

~~CSC363H5~~ CSC258H5 Tutorial 1

Paul's Revenge

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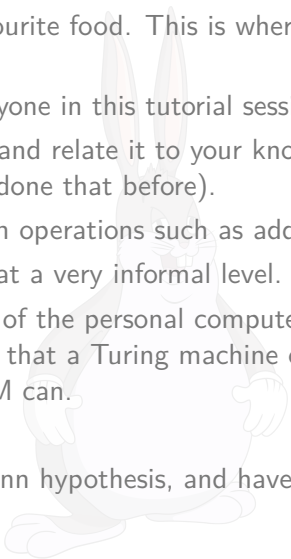
January 13, 2021



Learning objectives this tutorial

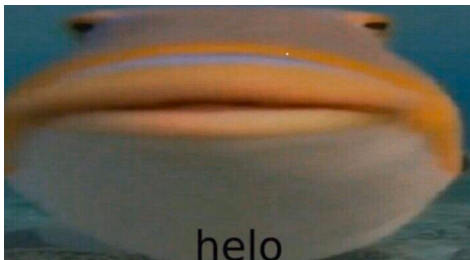
By the end of this tutorial, you should...

- ▶ Be able to name the TA and his favourite food. This is where your tuition is going.
- ▶ Have become good friends with everyone in this tutorial session.
- ▶ Be able to describe what a URM is, and relate it to your knowledge of assembly programming (if you've done that before).
- ▶ Be able to create URMs that perform operations such as addition.
- ▶ Grasp the idea of a Turing Machine at a very informal level.
- ▶ Appreciate the computational power of the personal computer, but realize that it only can do the things that a Turing machine can, which can only do things that a URM can.
- ▶ See `helo_fish.jpg` in your dreams.
- ▶ Have a proof for $P = NP$, the Riemann hypothesis, and have attained nirvana.



helo!

Welcome to CSC363! Here's `helo_fish.jpg`.



`helo_fish.jpg` shall revisit my tutorial from time to time. Today, `helo_fish.jpg` sends her greetings and hopes she will not haunt your dreams.

`helo_fish.jpg` will say goodbye for now. Say your farewells!

Protip...

`helo_fish.jpg` wants you to make friends in this tutorial session! Say hi to the people sitting right beside you.

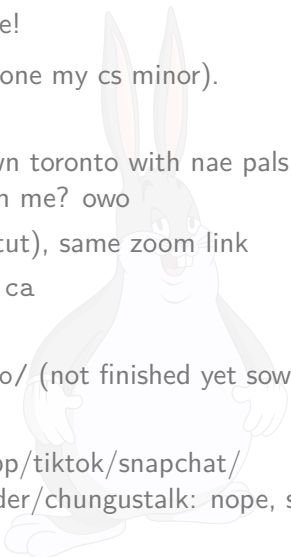
a bit about myself, i guess?

Hai! I'm paul (he/him), B.Sc., M.Sc, Ph.D, D.P.H, S.Sc.D, and others (in minecraft). Address me however you'd like!

I'm doing a mathematics specialist (i'm done my cs minor).
My favourite ice cream flavour is coffee.

Current status: sad and alone in downtown toronto with nae pals ;-; kinda lonely from time to time, wanna chat with me? owo

- ▶ office hours: Wed 5-6pm (after this tut), same zoom link
- ▶ email: pol.zhang@mail.utoronto.ca
- ▶ discord: [sjorv#0943](#)
- ▶ website: <https://sjorv.github.io/> (not finished yet sowwy)
- ▶ reddit: guess lol
- ▶ facebook/instagram/twitter/whatsapp/tiktok/snapchat/
vkontakte/line/amazon/quercus/tinder/chungustalk: nope, sorry :((

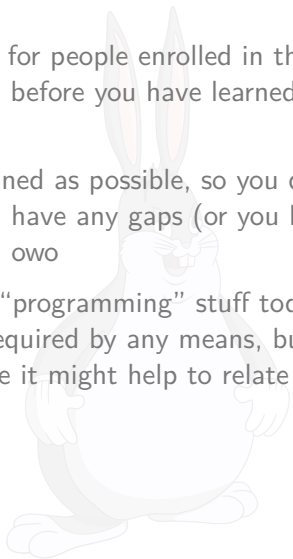


Oh yea, i just realized something...

When making those slides, I realized that for people enrolled in the Friday lecture, you will be attending this tutorial before you have learned any course content.

