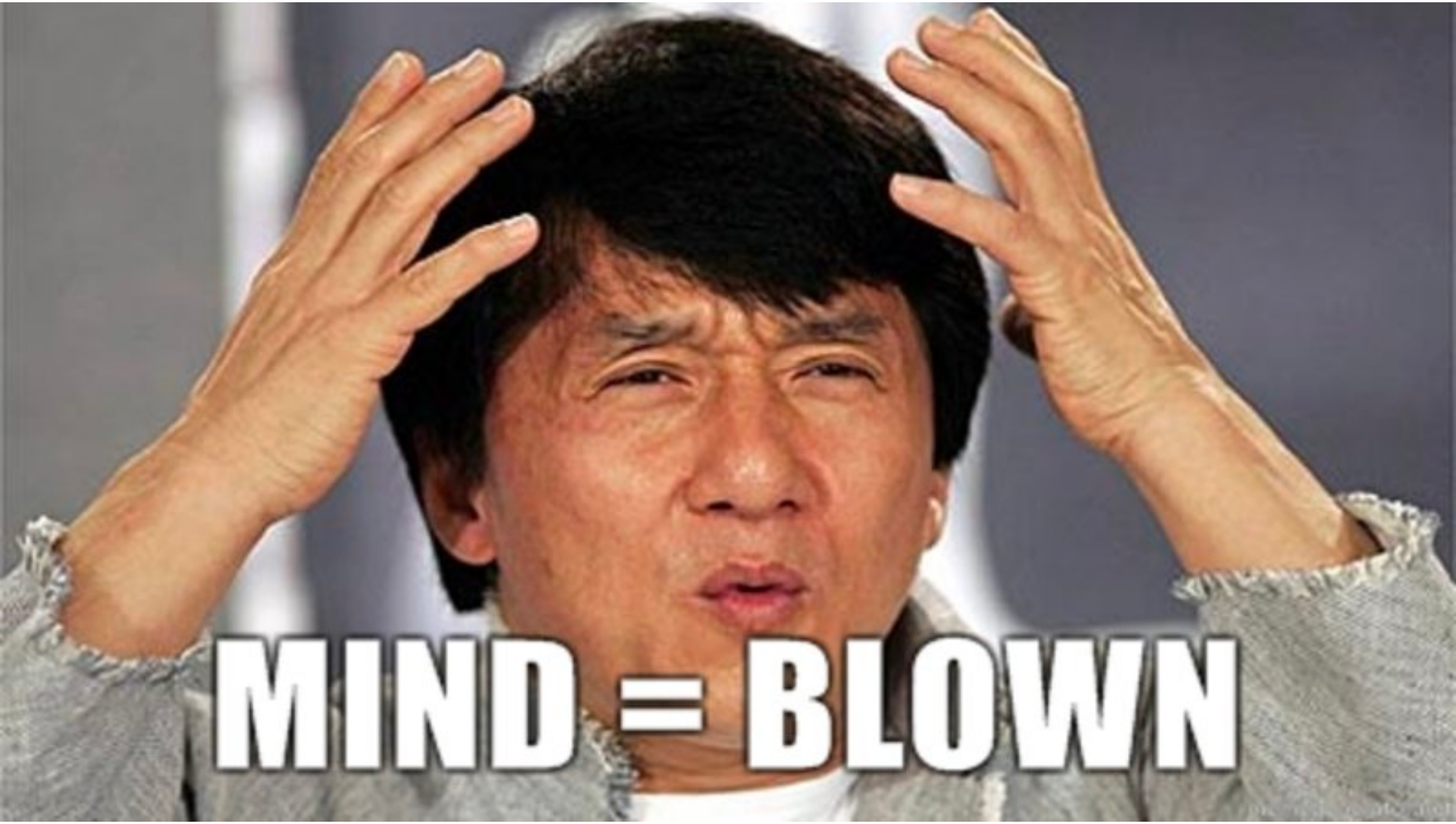
EECS 482
Introduction to Operating Systems

Winter 2018

Baris Kasikci

Slides by: Harsha V. Madhyastha



http://knowyourmeme.com/memes/mind-blown

Recap: Processes

- Hardware interface:

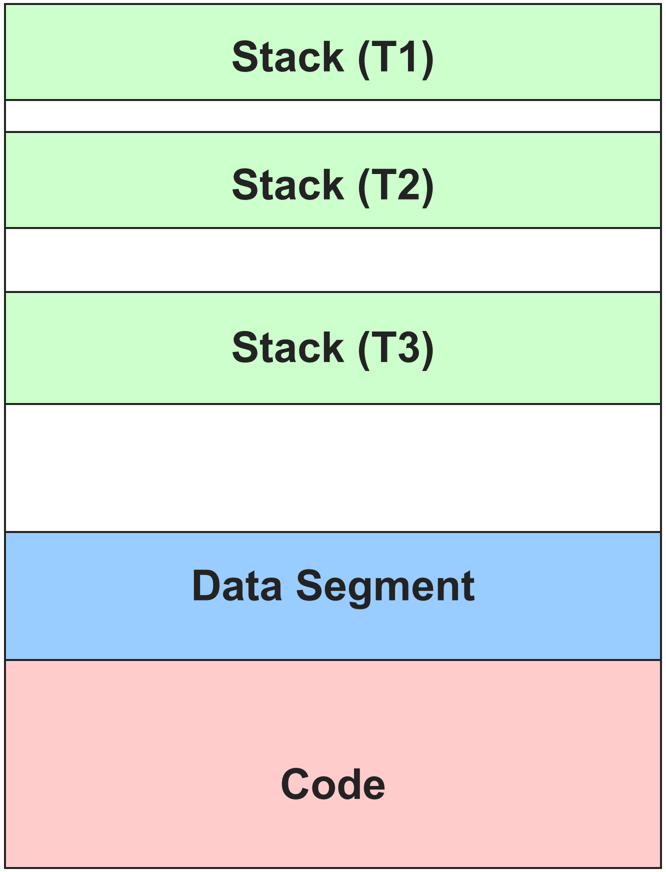
$$\frac{\texttt{app1+app2+app3}}{\texttt{CPU + memory}}$$

- 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?



