15-251
Great Theoretical Ideas in Computer Science

Lecture 1:
Introduction to the course

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What is computer science?

Is it:

"Writing programs that do certain tasks."

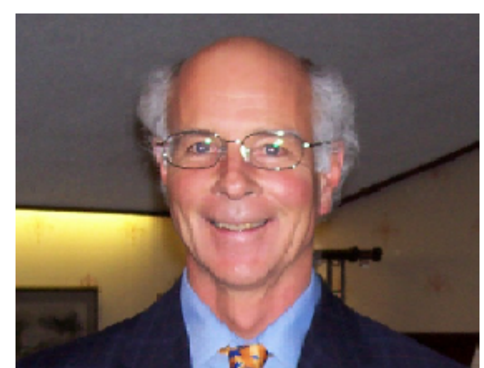
What is theoretical computer science?

Motivational Quote of the Course

"Computer Science is no more about computers than astronomy is about telescopes."

~~Edsger Dijkstra~~

- Michael Fellows

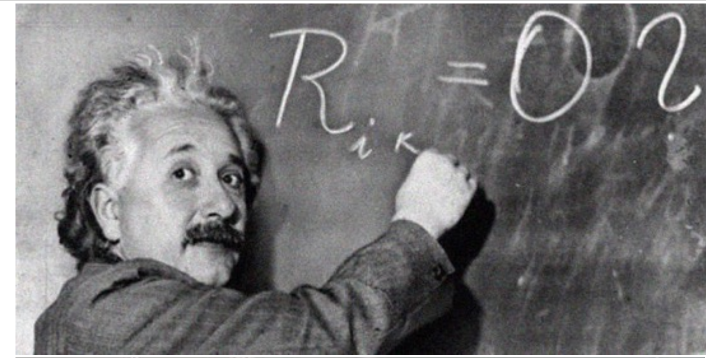


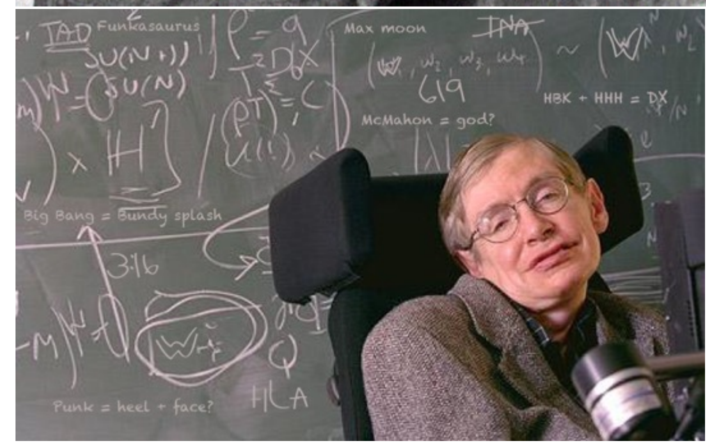
What is computer science?

Is it branch of:

- science?
- engineering?
- math?
- philosophy?
- sports?

Physics





Theoretical physics

- come up with mathematical models

  Nature's language is mathematics

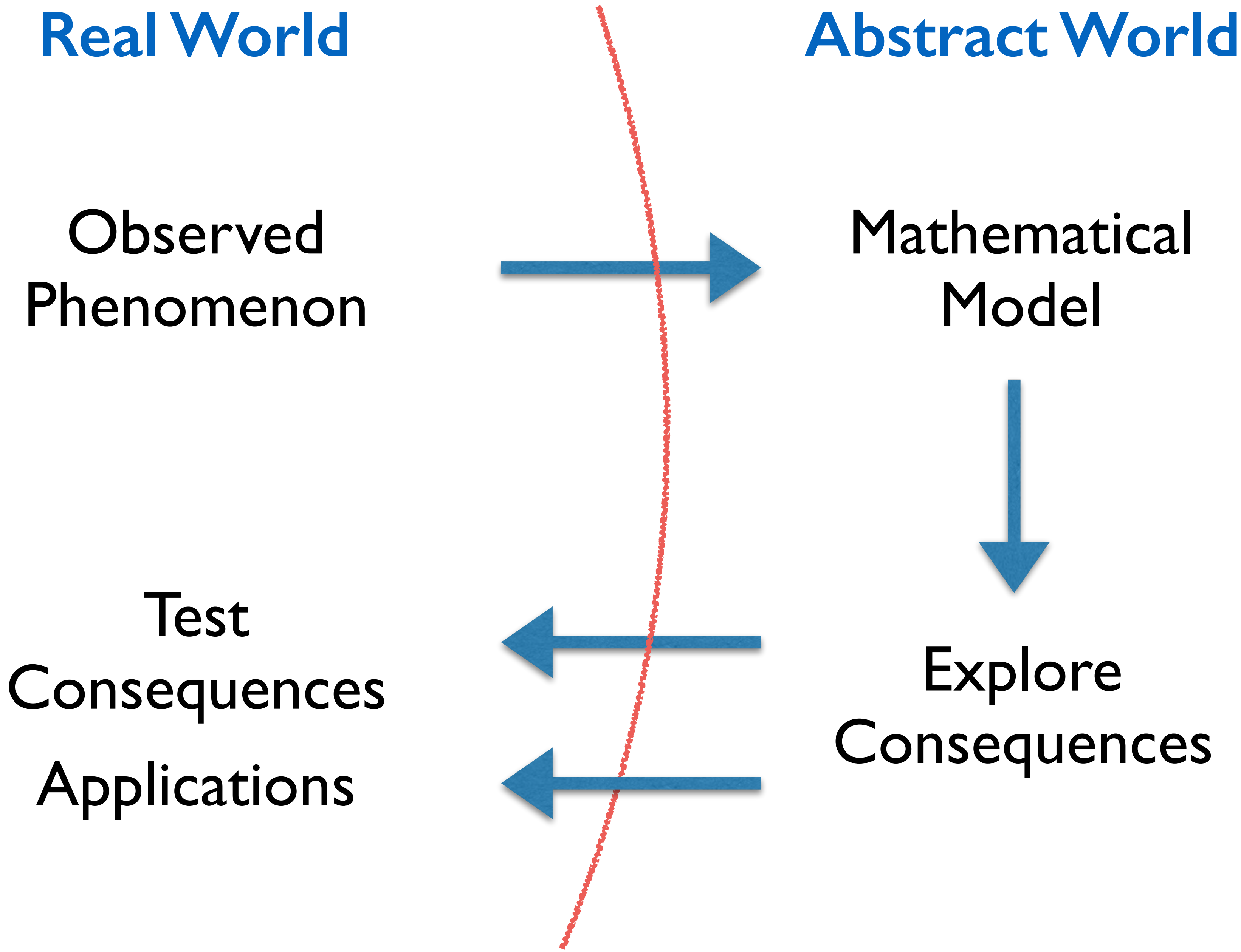
- derive the logical consequences

Experimental physics

- make observations about the universe
- test mathematical models with experiments

Applications/Engineering

The role of theoretical physics



Theoretical Physics

- science?
- engineering?
- math?
- philosophy?
- sports?