I've tried to make the slides as self-contained as possible, so you don't need knowledge from the lecture. But if I have any gaps (or you have questions), please don't hesitate to ask! owo

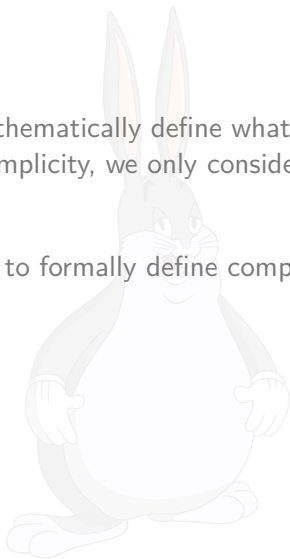
Also, we are doing some really **low level** “programming” stuff today. Knowledge of assembly language is not required by any means, but if you've done assembly programming before it might help to relate today's content to it.



What's a URM?

If you recall from class, we wanted to mathematically define what it means for a function to be “computable”. For simplicity, we only consider functions $f : \mathbb{N}^k \rightarrow \mathbb{N}$ for now.

A **U**niform **R**esource **M**achine is one way to formally define computability of functions.



What's a URM?

Consider a “tape” that extends infinitely in one direction. This tape can be thought of as memory in a computer (except we have infinite memory).

We will label the positions on the tape (or *registers*) R_1, R_2, \dots . Each register can store a **natural** number (including 0).



We will manipulate the values on the tape according a series of instructions, called a *URM program*. The instructions are very similar to assembly programming if you have done it before.

What's a URM?

A URM program consists of a series of *basic instructions*. The instructions are numbered $1, 2, \dots, m$, where m is the number of instructions the URM program has.

There are four basic instructions:

- ▶ The zero instruction $Z(n)$: replace the number in R_n (the n th position on the tape) with 0.
- ▶ The successor instruction $S(n)$: Add 1 to the number in R_n (i.e. increment it).
- ▶ The copy instruction $C(m, n)$: Replace the number in R_n with the number in R_m . This does not affect R_m .
- ▶ The jump instruction $J(m, n, q)$: If the numbers in R_m and R_n are equal, go to instruction q (otherwise go to the next instruction).¹

¹If $q > m$ (so the q th instruction doesn't exist), halt.

What's a URM?

The URM takes in a k -tuple $(a_1, a_2, \dots, a_k) \in \mathbb{N}^k$ as input.

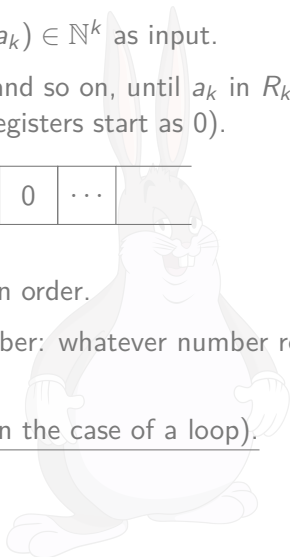
We start with values a_1 in R_1 , a_2 in R_2 , and so on, until a_k in R_k . For $i > k$, R_i starts with 0 (so all the other registers start as 0).

a_1	a_2	\dots	a_k	0	0	\dots
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Then the URM executes its instructions in order.

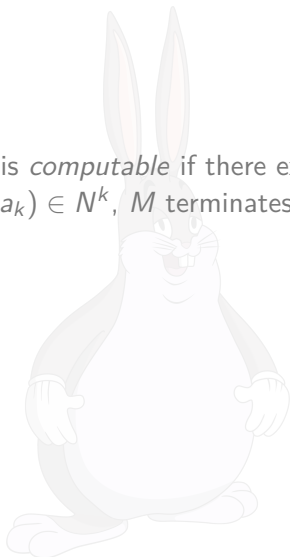
The output of the URM is a natural number: whatever number remains in R_1 at the end of execution is the output.

Note that some URMs don't terminate (in the case of a loop).



What's a URM?

Then, we can say a function $f : \mathbb{N}^k \rightarrow \mathbb{N}$ is *computable* if there exists a URM M such that for any input $(a_1, \dots, a_k) \in \mathbb{N}^k$, M terminates on input (a_1, \dots, a_k) and outputs $f(a_1, \dots, a_k)$.



