15-251

Great Theoretical Ideas in Computer Science

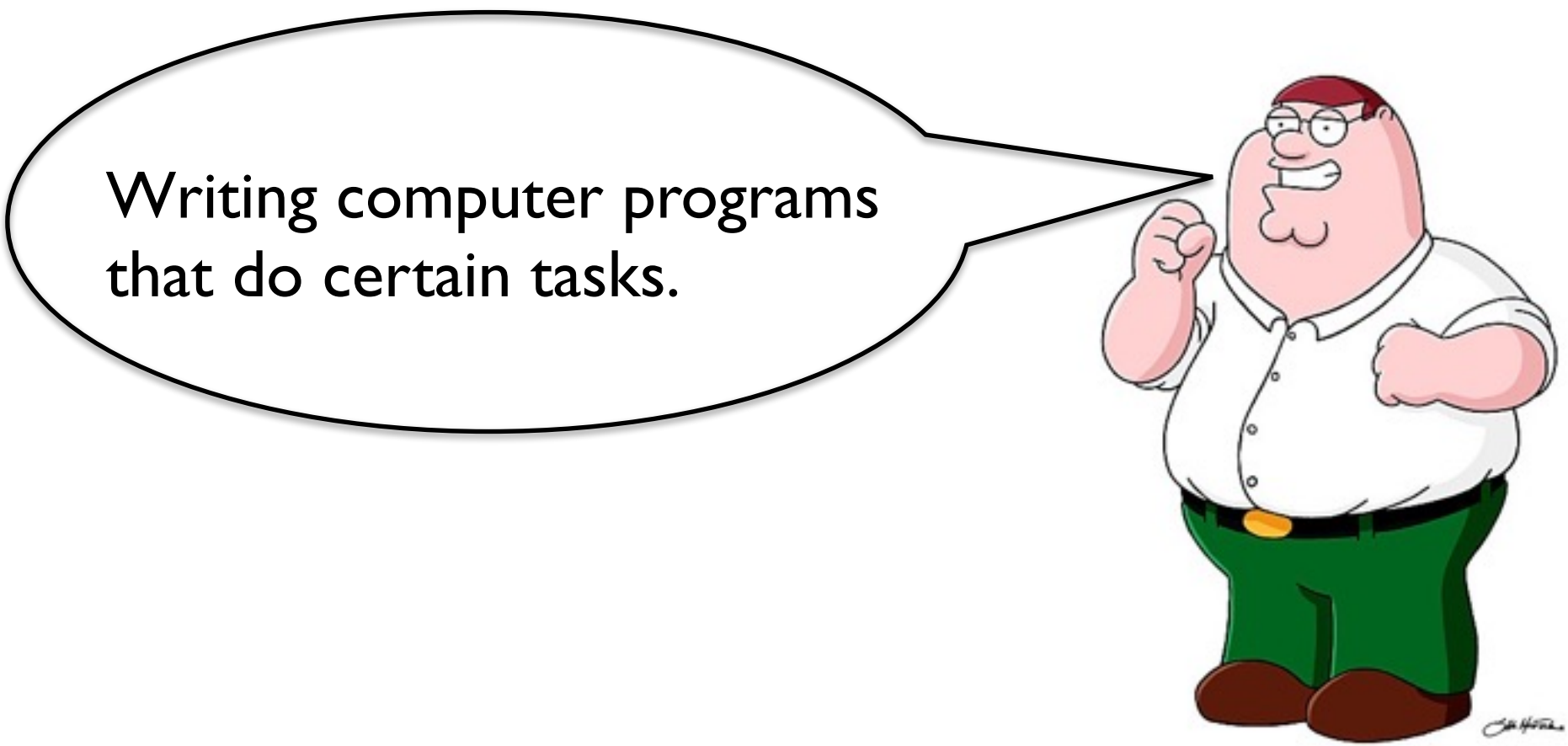
Introduction

Anil Ada

January 13th, 2015

What is theoretical computer science?

What is computer science?



