

# Unsolvable Problems

## Part One

# Outline for Today

- ***Self-Reference Revisited***
  - Programs that compute on themselves.
- ***Self-Defeating Objects***
  - Objects “too powerful” to exist.
- ***The Fortune Teller***
  - Can you escape your fate?
- ***Why Do Programs Loop?***
  - ... and can we eliminate loops?
- ***Undecidable Problems***
  - Something beyond the reach of algorithms.

Recap from Last Time

# R and RE

- A language  $L$  is **recognizable** if there is a TM  $M$  with the following property:

$$\forall w \in \Sigma^*. (M \text{ accepts } w \leftrightarrow w \in L).$$

- That is, for any string  $w$ :
  - If  $w \in L$ , then  $M$  accepts  $w$ .
  - If  $w \notin L$ , then  $M$  does not accept  $w$ .
  - **What does this mean?**
- This is a “weak” notion of solving a problem.
- The class **RE** consists of all the recognizable languages.

# R and RE

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  - If  $w \in L$ , then  $M$  accepts  $w$ .
  - If  $w \notin L$ , then  $M$  does not accept  $w$ .
    - It might reject  $w$ , or it might loop on  $w$ .
- This is a “weak” notion of solving a problem.
- The class **RE** consists of all the recognizable languages.

# R and RE

- A language  $L$  is **decidable** if there is a TM  $M$  with the following properties:

**$\forall w \in \Sigma^*. (M \text{ accepts } w \leftrightarrow w \in L).$**

**$M$  halts on all inputs.**

- That is, for any string  $w$ :
  - If  $w \in L$ , then  $M$  accepts  $w$ .
  - If  $w \notin L$ , then  $M$  rejects  $w$ .
- This is a “strong” notion of solving a problem.
- The class **R** consists of all the decidable languages.

# The Universal TM

- The *universal Turing machine*, denoted  $U_{TM}$ , is a TM with the following behavior: when run on a string  $\langle M, w \rangle$ , where  $M$  is a TM and  $w$  is a string,  $U_{TM}$  will
  - ... accept  $\langle M, w \rangle$  if  $M$  accepts  $w$ ,
  - ... reject  $\langle M, w \rangle$  if  $M$  rejects  $w$ , and
  - ... loop on  $\langle M, w \rangle$  if  $M$  loops on  $w$ .
- $A_{TM}$  is the language recognized by the universal TM. This is the language
$$A_{TM} = \{ \langle M, w \rangle \mid M \text{ is a TM and } M \text{ accepts } w \}$$
- $U_{TM}$  is a ??? for  $A_{TM}$ .

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- $U_{TM}$  is a **recognizer** for  $A_{TM}$ .



# Self-Referential Programs

- Computing devices can compute on their own source code:

***Theorem:*** It is possible to construct TMs that perform arbitrary computations on their own source code.

- This allows us to write programs that work on their own source code.

```
void cormorant() {  
    string me = /* source code of  
                * cormorant  
                */;  
    cout << me << endl;  
}
```

```
bool curlew(string input) {  
    string me = /* source code of  
                * curlew  
                */;  
    return input == me;  
}
```

```
int avocet() {  
    string me = /* source code of  
                * avocet  
                */;  
    int result = 0;  
    for (char ch: me) {  
        if (ch == 'a') result++;  
    }  
    return result;  
}
```

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What do each of these pieces of code do?

New Stuff!

# ***Part One:*** Self-Defeating Objects

A ***self-defeating object*** is an object whose essential properties ensure it doesn't exist.

***Question:*** Why is there no largest integer?

***Answer:*** Because if  $n$  is the largest integer, what happens when we look at  $n+1$ ?

# Self-Defeating Objects

***Theorem:*** There is no largest integer.

***Proof sketch:*** Suppose for the sake of contradiction that there is a largest integer. Call that integer  $n$ .

Consider the integer  $n+1$ .

Notice that  $n < n+1$ .

But then  $n$  isn't the largest integer.

Contradiction! ■-ish

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Contradiction! ■-ish

We're using  $n$  to construct something that undermines  $n$ , hence the term "self-defeating."



An Important Detail

Careful – we're assuming what we're trying to prove!

