Concurrency 3

CS 2110 – Spring 2017

Announcements

- Course evaluations: we care.
- We care so much we make it **1% of your grade**.

- At the end of **May 11th**, we see a list of which students submitted evaluations.
- After grades are submitted, we see the anonymized content of the evaluations.

- We read them all.
- When giving feedback, please strive for **specificity** and **constructiveness**.

Axiomatic Basis for Computer Programming. Tony Hoare, 1969

Provide a definition of programming language statements not in terms of how they are executed but in terms of proving them correct.

{precondition P}
Statement S
{Postcondition Q)

Meaning: If P is true, then execution of S is guaranteed to terminate and with Q true

Assignment statement x= e;

{true}
x= 5;
{x = 5}

{x+1 >= 0}
x= x + 1;
{x >= 0}

{2*x = 82}
x= 2*x;
{x = 82}

Definition of notation:
P[x:= e] (read P with x replaced by e) stands for a copy of expression P in which each occurrence of x is replaced by e

Example: (x >= 0)[x:= x+1] = x+1 >= 0

Definition of the assignment statement:
{P[x:= e]}
x= e;
{P}

Assignment statement x:= e;

Definition of the assignment statement:

{P[x:= e]}

x= e;

{P}

{x+1 >= 0}	{2*x = 82}
x= x + 1;	x= 2*x;
{x >= 0}	{x = 82}

{2.0xy + z = (2.0xy + z)/6 }

x= 2.0*x*y + z;

{x = x/6}

x = x/6

2.0xy + z = (2.0xy + z)/6

If statement defined as an "inference rule":

Definition of if statement: If

{P && B} ST {Q} and
{P && !B} SF {Q}

Then

{P}
if (B) ST
else SF
{Q}

The then-part, ST, must end with Q true
The else-part, SF, must end with Q true

Hoare's contribution 1969:
Axiomatic basis: Definition of a language in terms of how to prove a program correct.

But it is difficult to prove a program correct after the fact. How do we develop a program and its proof hand-in-hand?

Dijkstra showed us how to do that in 1975.
His definition, called "weakest preconditions" is defined in such a way that it allows us to "calculate" a program and its proof of correctness hand-in-hand, with the proof idea leading the way.

Dijkstra: *A Discipline of Programming*. Prentice Hall, 1976.
A research monograph

Gries: The Science of Programming. Springer Verlag, 1981.
Undergraduate text.

How to prove concurrent programs correct.

Use the principle of non-interference

Thread T1	Thread T2
{P0}	{Q0}
S1;	Z1;
{P1}	{Q1}
S2;	Z2;
{P2}	{Q2}
…	…
Sn;	Zm;
{Pn}	{Qm}

T1 and T2 are proved correct in isolation.

What happens when T1 and T2 execute simultaneously?

How many execution orders are there?

How to prove concurrent programs correct.

Use the principle of non-interference

S1; S2; … Sn;	Z1; Z2; … Zm;

T1 and T2 are proved correct in isolation.

What happens when T1 and T2 execute simultaneously?

How many execution orders are there?

m+n instructions to execute:

- choose m of them for the Z's
- S's in the rest.

$$\binom{m+n}{m} = \frac{(m+n)!}{m! * n!} = a\ very\ big\ number$$

How to prove concurrent programs correct.

Thread T1	Thread T2
{P0}	{Q0}
S1;	Z1;
{P1}	{Q1}
S2;	Z2;
{P2}	{Q2}
…	…
Sn;	Zm;
{Pn}	{Qm}

Turn what previously seemed to be an exponential problem, looking at all executions, into a problem of size n*m.

Prove that execution of T1 does not interfere with the proof of T2, and vice versa.

Basic notion: Execution of Si does not falsify an assertion in T2: e.g. {Pi && Q1} S2 {Q1}

Interference freedom.

Susan Owicki's Cornell thesis, under Gries, in 1975.