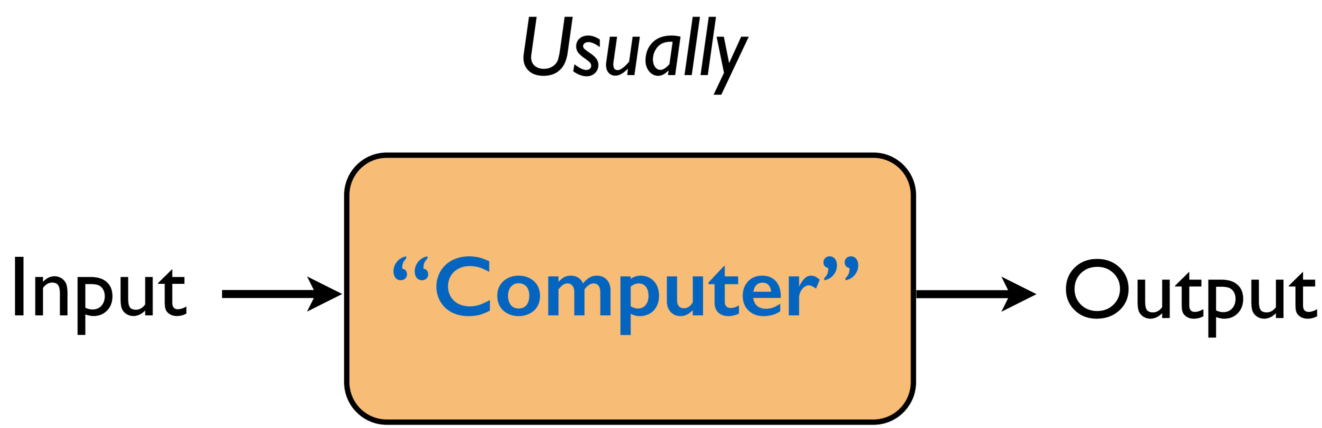
Computer Science

The science that studies computation.

Computation: manipulation of information/data.

Algorithm: description of how the data is manipulated.

Computational problem: the input-output pairs.



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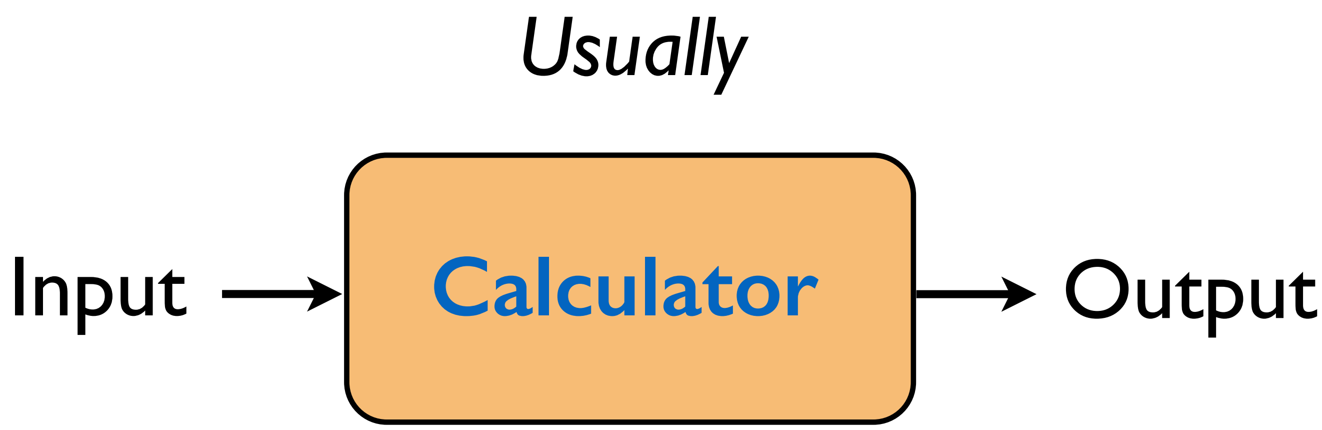

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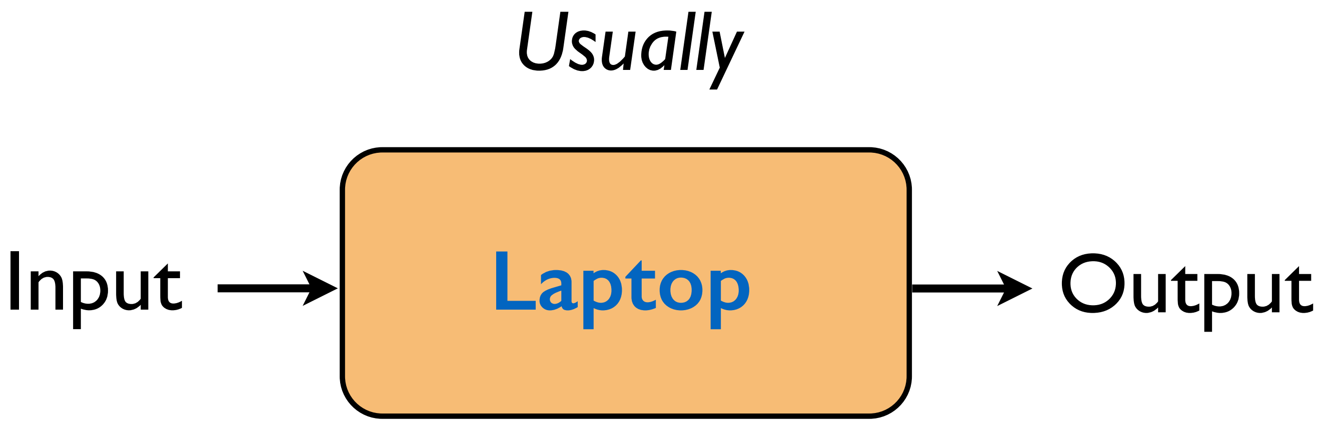

Computer Science

The science that studies computation.

Computation: manipulation of information/data.

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Computational problem: the input-output pairs.

Usually

“Computers” in early 20th century

Computer Science

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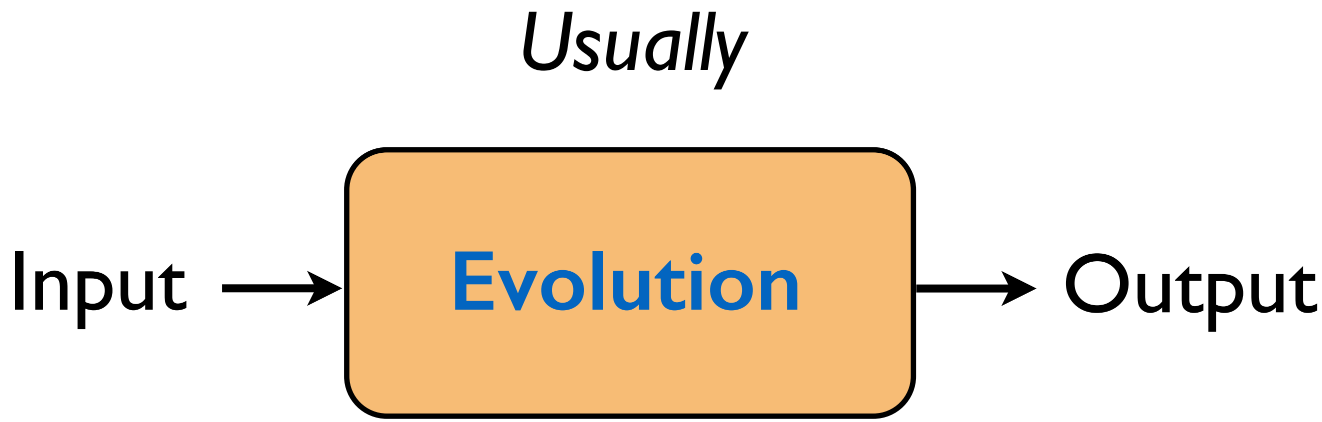


The computational lens

Computational physics

Computational biology

Computational chemistry

Computational neuroscience

Computational economics

Computational finance

Computational linguistics

Computational statistics

…

Defining computer science

“ Computer Science deals with the theoretical foundations of information and computation, together with practical techniques for the implementation and application of the foundations. ”

- *Wikipedia*

The role of theoretical computer science

Build a mathematical model for computation.

