CSC363 Tutorial #2

Turing machines and stuff

January 26, 2022

Learning objectives this tutorial

- Prove that some functions are primitive recursive.
- Prove more functions are primitive recursive.
- Talk about "computable sets".

A bit about myself?

Hi! I'm some 4th year student studying math/cs. I was sick last week ;w;

- Contact: pol.zhang@utoronto.ca, or if you prefer Discord, sjorv#0943
- Hobbies: Gaming, taking naps at inappropriate times

Not my cat. Cats are cute though.

- Favourite food: sushi juice
- Office hours: 1-2pm Friday
- Website (you can find tutorial slides there): sjorv.github.io

PRIM

Question: What does PRIM stand for?

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Question: What are the initial functions in PRIM?

PRIM

Recall that PRIM is a set of functions from $\mathbb{N}^k$ to $\mathbb{N}$, intuitively meant to capture what a "computable" function is.

DEFINITION 2.1.1 (The Primitive Recursive Functions)

1) The **initial functions** *(a) – (c) are primitive recursive:*

(a) The **zero function** *defined by*

$$\mathbf{0}(n) = 0, \qquad \forall n \in \mathbb{N},$$

(b) The **successor function** *defined by*

$$n' = n + 1, \qquad \forall n \in \mathbb{N},$$

(c) The **projection functions** U_i^k *defined by*

$$U_i^k(\overrightarrow{m}) = m_i, \qquad \text{each } k \geq 1, \text{ and } i = 1, \ldots, k,$$

(where we write $\overrightarrow{m} = m_1, \ldots, m_k$*).*

2) If $g, h, h_0, \ldots, h_l$ *are primitive recursive, then so is* f *obtained from* $g, h, h_0, \ldots, h_l$ *by one of the rules:*

(d) **Substitution**, *given by:*

$$f(\overrightarrow{m}) = g(h_0(\overrightarrow{m}), \ldots, h_l(\overrightarrow{m})),$$

(e) **Primitive recursion**, *given by:*

$$\begin{aligned} f(\overrightarrow{m}, 0) &= g(\overrightarrow{m}), \\ f(\overrightarrow{m}, n+1) &= h(\overrightarrow{m}, n, f(\overrightarrow{m}, n)). \end{aligned} \tag{2.1}$$

Keep this definition handy!

Constant functions are in prim

Task: Prove that $f_k : \mathbb{N} \to \mathbb{N}$, given by $f_k(n) = k$ for all $n \in \mathbb{N}$, is primitive recursive.

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Ans: We know $\mathbf{0}$ (the zero function) and S (the successor function) are primitive recursive, from (a) and (b). Thus repeatedly applying the substitution rule (d),

$$f_k(n) = \underbrace{S(S(\ldots(S(}_{k \text{ times}}\mathbf{0}(n)))\ldots))$$

is primitive recursive.

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Formal Proof: We have

$$+(x, 0) = P^1_1(x),$$

$$+(x, n+1) = g(x, n, +(x, n))$$

where $g(a, b, c) = S(P^3_3(a, b, c))$ is primitive recursive by the substitution rule.

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Informal Proof:

$$\times(x, 0) = 0,$$

$$\times(x, n+1) = +(\times(x, n), x)$$

so using the rule of primitive recursion (e), $\times$ is primitive recursive.
Formal Proof: We have

$$\times(x, 0) = \mathbf{0}(x),$$

$$\times(x, n+1) = g(x, n, \times(x, n))$$

where $g(a, b, c) = +(P^3_1(a, b, c), P^3_3(a, b, c))$ is primitive recursive by the substitution rule, since we've proven $+$ is primitive recursive.

“Subtraction” is in PRIM

Task: Show that $\delta : \mathbb{N} \to \mathbb{N}$, $\delta(n) = \begin{cases} n-1 & n \geq 1 \\ 0 & n = 0 \end{cases}$ is in PRIM.

Hint: Define $f(x, n) = n - 1$ (basically ignoring the first parameter). If we show f is primitive recursive, then $\delta(n) = f(n, n)$ is primitive recursive by the substitution rule.

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Proof: Define f as in the hint. We have

$$f(x, 0) = \mathbf{0}(x),$$

$$f(x, n+1) = P^3_2(x, n, f(x, n)) \quad (= n)$$

so f is primitive recursive. Thus $\delta(n) = f(n, n)$ is primitive recursive by substitution rule.

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Task: Show that $\dot{-} : \mathbb{N}^2 \to \mathbb{N}$, $\dot{-}(x, y) = \begin{cases} x - y & x \geq y \\ 0 & x < y \end{cases}$ is primitive recursive.