**Claim:** There is a largest integer.

**Proof:** Assume  $x$  is the largest integer. }

Notice that  $x > x - 1$ .

So there's no contradiction. ■-ish }

How do we know there's no contradiction? We just checked one case.

# Self-Defeating Objects

- If you can show

$$x \text{ exists} \rightarrow \perp$$

then you know that  $x$  doesn't exist. (This is a proof by contradiction.)

- If you can show

$$x \text{ exists} \rightarrow \top$$

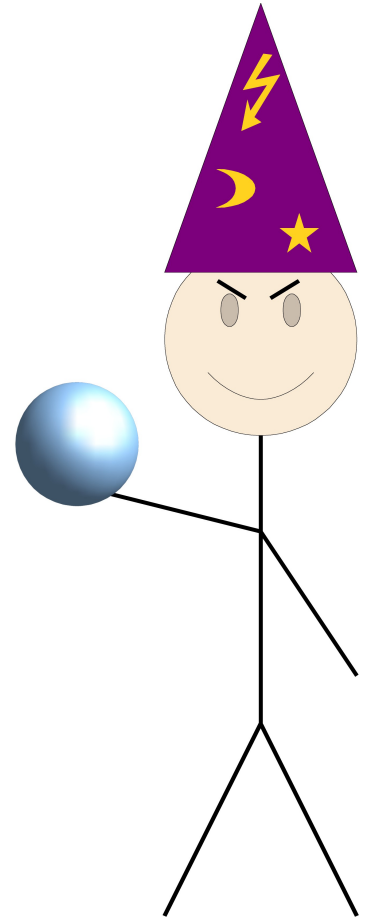
you cannot conclude that  $x$  exists. (This is not a valid proof technique.)

## ***Part Two:*** The Fortune Teller

# The Fortune Teller

- A fortune teller appears who claims they can see into the future.
- For a nominal fee, the fortune teller will tell you anything you want to know about the future.
- Of course, the fortune teller is a lying liar who lies. No one can see the future!
- The fortune teller makes a living taking money from unsuspecting townsfolk.

Someone needs to put an end to this!



# The Fortune Teller

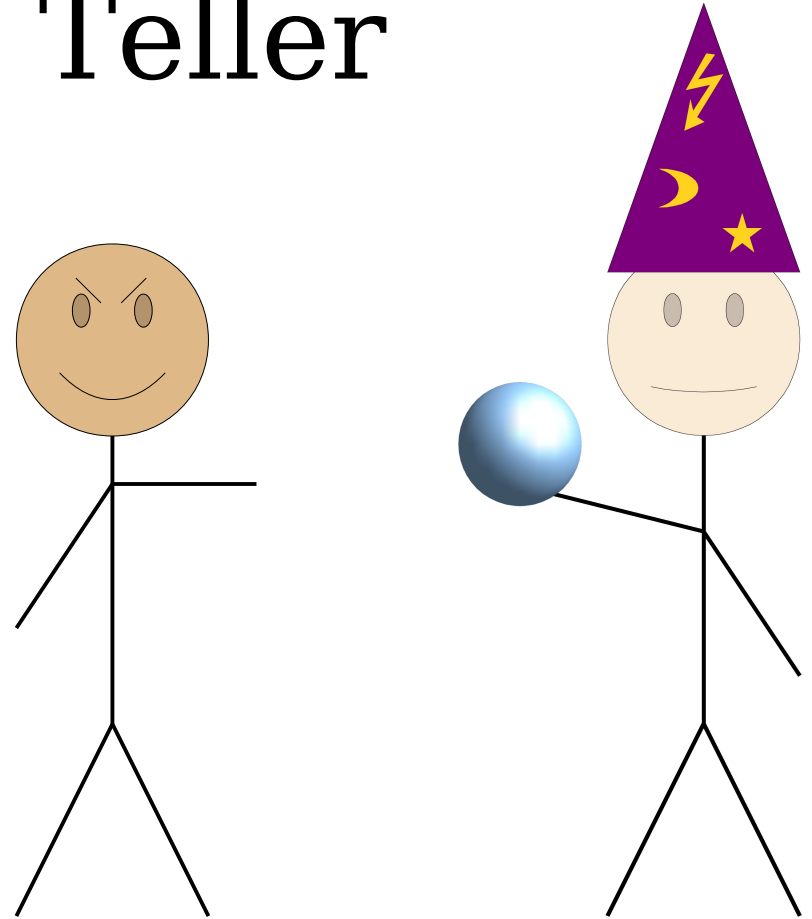
- One day, a trickster arrives. The trickster wants to expose that the fortune teller is a fraud.
- The trickster says the following:

*“I have a yes/no question about the future. But before I ask my question, let’s talk payment.*

*If you answer ‘yes,’ then I’ll pay you \$42.*

*If you answer ‘no,’ then I’ll pay you \$137.”*

- The fortune teller thinks for a moment, then agrees.



Trickster pays \$42 if the fortune teller answers “yes.”

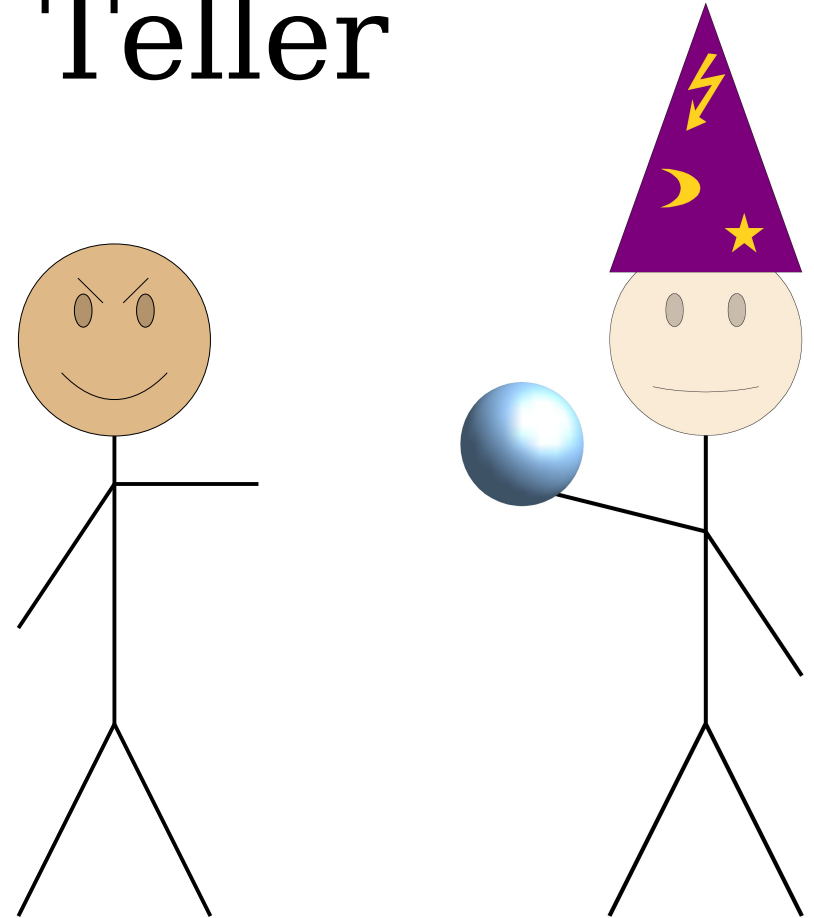
Trickster pays \$137 if the fortune teller answers “no.”

# The Fortune Teller

- The trickster then asks this question:

***“Am I going to pay you \$137?”***

- The fortune teller is trapped!
- Why?



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Trickster pays \$42 if the fortune teller answers “yes.”