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

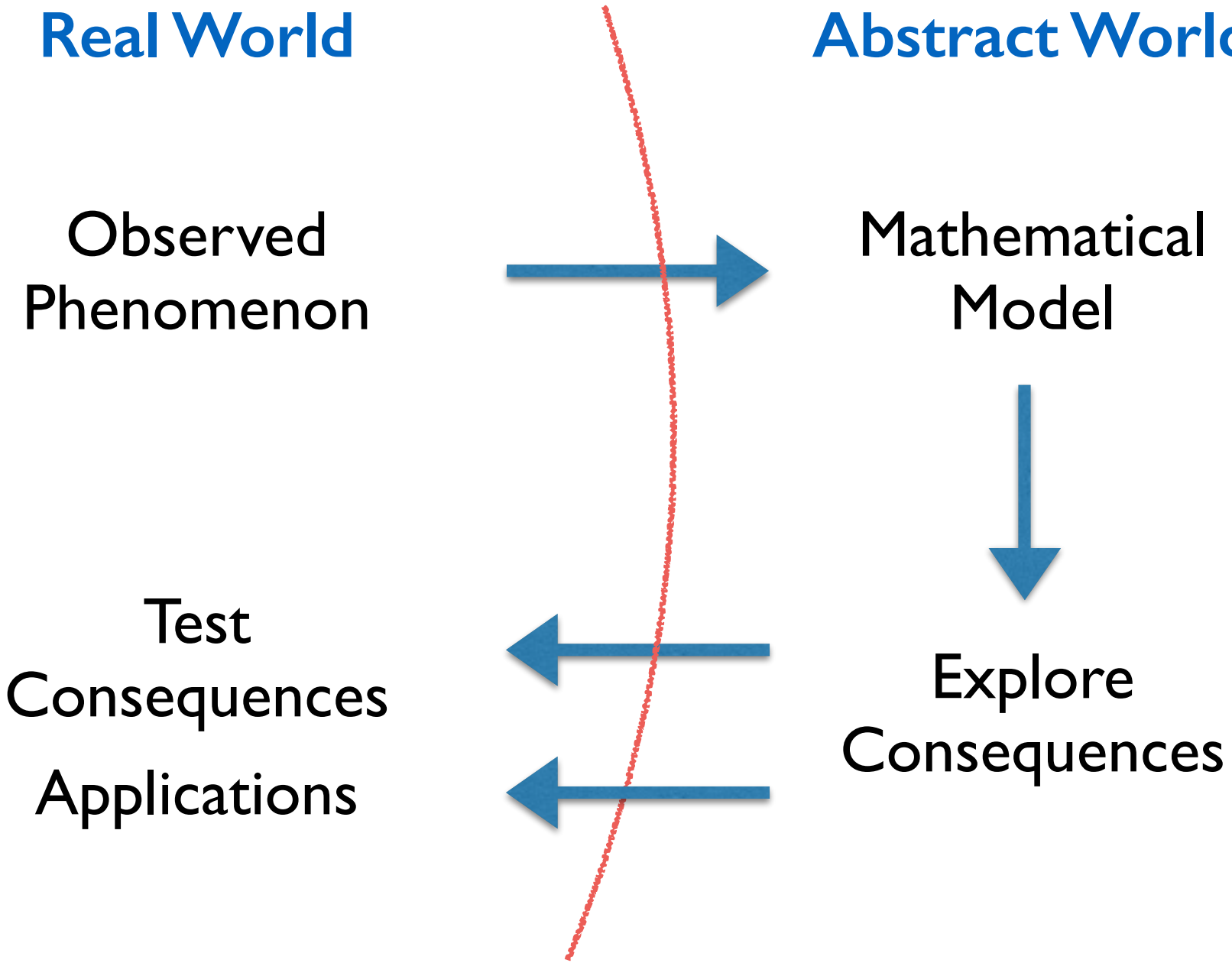
- derive the logical consequences

Experimental physics

- make observations about the universe
- test the model with experiments

Applications/Engineering

The role of theoretical physics



Theoretical Physics

- science?
- engineering?
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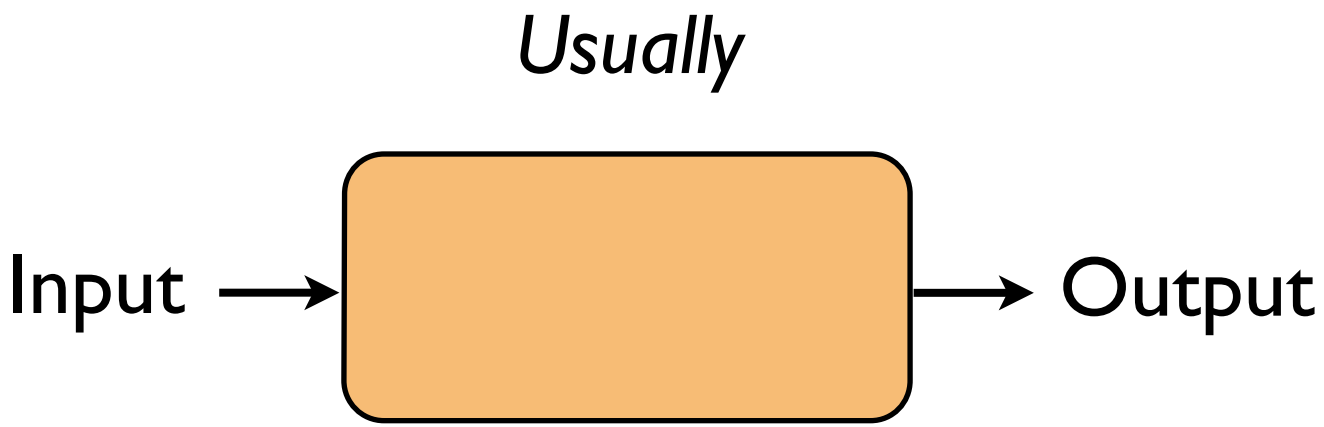
Computer Science

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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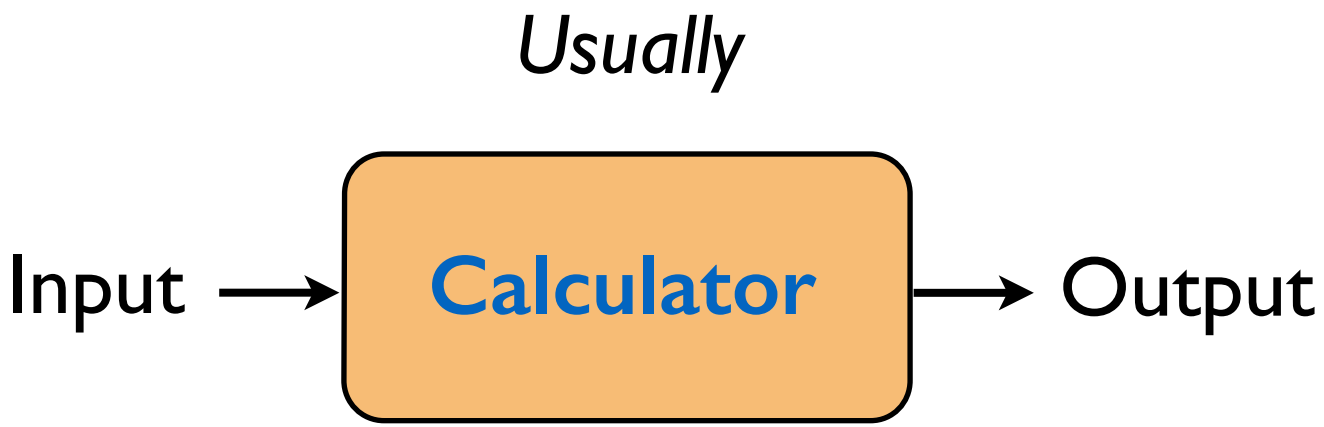