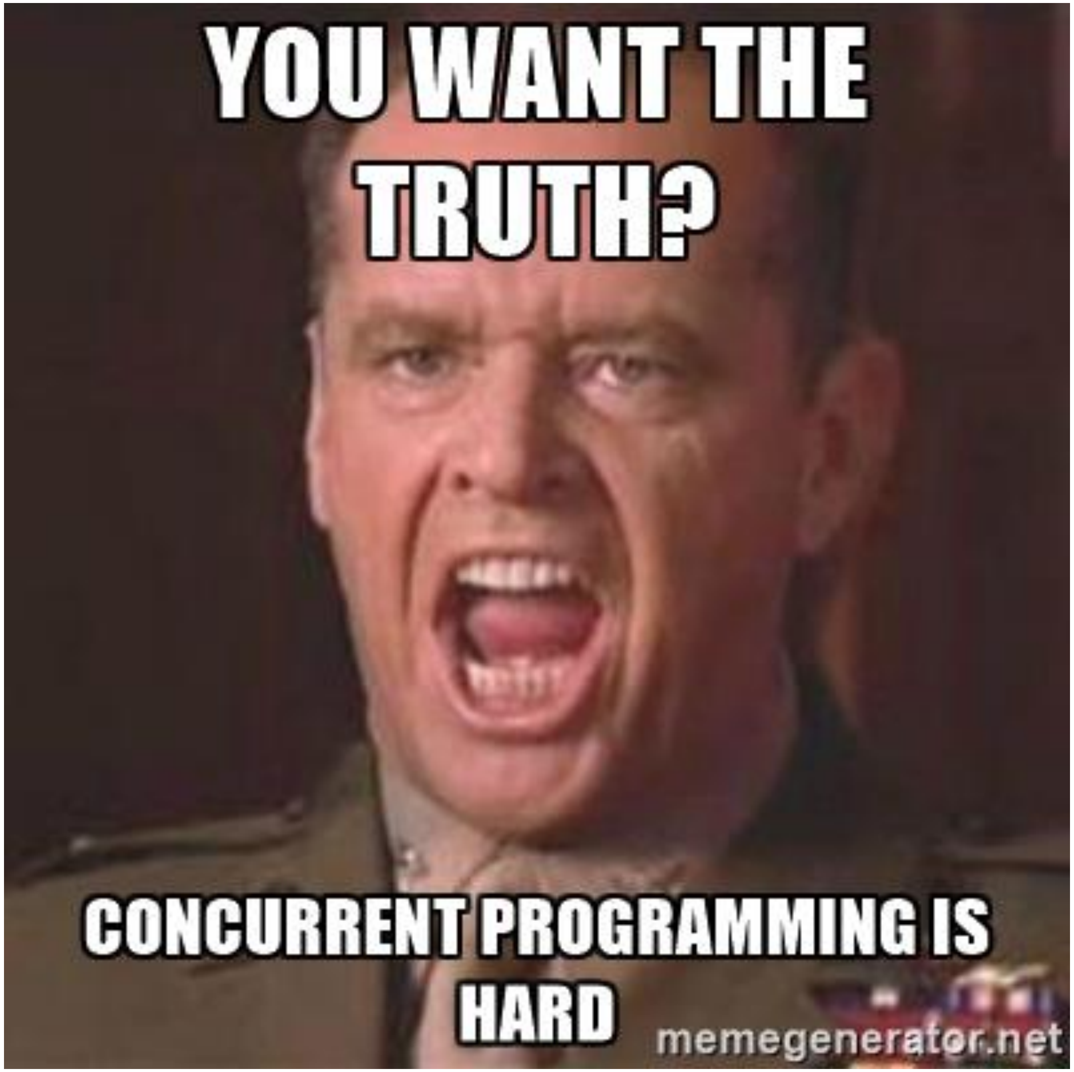
Thread T1	Thread T2
{P0}	{Q0}
S1;	Z1;
{P1}	{Q1}
S2;	Z2;
{P2}	{Q2}
…	…
Sn;	Zm;
{Pn}	{Qm}

A lot of progress since then! But still, there are a lot of hard issues to solve in proving concurrent programs correct in a practical manner.

Prove that execution of T1 does not interfere with the proof of T2, and vice versa.