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# The Fortune Teller

- The payment scheme the fortune teller agreed to means

*Fortune Teller Says Yes*  $\leftrightarrow$  *Trickster Pays \$42.*

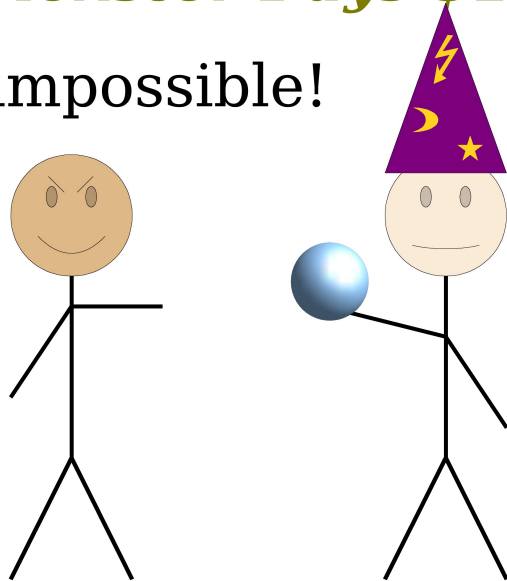
- The trickster's question to the fortune teller means

*Fortune Teller Says Yes*  $\leftrightarrow$  *Trickster Pays \$137.*

- Putting this together, we get

*Trickster Pays \$137*  $\leftrightarrow$  *Trickster Pays \$42.*

- This is impossible!



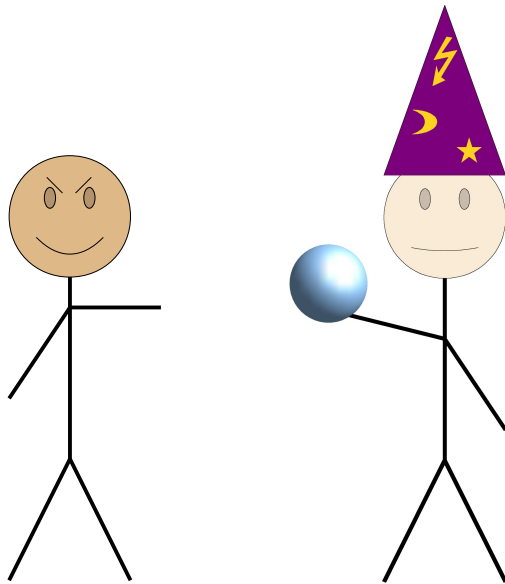
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# The Fortune Teller

- The fortune teller is a self-defeating object.
- The trickster's strategy is to couple the fortune teller's behavior to what the future holds.
  - The trickster's behavior is chosen in advance to make the fortune teller's answer wrong.
- Therefore, the fortune teller can't answer all questions about all people in the future.



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## ***Part Three:*** Why Do Programs Loop?

# Thoughts on Loops

- In practice, the programs we write sometimes go into infinite loops.
- In Theoryland, Turing machines are allowed to loop. This happens if they don't accept and don't reject.
- **Question:** Why are infinite loops possible?
- Or rather: are infinite loops an inherent part of computation, or are they some weird sort of “accident” in how we program computers?

# Thoughts on Loops

- **[Major] Theorem:** The language  $A_{TM}$  is recognizable, but undecidable.
  - There's a *recognizer* for  $A_{TM}$  (specifically, the universal Turing machine  $U_{TM}$ ).
  - It is impossible to build a *decider* for this language.
- Stated differently, there's a program we can write (a universal TM) that *has* to loop infinitely on some inputs.
- **Goal:** Prove this theorem, and explore its theoretical and philosophical implications.

# $A_{TM}$ Revisited

- As a refresher, the language  $A_{TM}$  is
$$A_{TM} = \{ \langle M, w \rangle \mid M \text{ is a TM and } M \text{ accepts } w \}.$$
- The universal TM  $U_{TM}$  has the following behavior when given as input a TM  $M$  and a string  $w$ :
  - If  $M$  accepts  $w$ , then  $U_{TM}$  accepts  $\langle M, w \rangle$ .
  - If  $M$  rejects  $w$ , then  $U_{TM}$  rejects  $\langle M, w \rangle$ .
  - If  $M$  loops on  $w$ , then  $U_{TM}$  loops on  $\langle M, w \rangle$ .
- $U_{TM}$  is a recognizer for  $A_{TM}$ , but because of that last case it's not a decider for  $A_{TM}$ .

# $A_{\text{TM}}$ Revisited

- As a refresher, the language  $A_{\text{TM}}$  is

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

- Given a TM  $M$  and a string  $w$ , a decider  $D$  for  $A_{\text{TM}}$  would need to have this behavior:
  - If  $M$  accepts  $w$ , then  $D$  ?  $\langle M, w \rangle$ .
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  - If  $M$  loops on  $w$ , then  $D$  ?  $\langle M, w \rangle$ .