Example

Let f be the function that adds two natural numbers:

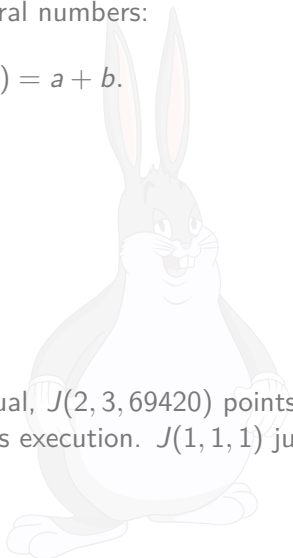
$$f : \mathbb{N}^2 \rightarrow \mathbb{N}, f(a, b) = a + b.$$

We construct a URM that computes f .

URM instructions:

- 1: $J(2, 3, 69420)$
- 2: $S(1)$
- 3: $S(3)$
- 4: $J(1, 1, 1)$

Note if the numbers in R_2 and R_3 are equal, $J(2, 3, 69420)$ points to a nonexistent instruction and therefore halts execution. $J(1, 1, 1)$ jumps to instruction 1 unconditionally.



Example

1: $J(2, 3, 69420)$

2: $S(1)$

3: $S(3)$

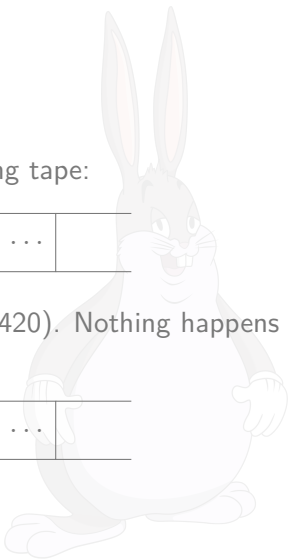
4: $J(1, 1, 1)$

On input $(3, 2)$, we start with the following tape:

3	2	0	0	...	
---	---	---	---	-----	--

We start executing from line 1: $J(2, 3, 69420)$. Nothing happens since $2 \neq 0$.

3	2	0	0	...	
---	---	---	---	-----	--



Example

1: $J(2, 3, 69420)$

2: $S(1)$

3: $S(3)$

4: $J(1, 1, 1)$

3	2	0	0	...	
---	---	---	---	-----	--

2: $S(1)$

4	2	0	0	...	
---	---	---	---	-----	--

3: $S(3)$

4	2	1	0	...	
---	---	---	---	-----	--



Example

- 1: $J(2, 3, 69420)$
- 2: $S(1)$
- 3: $S(3)$
- 4: $J(1, 1, 1)$

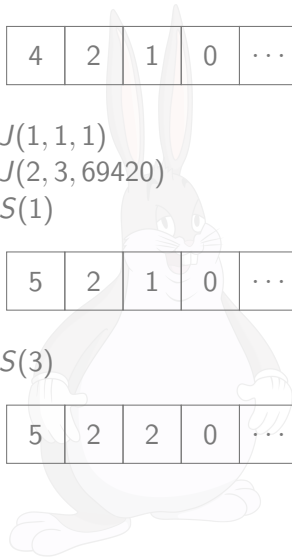
4	2	1	0	...	
---	---	---	---	-----	--

- 4: $J(1, 1, 1)$
- 1: $J(2, 3, 69420)$
- 2: $S(1)$

5	2	1	0	...	
---	---	---	---	-----	--

- 3: $S(3)$

5	2	2	0	...	
---	---	---	---	-----	--



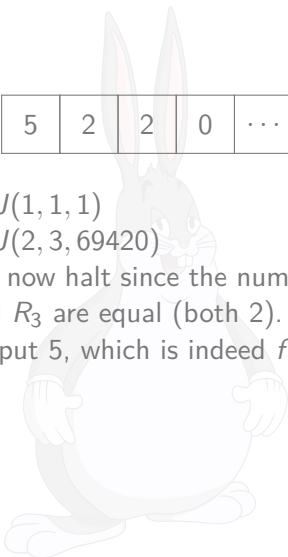
Example

- 1: $J(2, 3, 69420)$
- 2: $S(1)$
- 3: $S(3)$
- 4: $J(1, 1, 1)$

5	2	2	0	...	
---	---	---	---	-----	--

- 4: $J(1, 1, 1)$
- 1: $J(2, 3, 69420)$

We now halt since the numbers in R_2 and R_3 are equal (both 2). We output 5, which is indeed $f(3, 2)$.