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 the winner guaranteed to print first?
- Is it guaranteed that someone will win?

Example

Thread A

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

Thread B

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

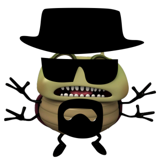
- If both threads run at the same speed and start within a few instructions, are they guaranteed to loop forever?

Atomic operations

- Before we can reason at all about cooperating threads, we must know that some operation is **atomic**
  - Indivisible, i.e., happens in its entirety or not at all
  - No events from other threads can occur in between

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

Debugging Multi-Threaded Programs

- Challenging due to non-deterministic interleaving
  
  - Heisenbug: a bug that occurs non-deterministically (and your program will be Breaking Badly soon enough).
- Something for you to worry about? YES!!!
  - Think Murphy's Law
- All possible interleavings must be correct

Therac 25

Northeastern Blackout

DIRTY COW

Dirty COW (CVE-2016-5195) is a privilege escalation vulnerability in the Linux Kernel

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

Announcements

- First project is out
  - Due in 2 weeks (Jan. 29th)
  - Office hour schedule on Google calendar on web page
  - Get familiar with git, gdb, valgrind, etc.
- Check out Piazza if looking for project group
- Discussion section questions for this Friday posted
- Send me your picture if you haven't already

Too much milk

- Problem definition
  - Tia and Baris want to keep their refrigerator stocked with at most one milk jug
  - If either sees fridge empty, she/he goes to buy milk
- Solution #0 (no synchronization)

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

Tia
```
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 needs to 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

Baris

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

Tia

```
→ 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 (otherwise you’ll see your note and think the other person left it)

Baris

```
leave noteBaris
if (no noteTia) {
    if (noMilk) {
        buy milk
    }
}
remove noteBaris
```

Tia

```
leave noteTia
if (no noteBaris) {
    if (noMilk) {
        buy milk
    }
}
remove noteTia
```

Problems?

Too much milk (solution #3)

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

Baris

```
leave noteBaris
while (noteTia) {
    do nothing
}
if (noMilk) {
    buy milk
}
remove noteBaris
```

Critical Section

Tia

```
leave noteTia

if (no noteBaris) {
    if (noMilk) {
        buy milk
    }
}
remove noteTia
```

Critical Section

- Baris's "while (noteTia)" prevents him from entering the critical section at the same time as Tia

Proof of correctness

- Tia
  - if no noteBaris, then Baris hasn’t started yet, so safe to buy
    - » Baris will wait for Tia to be done before checking
  - if noteBaris, then Baris will eventually buy milk if needed
    - » Note that Baris may be waiting for Tia to exit

- Baris
  - if no noteTia, safe to buy
    - » Already left noteBaris, which Tia will check
  - if noteTia, Baris waits to see what Tia does and accordingly decides whether to buy

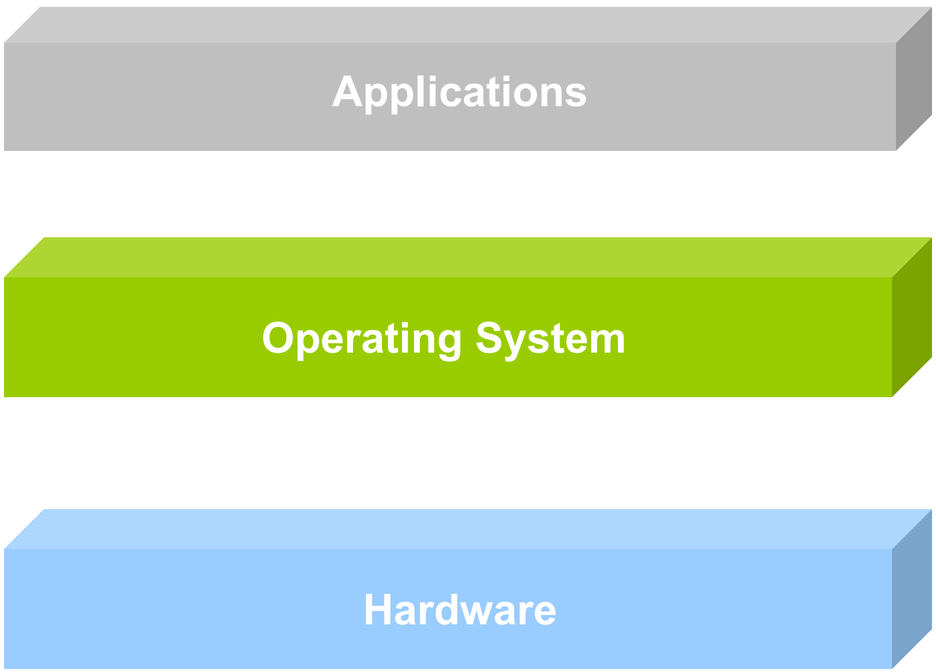
Analysis of solution #3

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

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

Higher-level synchronization

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



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)

- How to use a lock
  - Initialized to free
  - Thread acquires lock before entering critical section (waiting if needed)
  - Thread that has acquired lock should release when done with critical section
- All synchronization involves waiting
- Thread can be running or blocked

Baris

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

Tia

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

Efficiency

- But this prevents Tia from doing things while Baris is buying milk

- How to minimize the time the lock is held?

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()
}
```