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  - If  $M$  loops on  $w$ , then  $D$  ?  $\langle M, w \rangle$ .
- This is basically the same set of requirements as  $U_{TM}$ , except for what happens if  $M$  loops on  $w$ .
- Our goal is to prove that there is no way to build a program that meets these requirements.

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- This is basically the same set of requirements as  $U_{\text{TM}}$ , except for what happens if  $M$  loops on  $w$ .
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# $A_{TM}$ Revisited

- We can envision a decider for  $A_{TM}$  as a function

`bool willAccept(string fn, string input)`

that takes as input the source code of a function (fn) and a string representing an input to that function (input).

- It then does the following:
  - If `fn(input)` returns true, `willAccept(fn, input)` returns true.
  - If `fn(input)` returns false, `willAccept(fn, input)` returns false.
  - If `fn(input)` loops, then `willAccept(fn, input)` returns false.
- We're going to show it's impossible to write a function that actually does this. But for now, let's just explore what such a decider would do.

```
function = "bool f(string input) {  
    if (input == "") return false;  
    return input[0] == 'a';  
}";
```

input = "abbababba";

willAccept(function, input) = ?

```
function = "bool g(string input) {  
    while (true) {  
        input += input;  
    }  
}";
```

input = "yay! ";

willAccept(function, input) = ?

```
function = "bool h(string input) {  
    int n = input.length();  
    while (n > 1) {  
        if (n % 2 == 0) n /= 2;  
        else n = 3*n + 1;  
    }  
    return true;  
}";
```

input = /\* 10<sup>137</sup> a's \*/;

willAccept(function, input) = ?

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For each of these instances, what does  
willAccept(function, input) return?

# Deciding $A_{TM}$

- Surprising fact: until 2019, no one knew whether there were integers  $x$ ,  $y$ , and  $z$  where

$$x^3 + y^3 + z^3 = 33.$$

- A heavily optimized computer search found this answer:

$$x = 8,866,128,975,287,528$$

$$y = -8,778,405,442,862,239$$

$$z = -2,736,111,468,807,040$$

- As of November 2024, no one knows whether there are integers  $x$ ,  $y$ , and  $z$  where

$$x^3 + y^3 + z^3 = 114.$$

# Deciding $A_{TM}$

- Consider the language

$$L = \{ a^n \mid \exists x \in \mathbb{Z}. \exists y \in \mathbb{Z}. \exists z \in \mathbb{Z}. x^3 + y^3 + z^3 = n \}$$

- Here's code for a recognizer to see whether such a triple exists:

```
bool hasTriple(int n) {  
    for (int max = 0; ; max++)  
        for (int x = -max; x <= max; x++)  
            for (int y = -max; y <= max; y++)  
                for (int z = -max; z <= max; z++)  
                    if (x*x*x + y*y*y + z*z*z == n)  
                        return true;  
}
```

- Imagine calling `willAccept(/* hasTriple code */, 114)`.
  - If such a triple exists, `willAccept` returns true.
  - If no such triple exists, `willAccept` returns false.
- Key Intuition:** However `willAccept` is implemented, it has to be clever enough to resolve open problems in mathematics!

# Why is $A_{TM}$ Hard?

- **Intuition:** A decider for  $A_{TM}$  would be able to...
  - ... determine whether the hailstone sequence terminates for any input. (Write a recognizer that runs the hailstone sequence, then feed it into the decider for  $A_{TM}$ .)
  - ... see if any number is the sum of three cubes. (Write a recognizer that tries all infinitely many triples of integers, then feed it into the decider for  $A_{TM}$ .)
  - ... and much, much more.
- In other words, this seemingly simple problem of “is this program going to terminate?” accidentally scoops up a bunch of other seemingly harder problems.