Explore the logical consequences.
Gain insight about computation.

http://youtu.be/pTeZP-XfuKI

https://goo.gl/gGkpMv

http://youtu.be/J4TkHuTmHsg

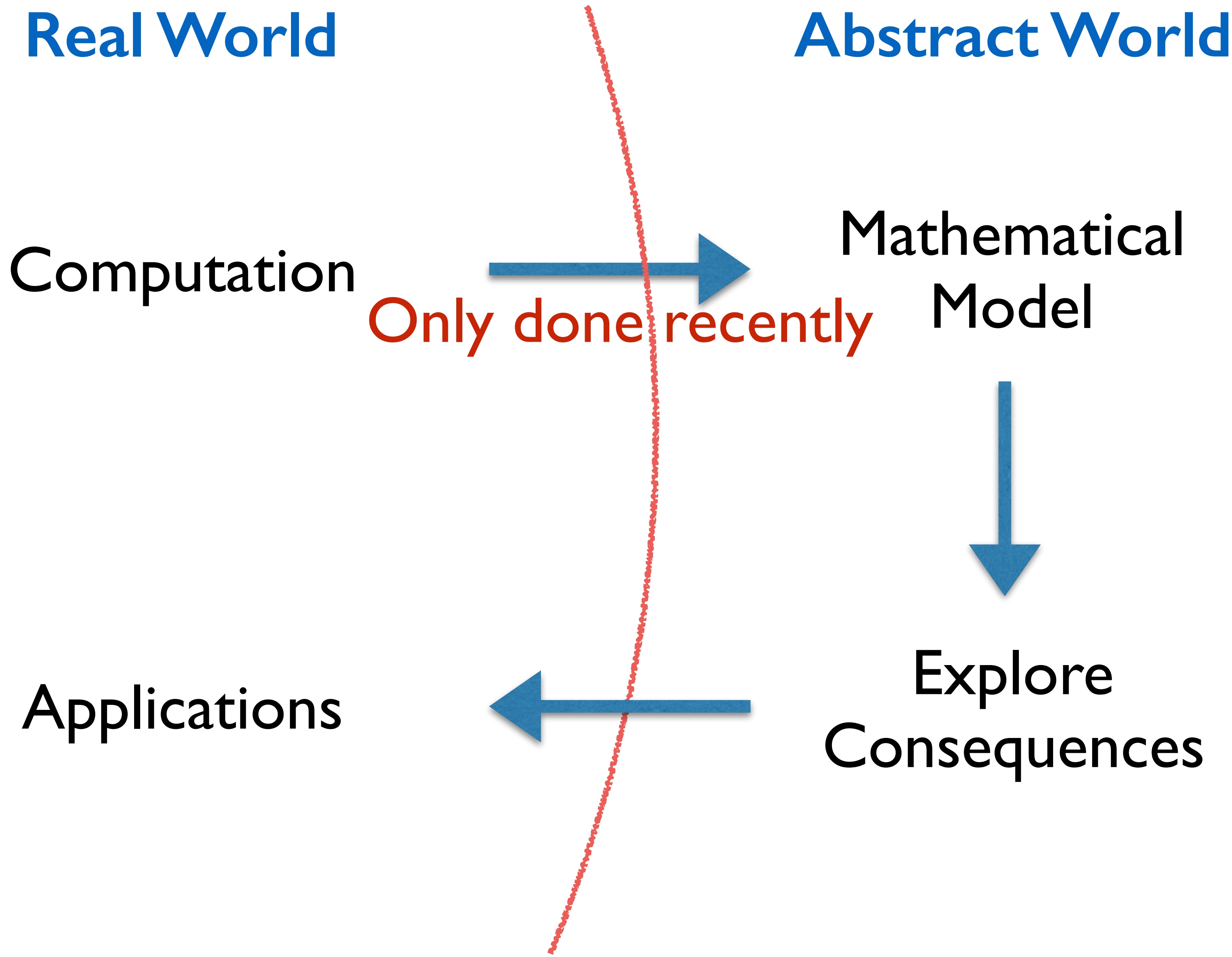
Look for interesting applications.

CMU undergrad

CMU Prof.

OK, we don't have everybody

The role of theoretical computer science



Simple examples of computation

We have been using algorithms for thousands of years.

$$
\begin{array}{r}
5127 \\
\times\ 4265 \\
\hline
25635 \\
307620 \\
1025400 \\
20508000 \\
\hline
21866655
\end{array}
$$

Simple examples of computation

We have been using algorithms for thousands of years.

Euclid's algorithm (~ 300BC):

```
def gcd(a, b):
    while (a != b):
        if (a > b):
            a = a - b
        else:
            b = b - a
    return a
```

Formalizing computation

We have been using algorithms for thousands of years.

Algorithm/Computation was only formalized in the 20th century!

Someone had to ask the right <u>question</u>.

David Hilbert, 1900

The Problems of Mathematics

"Who among us would not be happy to lift the veil behind which is hidden the future; to gaze at the coming developments of our science and at the secrets of its development in the centuries to come? What will be the ends toward which the spirit of future generations of mathematicians will tend? What methods, what new facts will the new century reveal in the vast and rich field of mathematical thought?"

2 of Hilbert's Problems

Hilbert's 10th problem (1900)

Is there a finitary procedure to determine if a given multivariate polynomial with integral coefficients has an integral solution?

e.g. $$5x^2yz^3 + 2xy + y - 99xyz^4 = 0$$

Entscheidungsproblem (1928)

Is there a finitary procedure to determine the validity of a given logical expression?

e.g. $$\neg\exists x, y, z, n \in \mathbb{N} : (n \geq 3) \wedge (x^n + y^n = z^n)$$

(Mechanization of mathematics)

2 of Hilbert's Problems

Fortunately, the answer turned out to be NO.

2 of Hilbert's Problems

Gödel (1934):

Discusses some ideas for mathematical definitions of computation. But not confident what is a good definition.

Church (1936):

Invents lambda calculus.
Claims it should be the definition of an "algorithm".

Gödel, Post (1936):

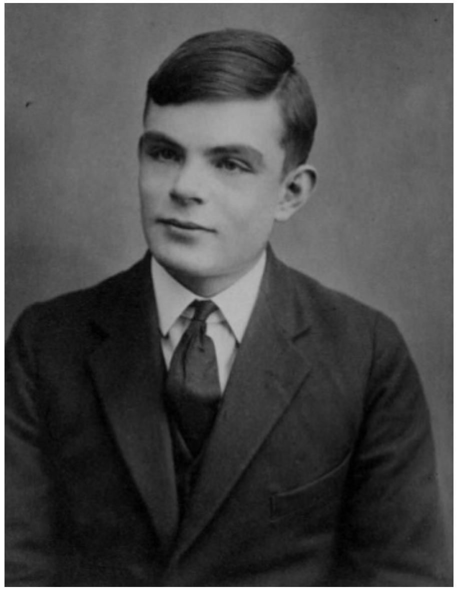
Arguments that Church's claim is not justified.