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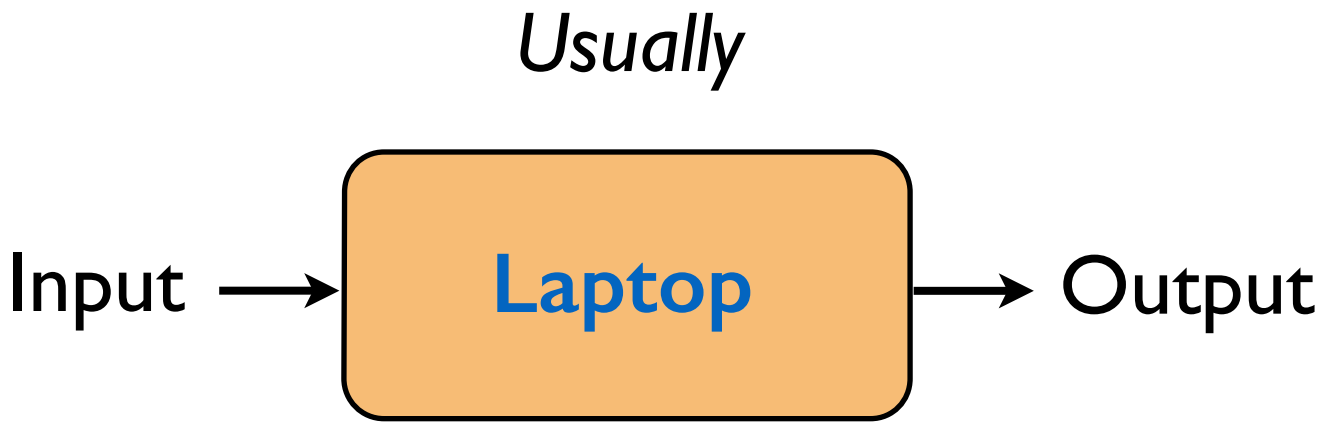

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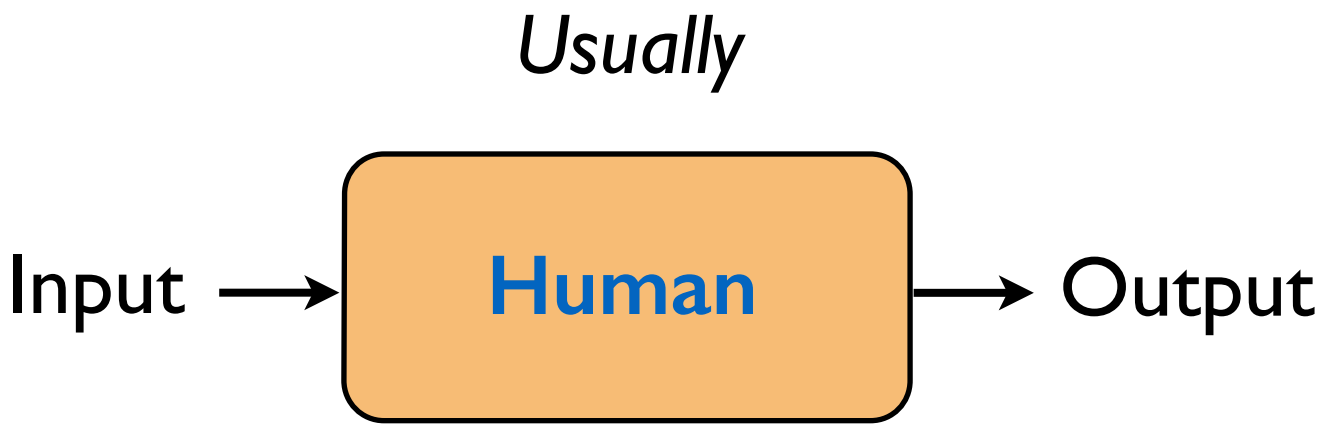

