Sect. 3: The URM

(a) Definition of the URM.
(b) Higher level programming concepts for URMs.
(c) URM computable functions.
(d) Configurations of URMs.
(e) The undecidability of the halting problem.
(a) Definition of the URM

A **model of computation** consists of a set of partial functions together with methods, which describe, how to compute those functions.

One aims at models of computation which are **complete**, which means that they compute all intuitively computable functions.

A model of computation is **Turing-complete**, if it is complete in that sense.

Since “intuitively computable” is not a mathematical notion, Turing-completeness is not a mathematical notion and cannot be proved mathematically.
Turing Completeness

Sometimes by “Turing complete” it is meant that the model computes all functions computable on a Turing machine – then one obtains a mathematical definition.
Models of Computation

Aim: an as simple model of computation as possible: constructs used minimised, while still being able to represent all intuitively computable functions.

Makes it easier to show for other models of computation, that the first model can be interpreted in it.

In mathematics one always aims at giving as simple and short definitions as possible, and to avoid unnecessary additions.

Models of computation are mainly used for showing that something is non-computable rather than for showing that something is computable in this model.
The URM

The URM (the unlimited register machine) is one model of computation.

- Particularly easy.
- It defines a virtual machine, i.e. a description how a computer would execute its program.
- The URM is not intended for actual implementation (although it can easily be implemented).
- It is not intended to be a realistic model of a computer.
- It is intended as a mathematical model, which is then investigated mathematically.
- Not many programs are actually written in it – one shows that in principal there is a way of writing a certain program in this language.
The URM

- Rather difficult to write actual programs for the URM.
- Low level programming language (only goto)
- URM idealised machine – no bounds on the amount of memory or execution time
  however all values will be finite.
- Many variants of URM – this URM will be particularly easy.
Description of the URM

- The URM consists of
  - infinitely many registers $R_i$
    - can store arbitrarily big natural number;
  - a finite sequence of instructions $I_0, I_1, I_2, \ldots I_n$;
  - and a program counter PC.
    - stores a natural number.
    - If PC contains a number $0 \leq i \leq n$, it points to instruction $I_i$.
    - If content of PC is outside this range, the program stops.
John Shepherdson (Bristol) (2nd from the right)

Developed together with Sturgis the URM.
The URM

\[ R_0 \quad R_1 \quad R_2 \quad R_3 \quad R_4 \quad R_5 \quad R_6 \quad R_7 \quad R_8 \quad \cdots \]

\[ I_0 \quad I_1 \quad I_2 \quad \cdots \quad I_n \]

PC

Execute Instruction
The URM

Program has terminated
URM Instructions

- 3 kinds of URM instructions.
- The successor instruction $\text{succ}(k)$, where $k \in \mathbb{N}$.
- Execution:
  - Add 1 to register $R_k$.
  - Increment PC by 1.
  - Execute next instruction or terminate.
- A more readable notation is
  $$R_k := R_k + 1$$
The **predecessor instruction**

\[ \text{pred}(k) \]

where \( k \in \mathbb{N} \).

**Execution:**
- If \( R_k \) contains value \( > 0 \), decrease the content by 1.
- If \( R_k \) contains value 0, leave it as it is.
- In all cases increment PC by 1.

A more readable notation is

\[ R_k := R_k - 1 \]
\[ x \cdot y \]

Here

\[ x \cdot y := \max\{x - y, 0\}, \]

i.e.

\[ x \cdot y = \begin{cases} x - y & \text{if } y \leq x, \\ 0 & \text{otherwise.} \end{cases} \]
The **conditional jump instruction**

\[ \text{ifzero}(k, q) \]

where \( k, q \in \mathbb{N} \). Execution:

- If \( R_k \) contains 0, PC is set to \( q \)
  - next instruction is \( I_q \), if \( I_q \) exists.
  - If no instruction \( I_q \) exists, the program stops.

- If \( R_k \) does not contain 0, the PC incremented by 1.
  - Program continues executing the next instruction, or terminates, if there is no next instruction.