## ***Part Four:*** Putting It All Together

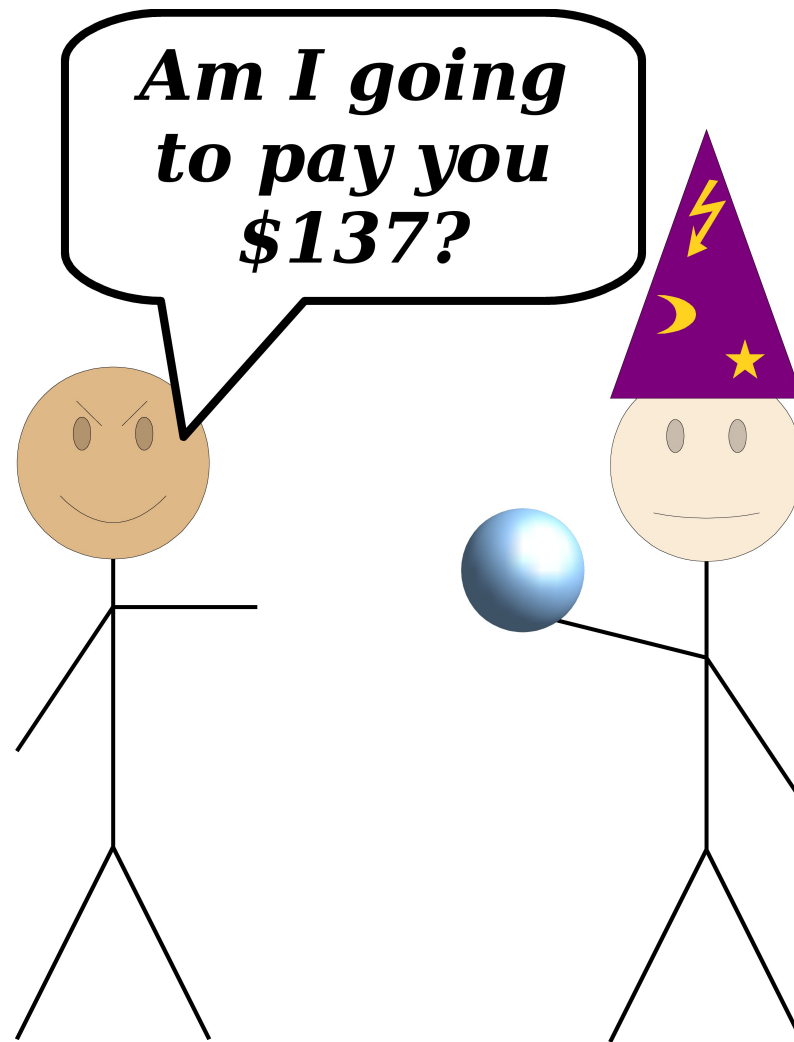
# To Recap

- We're assuming that, somehow, someone wrote a function

**bool** willAccept(string function, string input);

that takes the code of a function and an input to that function, then

- returns true if function(input) returns true, and
- returns false if function(input) doesn't return true.
- **Goal:** Show that this decider is “self-defeating;” its power is so great that it undermines itself.
- **Idea:** Convert the fortune teller story into a program.



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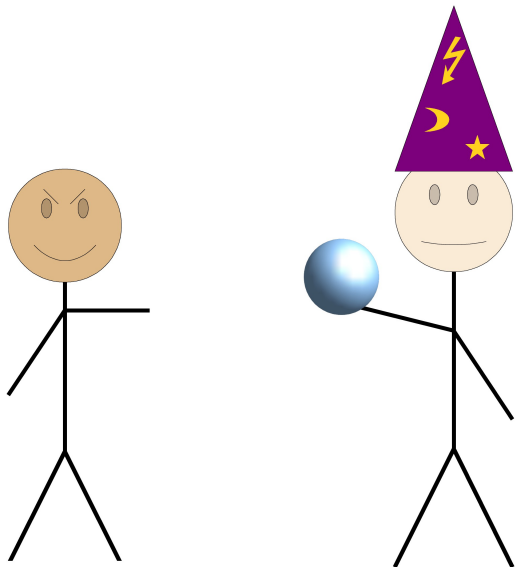
```

bool willAccept(string function, string input) {
    // Returns true if function(input) returns true.
    // Returns false otherwise.
}

bool trickster(string input) {
    string me = /* source code of trickster */;
    return !willAccept(me, input);
}

```

*A decider for  $A_{TM}$  has to have this behavior.*



trickster      willAccept

{  
 trickster(input) returns true  
 ↔  
 willAccept(me, input) returns true  
 ↔  
 trickster(input) does not return true  
 }

*Because of how we wrote trickster.*

```
bool willAccept(string function, string input) {  
    // Returns true if function(input) returns true.  
    // Returns false otherwise.  
}
```

A self-defeating  
object.

```
bool trickster(string input) {  
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}
```

Using that object  
against itself.