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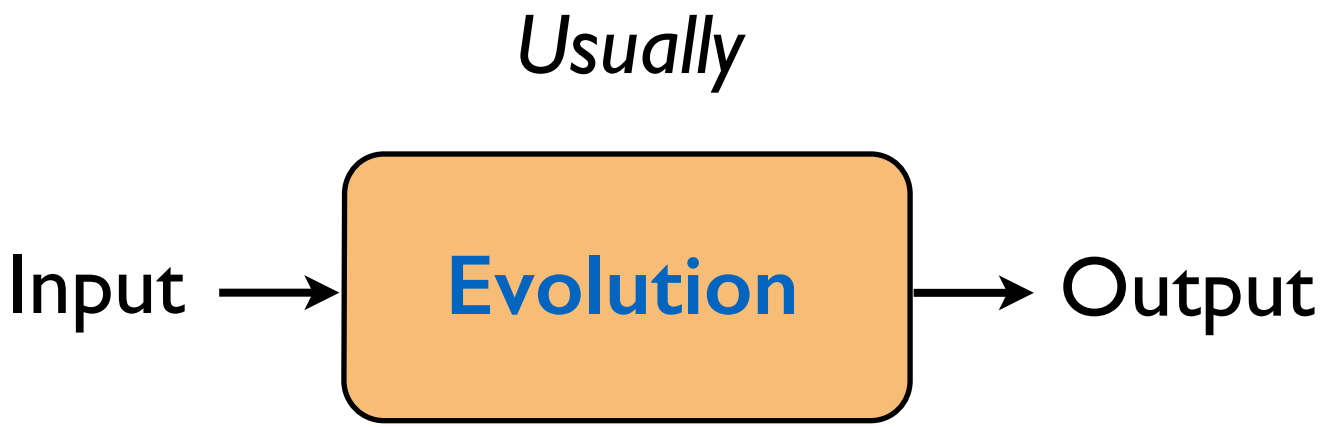


The computational lens

Computational physics

Computational biology

Computational chemistry

Computational neuroscience

Computational finance

…

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*

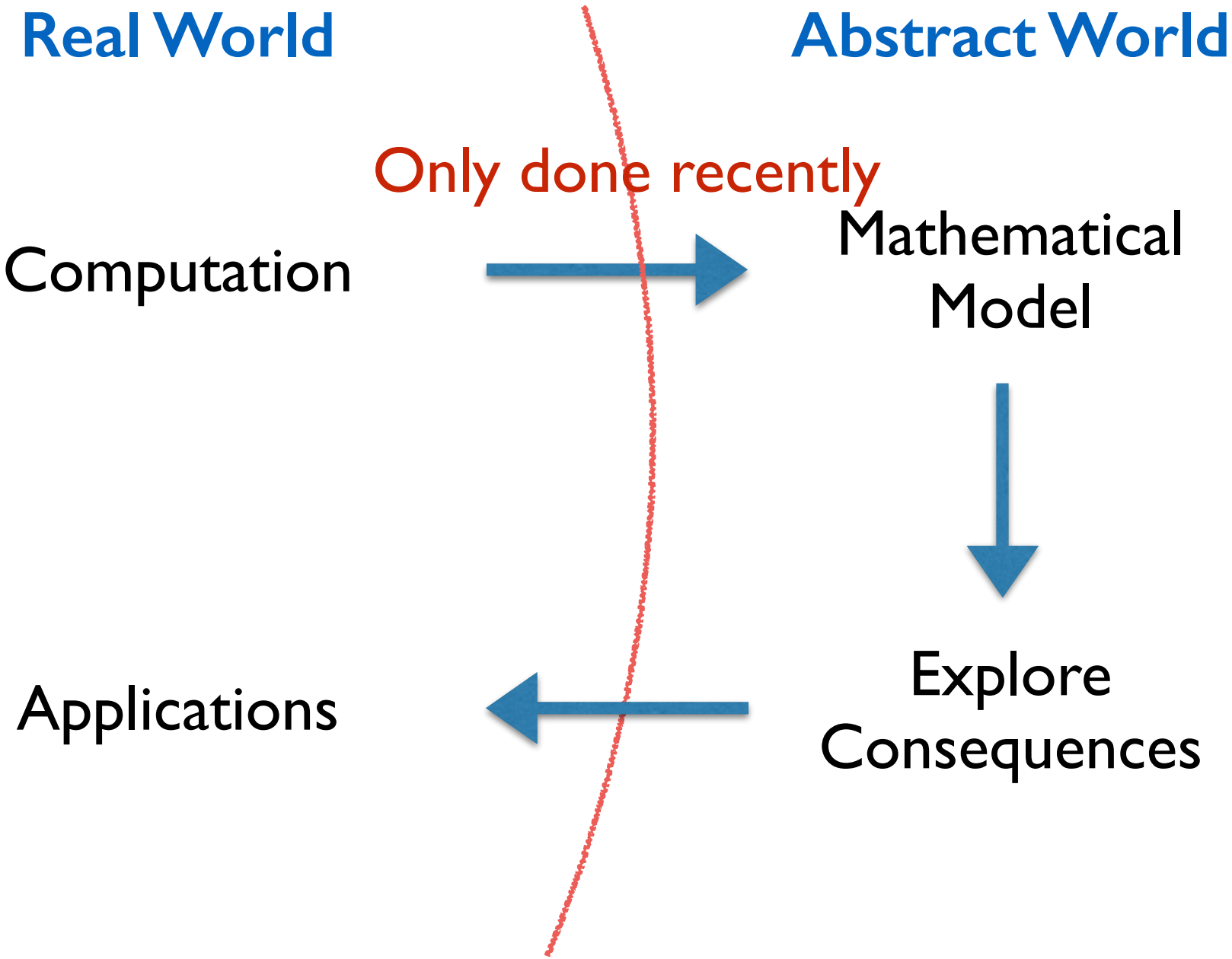
The role of theoretical computer science

Build a mathematical model for computation.

Explore the logical consequences.
Gain insight about computation.

Look for interesting applications.

The role of computer science



Simple examples of computation

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

Doing a calculation/computation by following a simple algorithm.

Simple examples of computation

Euclid's algorithm (~ 300BC):

```
def gcd(a, b):
    while (b != 0):
        t = b
        b = a % b
        a = t
    return a
```

We have been using algorithms for thousands of years.