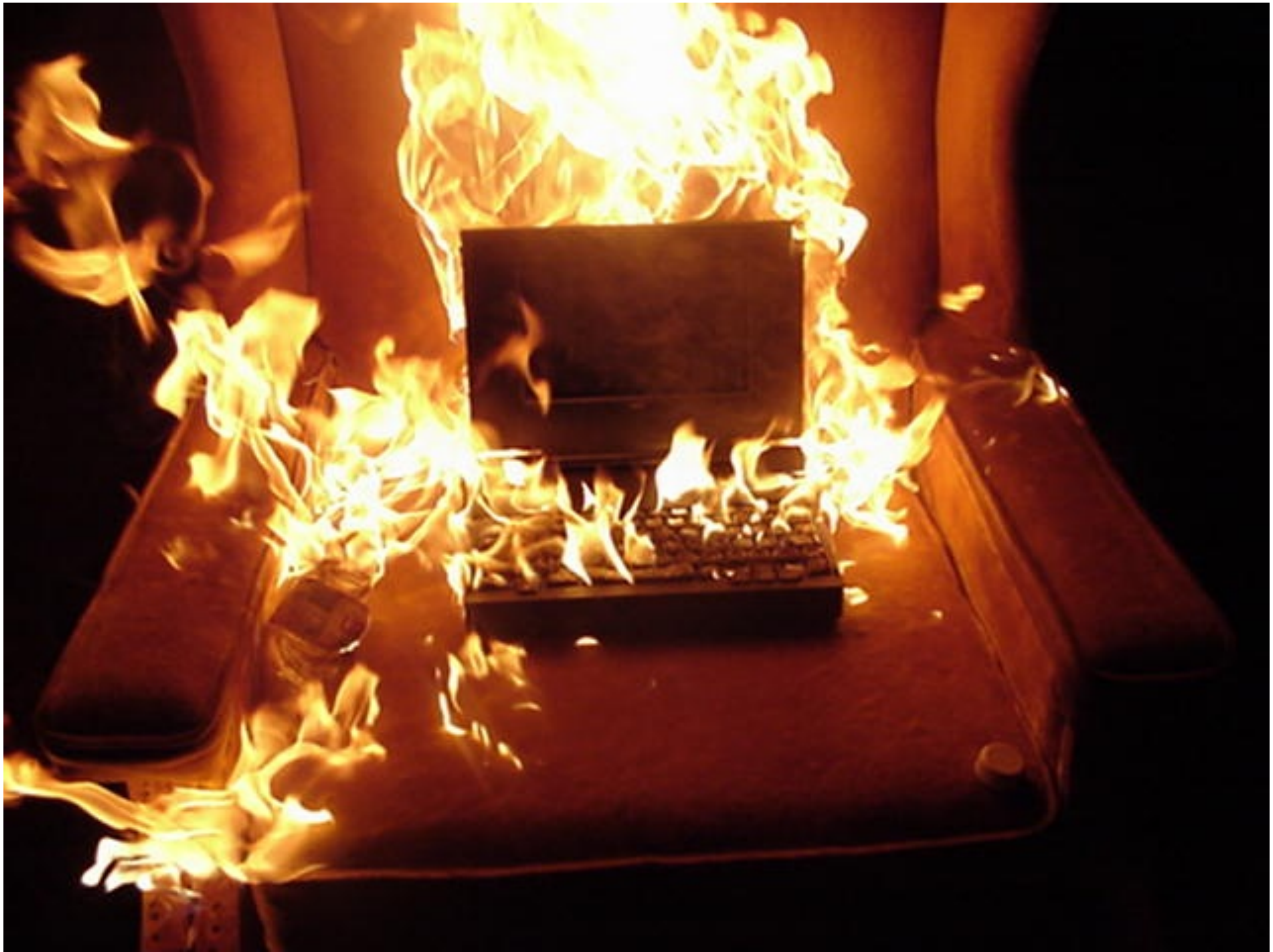
Basic notion: Execution of Si does not falsify an assertion in T2: e.g. {Pi && Q1} S2 {Q1}

The Harsh Truth



On the bright side…

A new way to melt your computer!