Meanwhile… in New Jersey… a certain British grad student, unaware of all these debates…

2 of Hilbert's Problems

Alan Turing (1936, age 22):

Describes a new model for computation, now known as the Turing Machine.™



Gödel, Kleene, and even Church:

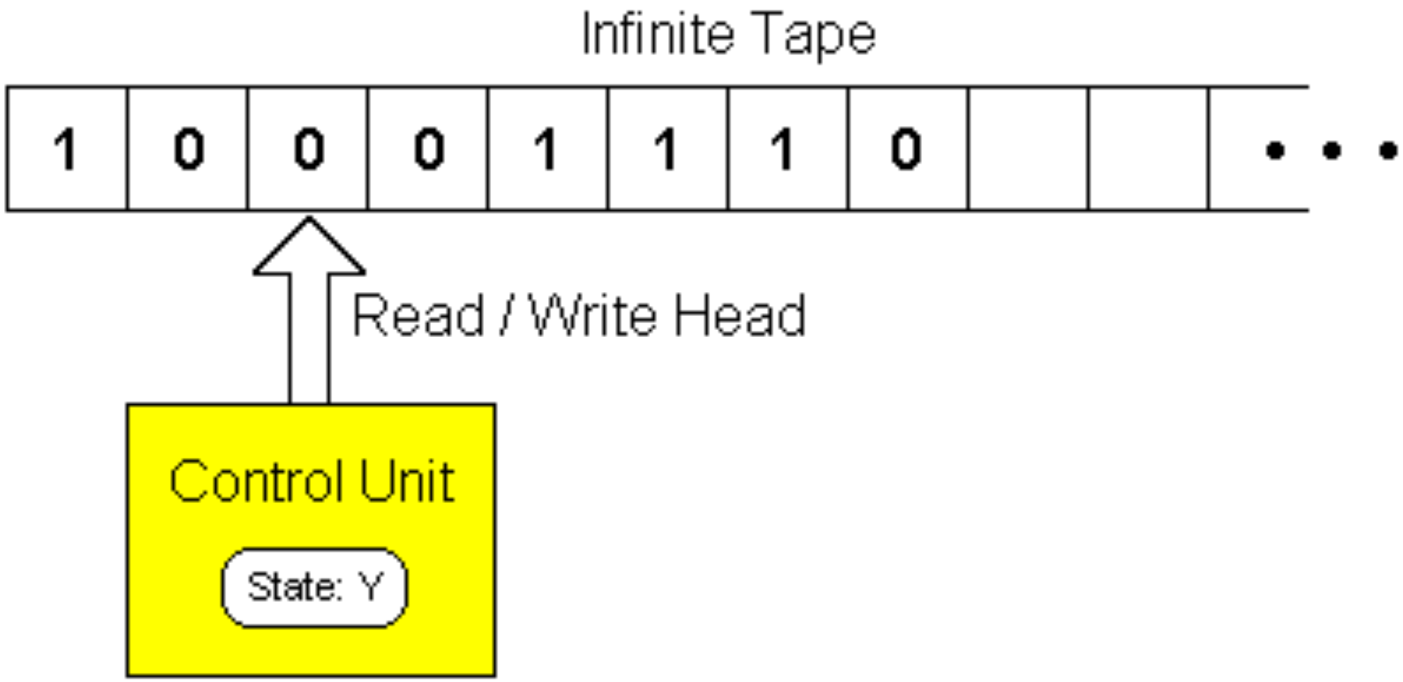
"Umm. Yeah. He nailed it. Game over. "Algorithm" defined."

Turing (1937):

TMs ≡ lambda calculus

Formalization of computation: Turing Machine

Turing Machine:



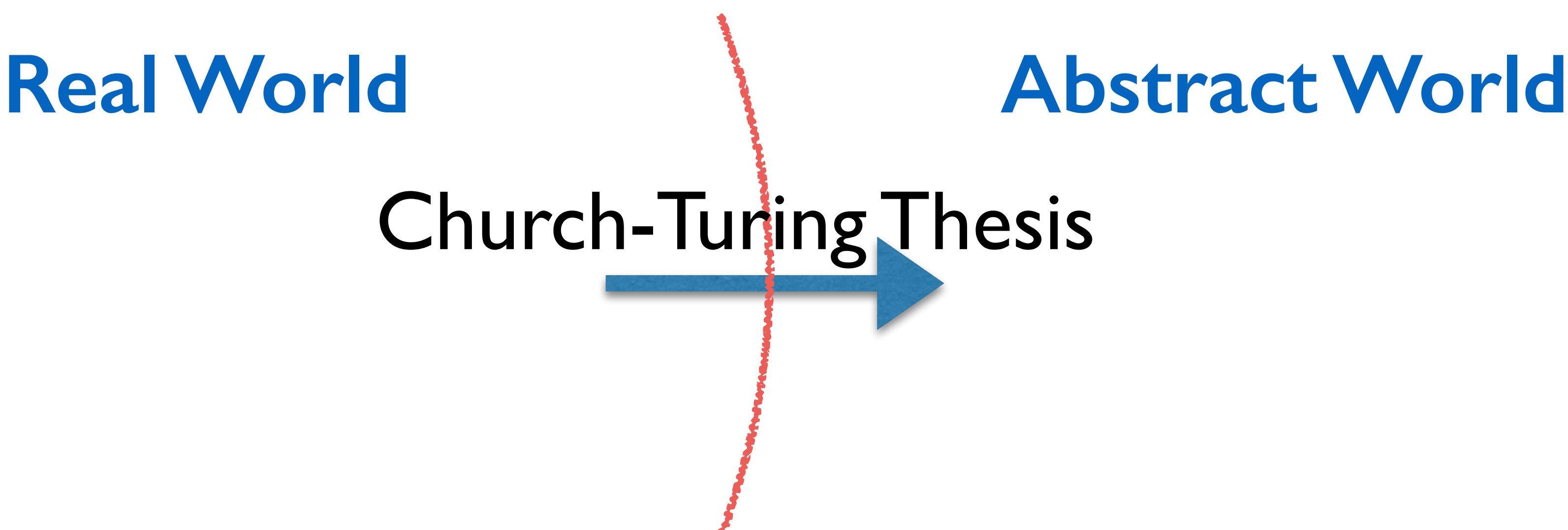
Church-Turing Thesis

Church-Turing Thesis:

The intuitive notion of "computable" is captured by functions computable by a Turing Machine.

(Physical) Church-Turing Thesis

Any computational problem that can be solved by a physical device, can be solved by a Turing Machine.



Back to Hilbert's Problems

Hilbert's 10th problem (1900)

Is there a finitary procedure to determine if a given multivariate polynomial with integral coefficients has an integral solution?

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(Mechanization of mathematics)

Back to Hilbert's Problems

Hilbert's 10th problem (1900)

Is there an algorithm (a TM) to determine if a given multivariate polynomial with integral coefficients has an integral solution?

e.g. $$5x^2yz^3 + 2xy + y - 99xyz^4 = 0$$

Entscheidungsproblem (1928)

Is there an algorithm (a TM) to determine the validity of a given logical expression?