A more readable notation is

\[ \text{if } R_k = 0 \text{ then goto } q \]
Finiteness

A URM program refers only to finitely many registers, namely those referenced explicitly in one of the instructions.
Example of a URM Program

The following is an example of a URM-program:

\[ I_0 = \text{ifzero}(0, 3) \]
\[ I_1 = \text{pred}(0) \]
\[ I_2 = \text{ifzero}(1, 0) \]
Example

\[ I_0 = \text{ifzero}(0, 3) \quad I_1 = \text{pred}(0) \quad I_2 = \text{ifzero}(1, 0) \]
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If we run this program with initial values $R_0 = 2$, $R_1 = 0$, we obtain the following trace of a run of this program:
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URM Stops
Behaviour of the Example

\[ I_0 = \text{ifzero}(0, 3) \]
\[ I_1 = \text{pred}(0) \]
\[ I_2 = \text{ifzero}(1, 0) \]

Assume \( R_1 \) is initially zero.

Then \( R_1 \) will never be changed by the program, so it will remain 0 for ever.

So in instruction 2 the URM will always jump to instr. 0.

Then the program will as long as \( R_0 \neq 0 \) decrease \( R_0 \) by 1.

The result is that \( R_0 \) is set to 0.

This corresponds to the instruction from a higher level language \( R_0 := 0 \).
URM-Computable Functions

For every $U$-program we define the function defined by it.

In fact there are many function which are defined by the same $U$-program:

- A unary function $U^{(1)}$, which stores its argument in $R_0$, sets all other registers to 0, then starts to run the $U$.
  - If the $U$ stops, the result is read off from $R_0$.
  - Otherwise the result is undefined.

- A binary function $U^{(2)}$, which stores its two arguments in $R_0$ and $R_1$, then operates as $U^{(1)}$.

And so on. In general we obtain a $k$-ary partial function $U^{(k)}$ for every $k \geq 1$. 
Definition \( U^{(k)} \)

- Let \( U = I_0, \ldots, I_n \) be a URM program, \( k \in \mathbb{N}, k \geq 1 \).
- We define a function

\[
U^{(k)} : \mathbb{N}^k \xrightarrow{\sim} \mathbb{N}
\]

by determining how it is computed:

- Assume we want to compute \( U^{(k)}(a_0, \ldots, a_{k-1}) \).
- **Initialisation:**
  - PC set to 0.
  - \( a_0, \ldots, a_{k-1} \) stored in registers \( R_0, \ldots, R_{k-1} \), respectively.
  - All other registers set to 0. (Sufficient to do this for registers referenced in the program).
**URM-Computable Functions**

- **Iteration:**
  As long as the PC points to an instruction, execute it. Continue with the next instruction as given by the PC.

- **Output:**
  - If PC value $> n$, the program stops.
  - The function returns the value in $R_0$.
  - So if $R_0$ contains $b$ then
    \[
    U^{(k)}(a_0, \ldots, a_{k-1}) \simeq b.
    \]
  - If the program never stops,
    \[
    U^{(k)}(a_0, \ldots, a_{k-1}) \uparrow.
    \]
URM-Computable Functions

$f : \mathbb{N}^k \sim \mathbb{N}$ is URM-computable, if $f = U^{(k)}$ for some $k \in \mathbb{N}$ and some URM program $U$. 
Change of Notation

- Until the academic year 2004/05, $P$ was used instead of $U$ to denote URM programs.
- $P$ will be used for Turing machines.
- In order to distinguish URM-programs and Turing machine programs, we write here $U$ instead of $P$.
- Please take this into account when looking at exams and slides from 2004/05 and before.
Example

Consider the example of a URM-program treated before:

$I_0 = \text{ifzero}(0, 3)$
$I_1 = \text{pred}(0)$
$I_2 = \text{ifzero}(1, 0)$

We have seen that if $R_1$ is initially zero, then the program reduces $R_0$ to 0 and then stops.
Example

\[ I_0 = \text{ifzero}(0, 3) \]
\[ I_1 = \text{pred}(0) \]
\[ I_2 = \text{ifzero}(1, 0) \]

A computation of \( U^{(1)}(k) \) is as follows:

- We set \( R_0 \) to \( k \), all other registers to 0.
- Then the URM program is executed, starting with instruction \( I_0 \).
- This program terminates, with \( R_0 \) containing 0.
- The value returned is the content of \( R_0 \), i.e. 0.
- Therefore \( U^{(1)}(k) \approx 0 \).
Example

\[ I_0 = \text{ifzero}(0, 3) \]
\[ I_1 = \text{pred}(0) \]
\[ I_2 = \text{ifzero}(1, 0) \]

- In order to compute \( U^{(2)}(k, l) \) we have to do the same, but set initially \( R_0 \) to \( k \), \( R_1 \) to \( l \).