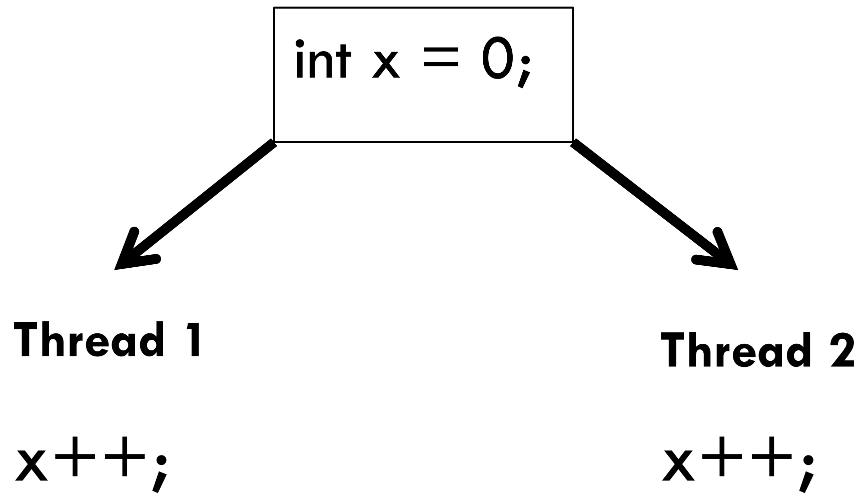
A new way to melt your computer!

```
public class ForkBomb extends Thread {
    public static void main(String[] args) {
        (new ForkBomb()).start();
    }

    public @Override void run() {
        (new ForkBomb()).start();
        (new ForkBomb()).start();
    }
}
```

A new way to melt your computer!

Atomicity



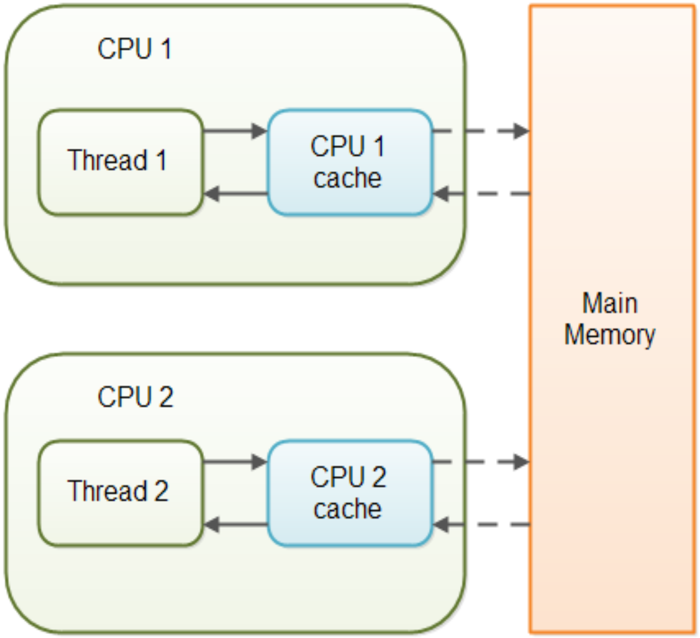
What is the value of x?

Can be either 1 or 2!

Caching and Volatile

- Concurrent programming is hard.
- Concurrent programming on real hardware is even harder!

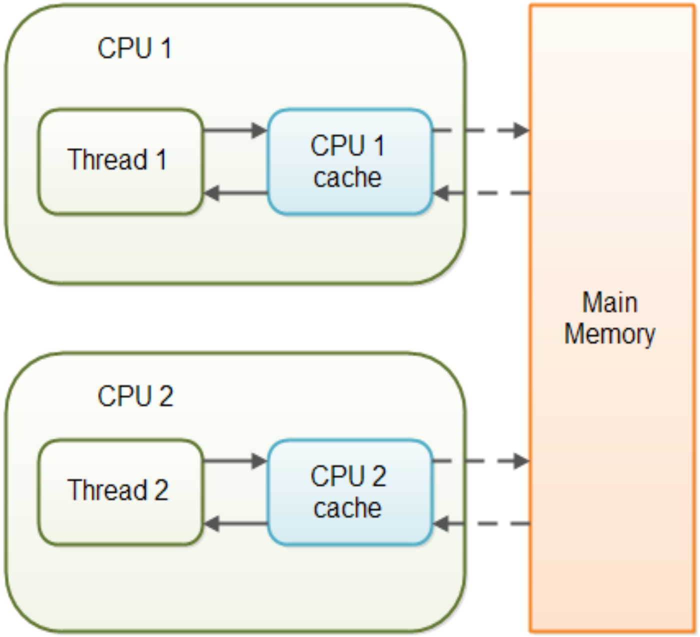
- Data is stored in caches
- Only written to main memory occasionally
- Huge efficiency gains!
- Huge concurrency headaches!