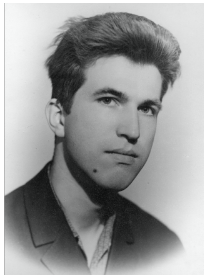
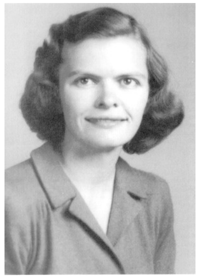
e.g. $$\neg\exists x, y, z, n \in \mathbb{N} : (n \geq 3) \wedge (x^n + y^n = z^n)$$

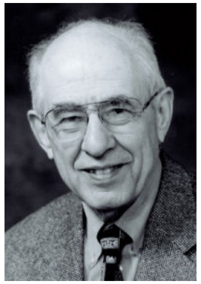
(Mechanization of mathematics)

Back to Hilbert's Problems

Hilbert's 10th problem (1900)

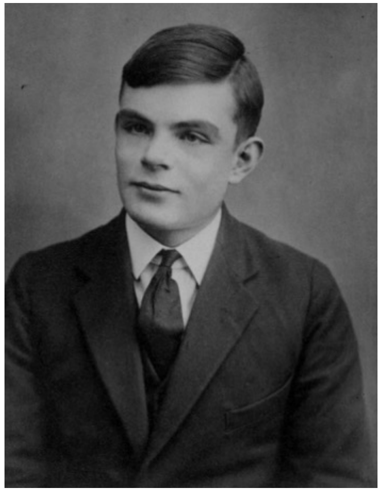
Matiyasevich-Robinson-Davis-Putnam (1970):



There is no algorithm to solve this problem.

Entscheidungsproblem (1928)



Turing (1936):

There is no algorithm to solve this problem.

Computer science

- science?
- engineering?
- math?
- philosophy?
- sports?

2 Main Questions in TCS

Computability of a problem:

Is there an algorithm to solve it?

Complexity of a problem:

Is there an efficient algorithm to solve it?

- time
- space (memory)
- randomness
- quantum resources

Computational Complexity

Complexity of a problem:

Is there an efficient algorithm to solve it?

- time
- space (memory)
- randomness
- quantum resources

2 camps:

- trying to come up with efficient algorithms (algorithm designers)
- trying to show no efficient algorithm exists (complexity theorists)

Computational Complexity

2 camps:

- trying to come up with efficient algorithms (algorithm designers)
- trying to show no efficient algorithm exists (complexity theorists)

multiplying two integers
factoring integers
sorting a list
protein structure prediction
simulation of quantum systems
computing Nash Equilibria of games

Some other interesting questions

If a problem has a space-efficient solution
does it also have a time-efficient solution?

Can every randomized algorithm be derandomized efficiently?

Can we use quantum properties of matter to build faster computers?

P vs NP

What will you learn in this course?

Topics Overview

Part 1: Formalizing the notions of problems, algorithms, and computability.

Part 2: Efficient computation:
basic algorithms and complexity

Part 3: Highlights of theoretical CS and the mathematics behind them.