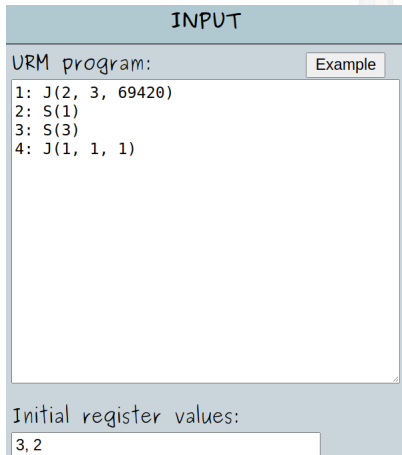
A useful tool

Try it out yourself!

<https://sites.oxy.edu/rnaimi/home/URMsim.htm>

(Sorry Firefox users, it's time to whip out Microsoft Edge.)

Note: The website uses $T(m, n)$ instead of $C(m, n)$ to denote the copy instruction.



The screenshot shows a web browser window titled "INPUT". Inside the window, there is a section labeled "URM program:" with a text area containing the following code:

```
1: J(2, 3, 69420)
2: S(1)
3: S(3)
4: J(1, 1, 1)
```

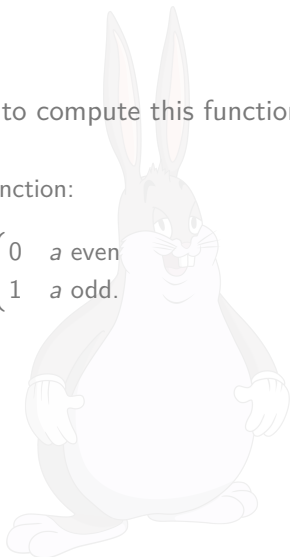
To the right of the text area is a button labeled "Example". Below the text area is a section labeled "Initial register values:" with a text input field containing the value "3,2".

Now it's your turn!

Let $f : \mathbb{N} \rightarrow \mathbb{N}$, $f(a) = 3a$. Build a URM to compute this function.

If you're done, try building a URM for this function:

$$f : \mathbb{N} \rightarrow \mathbb{N}, f(a) = \begin{cases} 0 & a \text{ even} \\ 1 & a \text{ odd.} \end{cases}$$

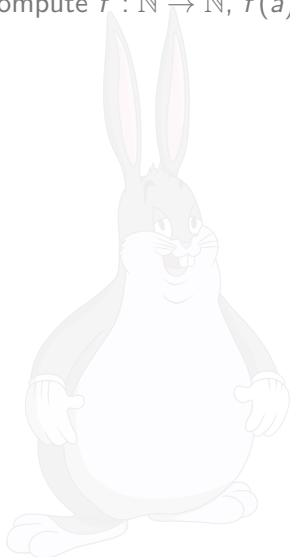


Solution

There are multiple different URMs that compute $f : \mathbb{N} \rightarrow \mathbb{N}$, $f(a) = 3a$.

Example:

- 1: $S(5)$
- 2: $S(5)$
- 3: $C(1, 2)$
- 4: $J(2, 3, 8)$
- 5: $S(1)$
- 6: $S(3)$
- 7: $J(1, 1, 4)$
- 8: $Z(3)$
- 9: $S(4)$
- 10: $J(4, 5, 2020)$
- 11: $J(1, 1, 4)$



Turing machines!

~~Now that you have the URM in the back of your mind, I can introduce Turing machines!~~

actually nvm it would take way too much time. Here's the informal idea of a Turing machine (don't worry if you don't understand everything here):²

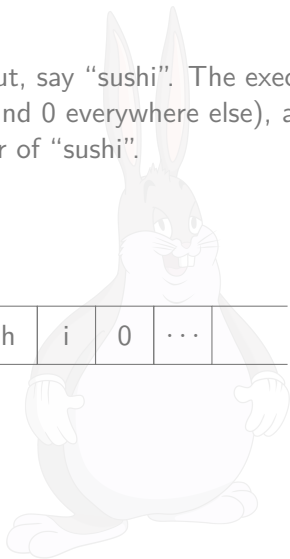
You have a tape, as before, but this tape extends infinitely in both directions. You also have a *read-write head*, pointing to a position on the tape.

Each position on the tape can store a symbol in a specified *alphabet* (remember CSC236!). For example, our alphabet could be $\{0, 1\}$, or it could be the set of all ASCII characters. There is a specially designated *empty symbol*, usually denoted by 0, that the tape is filled with.