- For \( l = 0 \) we obtain the same run of the URM program as before.
  - Therefore \( U^{(2)}(k, 0) \approx 0 \).

- What is \( U^{(2)}(k, l) \) for \( l > 0 \)?
Partial Computable Functions

For a **partial** function $f$ to be computable we need only:

- If $f(a) \downarrow$, then after finite amount of time we can determine this property, and the value of $f(a)$.

- If $f(a) \uparrow$, we will wait infinitely long for an answer, so we never determine that $f(a) \uparrow$.

**Turing halting problem** is the question: “Is $f(a) \downarrow$?”.

Turing halting problem is **undecidable**.

If we want to have always an answer, we need to refer to **total computable functions**.
Partial Computable Functions

In order to describe the total computable functions, we need to introduce the partial computable functions first.

There is no program language s.t.

- it is decidable whether a string is a program,
- and the program language describes all total computable functions.

- This is essentially a consequence of the undecidability of the Turing Halting Problem.
Example of URM-Comp. Function

\[ f : \mathbb{N}^2 \xrightarrow{\sim} \mathbb{N}, \ f(x, y) \sim x + y \] is URM computable. We derive a URM-program for it in several steps.

**Step 1:**
Initially \( R_0 \) contains \( x \), \( R_1 \) contains \( y \), and the other registers contain 0.

Program should then terminate with \( R_0 \) containing \( f(x, y) \), i.e. \( x + y \).

A higher level program is as follows:

\( R_0 := R_0 + R_1 \)
Example of URM-Comp. Function

\[ f : \mathbb{N}^2 \rightarrow \mathbb{N}, \; f(x, y) \sim x + y \]

**Step 2:**
Only successor and predecessor available, replace the program by the following:

\[
\text{while } R_1 \neq 0 \text{ do } \{ R_0 := R_0 + 1 \\
R_1 := R_1 \div 1 \} 
\]

- This increases \( R_0 \) by 1 as many times as the value contained in \( R_1 \).
- This means that the content of \( R_1 \) is added to \( R_0 \).
- Note that at the end of the run, \( R_1 \) contains 0. But this is no problem since the at the end we only read off the result from \( R_0 \), and ignore \( R_1 \).
Example of URM-Comp. Function

\[ f : \mathbb{N}^2 \sim \mathbb{N}, \quad f(x, y) \sim x + y \]

**Step 3:**
Replace while-loop by a goto:

LabelBegin:  if \( R_0 = 0 \) then goto LabelEnd;
\[ R_0 := R_0 + 1; \]
\[ R_1 := R_1 \div 1; \]
goto LabelBegin;

LabelEnd:
Example of URM-Comp. Function

\[ f : \mathbb{N}^2 \rightsquigarrow \mathbb{N}, \quad f(x, y) \approx x + y \]

**Step 4:**
Replace last goto by a conditional goto, depending on \( R_2 = 0 \).
\( R_2 \) is initially 0 and never modified, therefore this jump will always be carried out.

LabelBegin: if \( R_0 = 0 \) then goto LabelEnd;
\[ R_0 := R_0 + 1; \]
\[ R_1 := R_1 - 1; \]
if \( R_2 = 0 \) then goto LabelBegin;

LabelEnd:
Example of URM-Comp. Function

\[ f : \mathbb{N}^2 \sim \mathbb{N}, f(x, y) \simeq x + y \]

**Step 5:**
Translate the program into a URM program \( I_0, I_1, I_2, I_3 \):

\[
\begin{align*}
I_0 & = \text{ifzero}(0, 4) \\
I_1 & = \text{succ}(0) \\
I_2 & = \text{pred}(1) \\
I_3 & = \text{ifzero}(2, 0)
\end{align*}
\]
(b) High Level Progr. Constructs

In this Subsection we will introduce some higher level program constructs for URMs, and how to translate them back into the original URM language.

These constructs will be still be rather low level in terms of the theory of programming languages, but high enough in order to allow easily to introduce the programs needed in this module.
Convention Concerning Jump Addresses

- When inserting URM programs \( U \) as part of new URM programs, jump addresses will be adapted accordingly.

