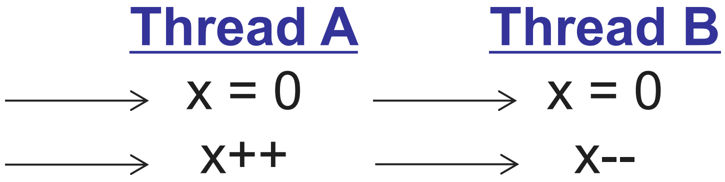
Non-deterministic ordering → Non-deterministic results

- Arithmetic example (y is initially 10)
  - Possible results?
    - » If A runs first: x = 11 and y = 20
    - » If B runs first: x = 21 and y = 20

Thread A	Thread B
x = y + 1	y = y * 2

- Another example (x is initially 0)
  - Possible results?
    - » x = 1 or -1
  - Impossible results?
    - » x = 0

Thread A	Thread B
x = 1	x = -1



Thread A	Thread B
x = 0	x = 0
x++	x--

Atomic operations

- To reason about cooperating threads, we must know which operations are **atomic**
  - Effects of operation are seen in entirety, or not at all

- Most computers:
  - Memory load and store are atomic
  - Many other instructions are not atomic
    - » Example: double-precision floating point
  - Need an atomic op to build a bigger atomic op

Example

Thread A

```
i=0
while (i < 10) {
    i++
}
print "A finished"
```

Thread B

```
i=0
while (i > -10) {
    i--
}
print "B finished"
```

- Which thread will exit its while loop first?
- Is thread that exits loop first guaranteed to print first?
- Is it guaranteed that someone will print?

Debugging Multi-Threaded Programs

- Challenging due to non-deterministic interleaving
  - Heisenbug: a bug that occurs non-deterministically

- Something for you to worry about? YES!!!
  - Think Murphy’s Law
- Famous errors:
  - Northeast blackout of 2003
  - Over-radiation in Therac-25

- All possible interleavings must be correct

Synchronization

- Constrain interleavings between threads such that all possible interleavings produce a correct result
- Trivial solution?
- Challenge:
    - Constrain thread executions as little as possible

- Insight:
    - Some events are independent → order is irrelevant
    - Other events are dependent → order matters

Too much milk

- Problem definition
  - Alice and Bob want to always have one can of milk
  - No room for two cans of milk
  - Whoever sees fridge empty goes to buy milk
- Solution #0 (no synchronization)

Bob

```
if (noMilk) {
    buy milk
}
```

Alice

```
if (noMilk) {
    buy milk
}
```

Problems?

Race condition!

First type of synchronization: Mutual exclusion

- Ensure that only 1 thread is doing a certain thing at any moment in time
  - *"Only 1 person goes shopping at a time"*
  - Constrains interleavings of threads

- Does this remind you of any other concept we've talked about?

Critical section

- Section of code that must be run atomically with respect to selected other pieces of code
- Critical sections must be atomic w.r.t each other because they access a shared resource
- In our example, critical section is:
  - *“if (no milk) { buy milk }”*
  - How do we make this critical section atomic?

Too much milk (solution #1)

- Leave note that you're going to check on the milk, so other person doesn't also buy
  - Assume only atomic operations are load and store

Bob

```
→ if (noNote) {
      leave note
      if (noMilk) {
          buy milk
      }
      remove note
  }
```

