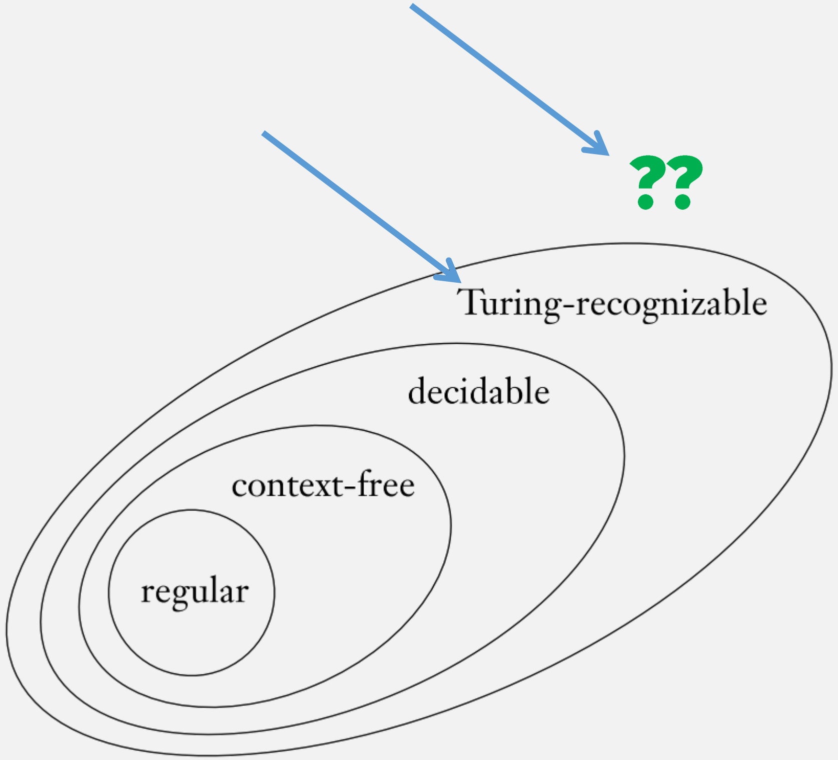
UMB CS 622

Undecidability

Friday, April 19, 2024



Announcements

- HW 9 out
  - due Wednesday 4/22 12pm noon

Lecture Participation Question

- Is the Universal Turing Machine (A_{TM}) a decider? A recognizer?

Language of DFA description + string pairs, i.e., <u>compute</u> whether a DFA accepts a string

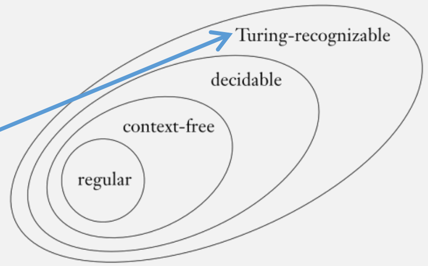
Recap: Decidability of Regular and CFLs

- $A_{\mathsf{DFA}} = \{\langle B, w\rangle \mid B \text{ is a DFA that accepts input string } w\}$ Decidable
- $A_{\mathsf{NFA}} = \{\langle B, w\rangle \mid B \text{ is an NFA that accepts input string } w\}$ Decidable
- $A_{\mathsf{REX}} = \{\langle R, w\rangle \mid R \text{ is a regular expression that generates string } w\}$ Decidable
- $E_{\mathsf{DFA}} = \{\langle A\rangle \mid A \text{ is a DFA and } L(A) = \emptyset\}$ Decidable
- $EQ_{\mathsf{DFA}} = \{\langle A, B\rangle \mid A \text{ and } B \text{ are DFAs and } L(A) = L(B)\}$ Decidable
- $A_{\mathsf{CFG}} = \{\langle G, w\rangle \mid G \text{ is a CFG that generates string } w\}$ Decidable
- $E_{\mathsf{CFG}} = \{\langle G\rangle \mid G \text{ is a CFG and } L(G) = \emptyset\}$ Decidable
- $EQ_{\mathsf{CFG}} = \{\langle G, H\rangle \mid G \text{ and } H \text{ are CFGs and } L(G) = L(H)\}$ *Undecidable?*
- $A_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ accepts } w\}$ *Undecidable?*

Compute something about DFA <u>language</u>, from its <u>description</u>

<u>compute</u> whether a TM accepts a string

Thm: A_{TM} is Turing-recognizable



$$A_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ accepts } w\}$$

U = "On input $\langle M, w\rangle$, where M is a TM and w is a string:

1. Simulate M on input w.
2. If M ever enters its accept state, *accept*; if M ever enters its reject state, *reject*."

Can go into infinite loop, causing U to loop

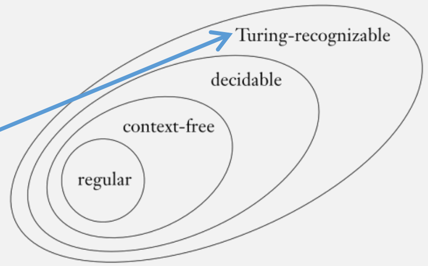
U = Implements TM computation steps $\alpha q_1 \mathbf{a} \beta \vdash \alpha \mathbf{x} q_2 \beta$

- i.e., "The Universal Turing Machine"
- "Program" simulating other programs (**interpreter**)
- Problem: U loops when M loops

Termination argument?