- E.g. in \( \text{pred}(0) \)
  \[ U \]
  \( \text{succ}(0) \)

  we add 1 to the jump addresses in the original version of \( U \).

- Furthermore, we assume that, if \( U \) terminates, it terminates with the PC containing the number of the first instruction following \( U \).

  Means that if we then insert \( U \), and a run of \( U \) terminates, the next instruction to be executed is the one following \( U \).
More Readable Statements

We use the more readable statements

\[
R_k := R_k + 1 \quad \text{for} \quad \text{succ}(k),
\]

\[
R_k := R_k - 1 \quad \text{for} \quad \text{pred}(k),
\]

\[
\text{if } R_k = 0 \text{ then goto } q \quad \text{for} \quad \text{ifzero}(k, q).
\]
Labelled URM programs

- We introduce labelled URM programs.
- It will be easier to translate them back into original URM programs.
- The label $\text{End}$ denotes the first instruction following a program.
- So instead of
  
  $I_0 = \text{if } R_0 = 0 \text{ then goto 3}$
  $I_1 = R_0 := R_0 - 1$
  $I_2 = \text{if } R_1 = 0 \text{ then goto 0}$

  we write

  $\text{LabelBegin: } I_0 = \text{if } R_0 = 0 \text{ then goto End}$
  $I_1 = R_0 := R_0 - 1$
  $I_2 = \text{if } R_1 = 0 \text{ then goto LabelBegin}$

  $\text{End:}$
Omitting $I_k =$

- We omit now "$I_k =$".
- Furthermore, labels don’t have to start with Label, so we can write Begin instead of LabelBegin.
- We obtain the following program:

  ```plaintext
  Begin : if $R_0 = 0$ then goto End
  
  $R_0 := R_0 - 1$

  if $R_1 = 0$ then goto Begin
  
  End :
  ```

- Since End : is always the first instruction following the program, we will omit the last line End :.
Replacing Registers by Variables

We write variable names instead of registers. So if \(x, y\) denote \(R_0, R_1\), respectively, we write instead of

\[
\begin{align*}
\text{Begin:} & \quad \text{if } R_0 = 0 \text{ then goto End} \\
& \quad R_0 := R_0 - 1 \\
& \quad \text{if } R_1 = 0 \text{ then goto Begin}
\end{align*}
\]

the following

\[
\begin{align*}
\text{Begin:} & \quad \text{if } x = 0 \text{ then goto End} \\
& \quad x := x - 1 \\
& \quad \text{if } y = 0 \text{ then goto Begin}
\end{align*}
\]
Goto

goto mylabel;
stands for the (labelled) URM statement
if aux0 = 0 then goto mylabel;

Here aux0 is a register (which we can keep fixed), which is initially zero and never modified in the URM program, so it contains always 0.
while \( x \neq 0 \) do 

\[
\langle Instructions \rangle
\]

stands for the following URM program:

LabelLoop: if \( x = 0 \) then goto End;

\[
\langle Instructions \rangle
\]

goto LabelLoop;
More Complex Statements

repeat{
    \langle Instructions \rangle
} until x = 0;

stands for the following URM program:

\langle Instructions \rangle;
while x ≠ 0 do {
    \langle Instructions \rangle;
}

Note that this results in doubling of \langle Instructions \rangle.

One can avoid this.

But the length of the resulting program is not a problem as long as we are not dealing with complexity theory.
More Complex Statements

\[ x := 0 \]

stands for the following program:

\[
\text{while } x \neq 0 \text{ do } \{ x := x - 1; \}; \]
More Complex Statements

\[ y := x; \]
stands for (if \( x, y \) denote different registers, \( aux \) is new):

\[ aux := 0 \]
while \( x \neq 0 \) do {
    \[ x := x \div 1; \]
    \[ aux := aux + 1; \]
};
\[ y := 0; \]
while \( aux \neq 0 \) do {
    aux := aux \div 1;
    \[ x := x + 1; \]
    \[ y := y + 1; \]
};

If \( x, y \) are the same register, \( y := x \) stands for the empty statement.
More Complex Statements

Assume $x$, $y$, $z$ denote different registers.