This is a “big picture” course

Finite automata

Error correcting codes

Turing machines

Cryptography

Interactive proofs

Graph theory

Fields and polynomials

NP-completeness

Communication complexity

Generating functions

Combinatorial games

Markov chains

Approximation algorithms

Randomized algorithms

Group theory

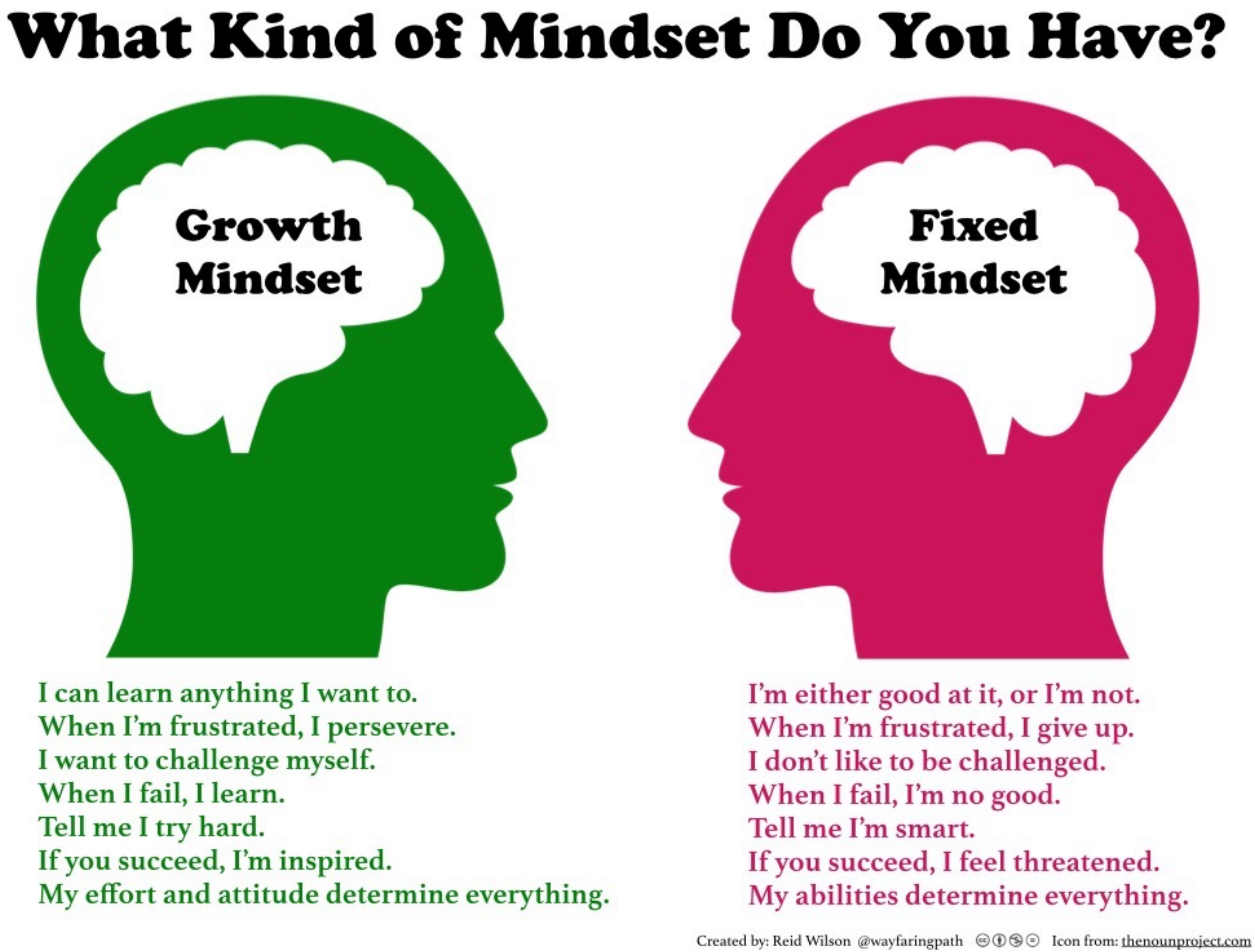
Probability

Basic number theory

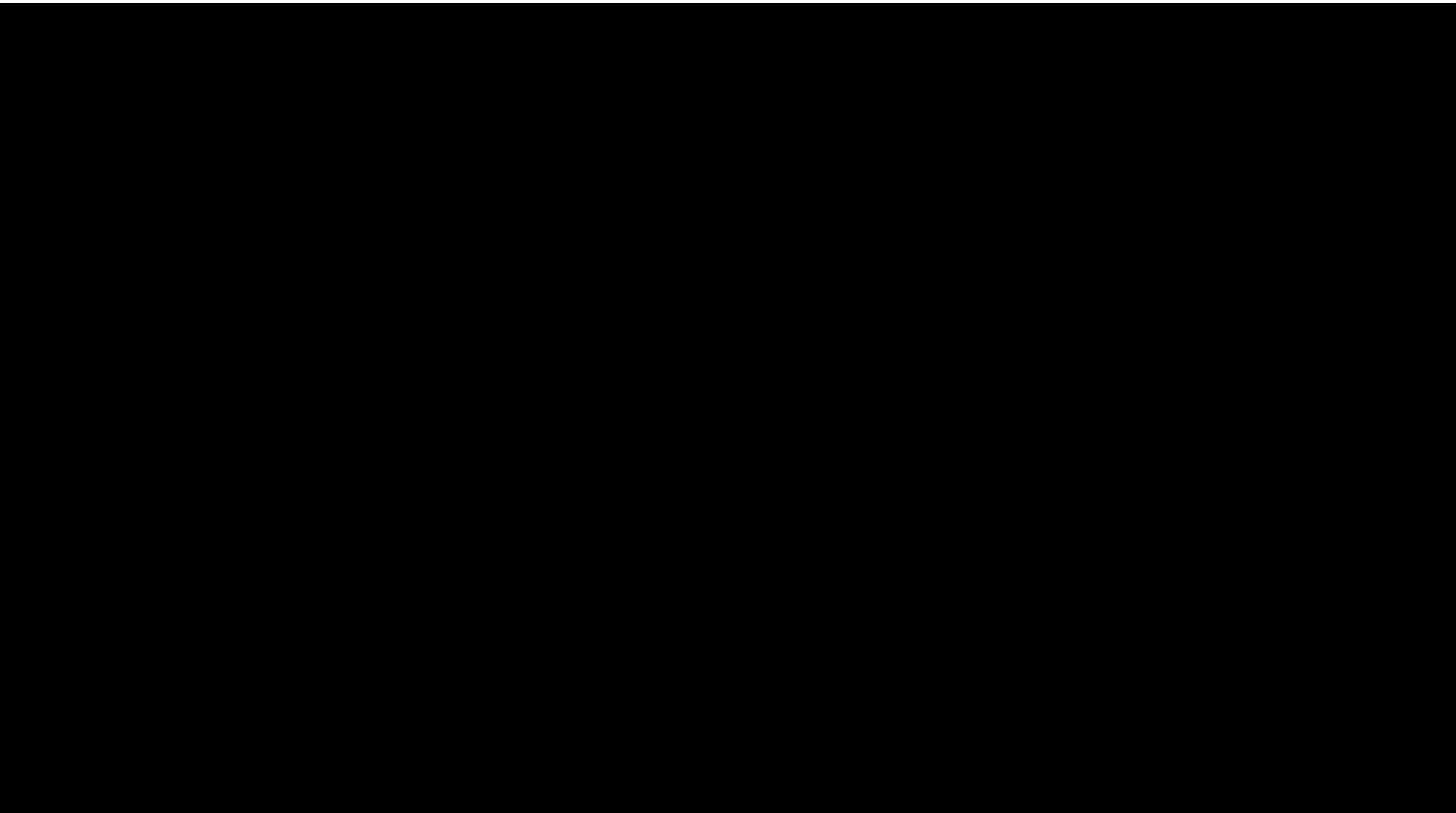
Goals

1. Learn about the theoretical foundations of computation.
2. Learn the mathematical language and tools we need.
3. Become better problem solvers.
4. Become better at rigorous, logical, abstract thinking.
5. Become better at expressing yourself clearly.
6. Become better at working with other people.

This is a challenging course



Video



A review of the course syllabus

A quick review of the course syllabus

Course webpage: www.cs.cmu.edu/~15251

A quick review of the course syllabus

Grading:

11 homework assignments, lowest 2 half-weighted

30%

2 midterm exams

Oct 5, Nov 16
6:30pm-9:30pm

20% + 20% = 40%

1 final exam

25%

Participation (attending classes and recitations)

5%

A poll

What is your favorite TV show?

- Game of Thrones
- Breaking Bad
- Seinfeld
- Friends
- The Wire
- Sesame Street
- None of the above
- I don't watch TV!

Homeworks

Most important part of the course!

They are meant to be challenging.

Make use of the office hours!!!

Homeworks prepare you for the exams.
Seriously!

Homeworks

Homework System:

3 types of questions:

SOLO, GROUP, OPEN COLLABORATION

SOLO - work by yourself

GROUP - work in groups of 3 or 4

OPEN - work with anyone you would like from class

Homeworks

Homework System:

3 types of questions:

SOLO, GROUP, OPEN COLLABORATION

Don't share written material with anyone.

Erase public whiteboard when done.

Can search books to learn more about a subject.

Can't Google specific keywords from the homework.

Always cite your sources!

Think about a problem before you collaborate.

Homeworks

Homework System:

Homework writing sessions:

Wednesdays 6:30pm to 7:50pm at DH 2315

Write the solutions to a random subset of the problems.

You must practice writing the solutions beforehand!!!

You will lose points for poor presentation.

You get 25% of the credit for the question if you write:

- nothing
- "I don't know", or
- "WTF!"

Homeworks

Homework System:

Feedback/grading:

Done by recitation on Friday.

You will know who graded which question.

Go see TA if:

- you think there has been a mistake in grading
- you don't understand why you lost points

Piazza

Everyone must sign up.

Course announcements will be made on Piazza.
You have to check it every day.

Great resource, make use of it.

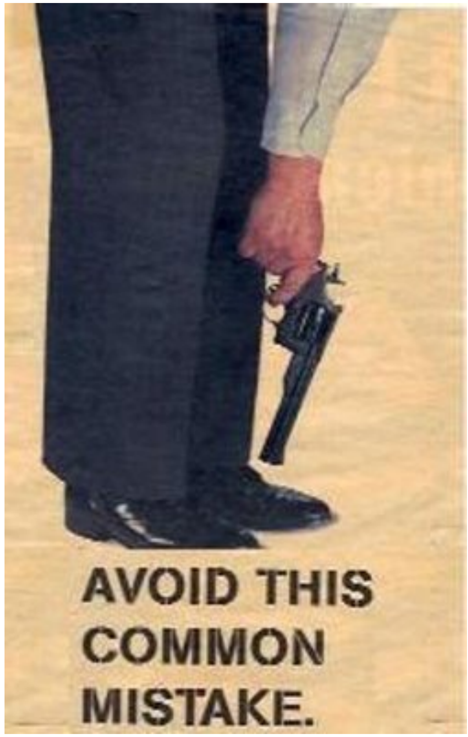
Please be polite.

Don't give away any hints.