So it's a **recognizer**, not a decider

Thm: A_{TM} is Turing-recognizable



$$A_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ accepts } w\}$$

U = "On input $\langle M, w\rangle$, where M is a TM and w is a string:

1. Simulate M on input w.
2. If M ever enters its accept state, *accept*; if M ever enters its reject state, *reject*."

"Actual" behavior

"Expected" behavior

Example Str	M on input w?	U?	In A_{TM} lang?
<M_1, `01#01`>	Accept	Accept	Yes
<M_1, `00#11`>	Reject	Reject	No
<M_{loop}, *>	Loop!	Loop!	No

Let:
- M_1 = "$w\#w$" lang decider
- M_{loop} = looping TM

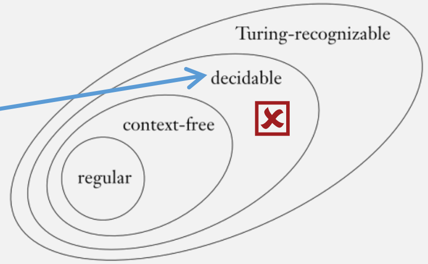
Columns must match!

Is this right?

Yes!

Thm: A_{TM} is undecidable

How to prove … not in here?



$$A_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ accepts } w\}$$

- ???

Flashback

Prove: Spider-Man does not exist ???

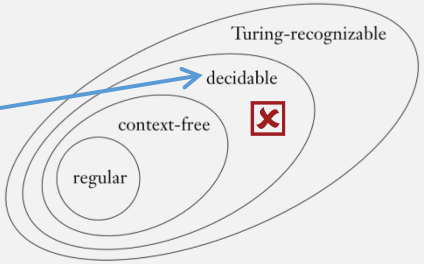
In general, **proving something not true** is **different** (and harder) **than proving it true**

In some cases, **it's possible,** but **typically requires new proof techniques!**

Example (**Regular** Languages)
Prove a language is **regular:**
- Create a DFA

Prove a language is **not regular:**
- Proof by contradiction using **Pumping Lemma**

Not in here?



Thm: A_{TM} is undecidable

$$A_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ accepts } w\}$$

Example (**decidable** languages)

Prove a language is **decidable**:

- Create a **decider** TM (with termination argument)

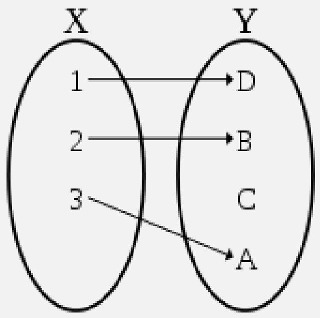
today

Prove a language is **not decidable**:

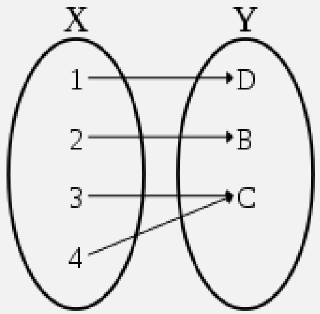
- ????

Kinds of Functions (a fn maps DOMAIN → RANGE)

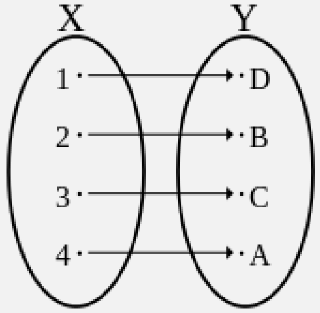
- **Injective,** a.k.a., "one-to-one"
  - Every element in DOMAIN has a unique mapping
  - How to remember:
    - Entire DOMAIN is mapped "**in**" to the RANGE



- **Surjective,** a.k.a., "onto"
  - Every element in RANGE is mapped to
  - How to remember:
    - "**Sur**" = "over" (eg, <u>sur</u>vey); DOMAIN is mapped "over" the RANGE



- **Bijective,** a.k.a., "correspondence" or "one-to-one correspondence"
  - Is both injective and surjective
  - Unique pairing of every element in DOMAIN and RANGE



Countability

- A set is "**countable**" if it is:
  - Finite
  - Or, there exists a **bijection** between the set and the natural numbers
    - In this case, the set has the <u>same size</u> as the set of natural numbers
    - This is called "**countably infinite**"

Exercise: Which set is larger?

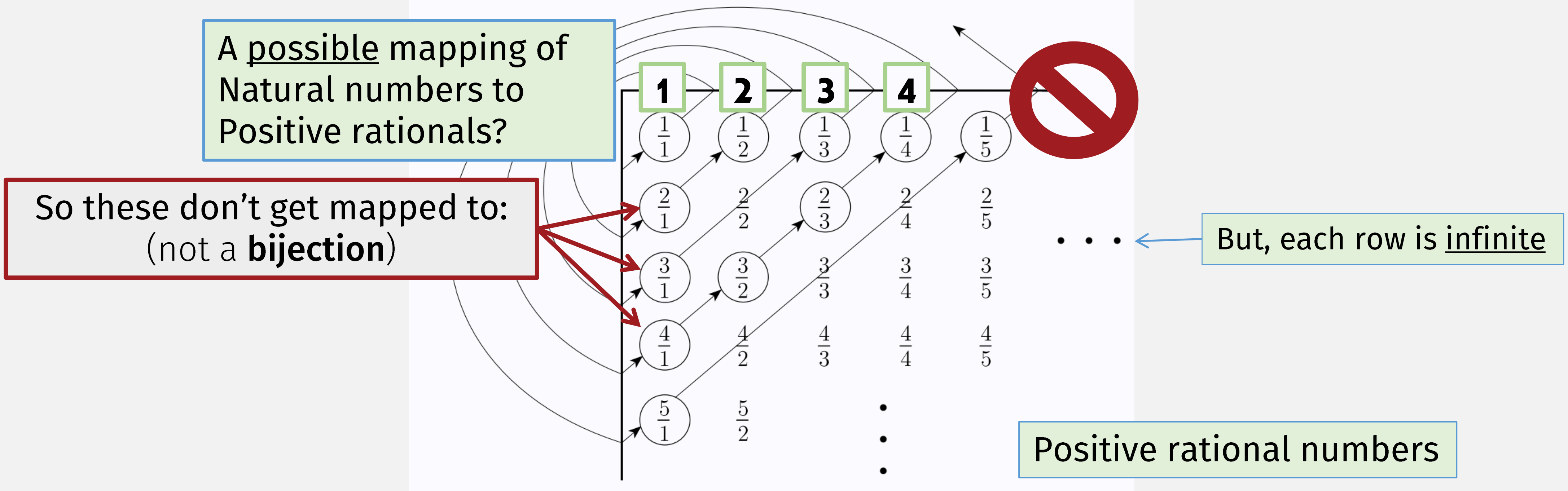
- The set of:
  - Natural numbers, or
  - Even numbers?
- They are the same size! Both are **countably infinite**
  - Proof: Bijection:

n	$f(n) = 2n$
1	2
2	4
3	6
$\vdots$	$\vdots$
Natural numbers	Even numbers

Every natural number maps to a unique even number, and vice versa

Exercise: Which set is larger?

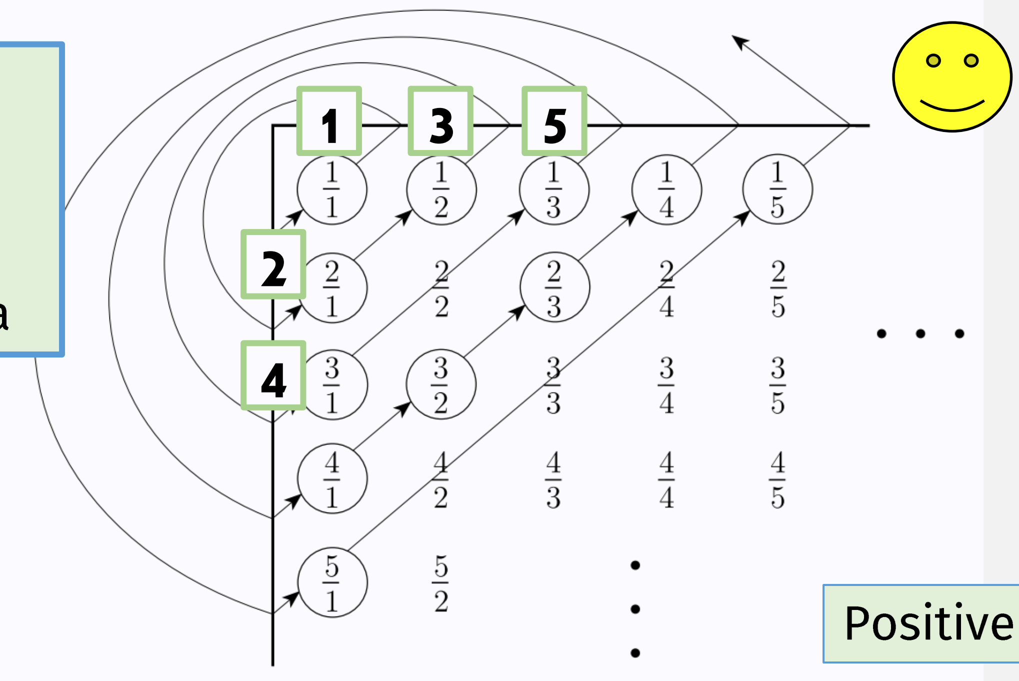
- The set of:
  - Natural numbers $\mathcal{N}$, or
  - Positive rational numbers? $\mathcal{Q} = \{\frac{m}{n} | m, n \in \mathcal{N}\}$
- They are the same size! Both are **countably infinite**



Exercise: Which set is larger?

- The set of:
  - Natural numbers $\mathcal{N}$, or
  - Positive rational numbers? $\mathcal{Q} = \{\frac{m}{n} \mid m, n \in \mathcal{N}\}$
- They are the same size! Both are **countably infinite**

Another mapping:
This is a **bijection** bc
every natural number
maps to a unique
fraction, and vice versa



Positive rational numbers

Exercise: Which set is larger?

- The set of:
  - Natural numbers $\mathcal{N}$, or
  - Real numbers? $\mathcal{R}$
- There are more real numbers. It is **uncountably infinite.**

This proof technique is called **diagonalization**

Proof, by contradiction:

- Assume a bijection between natural and real numbers exists.
  - So: every natural num maps to a unique real, and vice versa
- But we show that in any given mapping, ... e.g.:

n	$f(n)$
1	$3.\underline{1}4159\ldots$
2	$55.5\underline{5}555\ldots$
3	$0.12\underline{3}45\ldots$
4	$0.500\underline{0}0\ldots$
$\vdots$	$\vdots$

A hypothetical mapping

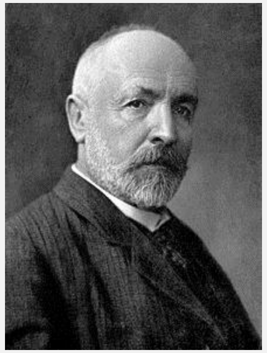
  - Some real number is not mapped to ...
  - E.g., a number that has different digits at each position:

different

$$x = 0.\boxed{4}\boxed{6}\boxed{4}1\ \ldots$$

  - This number cannot be in the mapping ...
  - ... So we have a **contradiction**!

Georg Cantor



- Invented set theory
- Came up with **countable infinity** (1873)
- And **uncountability**:
  - Also: how to show uncountability with “**diagonalization**” technique

A formative day for Georg Cantor.