$x := y + z$; stands for the following program ($aux$ is an additional variable):

\[
x := y;
aux := z;
\text{while } aux \neq 0 \text{ do }
\begin{cases}
    aux := aux - 1; \\
x := x + 1;
\end{cases}
\]
More Complex Statements

Assume \(x, y, z\) denote different registers. Remember, that \(a \cdot b := \max\{0, a - b\}\).

\[
x := y \cdot z;
\]

is computed as follows (\(aux\) is an additional variable):

\[
x := y;
\]
\[
aux := z;
\]
\[
\text{while } aux \neq 0 \text{ do } \{
\quad aux := aux \cdot 1;
\quad x := x \cdot 1;
\}\]
More Complex Statements

Assume $x$, $y$ denote different registers.

while $x \neq y$ do {
    \langle Statements \rangle;

stands for ($aux$, $aux_i$ denote new registers):

$aux_0 := x \div y$;
$aux_1 := y \div x$;
$aux := aux_0 + aux_1$;

while $aux \neq 0$ do {
    \langle Statements \rangle
    $aux_0 := x \div y$;
    $aux_1 := y \div x$;
    $aux := aux_0 + aux_1$;
};
We introduce some constructions for introducing URM-computable functions.

We will later introduce the set of partial recursive functions as the least set of functions closed under these constructions.

Then by the fact that the URM-computable functions are closed under these operations it follows that all partial recursive functions are URM-computable.

We introduce first names for all functions constructed this way.
Notations for Partial Functions

**Definition 3.1**

(a) Define the **zero function** $\text{zero} : \mathbb{N} \rightarrow \mathbb{N}$, $\text{zero}(x) = 0$.

(b) Define the **successor function** $\text{succ} : \mathbb{N} \rightarrow \mathbb{N}$, $\text{succ}(x) = x + 1$.

(c) Define for $0 \leq i < n$ the **projection function** $\text{proj}_i^n : \mathbb{N}^n \rightarrow \mathbb{N}$, $\text{proj}_i^n(x_0, \ldots, x_{n-1}) = x_i$.

**Remark**

- Note that all total functions are as well partial, so we have for instance as well $\text{zero} : \mathbb{N} \rightsquigarrow \mathbb{N}$.
- $\text{proj}_0^1 : \mathbb{N} \rightarrow \mathbb{N}$ is the identity function: $\text{proj}_0^1(x) = x$. 
(d) Assume

\[ g : (B_0 \times \cdots \times B_{k-1}) \sim \to C \, , \]
\[ h_i : A_0 \times \cdots \times A_{n-1} \sim \to B_i \, . \quad i = 0, \ldots , k - 1 \]

Define

\[ f := g \circ (h_0, \ldots , h_{k-1}) : A_0 \times \cdots \times A_{n-1} \sim \to C \, : \]

\[ f(\vec{a}) := g(h_0(\vec{a}), \ldots , h_{k-1}(\vec{a})) \]

- In case of \( k = 1 \) we write \( g \circ h \) instead of \( g \circ (h) \).
- Furthermore as usual

\[ g_1 \circ g_2 \circ \cdots \circ g_n := g_1 \circ (g_2 \circ (\cdots \circ (g_{n-1} \circ g_n))) \, . \]
(e) Assume

\[
g : \mathbb{N}^k \rightarrow \mathbb{N}, \\
\]

\[
h : \mathbb{N}^{k+2} \rightarrow \mathbb{N}.
\]

Then we can define a function \( f : \mathbb{N}^{k+1} \rightarrow \mathbb{N} \) defined by \textbf{primitive recursion} from \( g \) and \( h \) as follows:

\[
f(\vec{n}, 0) : \simeq g(\vec{n}) \\
f(\vec{n}, m + 1) : \simeq h(\vec{n}, m, f(\vec{n}, m))
\]

We write \texttt{primrec}(g, h) for the function \( f \) just defined.

So \texttt{primrec}(g, h) : \mathbb{N}^{k+1} \rightarrow \mathbb{N}.