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 question.

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?"

Hilbert's 10th problem

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

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)

Hilbert's 10th problem

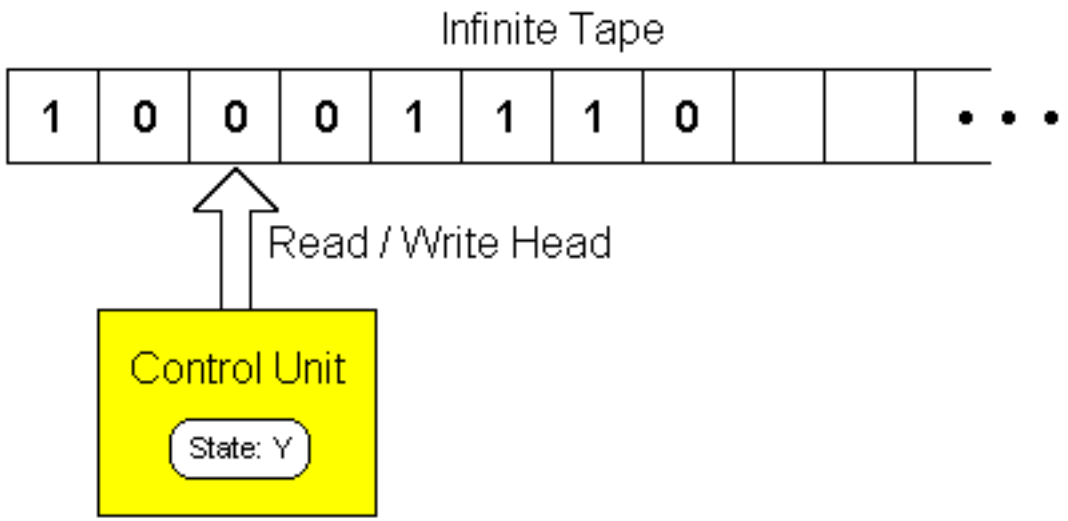
Fortunately, the answer turned out to be NO.

This question was answered by Church and Turing.

It lead Turing to define (1936) what we now call a Turing Machine.

The formalization of "computation"

Turing Machine:



→ **Universal Turing Machine**

The mathematical model for your laptop.

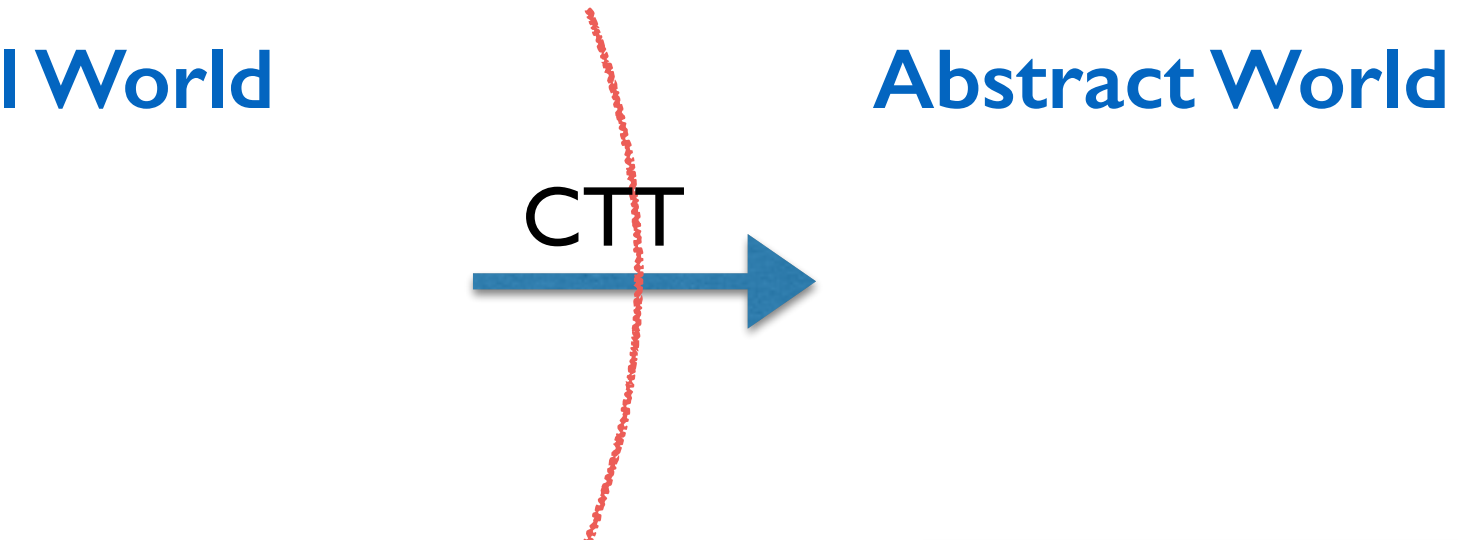
Church-Turing Thesis

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.



Theoretical computer science

- science?
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- 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)

matrix multiplication

stock trading

protein structure prediction

simulation of quantum systems

integer factorization

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?

What will you learn in this course?