Diagonalization with Turing Machines

<u>Diagonal</u>: Result of Giving a TM its own Encoding as Input

All TM Encodings

	$\langle M_1 \rangle$	$\langle M_2 \rangle$	$\langle M_3 \rangle$	$\langle M_4 \rangle$	$\cdots$	$\langle D \rangle$	$\cdots$
M_1	<u>*accept*</u>	*reject*	*accept*	*reject*		*accept*	
M_2	*accept*	<u>*accept*</u>	*accept*	*accept*	$\cdots$	*accept*	$\cdots$
M_3	*reject*	*reject*	<u>*reject*</u>	*reject*		*reject*	
M_4	*accept*	*accept*	*reject*	<u>*reject*</u>		*accept*	
$\vdots$			$\vdots$		$\ddots$		
~~D~~	~~*reject*~~	~~*reject*~~	~~*accept*~~	~~*accept*~~		~~<u>?</u>~~	
$\vdots$			$\vdots$				

opposites

All TMs

Try to construct "opposite" TM D

TM D can't exist!

What should happen here?

It must both accept and reject!

3 Easy Steps!

Thm: A_{TM} is undecidable

$$A_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ accepts } w\}$$

Proof by contradiction:

1. Assume A_{TM} is decidable. So there exists a decider H for it:

$$H(\langle M, w\rangle) = \begin{cases} \mathit{accept} & \text{if } M \text{ accepts } w \\ \mathit{reject} & \text{if } M \text{ does not accept } w \end{cases}$$

2. Use H in another TM … the impossible "opposite" machine:

$D =$ "On input $\langle M\rangle$, where M is a TM:

1. Run H on input $\langle M, \langle M\rangle\rangle$.
2. Output the opposite of what H outputs. That is, if H accepts, *reject*; and if H rejects, *accept*."

From previous slide (does opposite of what input TM would do if given itself)

H computes M's result with itself as input

Do the opposite

3 Easy Steps!

Thm: A_{TM} is undecidable

$$A_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ accepts } w\}$$

Proof by contradiction:

This cannot be true

1. **Assume** A_{TM} is decidable. So there exists a decider H for it:

$$H(\langle M, w\rangle) = \begin{cases} \mathit{accept} & \text{if } M \text{ accepts } w \\ \mathit{reject} & \text{if } M \text{ does not accept } w \end{cases}$$

2. **Use** H in another TM … the impossible "opposite" machine:

$D =$ "On input $\langle M\rangle$, where M is a TM:

  1. Run H on input $\langle M, \langle M\rangle\rangle$.
  2. Output the opposite of what H outputs. That is, if H accepts, *reject*; and if H rejects, *accept*."

3. But D does not exist! **Contradiction**! So the assumption is false.

Easier Undecidability Proofs

- **We proved** $A_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ accepts } w\}$ **undecidable …**
- … by **contradiction:**
  - Use **hypothetical** A_{TM} **decider to** create an impossible **decider "D"!**

reduce "D problem" to A_{TM}

- Step # 1: **coming up with "D"** --- hard!
  - Need to invent **diagonalization**

	$\langle M_1\rangle$	$\langle M_2\rangle$	$\langle M_3\rangle$	$\langle M_4\rangle$	$\cdots$	$\langle D\rangle$
M_1	*accept*	*reject*	*accept*	*reject*		*accept*
M_2	*accept*	*accept*	*accept*	*accept*	$\cdots$	*accept*
M_3	*reject*	*reject*	*reject*	*reject*		*reject*
M_4	*accept*	*accept*	*reject*	*reject*		*accept*
$\vdots$			$\vdots$		$\ddots$	
D	*reject*	*reject*	*accept*	*accept*		?

- Step # 2: **reduce "D" problem to A_{TM}** --- easier!

- From now on: **undecidability proofs only need step # 2!**
  - And we now **have two "impossible" problems to choose from**

The Halting Problem

$$HALT_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ halts on input } w\}$$

Thm: $HALT_{\mathsf{TM}}$ is undecidable

Proof, by **contradiction**:

reduce (from known **undecidable**) A_{TM} to $HALT_{\mathsf{TM}}$

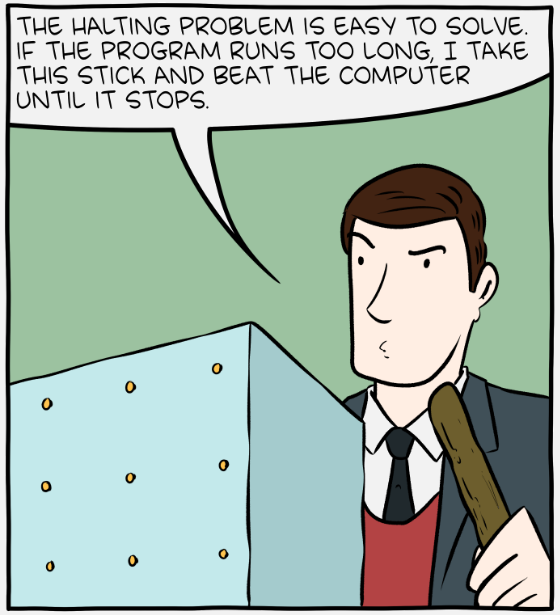
- Assume: $HALT_{\mathsf{TM}}$ has *decider* R; use it to create decider for A_{TM}:

$$A_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ accepts } w\}$$

- ...

contradiction

- But A_{TM} is undecidable and has no decider!



What if Alan Turing had been an engineer?

The Halting Problem

$HALT_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ halts on input } w\}$

Thm: $HALT_{\mathsf{TM}}$ is undecidable

Proof, by **contradiction**:

Using our hypothetical $HALT_{\mathsf{TM}}$ decider R

- Assume: $HALT_{\mathsf{TM}}$ has *decider* R; use it to create decider for A_{TM}:

$A_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ accepts } w\}$

S = "On input $\langle M, w\rangle$, an encoding of a TM M and a string w:

1. Run TM R on input $\langle M, w\rangle$.
2. If R rejects, *reject*. ← This means M loops on input w
3. If R accepts, simulate M on w until it halts. ← This step always halts
4. If M has accepted, *accept*; if M has rejected, *reject*."