Notations for Partial Functions

In the special case \( k = 0 \), it doesn’t make sense to use \( g() \). Instead replace in this case \( g \) by some natural number. So the case \( k = 0 \) reads as follows:

Assume \( a \in \mathbb{N}, \ h : \mathbb{N}^2 \sim \mathbb{N} \).
Define

\[
\begin{align*}
f : \mathbb{N} &\sim \mathbb{N} \\
f(0) &\simeq a \\
f(m + 1) &\simeq h(m, f(m))
\end{align*}
\]

We write \( \text{primrec}(a, h) \) for \( f \), so \( \text{primrec}(a, h) : \mathbb{N} \sim \mathbb{N} \).
In Haskell we can define \texttt{primrec} as a higher-order function as follows:

\begin{verbatim}
data Nat = Z | S Nat
  deriving Show
\end{verbatim}

- - \texttt{primrec0} is the operator for primitive recursion
- - defining a 1-ary function \texttt{primrec0} \(f \ a :: \text{Nat} \to \text{Nat}\)
- - from \(f: \text{Nat} \to \text{Nat} \to \text{Nat}\) and \(a: \text{Nat}\)

\begin{verbatim}
primrec0 :: Nat \to (Nat \to Nat \to Nat) \to Nat \to Nat
primrec0 a g Z = a
primrec0 a g (S n) = g n (primrec0 a g n)
\end{verbatim}
primrec in Haskell (Cont.)

- - primrec1 is the operator for primitive recursion
- - defining a 2-ary function primrec1 \( f, g : \text{Nat} \rightarrow \text{Nat} \rightarrow \text{Nat} \)
  - - from \( f : \text{Nat} \rightarrow \text{Nat} \rightarrow \text{Nat} \rightarrow \text{Nat} \) and \( g : \text{Nat} \rightarrow \text{Nat} \rightarrow \text{Nat} \)

\[
\begin{align*}
\text{primrec1} & : (\text{Nat} \rightarrow \text{Nat}) \\
                  & \rightarrow (\text{Nat} \rightarrow \text{Nat} \rightarrow \text{Nat} \rightarrow \text{Nat}) \\
                  & \rightarrow \text{Nat} \rightarrow \text{Nat} \rightarrow \text{Nat} \\
\text{primrec1} \cdot g \cdot h \cdot n \cdot Z & = g \cdot n \\
\text{primrec1} \cdot g \cdot h \cdot n \cdot (\text{S} \cdot m) & = h \cdot n \cdot m \cdot (\text{primrec1} \cdot g \cdot h \cdot n \cdot m)
\end{align*}
\]
Addition can be defined using primitive recursion:
Let \( \text{add} : \mathbb{N}^2 \to \mathbb{N} \), \( \text{add}(x, y) := x + y \). We have

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

Therefore

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

where

\[
\begin{align*}
g : \mathbb{N} \to \mathbb{N}, & \quad g(x) := x \\
h : \mathbb{N}^3 \to \mathbb{N}, & \quad h(x, y, z) := z + 1
\end{align*}
\]

So \( \text{add} = \text{primrec}(g, h) \).
Addition ($\text{add}$)

$g : \mathbb{N} \rightarrow \mathbb{N} \ , \quad g(x) := x$ ,  
$h : \mathbb{N}^3 \rightarrow \mathbb{N} \ , \quad h(x, y, z) := z + 1$ ,  
$\text{add} := \text{primrec}(g, h)$

We have

$\text{add}(x, 0) = g(x) = x = x + 0$.  
$\text{add}(x, 1) = h(x, 0, \text{add}(x, 0)) = \text{add}(x, 0) + 1 = x + 1$.  
$\text{add}(x, 2) = h(x, 1, \text{add}(x, 1)) = \text{add}(x, 1) + 1 = (x + 1) + 1$.  
$\text{etc.}$
In Haskell we can define $\text{add}$ from primrec as follows:

$$\text{add} :: \text{Nat} \to \text{Nat} \to \text{Nat}$$

$$\text{add} = \text{primrec1} \ (\lambda n \to n) \ (\lambda n \ m \ k \to S \ k)$$
Examples for Primitive Recursion

Multiplication can be defined using primitive recursion:

Let \( \text{mult} : \mathbb{N}^2 \to \mathbb{N}, \text{mult}(x, y) := x \cdot y \). We have

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

Therefore

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

where

\[
\begin{align*}
g : \mathbb{N} &\to \mathbb{N} \ , \quad g(x) := 0 \\
h : \mathbb{N}^3 &\to \mathbb{N} \ , \quad h(x, y, z) := z + x
\end{align*}
\]

So \( \text{mult} = \text{primrec}(g, h) \).
Multiplication \((\text{mult})\)

\[
g : \mathbb{N} \to \mathbb{N} , \quad g(x) := 0 ,
\]

\[
h : \mathbb{N}^3 \to \mathbb{N} , \quad h(x, y, z) := z + x ,
\]