Caching and Volatile

- Concurrent programming is hard.
- Concurrent programming on real hardware is even harder!

- Volatile keyword
  - Fields can be declared **volatile**
  - All local changes are made visible to other threads
- **Does not guarantee atomicity!**
  - x+= 1 still does get, add, set; these may still be interleaved



Atomicity

```
volatile int x = 0;
```

Thread 1

```
x++;
```

Thread 2

```
x++;
```

What is the value of x?

Can be either 1 or 2!

Can we get atomicity without locks?

- class AtomicInteger, AtomicReference<T>, …
  - Represents a value
- method set(newValue)
  - has the effect of writing to a volatile variable
- method get()
  - returns the current value

- If the OS controls thread execution, how can the language ever guarantee atomicity?
  - New concurrency primitives: atomic operations.

Compare and Set (CAS)

- boolean compareAndSet(expectedValue, newValue)
  - If value doesn't equal expectedValue, return false
  - if equal, store newValue in value and return true
  - executes as a single atomic action!
  - supported by many processors – as **hardware instructions**
  - does not use locks!

```
AtomicInteger n = new AtomicInteger(5);
n.compareAndSet(3, 6); // return false – no change
n.compareAndSet(5, 7); // returns true – now is 7
```

Incrementing with CAS

```
/** Increment n by one. Other threads use n too. */
public static void increment(AtomicInteger n) {
        int i = n.get();
        while (n.compareAndSet(i, i+1))
                i = n.get();
}

// AtomicInteger has increment methods that do this
```

Lock-Free Data Structures

- Usable by many concurrent threads
- using only atomic actions – no locks!
- compare and swap is your best friend
- but it only atomically updates one variable at a time!

Let's look at one!

- Lock-free binary search tree [Ellen et al., 2010]
  http://www.cs.vu.nl//~tcs/cm/cds/ellen.pdf

Concurrency in other languages

- Concurrency is an OS-level concern
- Platform-independent languages often provide abstractions on top of these.
  - Java, Python, Matlab, …
- Different platforms have different concurrency APIs for compiled languages.
  - Unix/Linux: POSIX Threads (Pthreads)
  - Mac OS (based on Unix!): Pthreads, NSThread
  - Windows APIs
  - iOS: ??
  - Android: ??

Graph Search

- Do you need to **travel** to a node to visit it?

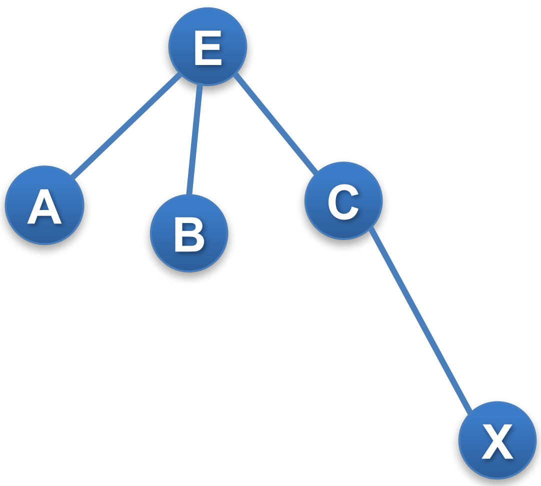
VS

Graph Search

- Do you need to **travel** to a node to visit it?
  - Depends on what information you have about the graph.
- Self-driving car (e.g., Uber) with nothing but sensors:
  - needs to explore to find its destination.
- Self-driving car (e.g. Waymo) with Google Maps:
  - compute a path, then follow it.

