Outline

1. Function Composition
2. Recursion
3. Primitive Recursively Closed Classes
4. Building the Class of Primitive Recursive Functions
Definition

Let \( f \) be a function of \( k \) variables and let \( g_1, \ldots, g_k \) be functions of \( n \) variables. The function \( h \) defined as

\[
h(x_1, \ldots, x_n) = f(g_1(x_1, \ldots, x_n), \ldots, g_k(x_1, \ldots, x_n))
\]

is said to be obtained from \( f \) and \( g_1, \ldots, g_k \) by composition.

The functions \( f, g_1, \ldots, g_k \) need not be total. \( h(x_1, \ldots, x_n) \) is defined when all of \( z_1 = g_1(x_1, \ldots, x_n), \ldots, z_k = g(x_1, \ldots, x_n) \) are defined and \( f(z_1, \ldots, z_n) \) is defined.
**Theorem**

*If h is obtained from the computable functions f, g₁, ..., gₖ by composition, then h is computable.*

**Proof.**

The following program computes h:

\[ Z₁ \leftarrow g₁(X₁, \ldots, Xₙ) \]
\[ \vdots \]
\[ Zₖ \leftarrow gₖ(X₁, \ldots, Xₙ) \]
\[ Y \leftarrow f(Z₁, \ldots, Zₖ) \]
Function Composition

Example

We saw that the functions

\[ x, x + y, x \cdot y, x - y \]

are partially computable. Therefore, \(2x = x + x\) and \(4x^2 = (2x) \cdot (2x)\) are partially computable. So are \(4x^2 + 2x\) and \(4x^2 - 2x\). Note that \(4x^2 - 2x\) is total although is obtained from a non-total function \(x - y\) by composition with \(4x^2\) and \(2x\).
Recursion is a modality of constructing a new function from a given one.

**Definition**

Suppose that $g$ is a total function of two variables and $k$ is a fixed number, $k \in \mathbb{N}$. The function $h : \mathbb{N} \rightarrow \mathbb{N}$ is obtained from $g$ by **primitive recursion** if

$$
\begin{align*}
h(0) &= k, \\
h(t + 1) &= g(t, h(t)).
\end{align*}
$$
Theorem

If $h$ is obtained from the computable function $g$ by primitive recursion, then $h$ is also computable.

Proof.

Note that the constant function $f(x) = k$ is computed by the program

$$
Y \leftarrow Y + 1 \\
Y \leftarrow Y + 1 \\
\vdots \\
Y \leftarrow Y + 1
$$

that contains $k$ lines.
Proof cont’d

Proof.

This shows that we can use the macro $Y \leftarrow k$. The following is a program that computed $h(x)$:

\[
\begin{align*}
Y & \leftarrow k \\
\text{[A]} & \quad \text{IF } X = 0 \text{ GOTO } E \\
Y & \leftarrow g(Z, Y) \\
Z & \leftarrow Z + 1 \\
X & \leftarrow X - 1 \\
\text{GOTO } A
\end{align*}
\]

Note that if $Y$ has the value $h(z)$ before executing instruction labeled $A$, then it has the value $g(z, h(z)) = h(z + 1)$ after executing $Y \leftarrow g(Z, Y)$. 
Recursion

A slightly more complicated kind of recursion

The function $h : \mathbb{N}^{n+1} \rightarrow \mathbb{N}$ is defined starting from the functions $f : \mathbb{N}^n \rightarrow \mathbb{N}$ and $g : \mathbb{N}^{n+2} \rightarrow \mathbb{N}$ as

$$h(x_1, \ldots, x_n, 0) = f(x_1, \ldots, x_n),$$
$$h(x_1, \ldots, x_n, t + 1) = g(t, h(x_1, \ldots, x_n, t), x_1, \ldots, x_n).$$

This modality of constructing $h$ is known as primitive recursion.
The functions $f$ and $g$ are total.
Recursion

**Theorem**

Let $f : \mathbb{N}^n \rightarrow \mathbb{N}$ and $g : \mathbb{N}^{n+2} \rightarrow \mathbb{N}$ be two computable functions. The function $h$ defined from $f$ and $g$ by primitive recursion is computable.
Proof.

The following program computes $h(x_1, \ldots, x_n, x_{n+1})$:

\[
\begin{align*}
    & Y \leftarrow f(X_1, \ldots, X_n) \\
    & [A] \quad \text{IF } X_{n+1} = 0 \text{ GOTO E} \\
    & \quad Y \leftarrow g(Z, Y, X_1, \ldots, X_n) \\
    & \quad Z \leftarrow Z + 1 \\
    & \quad X_{n+1} \leftarrow X_{n+1} - 1 \\
    & \quad \text{GOTO A}
\end{align*}
\]
Definition

The set of *initial functions* consists of the following:

- the *successor function* $s : \mathbb{N} \rightarrow \mathbb{N}$ defined by $s(x) = x + 1$ for $x \in \mathbb{N}$;
- the *null function* $n : \mathbb{N} \rightarrow \mathbb{N}$ defined by $n(x) = 0$ for $x \in \mathbb{N}$;
- the *projection functions* $u_i^n : \mathbb{N}^n \rightarrow \mathbb{N}$ given by $u_i^n(x_1, \ldots, x_n) = x_i$ for $1 \leq i \leq n$.