Goals

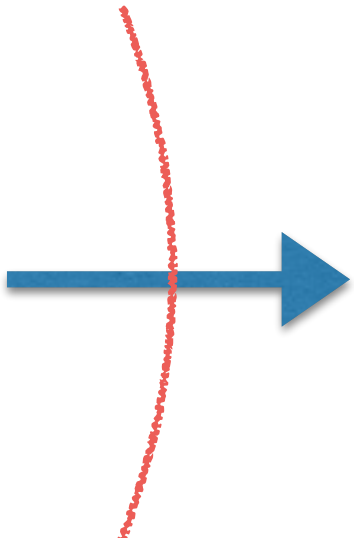
1. Learn about the theoretical foundations of computation

2. Learn the basic math topics, i.e. the language

3. Become better at reasoning abstractly and formally.

4. Become better problem solvers

Real World



Abstract World

The land of rigor

Video

The land of rigor: Proofs

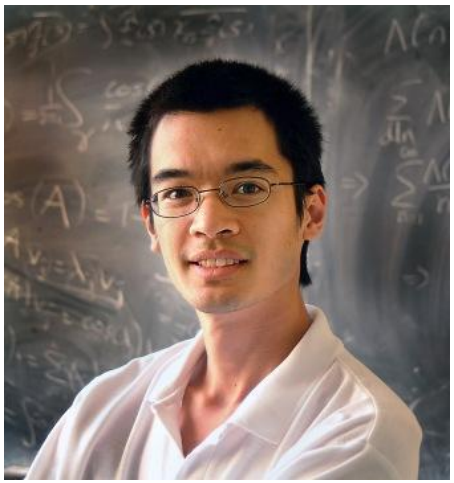
finding and writing algorithms <—> finding and writing proofs

A skill that is learnt. Practice Practice Practice!

How much detail is good enough?

The land of rigor: Proofs

No Eureka effect



Terence Tao

(Fields Medalist, "MacArthur Genius", …)

I don't have any magical ability. … When I was a kid, I had a romanticized notion of mathematics, that hard problems were solved in 'Eureka' moments of inspiration. [But] with me, it's always, 'Let's try this. That gets me part of the way, or that doesn't work. Now let's try this. Oh, there's a little shortcut here.' You work on it long enough and you happen to make progress towards a hard problem by a back door at some point. At the end, it's usually, 'Oh, I've solved the problem.'

The land of rigor: Proofs

Some suggestions:

Make 1% progress for 100 days.
(Make 15% progress for 7 days.)

Give breaks, let the unconscious brain do some work.

Figure out some meaningful special cases (e.g. n=1, n=2).

Put yourself in the mind of the adversary.
(What are the worst-case examples/scenarios?)

Develop good notation.

Use paper, draw pictures.

Collaborate.

A quick 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 score dropped

33%

3 midterm exams, lowest score half weighted

7% + 14% + 14% = 35%

Feb 11, Mar 18, Apr 15
6:30pm-9:30pm

1 final exam

25%

~11 quizzes, lowest score dropped

5%

Participation (not being a ghost)

2%

Homeworks

Most important part of the course!

They are meant to be challenging.

More effort from you —> More help from us

Make use of the office hours!!!
(some questions are designed with this in mind)

Homeworks prepare you for the exams.

Homeworks

Homework System:

3 types of questions:
SOLO, GROUP, OPEN COLLABORATION

SOLO - work by yourself

GROUP - work in groups of 2 or 3

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 Google general concepts.

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 2210

Write the solutions to a random subset of the Problems.

You must practice writing the solutions beforehand!!!

20% credit reserved for presentation.

Quizzes

Most Tuesdays from 9:00am to 9:07am.

Just a check that you remember the previous week.

Piazza

Everyone must sign up.

Course announcements will be made on Piazza.

Great resource, make use of it.

Please be polite.

Don’t give away any hints.