Graph Search

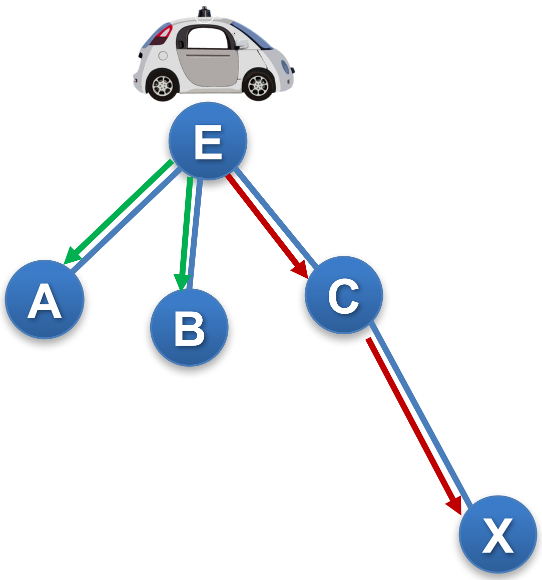
- Let's consider BFS.




```
/** Visit all nodes REACHABLE* from u.
Pre: u is unvisited. */
public static void bfs(int u) {
    Queue q= (u);
    while q is not empty) {
        u= q.popFirst();
        if (u has not been visited) {
            visit u;
            for each edge (u, v) leaving u:
                q.append(v);
        }
    }
}
```

Graph Search

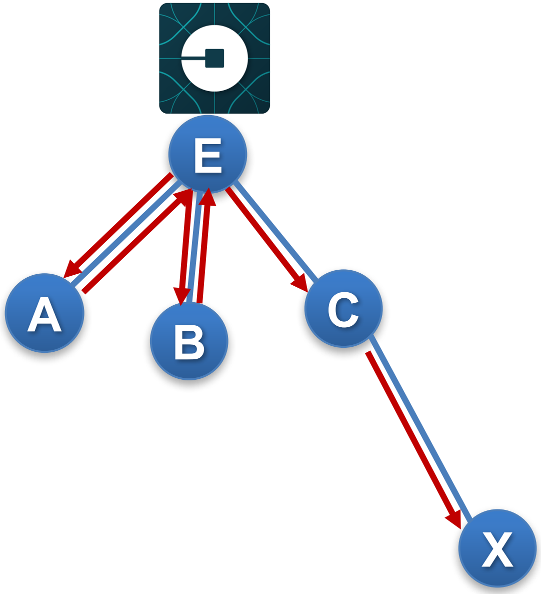
- Let's consider BFS if you're Google.




```
/** Visit all nodes REACHABLE* from u.
Pre: u is unvisited. */
public static void bfs(int u) {
    Queue q= (u);
    while q is not empty) {
        u= q.popFirst();
        if (u has not been visited) {
            visit u;
            for each edge (u, v) leaving u:
                q.append(v);
        }
    }
}
```

Graph Search

- Let's consider BFS if you're Uber (no Google Maps!*).




```
/** Visit all nodes REACHABLE* from u.
Pre: u is unvisited. */
public static void bfs(int u) {
    Queue q= (u);
    while q is not empty) {
        u= q.popFirst();
        if (u has not been visited) {
            visit u;
            for each edge (u, v) leaving u:
                q.append(v);
        }
    }
}
```

*allegedly

If a method moves a robot…

- Your method's spec needs to say where the robot starts and ends in all possible scenarios.

```
/** Drive in a square with side length size, starting out
in the current direction. Car ends in the same location
and direction as it started. */
public void driveInSquare(int size) {
    for (int i = 0; i < 4; i += 1) {
            forward(size);
            turn(90);
    }
}
```

Wrapping up the course

- What is this course good for?
- Where can you go from here?

Coding Interviews

- A quick web search reveals: **We've taught you most of what you need for coding interviews.**
  - https://www.reddit.com/r/cscareerquestions/comments/20ahfq/heres_a_pretty_big_list_of_programming_interview/
  - http://maxnoy.com/interviews.html
  - …
- Your interviewer will be **impressed*** if you:
  - Write specs before you write methods.
  - Talk about/write invariants for your loops.
  - ...

*If not, don't work there.

What else is there?

- This course scratches the surface of many subfields of CS.
- Topics that have 4000-level courses:
  - Analysis of algorithms
  - Computational complexity
  - Compilers (parsing, grammars)
  - Programming Languages (formal semantics, ...)
  - Applied Logic (correctness proofs, ...)
  - Operating Systems (concurrency, caching, …)
  - Artificial Intelligence (graph searching, ...)
- ...among others.

*If not, don’t work there.