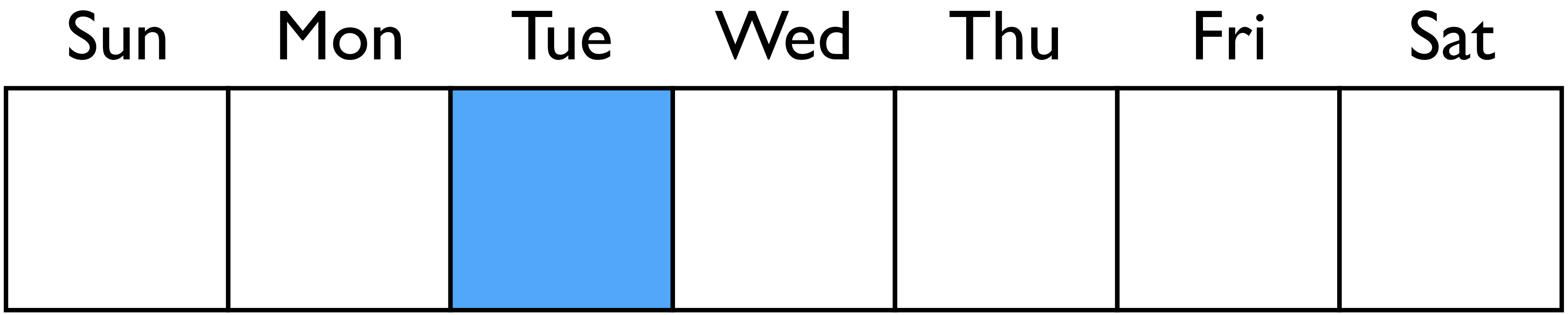
Office hours

See course webpage.

You have to use the OHs!



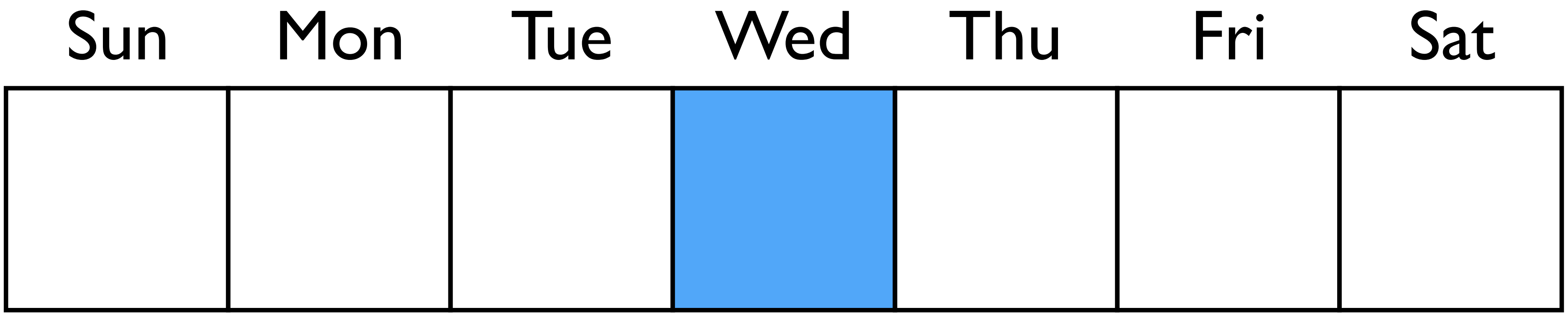
A typical week



Lecture 1

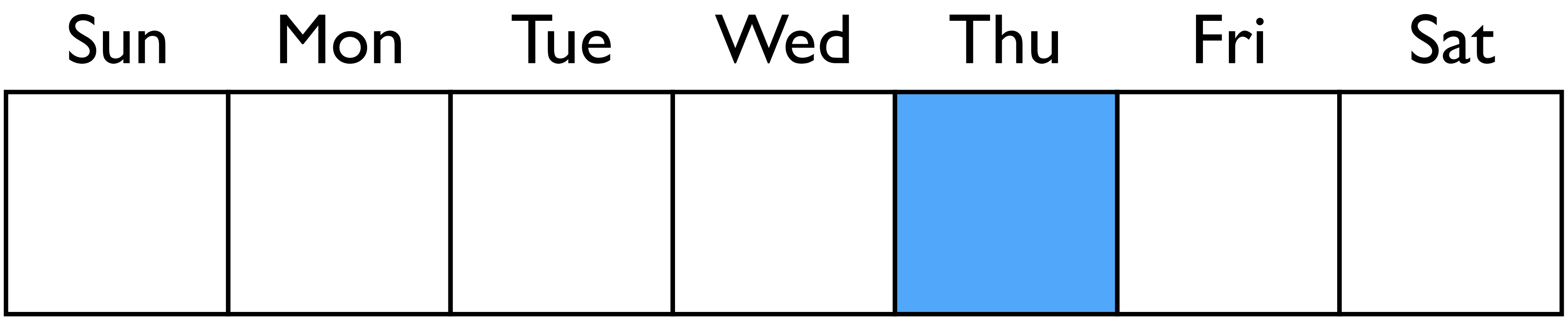
Office hour (Anil)

A typical week



Lecture 1.5 (6:30 - 7:50pm)

A typical week



Lecture 2

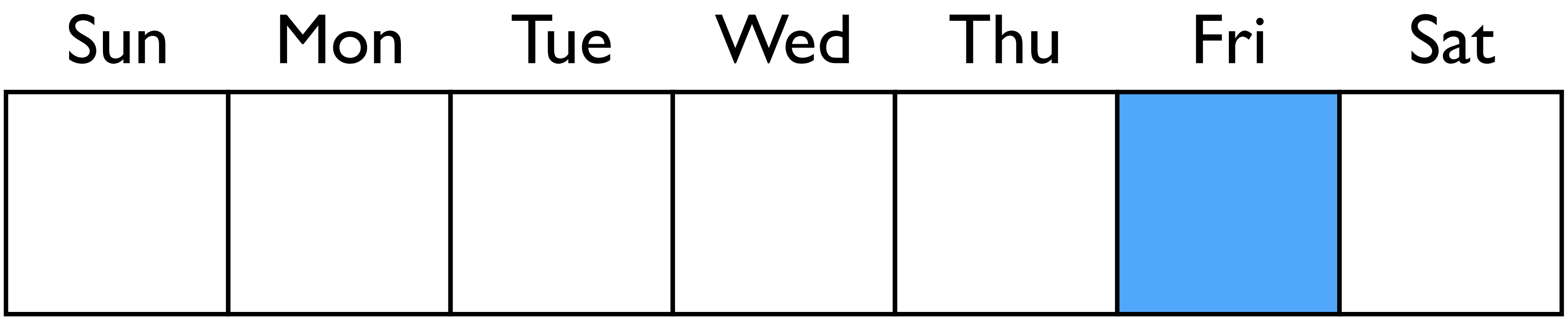
Office hour (Anil)

Review that week's material.

Homework comes out.

Maybe start working on the SOLO problems.