\text{mult} := \text{primrec}(g, h)

We have

\[
\text{mult}(x, 0) = g(x) = 0 = x \cdot 0 .
\]

\[
\text{mult}(x, 1) = h(x, 0, \text{mult}(x, 0)) = \text{mult}(x, 0) + x = 0 + x = x .
\]

\[
\text{mult}(x, 2) = h(x, 1, \text{mult}(x, 1)) = \text{mult}(x, 1) + x = (x \cdot 1) + x .
\]

etc.
Examples for Primitive Recursion

Let \( \text{pred} : \mathbb{N} \rightarrow \mathbb{N} \), \( \text{pred}(n) := n - 1 = \begin{cases} n - 1 & \text{if } n > 0, \\ 0 & \text{otherwise}. \end{cases} \)

\( \text{pred} \) can be defined using primitive recursion:

- \( \text{pred}(0) = 0 \)
- \( \text{pred}(x + 1) = x \)

Therefore

- \( \text{pred}(0) = 0 \)
- \( \text{pred}(x + 1) = h(x, \text{pred}(x)) \)

where

- \( h : \mathbb{N}^2 \rightarrow \mathbb{N} \), \( h(x, y) := x \)

So \( \text{pred} = \text{primrec}(0, h) \).
$x \div y$ can be defined using primitive recursion:

Let $f(x, y) := x \div y$. We have

\[
\begin{align*}
f(x, 0) &= x \div 0 = x \\
f(x, y + 1) &= x \div (y + 1) = (x \div y) \div 1 \\
&= \text{pred}(x \div y) = \text{pred}(f(x, y))
\end{align*}
\]

Therefore

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

where

\[
\begin{align*}
g : \mathbb{N} &\to \mathbb{N} , \quad g(x) := x \\
h : \mathbb{N}^3 &\to \mathbb{N} , \quad h(x, y, z) := \text{pred}(z)
\end{align*}
\]

So $f = \text{primrec}(g, h)$. 
Remark

If $f = \text{primrec}(g, h)$, then

$$f(\vec{n}, m)^\uparrow \rightarrow \forall k \geq m. f(\vec{n}, k)^\uparrow$$

Proof:

We have

$$f(\vec{n}, m + 1) \simeq h(\vec{n}, m, f(\vec{n}, m))$$

All functions are strict.

So if $f(\vec{n}, m)^\uparrow$, then

$$f(\vec{n}, m + 1) \simeq h(\vec{n}, m, f(\vec{n}, m))^\uparrow$$

therefore

$$f(\vec{n}, m + 1)^\uparrow$$
Proof of Remark

Therefore we have

\[ f(\vec{n}, m) \uparrow \rightarrow f(\vec{n}, m + 1) \uparrow . \]

By induction it follows that \( f(\vec{n}, m) \uparrow \) implies

\[ \forall k \geq m. f(\vec{n}, k) \uparrow . \]
Example

Let

\[ h : \mathbb{N}^2 \sim \mathbb{N} , \quad h(n, m) \sim \begin{cases} 
  m \div 1 & \text{if } m > 0, \\
  \bot & \text{otherwise.}
\end{cases} \]

Let

\[ f : \mathbb{N} \sim \mathbb{N} , \quad f := \text{primrec}(1, h) , \]

i.e.

\[ f(0) \sim 1 , \quad f(n + 1) \sim h(n, f(n)) . \]

Then

\[ f(0) \sim 1 \]
\[ f(1) \sim h(0, f(0)) \sim h(0, 1) \sim 0 \]
\[ f(2) \sim h(1, f(1)) \sim h(1, 0) \uparrow \]
\[ \forall m \geq 2 . f(m) \uparrow \]
Primitive-Recursive Functions

The functions, which can be defined from zero, succ, \( \text{proj}_{i}^{k} \) by using composition (\( \circ \)) and primitive recursion (\( \text{primrec} \)) are called the \textbf{primitive recursive functions}.

The primitive-recursive functions will be studied more in detail in Sect. 5.

There we will see that they are powerful, but \textbf{not Turing-complete}.
Notations for Partial Functions

Let \( g : \mathbb{N}^{n+1} \xrightarrow{*} \mathbb{N} \).