Termination argument:
Step 1: R is a decider so always halts
Step 3: M always halts because R said so

The Halting Problem

Undecidability Proof Technique #1:
Reduce (directly) from A_{TM}
(by **creating** A_{TM} **decider**)

$HALT_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ halts on input } w\}$

Thm: $HALT_{\mathsf{TM}}$ is undecidable

Proof, by **contradiction**:

- Assume: $HALT_{\mathsf{TM}}$ **has** *decider* R; **use it to create decider for** A_{TM}:

$A_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ accepts } w\}$

~~S = "On input $\langle M, w\rangle$, an encoding of a TM M and a string w:~~
~~**1.** Run TM R on input $\langle M, w\rangle$.~~
~~**2.** If R rejects, *reject*.~~
~~**3.** If R accepts, simulate M on w until it halts.~~
~~**4.** If M has accepted, *accept*; if M has rejected, *reject*."~~

Now we have three "impossible" deciders to choose from

- But A_{TM} **is undecidable!** I.e., **this decider does not exist!**
  - **So** $HALT_{\mathsf{TM}}$ **is also undecidable!**

Interlude: Reducing from $HALT_{TM}$

A practical thought experiment …
… about **compiler optimizations**

Your compiler changes your program!

```
If TRUE then A else B   ⇨   A

            1 + 2 + 3   ⇨   6
```

Compiler Optimizations

Optmization - docs

- -O0
  - No optmization, faster compilation time, better for debugging builds.
- -O2
- -O3
  - Higher level of optmization. Slower compile-time, better for production builds.
- -OFast
  - Enables higher level of optmization than (-O3). It enables lots of flags as can be seen src (-ffloat-store, -ffsast-math, -ffinite-math-only, -O3 …)
- -finline-functions
- -m64
- -funroll-loops
- -fvectorize
- -fprofile-generate

Types of optimization [edit]

Techniques used in optimization can be broken up among various *scopes* which can affect anything from a single statement to the entire program. Generally speaking, locally scoped techniques are easier to implement than global ones but result in smaller gains. Some examples of scopes include:

Peephole optimizations

These are usually performed late in the compilation process after machine code has been generated. This form of optimization examines a few adjacent instructions (like "looking through a peephole" at the code) to see whether they can be replaced by a single instruction or a shorter sequence of instructions.[2] For instance, a multiplication of a value by 2 might be more efficiently executed by left-shifting the value or by adding the value to itself (this example is also an instance of strength reduction).

Local optimizations

These only consider information local to a basic block.[3] Since basic blocks have no control flow, these optimizations need very little analysis, saving time and reducing storage requirements, but this also means that no information is preserved across jumps.

Global optimizations

These are also called "intraprocedural methods" and act on whole functions.[3] This gives them more information to work with, but often makes expensive computations necessary. Worst case assumptions have to be made when function calls occur or global variables are accessed because little information about them is available.

Loop optimizations

These act on the statements which make up a loop, such as a *for* loop, for example loop-invariant code motion. Loop optimizations can have a significant impact because many programs spend a large percentage of their time inside loops.[4]

Prescient store optimizations

These allow store operations to occur earlier than would otherwise be permitted in the context of threads and locks. The process needs some way of knowing ahead of time what value will be stored by the assignment that it should have followed. The purpose of this relaxation is to allow compiler optimization to perform certain kinds of code rearrangement that preserve the semantics of properly synchronized programs.[5]

Interprocedural, whole-program or link-time optimization

These analyze all of a program's source code. The greater quantity of information extracted means that optimizations can be more effective compared to when they only have access to local information, i.e. within a single function. This kind of optimization can also allow new techniques to be performed. For instance, function inlining, where a call to a function is replaced by a copy of the function body.

Machine code optimization and object code optimizer

These analyze the executable task image of the program after all of an executable machine code has been linked. Some of the techniques that can be applied in a more limited scope, such as macro compression which saves space by collapsing common sequences of instructions, are more effective when the entire executable task image is available for analysis.[6]

The Optimal Optimizing Compiler

"Full Employment" Theorem

Thm: **The Optimal (C++) Optimizing Compiler does not exist**

Proof, by **contradiction**:

Assume: OPT **is the Perfect Optimizing Compiler**

Use it **to create** $HALT_{\mathrm{TM}}$ **decider** (**accept**s $<M,w>$ if M halts with w, else **reject**s):

S = **On input** $<M, w>$, where M is **C++** program and w is string:

- If $OPT(M)$ == `for(;;)`
  a) Then **Reject**
  b) Else **Accept**

In computer science and mathematics, a **full employment theorem** is a term used, often humorously, to refer to a theorem which states that no algorithm can optimally perform a particular task done by some class of professionals. The name arises because such a theorem ensures that there is endless scope to keep discovering new techniques to improve the way at least some specific task is done.

For example, the *full employment theorem for compiler writers* states that there is no such thing as a provably perfect size-optimizing compiler, as such a proof for the compiler would have to detect non-terminating computations and reduce them to a one-instruction infinite loop. Thus, the existence of a provably perfect size-optimizing compiler would imply a solution to the halting problem, which cannot exist. This also implies that there may always be a better compiler since the proof that one has the best compiler cannot exist. Therefore, compiler writers will always be able to speculate that they have something to improve.