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```

"The largest  
integer  $n$ ."

"The integer  
 $n + 1$ ."

**Theorem:** There is no largest integer.

**Proof sketch:** Suppose for the sake of contradiction that there is a largest integer. Call that integer  $n$ .

Consider the integer  $n+1$ .

Notice that  $n < n+1$ .

But then  $n$  isn't the largest integer.

Contradiction! ■-ish

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**Theorem:**  $A_{TM} \notin \mathbf{R}$ .

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`bool willAccept(string function, string w);`

that takes in the source code of a function `function` and a string `w`, then returns true if `function(w)` returns true and returns false otherwise.



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Given how `trickster` is written, we see that

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This is impossible.

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}
```

Since `willAccept` decides  $A_{TM}$  and `me` holds the source of `trickster`, we know that

`willAccept(me, input)` returns true if and only if `trickster(input)` returns true.

Given how `trickster` is written, we see that

`willAccept(me, input)` returns true if and only if `trickster(input)` doesn't return true.

This means that

`trickster(input)` returns true if and only if `trickster(input)` doesn't return true.

This is impossible. We've reached a contradiction, so our assumption was wrong and  $A_{TM}$  is undecidable.

**Theorem:**  $A_{\text{TM}} \notin \mathbf{R}$ .

**Proof:** By contradiction; assume that  $A_{\text{TM}} \in \mathbf{R}$ . Then there is a decider  $D$  for  $A_{\text{TM}}$ . We can represent  $D$  as a function

```
bool willAccept(string function, string w);
```

that takes in the source code of a function `function` and a string `w`, then returns true if `function(w)` returns true and returns false otherwise. Given this, consider this function `trickster`:

```
bool trickster(string input) {  
    string me = /* source code of trickster */;  
    return !willAccept(me, input);  
}
```

Since `willAccept` decides  $A_{\text{TM}}$  and `me` holds the source of `trickster`, we know that

`willAccept(me, input)` returns true if and only if `trickster(input)` returns true.

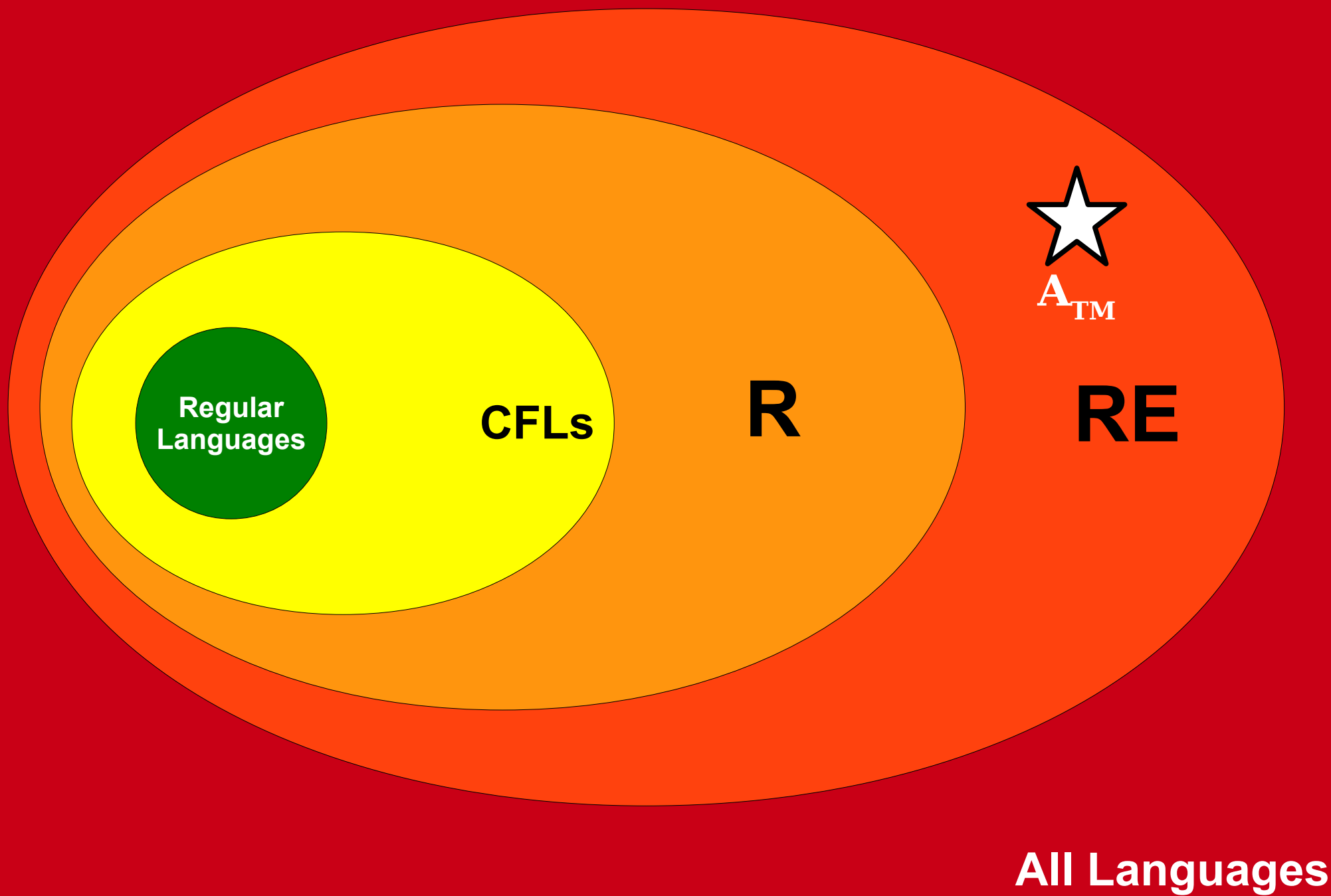
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This means that

`trickster(input)` returns true if and only if `trickster(input)` doesn't return true.

This is impossible. We've reached a contradiction, so our assumption was wrong and  $A_{\text{TM}}$  is undecidable. ■





# What Does This Mean?

- In one fell swoop, we've proven that
  - $A_{\text{TM}}$  is *undecidable*; there is no general algorithm that can determine whether a TM will accept a string.
  - $\mathbf{R} \neq \mathbf{RE}$ , because  $A_{\text{TM}} \notin \mathbf{R}$  but  $A_{\text{TM}} \in \mathbf{RE}$ .
- What do these three statements really mean? As in, why should you care?

$$A_{\text{TM}} \notin \mathbf{R}$$

- What exactly does it mean for  $A_{\text{TM}}$  to be undecidable?

***Intuition: The only general way to find out what a program will do is to run it.***

- As you'll see, this means that it's provably impossible for computers to be able to answer most questions about what a program will do.

$$A_{\text{TM}} \notin \mathbf{R}$$

- At a more fundamental level, the existence of undecidable problems tells us the following:

***There is a difference between what is true and what we can discover is true.***

- Given a TM  $M$  and a string  $w$ , one of these two statements is true:

**$M$  accepts  $w$**

**$M$  does not accept  $w$**

But since  $A_{\text{TM}}$  is undecidable, there is no algorithm that can always determine which of these statements is true!

# $R \neq RE$

- Because  $R \neq RE$ , there is a difference between decidability and recognizability:

*In some sense, it is fundamentally harder to solve a problem than it is to check an answer.*

- There are problems where, when the answer is “yes,” you can confirm it (run a recognizer), but where if you don’t have the answer, you can’t come up with it in a mechanical way (build a decider).

# Next Time

- ***Why All This Matters***
  - Important, practical, undecidable problems.
- ***Intuiting RE***
  - What exactly is the class **RE** all about?
- ***Verifiers***
  - A totally different perspective on problem solving.
- ***Beyond RE***
  - Finding an impossible problem using very familiar techniques.