Alice

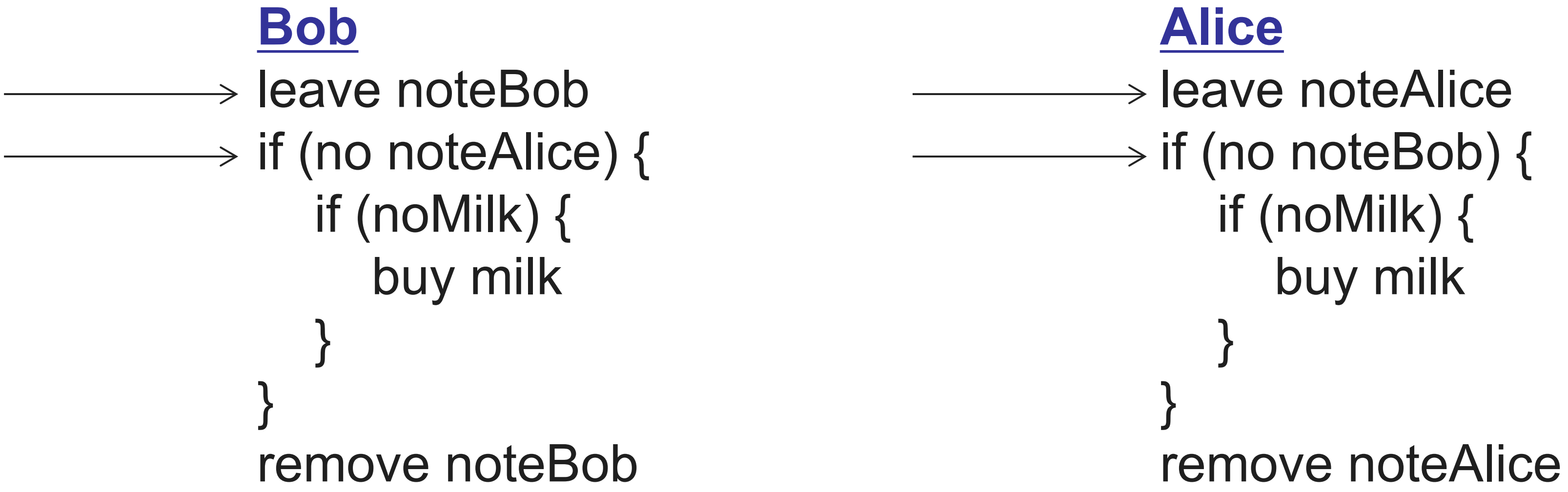
```
→ if (noNote) {
      leave note
      if (noMilk) {
          buy milk
      }
      remove note
  }
```

Does this work?

Better solution than #0?

Too much milk (solution #2)

- Change the order of “leave note” and “check note”
- Notes need to be labelled



Bob

```
leave noteBob
if (no noteAlice) {
    if (noMilk) {
        buy milk
    }
}
remove noteBob
```

Alice

```
leave noteAlice
if (no noteBob) {
    if (noMilk) {
        buy milk
    }
}
remove noteAlice
```

Problems?

Announcements

- First project is out
  - Due on Jan. 29th
  - Office hour schedule on Google calendar on web page
  - Get familiar with git, gdb, valgrind, etc.

- Mid-term: 6:30-8:30pm on February 20th

Too much milk (solution #3)

- Decide who will buy milk when both leave notes at the same time. Bob hangs around to make sure job is done.

Bob

```
leave noteBob
while (noteAlice) {
    do nothing
}
if (noMilk) {
    buy milk
}
remove noteBob
```

Alice

```
leave noteAlice

if (no noteBob) {
    if (noMilk) {
        buy milk
    }
}
remove noteAlice
```

- Bob’s “while (noteAlice)” prevents him from entering the critical section at the same time as Alice

Proof of correctness

- Alice
  - if no noteBob, then Bob hasn't started yet, so safe to buy
    - Bob will wait for Alice to be done before checking
  - if noteBob, then Bob will eventually buy milk if needed
    - Note that Bob may be waiting for Alice to exit

- Bob
  - if no noteAlice, safe to buy
    - Already left noteBob, which Alice will check
  - if noteAlice, Bob waits to see what Alice does and accordingly decides whether to buy