A typical week



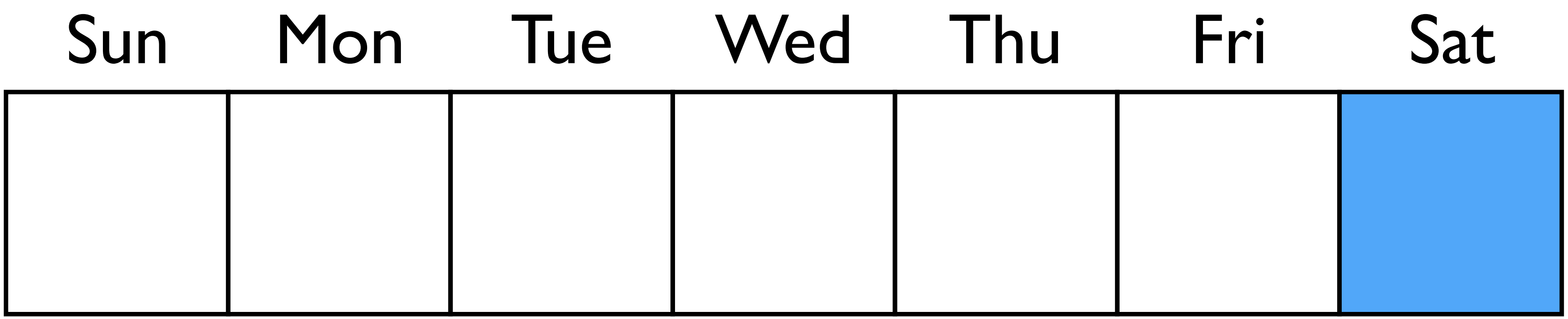
Recitation

Make progress on SOLO problems.

Start thinking about the GROUP problems.

Make appointments to meet with your group over the weekend.

A typical week



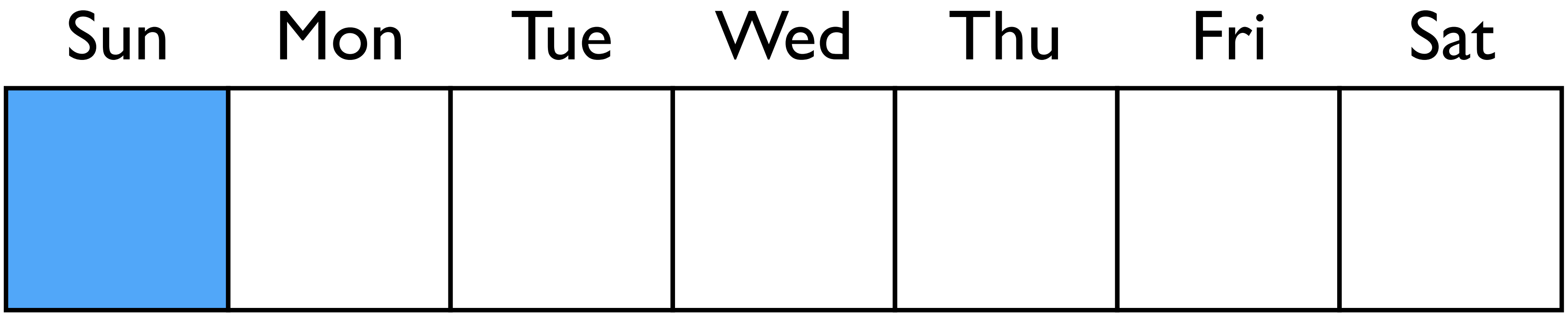
Meet with your group.

Make some progress on the questions.

Maybe solve some of them.

Go to office hours.

A typical week

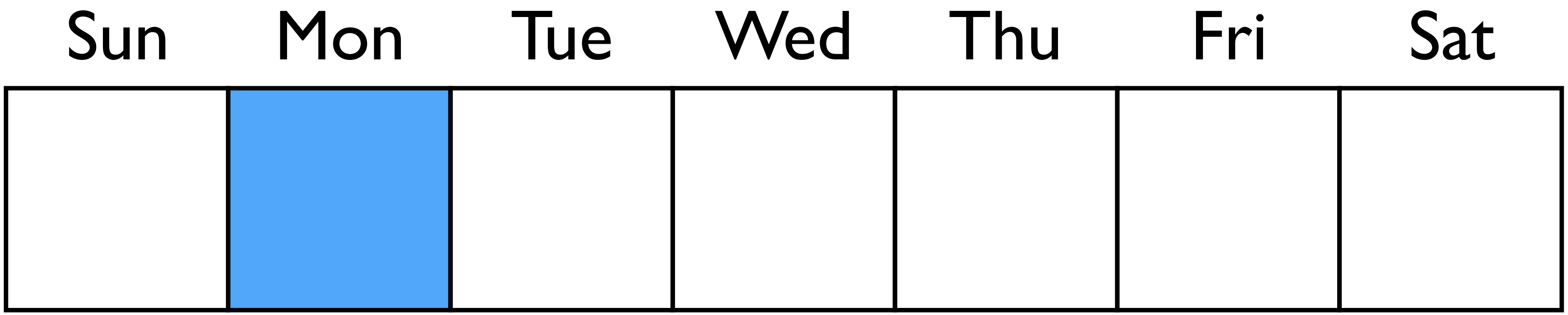


Meet with your group.

Go to office hours, get some help.

Solve some more problems.

A typical week



Finish up GROUP problems.

Go to office hours.

A typical week

Sun	Mon	Tue	Wed	Thu	Fri	Sat

Realize that you still need to do the OPEN problem(s)!

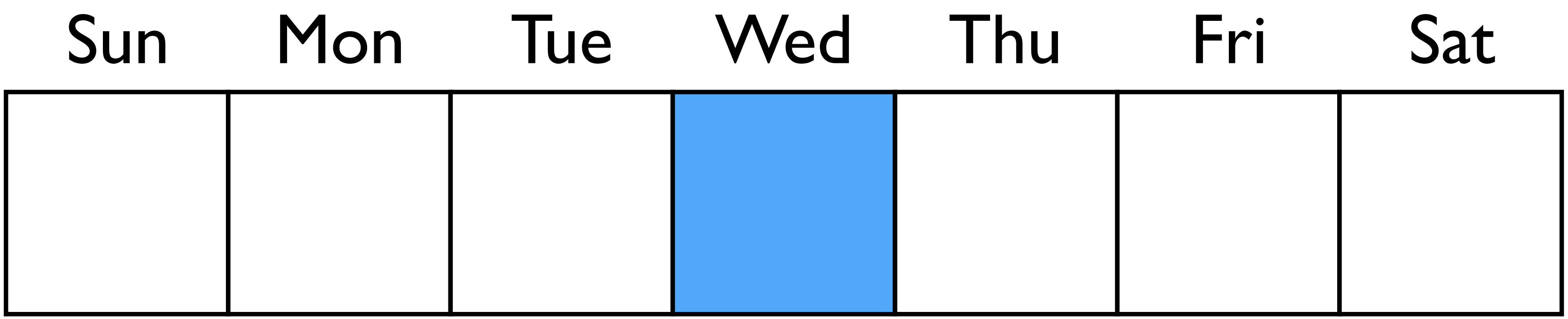
Express hate towards the professors.

Lecture

Rush to OH to get help.

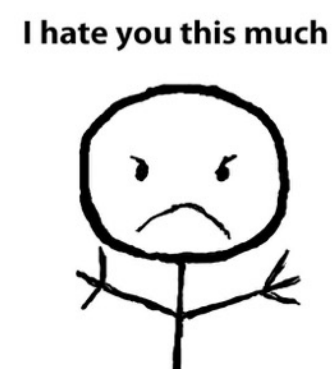
Don't sleep until you solve the hardest problem.

A typical week



Practice writing up the solutions to the problems.

Realize you have a mistake in one of the questions.



Express hate towards the professors.

Learning moment:
write solution down once you think you figured it out.

Keys to success in this course

- Be awake during lectures, and review them on time.
- Use office hours. Use Piazza.
- Find good group members.
- If you are not happy with your group, break up.
- Take the "writing up the proof" part seriously.
- Make sure you understand the mistakes you make.
- Embrace the challenge.