Hint: primitive recursion, using δ from before!

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Hint: primitive recursion, using δ from before!

Proof: We have

$$\dot{-}(x, 0) = P_1^1(x),$$

$$\dot{-}(x, n+1) = \delta(\dot{-}(x, n))$$

so $\dot{-}$ is primitive recursive.

we're being a little informal here! but hopefully you can translate this into a "formal proof" as before.

What is in PRIM?

So far, we've shown the following are in PRIM:

- Any constant function f_k.
- Addition, multiplication.
- "Subtraction" (which doesn't go below zero, to make $\mathbb{N}$ happy).

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What about the following functions?

- Absolute difference $(x, y) \mapsto |x - y|$.
- The "is zero?" function (inverse sign function):

$$\overline{\mathrm{sg}}(x) = \begin{cases} 1 & x = 0 \\ 0 & x \neq 0. \end{cases}$$

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They are all primitive recursive!

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In our upcoming definition of a "computable set", we only assume PRIM functions are "computable". This is not true! There are functions not in PRIM that are also computable, such as the Ackermann function.

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Either way, every "computable set" from our definition will turn out to be "computable" in the actual definition.

Computable sets

Consider $S \subseteq \mathbb{N}$. How do we define the statement "S is computable", in terms of primitive recursion?

[1] I am lying to you here! The actual definition uses "recursive" instead of "primitive recursive", and "recursive" constitutes a larger class of functions. You'll learn (or have learned) about it in this week's lecture.

Computable sets

Consider $S \subseteq \mathbb{N}$. How do we define the statement "S is computable", in terms of primitive recursion?

A natural way would be to define "S is computable" by looking at its *characteristic function* $\chi_S : \mathbb{N} \to \mathbb{N}$, given by

$$\chi_S(n) = \begin{cases} 0 & n \notin S \\ 1 & n \in S. \end{cases}$$

Definition: A set $S \subseteq \mathbb{N}$ is *computable* when its characteristic function χ_S is primitive recursive.[1]

Task: Show that the empty set is computable.

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Definition: A set $S \subseteq \mathbb{N}$ is *computable* when its characteristic function χ_S is primitive recursive.[1]
Task: Show that the empty set is computable.
Ans: The empty set's characteristic function is just the zero function, which is primitive recursive.

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Computable sets

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Ans: The characteristic function of $\{0\}$ is just the inverse sign function

$$\overline{\mathrm{sg}}(x) = \begin{cases} 1 & x = 0 \\ 0 & x \neq 0. \end{cases}$$

which, as we have shown, is computable.

Computable sets

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Task: Show that any singleton set $\{k\}$, with $k \in \mathbb{N}$ is computable.
Ans: The absolute difference $(x, y) \mapsto |x - y|$ is primitive recursive. Thus

$$\overline{\mathrm{sg}}(|x-k|) = \begin{cases} 1 & x = k \\ 0 & x \neq k \end{cases}$$

is primitive recursive. But this is just the characteristic function of $\{k\}$!

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Ans: What if we added the indicator functions of each singleton set $\{k_1\}, \ldots, \{k_m\}$? Notice that

$$\overline{\mathrm{sg}}(|x - k_1|) + \ldots + \overline{\mathrm{sg}}(|x - k_m|) > 0$$

if and only if x is in $\{k_1, \ldots, k_m\}$. Thus

$$\mathrm{sg}(\overline{\mathrm{sg}}(|x - k_1|) + \ldots + \overline{\mathrm{sg}}(|x - k_m|)) = 1$$

if and only if x is in $\{k_1, \ldots, k_m\}$, so our characteristic function is primitive recursive.

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Ans: Add the indicator functions!

$$\mathrm{sg}(\chi_{S_1}(x) + \chi_{S_2}(x)) = 1$$

if and only if x is in S_1 or x is in S_2, so our characteristic function is primitive recursive.

Computable sets

What other sets are computable?

- The even numbers $\{0, 2, 4, \ldots\}$. (Prove the remainder function $(x, y) \mapsto x\%y$ is in PRIM!)
- The prime numbers.
- Pretty much every set that ever comes up in number theory!

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We're trying to build a mathematical definition of "computable", from multiple different perspectives:

- Computation with Turing machines;

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These all turn out to give an "equivalent" definition of what is computable. Fundamentally, there are things that computers cannot do, regardless of the framework of computation we use!
Primitive recursion is probably the most "abstract" and thus the hardest to grasp intuitively, but it is worthwhile from a historical perspective.

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