²There are many equivalent ways of defining the Turing machine. This may differ from what is defined in this class later.

Turing machines!

The Turing machine takes in a string input, say “sushi”. The execution starts with “sushi” written on the tape (and 0 everywhere else), and the read-write head pointing to the first letter of “sushi”.



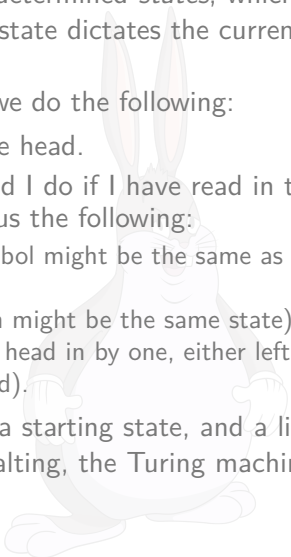
Turing machines!

The Turing machine also has a set of predetermined *states*, which can be encoded in a DFA (from CSC236). Each state dictates the current behaviour of the Turing machine.

In each iteration of the Turing machine, we do the following:

1. Read the symbol, from the read-write head.
2. Inquire the current state: what should I do if I have read in this symbol? The current state will give us the following:
 - ▶ A symbol to write back. (This symbol might be the same as the symbol we read in.)
 - ▶ A new state to transition to (which might be the same state).
 - ▶ A direction to move the read-write head in by one, either left or right (we **must** move the read-write head).

In addition, the Turing machine specifies a starting state, and a list of halting states, just like in a DFA. After halting, the Turing machine outputs whatever is left on the tape.



Turing machines!

That was very informal. Here's the formal definition from Wikipedia:

Formal definition (edit)

Following Hopcroft & Ullman (1979, p. 443), a (one-tape) Turing machine can be formally defined as a 7-tuple $M = (Q, \Gamma, A, \Sigma, \delta, q_0, F)$ where

- Q is a finite, non-empty set of states;
- Γ is a finite, non-empty set of tape alphabet symbols;
- $A \in \Gamma$ is the blank symbol (the only symbol allowed to occur on the tape infinitely often at any step during the computation);
- $\Sigma \subseteq \Gamma \setminus \{A\}$ is the set of input symbols, that is, the set of symbols allowed to appear in the initial tape contents;
- $q_0 \in Q$ is the initial state;
- $F \subseteq Q$ is the set of final states or accepting states. The initial tape contents is said to be accepted by M if it eventually halts in a state from F ;
- $\delta: (Q \setminus F) \times \Gamma \rightarrow Q \times \Gamma \times \{L, R\}$ is a partial function called the transition function, where L is left shift, R is right shift. If δ is not defined on the current state and the current tape symbol, then the machine halts.^[1]

In addition, the Turing machine can also have a reject state to make rejection more explicit, in that case there are three possibilities: accepting, rejecting, and running forever. Another possibility is to regard the final values on the tape as the output. However, if the only output is the final state the machine ends up in (or never halting), the machine can still effectively output a longer string by taking in an integer that tells it which bit of the string to output.

A relatively uncommon variant allows "no shift", say N , as a third element of the set of directions $\{L, R\}$.

The 3-state busy beaver looks like this (see more about this busy beaver at Turing machine examples):

- $Q = \{A, B, C, \text{HALT}\}$ (states);
- $\Gamma = \{0, 1\}$ (tape alphabet symbols);
- $A = 0$ (blank symbol);
- $\Sigma = \{1\}$ (input symbols);
- $q_0 = A$ (initial state);
- $F = \{\text{HALT}\}$ (final states);
- $\delta =$ see state-table below (transition function).

Initially all tape cells are marked with 0.

State table for 3-state, 2-symbol busy beaver

Tape symbol	Current state A				Current state B				Current state C			
	write symbol	move tape	next state	write symbol	move tape	next state	write symbol	move tape	next state	write symbol	move tape	next state
0	1	R	B	1	L	A	1	L	B			
1	1	L	C	1	R	B	1	R	HALT			

Greek letters scare people so that's why I didn't feel like giving a full overview of the Turing machine today, sowwy owo

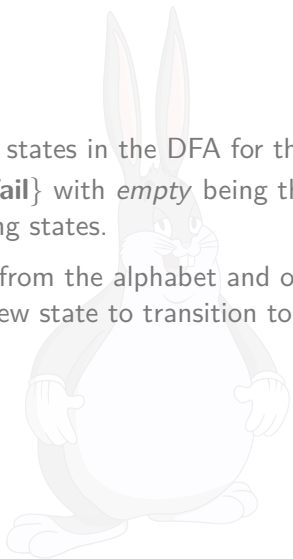
The catchline is that although Turing machines are more complicated than URMs, whatever Turing machines can compute, URMs can also compute, and vice versa. So in some sense their "computational power" is equivalent! In fact, theoretically you could simulate a Turing machine inside a URM, and vice versa.