Note that because the initial functions contain the projection functions, the class of initial functions contains an infinite number of functions.
Example

The *projection function* \( u_2^5 : \mathbb{N}^5 \rightarrow \mathbb{N} \) is given by

\[
u_2^5(x_1, x_2, x_3, x_4, x_5) = x_2
\]

for \( x_1, x_2, x_3, x_4, x_5 \in \mathbb{N} \).
Definition

A *primitive recursively closed class* (a PRC class) is a set of *total functions* \( C \) that satisfies the following conditions:

1. the initial functions belong to \( C \), and
2. a function obtained from functions belonging to \( C \) by either composition or recursion belongs to \( C \).
Theorem

The class of computable functions is a PRC class.

Proof.

It suffices to show that the initial functions are computable.

- The function \( s(x) = x + 1 \) is computable by \( Y \leftarrow X + 1 \).
- \( n(x) \) is computed by the empty program, and
- \( u^n_i(x_1, \ldots, x_n) \) is computed by the program
  \[
  Y \leftarrow X_i
  \]
Definition

A function is *primitive recursive* if it can be obtained from the initial functions by a finite number of applications of composition and recursion.

It is clear that the class of primitive recursive functions is a PRC class.
Theorem

A function is primitive recursive if and only if it belongs to every PRC class.

Proof.

If a function belongs to every PRC class then, in particular, it belongs to the class of primitive recursive functions. Conversely, let $f$ be a primitive recursive function and let $C$ be some PRC class. Since $f$ is primitive recursive, there is a list $f_1, \ldots, f_n$ of functions such that $f_n = f$ and each $f_i$ is either an initial function or it can be obtained from preceding functions by composition or recursion. The initial functions belong to $C$ and we saw that the application of composition or recursion to functions in $C$ results in a function in $C$. Hence any function in $f_1, \ldots, f_n$ belongs to $C$. In particular, $f_n = f \in C$. \qed
Corollary

*Every primitive recursive function is computable.*

Proof.

Every primitive recursive function belongs to the PRC class of computable functions.
Example

Let \( f(x, y) = x + y \). We have

\[
f(x, 0) = x = u_1^1(x),
\]
\[
f(x, y + 1) = f(x, y) + 1.
\]

The second equality can be written as

\[
f(x, y + 1) = g(y, f(x, y), x),
\]

where

\[
g(x_1, x_2, x_3) = 1 + x_2 = s(u_2^3(x_1, x_2, x_3)).
\]

Thus, \( g \) is primitive recursive and \( f \) is primitive recursive because \( f \) is obtained by primitive recursion from primitive recursive functions.
Example

Let $h(x, y) = x \cdot y$. We have:

\[
\begin{align*}
    h(x, 0) &= 0, \\
    h(x, y + 1) &= h(x, y) + x,
\end{align*}
\]

or

\[
\begin{align*}
    h(x, 0) &= n(x), \\
    h(x, y + 1) &= g(y, h(x, y), x),
\end{align*}
\]

where

\[
g(x_1, x_2, x_3) = f(u_2^3(x_1, x_2, x_3), u_3^3(x_1, x_2, x_3)) = f(x_2, x_3),
\]

where $f(x, y) = x + y$ was shown to be primitive recursive on Slide 19.
Example

Let $\ell : \mathbb{N} \rightarrow \mathbb{N}$ be defined as $\ell(x) = x!$. The recursion equations are $\ell(0) = 1$ and $\ell(x + 1) = \ell(x) \cdot s(x)$, which represent the equalities:

$$0! = 1 \text{ and } (x + 1)! = x!(x + 1).$$

Formally, we have:

$$\ell(0) = 1,$$
$$\ell(t + 1) = g(t, \ell(t)),$$

where $g(x_1, x_2) = s(x_1) \cdot x_2$. The function $g$ is primitive recursive because $g(x_1, x_2) = s(u_1^2(x_1, x_2)) \cdot u_2^2(x_1, x_2)$ and multiplication is already known to be primitive recursive.
Example

The exponentiation function $x^y$:
The recursion equations are

\[
\begin{align*}
x^0 &= 1, \\
x^{y+1} &= x^y \cdot x
\end{align*}
\]

Note that for the “special case” $0^0$ we have $0^0 = 1$. 
Example

The *predecessor function* defined as

\[
p(x) = \begin{cases} 
  x - 1 & \text{if } x \neq 0, \\
  0 & \text{if } x = 0,
\end{cases}
\]

is primitive recursive because we have

\[
\begin{align*}
p(0) &= 0, \\
p(t + 1) &= t.
\end{align*}
\]
The function \( x \div y \) defined as

\[
x \div y = \begin{cases} 
  x - y & \text{if } x \geq y \\
  0 & \text{if } x < y 
\end{cases}
\]

should not be confused with the partial function \( x - y \) which is undefined if \( x < y \). The function \( x \div y \) is a total function and is defined by

\[
x \div 0 = 0,
\]

\[
x \div (t + 1) = p(x \div t).
\]

Note: the symbol \( \div \) is read “monus”.

Example

The function $|x - y|$ is primitive recursive because

$$|x - y| = (x \div y) + (y \div x).$$
Example

The function $\alpha(x)$, where

$$
\alpha(x) = \begin{cases} 
1 & \text{if } x = 0, \\
0 & \text{if } x \neq 0,
\end{cases}
$$

is primitive recursive because $\alpha(x) = 1 \div x$.

Alternatively, we can write the recursion equations:

$$
\begin{align*}
\alpha(0) & = 1, \\
\alpha(t + 1) & = 0.
\end{align*}
$$