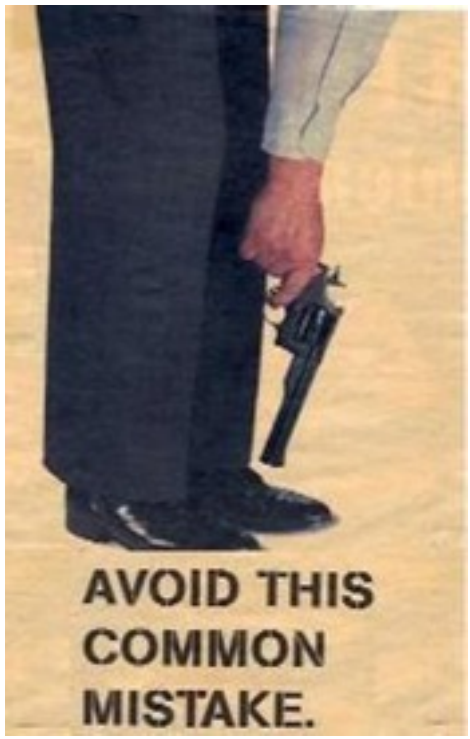
Office hours

Ryan: Tuesdays, Thursdays 10:30am-12:00pm

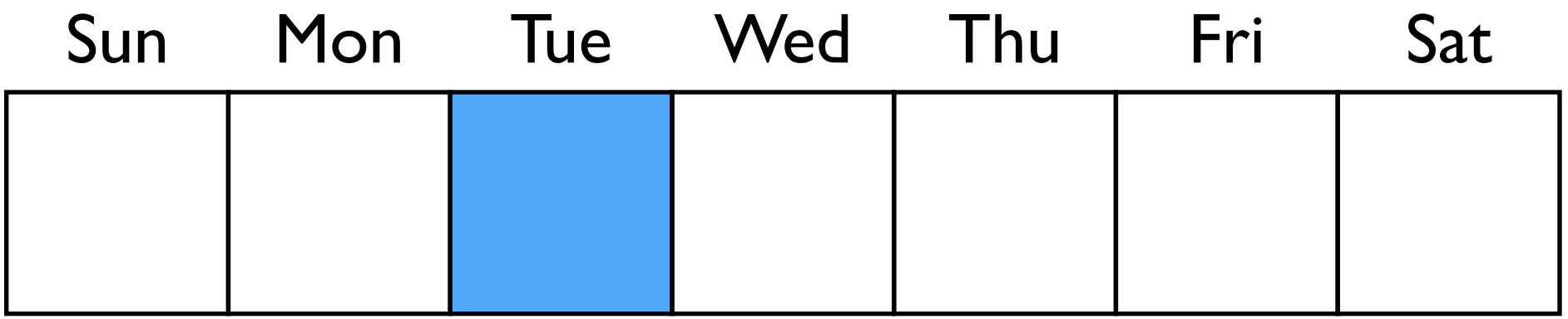
Anil: Tuesdays, Thursdays 12:00pm-1:30pm

TAs: see course webpage

You have to use the OHs!



A typical week



Lecture

Office hour (Ryan)

Office hour (Anil)

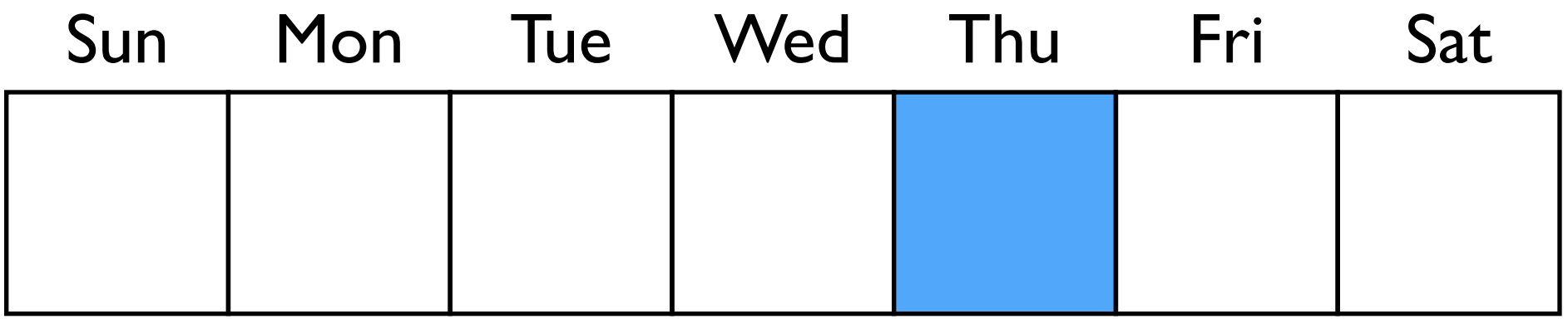
A typical week

Sun	Mon	Tue	Wed	Thu	Fri	Sat

Homework writing session:

A chance to get to know the TAs and find group members

A typical week



Lecture

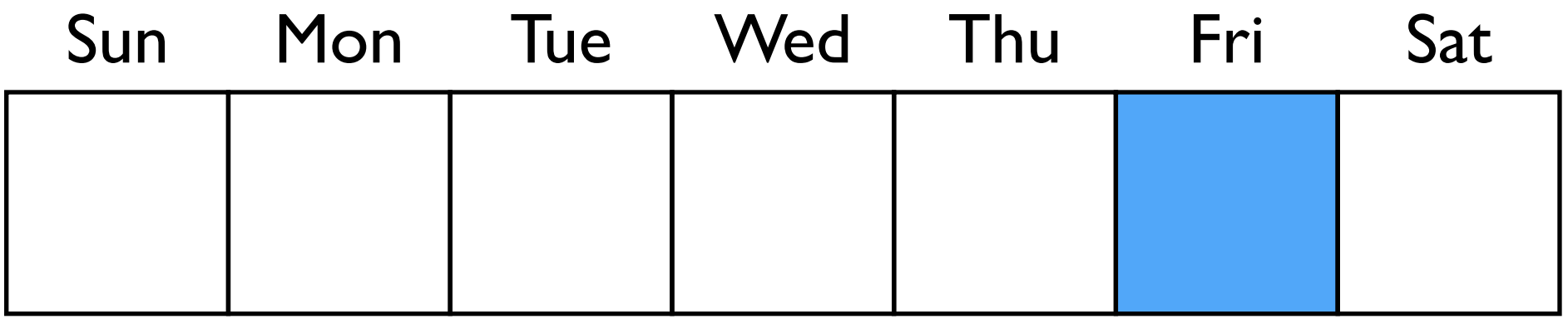
Office Hours

Homework comes out

Read every question

Start working on the SOLO problems

A typical week



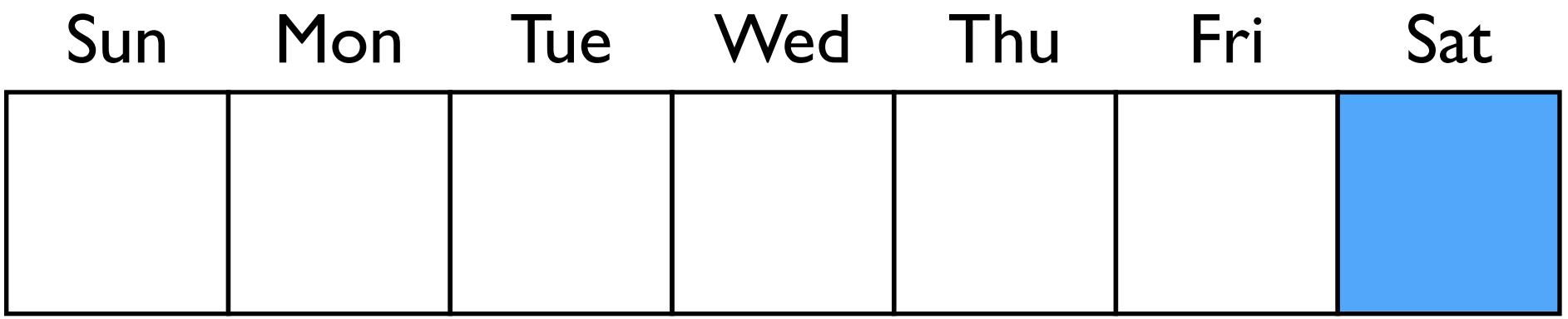
Recitation

Try to finish SOLO problems.

Start thinking about the GROUP problems.

Make appointments to meet with your group over the weekend.

A typical week



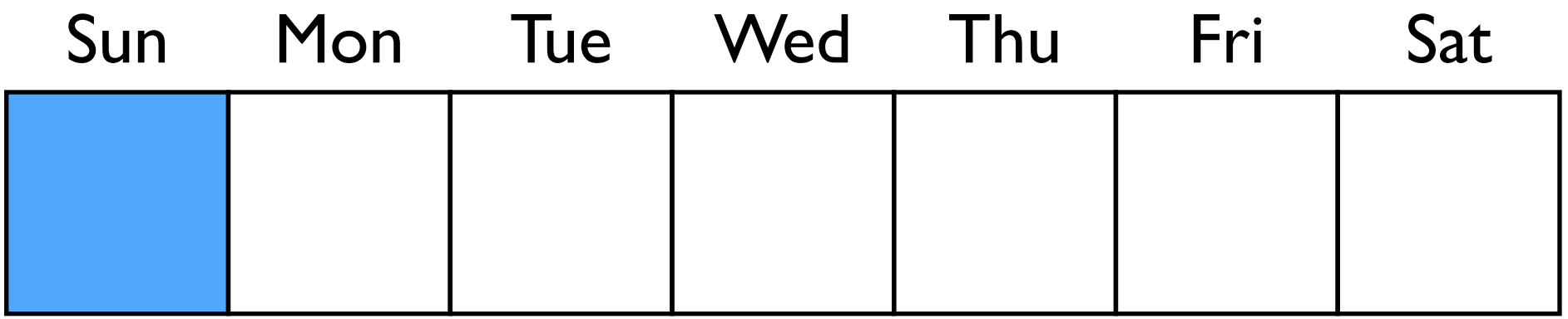
Meet with your group.

Make some progress on the questions.

Maybe solve some of them.

Go to office hours.

A typical week

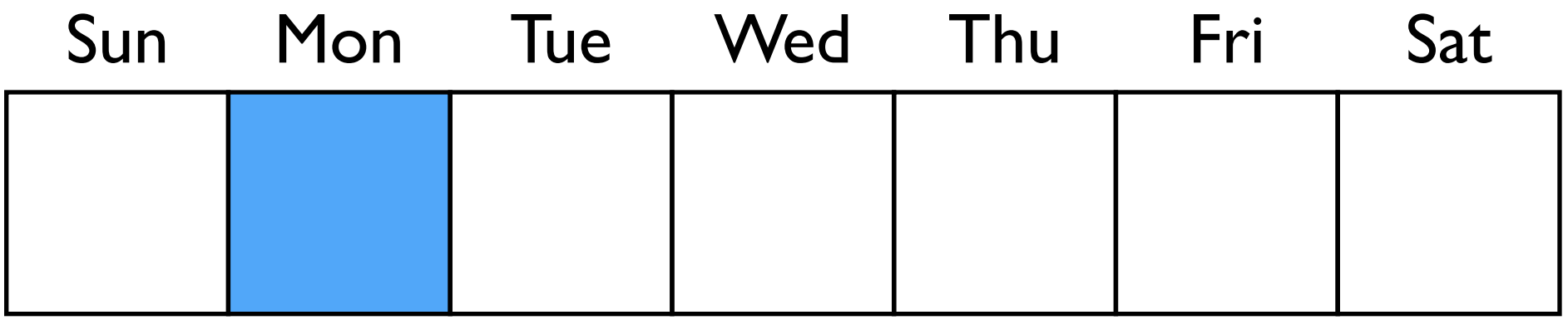


Meet with your group.

Go to office hours, get some help.

Solve some more problems.

A typical week



Finish up GROUP problems.

Do a quick review of last week.

A typical week

Sun	Mon	Tue	Wed	Thu	Fri	Sat

Realize that you still need to do the OPEN problems!

Express hate towards the professors.

Waking up early sucks!

Lecture

Rush to OH to get help.

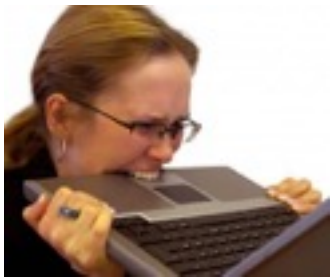
Don't sleep until you solve the hardest problem.

A typical week

Sun	Mon	Tue	Wed	Thu	Fri	Sat

Practice writing up the solutions to the problems.

Realize you have a mistake in one of the questions.



Express hate towards the professors.

Realize that you have to write the solution down once you think you have figured it out.

Video