Summary: The Limits of Algorithms

- $A_{\textsf{DFA}} = \{\langle B, w\rangle \mid B \text{ is a DFA that accepts input string } w\}$ — Decidable
- $A_{\textsf{CFG}} = \{\langle G, w\rangle \mid G \text{ is a CFG that generates string } w\}$ — Decidable
- $A_{\textsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ accepts } w\}$ — **Undecidable**
- $HALT_{\textsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ halts on input } w\}$ — **Undecidable**

Similar languages

It's straightforward to use hypothetical $HALT_{\mathrm{TM}}$ decider to create A_{TM} decider

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- $A_{\text{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ accepts } w\}$ **Undecidable**
- $HALT_{\text{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ halts on input } w\}$ **Undecidable**
- $E_{\text{DFA}} = \{\langle A\rangle \mid A \text{ is a DFA and } L(A) = \emptyset\}$ Decidable
- $E_{\text{CFG}} = \{\langle G\rangle \mid G \text{ is a CFG and } L(G) = \emptyset\}$ Decidable
- $E_{\text{TM}} = \{\langle M\rangle \mid M \text{ is a TM and } L(M) = \emptyset\}$ **Undecidable**

next

Not as similar languages

How can we use a hypothetical E_{TM} decider to create A_{TM} or $HALT_{\text{TM}}$ decider?

Reducibility: Modifying the TM

$E_{\mathsf{TM}} = \{\langle M \rangle \mid M \text{ is a TM and } L(M) = \emptyset\}$

Thm: E_{TM} is undecidable

Proof, by **contradiction**:

- Assume E_{TM} has *decider* R; use it to create *decider* for A_{TM}:

S = "On input $\langle M, w \rangle$, an encoding of a TM M and a string w:

First, construct M_1

- Run R on input $\langle M_1 \rangle$

Note: M_1 is only used as arg to R; we never run it!

- If R accepts, *reject* (because it means $\langle M \rangle$ doesn't accept w)
- if R rejects, then *accept* ($\langle M \rangle$ accepts w)

- Idea: Wrap $\langle M \rangle$ in a new TM that can *only* accept w:

M_1 = "On input x:

1. If $x \neq w$, *reject*.
2. If $x = w$, run M on input w and *accept* if M does."

Input not w, always reject

Input is w, maybe accept

M_1 accepts w if M does

Reducibility: Modifying the TM

$E_{\mathsf{TM}} = \{\langle M\rangle \mid M \text{ is a TM and } L(M) = \emptyset\}$

Thm: E_{TM} is undecidable

Proof, by contradiction:

This decider for A_{TM} cannot exist!

- Assume E_{TM} has *decider* R; use it to create *decider* for A_{TM}:

~~$S =$ "On input $\langle M, w\rangle$, an encoding of a TM M and a string w:~~

First, construct M_1

- ~~Run R on input $\langle M_{\boxed{1}} \rangle$~~
- ~~If R accepts, *reject* (because it means $\langle M\rangle$ doesn't accept $\boxed{w}$)~~
- ~~if R rejects, then $\boxed{accept}$ ($\langle M\rangle$ accepts $\boxed{w}$)~~

- Idea: Wrap $\langle M\rangle$ in a new TM that can only accept w:

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- $A_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ accepts } w\}$ **Undecidable**
- $E_{\mathsf{DFA}} = \{\langle A\rangle \mid A \text{ is a DFA and } L(A) = \emptyset\}$ Decidable
- $E_{\mathsf{CFG}} = \{\langle G\rangle \mid G \text{ is a CFG and } L(G) = \emptyset\}$ Decidable
- $E_{\mathsf{TM}} = \{\langle M\rangle \mid M \text{ is a TM and } L(M) = \emptyset\}$ needs **Undecidable**
- $EQ_{\mathsf{DFA}} = \{\langle A, B\rangle \mid A \text{ and } B \text{ are DFAs and } L(A) = L(B)\}$ Decidable
- $EQ_{\mathsf{CFG}} = \{\langle G, H\rangle \mid G \text{ and } H \text{ are CFGs and } L(G) = L(H)\}$ **Undecidable**

next

- $EQ_{\mathsf{TM}} = \{\langle M_1, M_2\rangle \mid M_1 \text{ and } M_2 \text{ are TMs and } L(M_1) = L(M_2)\}$ **Undecidable**

Undecidability Proof Technique #3

Reduce to something else: EQ_{TM} is undecidable

$EQ_{\mathsf{TM}} = \{\langle M_1, M_2\rangle \mid M_1 \text{ and } M_2 \text{ are TMs and } L(M_1) = L(M_2)\}$

Proof, by **contradiction**:

- Assume: EQ_{TM} has *decider* R; use it to create *decider* for ~~A_{TM}~~:

$E_{\mathsf{TM}} = \{\langle M\rangle \mid M \text{ is a TM and } L(M) = \emptyset\}$

S = "On input $\langle M\rangle$, where M is a TM:

1. Run R on input $\langle M, M_1\rangle$, where M_1 is a TM that rejects all inputs.
2. If R accepts, *accept*; if R rejects, *reject*."

Reduce to something else: EQ_{TM} is undecidable

$EQ_{\mathsf{TM}} = \{\langle M_1, M_2\rangle \mid M_1 \text{ and } M_2 \text{ are TMs and } L(M_1) = L(M_2)\}$

Proof, by **contradiction**:

- Assume: EQ_{TM} has *decider* R; use it to create *decider* for E_{TM}:

$= \{\langle M\rangle \mid M \text{ is a TM and } L(M) = \emptyset\}$

$S =$ "On input $\langle M\rangle$, where M is a TM:

1. Run R on input $\langle M, M_1\rangle$, where M_1 is a TM that rejects all inputs.
2. If R accepts, *accept*; if R rejects, *reject*."

- But E_{TM} is undecidable!