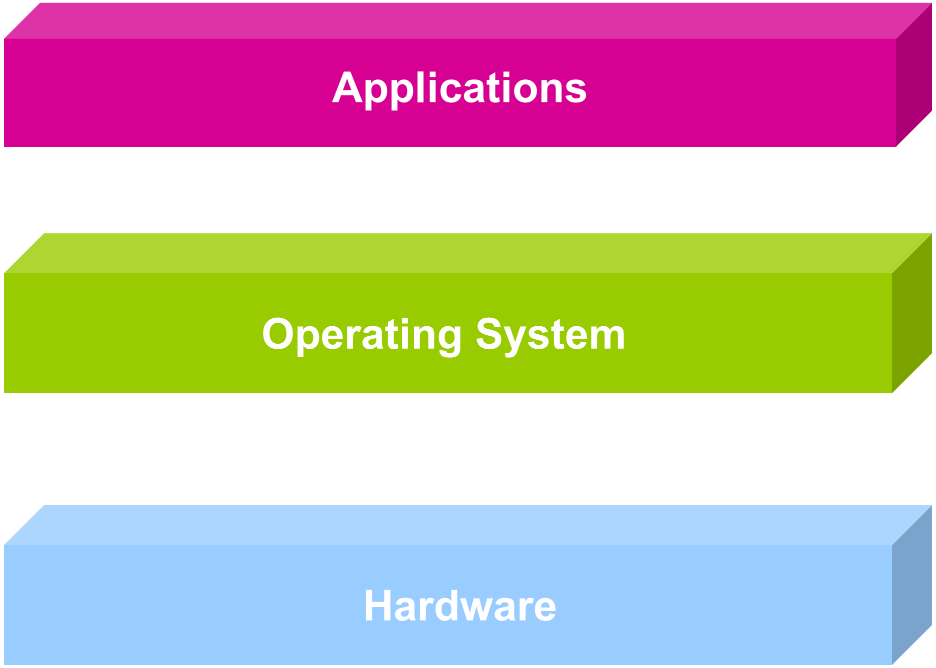
Analysis of solution #3

- Good
  - It works!
  - Relies on simple atomic operations

- Bad
  - Complicated; not obviously correct
  - Asymmetric
  - Not obvious how to scale to three people
  - Bob consumes CPU time while waiting
    - Called **busy-waiting**

Higher-level synchronization

- Raise the level of abstraction to make life easier for programmers



Applications

Operating System

Hardware

Concurrent programs

Higher-level synchronization primitives
(lock, monitor, semaphore)

Atomic operations
(load/store, interrupt enable/disable, test&set)

Locks (mutexes)

- A lock prevents another thread from entering a critical section
  - *“Lock fridge while checking milk status and shopping”*
- Two operations
  - lock(): wait until lock is free, then acquire it

```
do {
    if (lock is free) {
        acquire lock
        break
    }
} while (1)
```

Atomic

  - unlock(): release lock

Locks (mutexes)

- A lock prevents another thread from entering a

Why was the note in *Too much milk* (solutions #1 and #2) not a good lock?

- Two operations
  - lock(): wait until lock is free, then acquire it

```
do {
    if (lock is free) {
        acquire lock
        break
    }
} while (1)
```

Atomic

  - unlock(): release lock

Locks (mutexes)

- Lock usage
  - Initialize to free
  - Acquire lock before entering critical section
  - Release lock when done with critical section
- All synchronization involves waiting
- Thread can be running or blocked

Bob

```
milk.lock();
if (noMilk) {
    buy milk
}
milk.unlock()
```

Alice

```
milk.lock()
if (noMilk) {
    buy milk
}
milk.unlock()
```

Efficiency

- But this prevents Alice from doing things while Bob is buying milk
- How to minimize the time the lock is held?

Bob

```
milk.lock();
if (noMilk) {
    buy milk
}
milk.unlock()
```

Alice

```
milk.lock()
if (noMilk) {
    buy milk
}
milk.unlock()
```

Efficiency

- Use lock to protect posting/looking up of note

```
note.lock()
if (noNote) {
    leave note
    note.unlock()
    if (noMilk) {
        buy milk
    }
    note.lock()
    remove note
    note.unlock()
}
else {
    note.unlock()
}
```