Example of Turing machine!

Let's make sushi! owo






Our alphabet will be $\{0, \text{🐟}, \text{🍣}, \text{🍱}\}$. The states in the DFA for the Turing machine will be $\{\textit{empty}, \textit{rice}, \textit{fish}, \textbf{finish}, \textbf{fail}\}$ with *empty* being the starting state and bold states being halting states.

Remember, each state takes in a symbol from the alphabet and outputs three things: a symbol to write back, a new state to transition to, and a direction to move the read-write head.

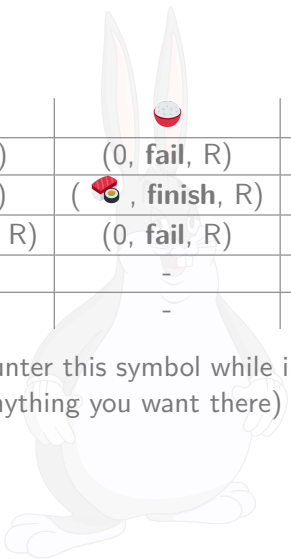


Example of Turing machine!

Consider the following table:

State	0			
<i>empty</i>	(0, fail , R)	(0, fish, R)	(0, fail , R)	-
fish	(0, fail , R)	(0, fail , R)	( , finish , R)	-
rice	(0, fail , R)	( , finish , R)	(0, fail , R)	-
finish	-	-	-	-
fail	-	-	-	-

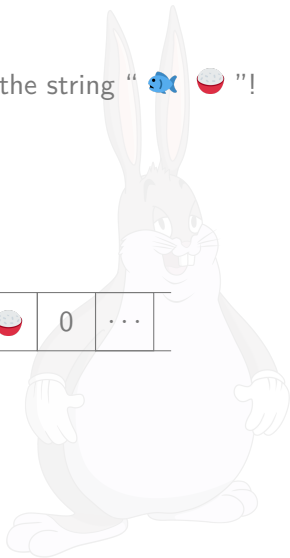
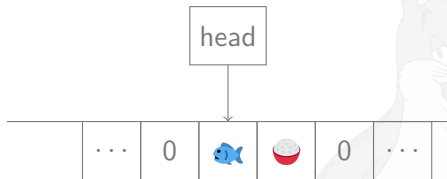
where — denotes that we will never encounter this symbol while in this state (if you wanna be formal, just put anything you want there)



Example of Turing machine!

Let's try executing our sushi machine on the string "🐟🍣"!

Current State: *empty*



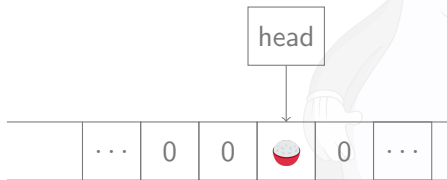
Example of Turing machine!

We read in 🐟, and consult our current state *empty*.

State	0	🐟	🍣	🍱
<i>empty</i>	(0, fail , R)	(0, fish, R)	(0, fail , R)	-

Our current state returns (0, fish, R). So we write back 0, go to the fish state, and move the head right.

Current State: fish



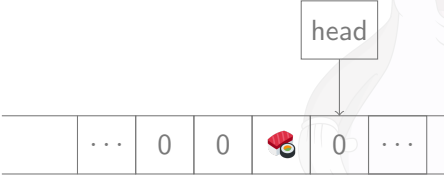
Example of Turing machine!

We read in 🍣, and consult our current state fish.

State	0	🐟	🍣	🍣
fish	(0, fail , R)	(0, fail , R)	(🍣, finish , R)	-

Our current state returns (🍣, **finish**, R). So we write back 🍣, go to the **finish** state, and move the head right.

Current State: **finish**



Then we halt since **finish** is a halting state, and return 🍣!



bye!

hope you learned something today!

i'll probably post the slides later, and set up a pateron to fund my sushi addiction.



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