Summary: Undecidability Proof Techniques

- Proof Technique #1:
  - Use hypothetical decider to implement impossible A_{TM} decider
  - Example **Proof:** $HALT_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ halts on input } w\}$

$A_{\mathsf{TM}} = \{\langle M, w\rangle \mid M \text{ is a TM and } M \text{ accepts } w\}$

Reduce

- Proof Technique #2:
  - Use hypothetical decider to implement impossible A_{TM} decider
  - But first modify the input M
  - Example **Proof:** $E_{\mathsf{TM}} = \{\langle M\rangle \mid M \text{ is a TM and } L(M) = \emptyset\}$

Reduce

- Proof Technique #3:
  - Use hypothetical decider to implement non-A_{TM} impossible decider
  - Example **Proof:** $EQ_{\mathsf{TM}} = \{\langle M_1, M_2\rangle \mid M_1 \text{ and } M_2 \text{ are TMs and } L(M_1) = L(M_2)\}$

Summary: Decidability and Undecidability

- $A_{\text{DFA}} = \{\langle B, w\rangle |\ B \text{ is a DFA that accepts input string } w\}$ — Decidable
- $A_{\text{CFG}} = \{\langle G, w\rangle |\ G \text{ is a CFG that generates string } w\}$ — Decidable
- $A_{\text{TM}} = \{\langle M, w\rangle |\ M \text{ is a TM and } M \text{ accepts } w\}$ — **Undecidable**
- $E_{\text{DFA}} = \{\langle A\rangle |\ A \text{ is a DFA and } L(A) = \emptyset\}$ — Decidable
- $E_{\text{CFG}} = \{\langle G\rangle |\ G \text{ is a CFG and } L(G) = \emptyset\}$ — Decidable
- $E_{\text{TM}} = \{\langle M\rangle |\ M \text{ is a TM and } L(M) = \emptyset\}$ — **Undecidable**
- $EQ_{\text{DFA}} = \{\langle A, B\rangle |\ A \text{ and } B \text{ are DFAs and } L(A) = L(B)\}$ — Decidable
- $EQ_{\text{CFG}} = \{\langle G, H\rangle |\ G \text{ and } H \text{ are CFGs and } L(G) = L(H)\}$ — **Undecidable**
- $EQ_{\text{TM}} = \{\langle M_1, M_2\rangle |\ M_1 \text{ and } M_2 \text{ are TMs and } L(M_1) = L(M_2)\}$ — **Undecidable**

Also Undecidable …

next

- $REGULAR_{\mathrm{TM}} = \{<M> \mid M \text{ is a TM and } L(M) \text{ is a regular language}\}$

Undecidability Proof Technique #2:
Modify input TM M

Thm: $REGULAR_{\mathsf{TM}}$ is undecidable

$REGULAR_{\mathsf{TM}} = \{\langle M \rangle \mid M \text{ is a TM and } L(M) \text{ is a regular language}\}$

Proof, by **contradiction**:

- Assume: $REGULAR_{\mathsf{TM}}$ has *decider* R; use it to create *decider* for A_{TM}:

$S =$ "On input $\langle M, w \rangle$, an encoding of a TM M and a string w:

- First, construct M_2 (??)
- Run R on input $\langle M_2 \rangle$
- If R accepts, *accept*; if R rejects, *reject*

Want: $L(M_2)$ =
- **regular**, if M accepts w
- **nonregular**, if M does not accept w

Thm: $REGULAR_{\mathsf{TM}}$ is undecidable (continued)

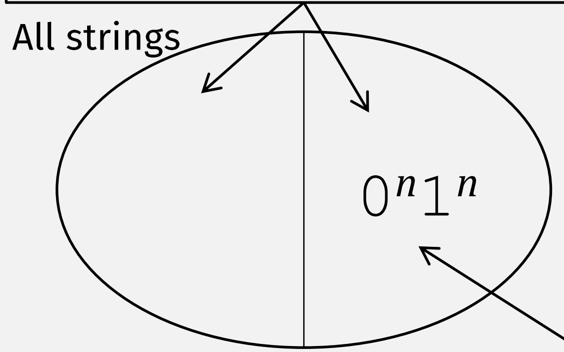
$REGULAR_{\mathsf{TM}} = \{\langle M \rangle \mid M \text{ is a TM and } L(M) \text{ is a regular language}\}$

$M_2 =$ "On input x:
1. If x has the form 0^n1^n, *accept*.
2. If x does not have this form, run M on input w and *accept* if M accepts w."

Always accept strings 0^n1^n
$L(M_2)$ = **nonregular**, so far

If M accepts w, accept everything else, so $L(M_2) = \Sigma^* =$ **regular**

if M does not accept w, M_2 accepts all strings (**regular** lang)



if M accepts w, M_2 accepts this **nonregular** lang

Want: $L(M_2)$ =
- **regular**, if M accepts w
- **nonregular**, if M does not accept w

Also Undecidable …

Seems like no algorithm can compute
anything about
the language of a Turing Machine,
i.e., about the runtime behavior of programs …

- $REGULAR_{\mathrm{TM}}$ = {<M> | M is a TM and $L(M)$ is a regular language}
- $CONTEXTFREE_{\mathrm{TM}}$ = {<M> | M is a TM and $L(M)$ is a CFL}
- $DECIDABLE_{\mathrm{TM}}$ = {<M> | M is a TM and $L(M)$ is a decidable language}
- $FINITE_{\mathrm{TM}}$ = {<M> | M is a TM and $L(M)$ is a finite language}

An Algorithm About Program Behavior?

```
main()
{
    printf("hello, world\n");
}
```

Write a program that,
given another program as its argument,
returns TRUE if that argument prints
“`Hello, World!`”

TRUE

Fermat's Last Theorem
(unknown for ~350 years,
solved in 1990s)

main()
{
  If $\boxed{x^n + y^n = z^n, \text{ for any integer } n > 2}$
    printf("hello, world\n");
}

Write a program that,
given another program as its argument,
returns TRUE if that argument prints
"`Hello, World!`"

?????

Also Undecidable …

Seems like no algorithm can compute **anything** about the language of a Turing Machine, i.e., about the runtime behavior of programs …

- $REGULAR_{\mathsf{TM}}$ = {<M> | M is a TM and $L(M)$ is a regular language}
- $CONTEXTFREE_{\mathsf{TM}}$ = {<M> | M is a TM and $L(M)$ is a CFL}
- $DECIDABLE_{\mathsf{TM}}$ = {<M> | M is a TM and $L(M)$ is a decidable language}
- $FINITE_{\mathsf{TM}}$ = {<M> | M is a TM and $L(M)$ is a finite language}
- …

Rice's Theorem

- $ANYTHING_{\mathsf{TM}}$ = {<M> | M is a TM and "… **anything** …" about $L(M)$}

Rice's Theorem: $ANYTHING_{\mathsf{TM}}$ is Undecidable

$ANYTHING_{\mathsf{TM}}$ = {<M> | M is a TM and … **anything** … about $L(M)$}

- "… **Anything** …", more precisely:

  For any M_1, M_2,
  - if $L(M_1) = L(M_2)$
  - then $M_1 \in ANYTHING_{\mathsf{TM}} \Leftrightarrow M_2 \in ANYTHING_{\mathsf{TM}}$

- Also, "… **Anything** …"must be "non-trivial":
  - $ANYTHING_{\mathsf{TM}}$!= {}
  - $ANYTHING_{\mathsf{TM}}$!= set of all TMs

Rice's Theorem: $ANYTHING_{\text{TM}}$ is Undecidable

$ANYTHING_{\text{TM}}$ = {<M> | M is a TM and … **anything** … about $L(M)$}

Proof by **contradiction**

- Assume some language satisfying $ANYTHING_{\text{TM}}$ has a decider R.
  - Since $ANYTHING_{\text{TM}}$ is non-trivial, then there exists $M_{ANY} \in ANYTHING_{\text{TM}}$
  - Where R accepts M_{ANY}
- Use R to create decider for A_{TM}:

On input <M, w>:

- Create M_w:

M_w = on input x:
- Run M on w
  - If M rejects w: reject x
  - If M accepts w:
    Run M_{ANY} on x and accept if it accepts, else reject

If M accepts w: M_w = M_{ANY}
If M doesn't accept w: M_w accepts nothing

These two cases must be <u>different</u>, (so R can distinguish when M accepts w)

- Run R on M_w
  - If it accepts, then M_w = M_{ANY}, so M accepts w, so accept
  - Else reject

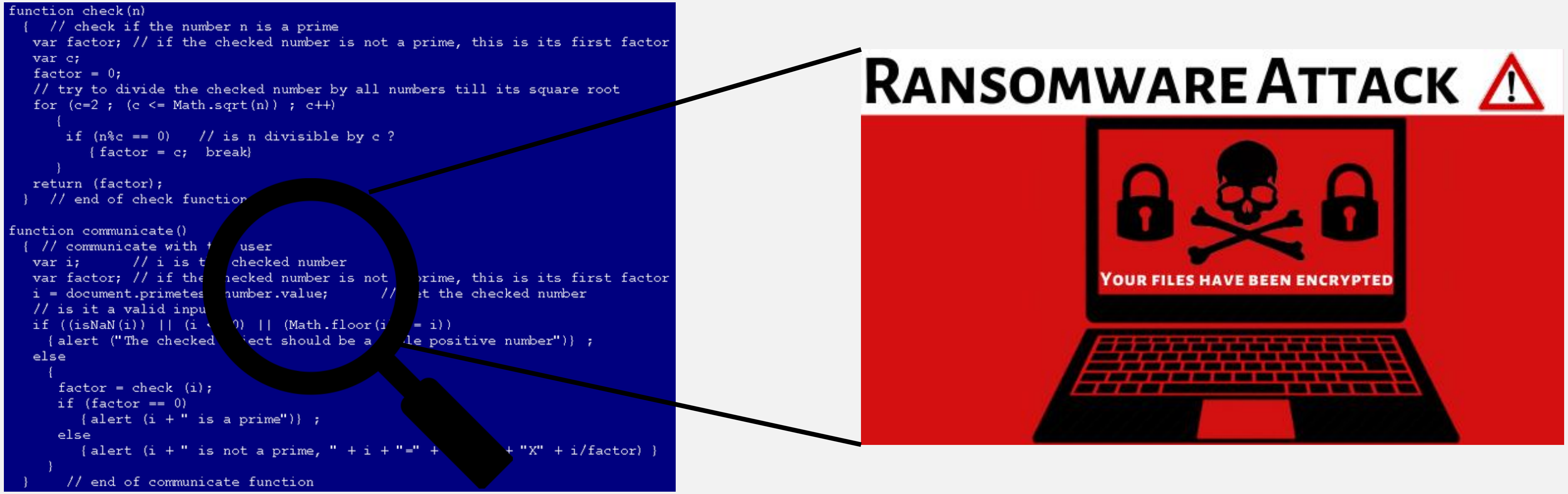
Wait! What if the TM that accepts nothing is in $ANYTHING_{\text{TM}}$!

Proof still works! Just use the complement of $ANYTHING_{\text{TM}}$ instead!

Rice's Theorem Implication

{<M> | M is a TM that installs malware}

Undecidable!
(by Rice's Theorem)



Submit in-class participation question

On gradescope