We define \( \mu y. g(\vec{x}, y) \simeq 0 \):

\[
(\mu y. g(\vec{x}, y) \simeq 0) : \begin{cases}
\text{the least } y \in \mathbb{N} \text{ s.t. } \\
g(\vec{x}, y) \simeq 0 \\
\text{and for } 0 \leq y' < y \\
\text{there exists a } z' \neq 0 \\
\text{s.t. } g(\vec{x}, y') \simeq z' \\
\text{if such } y \\
\perp \text{ exists,} \\
\text{otherwise}
\end{cases}
\]
Now define $h : \mathbb{N}^n \xrightarrow{\sim} \mathbb{N}$,

$$h(\vec{x}) \equiv (\mu y. g(\vec{x}, y) \equiv 0)$$

We write $\mu(g)$ for this function $h$. 
Examples

Assume

\[ g(x, 0) \simeq 1 \]
\[ g(x, 1) \uparrow \]
\[ g(x, 2) \simeq 0 \]

Then

\[ (\mu y . g(x, y) \simeq 0) \uparrow \]

Assume instead

\[ g(x, 0) \simeq 1 \]
\[ g(x, 1) \simeq 5 \]
\[ g(x, 2) \simeq 0 \]

Then

\[ (\mu y . g(x, y) \simeq 0) \simeq 2 \]
Computation of $\mu(g)$

$\mu(g)(\vec{x}) \simeq \mu y. (g(\vec{x}, y) \simeq 0)$.

If $g$ is intuitively computable, we see that $h := \mu(g)$ is intuitively computable as follows:

- In order to compute $h(\vec{x})$ we first compute $g(\vec{x}, 0)$.
  - If this computation never terminates $g(\vec{x}, 0) \uparrow$ and $(\mu y. g(\vec{x}, y) \simeq 0) \uparrow$ as well.
  - If it terminates, and we have $g(\vec{x}, 0) \simeq 0$, we obtain $(\mu y. g(\vec{x}, y) \simeq 0) \simeq 0$.
- Otherwise, repeat the above with testing of $g(\vec{x}, 1) \simeq 0$.
  - If successful $(\mu y. g(\vec{x}, y) \simeq 0) \simeq 1$.
  - If unsuccessful repeat it with $2$, $3$, etc.
Computation of \( \mu(g) \)

Note that \( \mu(g)(\vec{x}) \uparrow \) in case there is a \( y \) s.t.

\[ g(\vec{x}, y) \uparrow \]

and for \( y' < y \) we have \( g(\vec{x}, y') \downarrow \) but \( g(\vec{x}, y') \simeq z \) for some \( z > 0 \).

This coincides with computation by the above mentioned intuitive computation:

In this case, the program will compute \( g(\vec{x}, 0), g(\vec{x}, 1), \ldots, g(\vec{x}, y - 1) \) and get as result that these values are \( \neq 0 \).

Then it will try to compute \( g(\vec{x}, y) \), and this computation never terminates.

So the value of this program is undefined, as is \( (\mu g)(\vec{x}) \).
Computation of $\mu(g)$

If we defined $\mu(g)(\vec{x})$ to be the least $z$ s.t.

$$g(\vec{x}, y) \simeq 0$$

independently of whether $g(\vec{x}, y') \downarrow$ for all $y' < y$, then we would obtain a non computable function.
Examples for $\mu$

Let $f : \mathbb{N}^2 \to \mathbb{N}, \ f(x, y) := x \div y$. Then

$$(\mu y.f(x,y) \simeq 0) \simeq x$$

so $\mu(f)(x) \simeq x$.

Let $f : \mathbb{N} \leadsto \mathbb{N}$,

$f(0) \uparrow$,

$f(n) := 0$ for $n > 0$.

Then

$$(\mu y.f(y) \simeq 0) \uparrow$$
Examples for $\mu$

Let $f : \mathbb{N} \rightarrow \mathbb{N}$,

$$f(n) := \begin{cases} 
1 & \text{if there exist primes } p, q < 2n + 4 \\
0 & \text{otherwise}
\end{cases} \text{ s.t. } 2n + 4 = p + q,$$

$\mu y. f(y) \simeq 0$ is the first $n$ s.t. there don’t exist primes $p, q$ s.t. $2n + 4 = p + q$.

Goldbach’s conjecture says that every even number $\geq 4$ is the sum of two primes. This is equivalent to $(\mu y. f(y) \simeq 0)^\uparrow$.

It is one of the most important open problems in mathematics to show (or refute) Goldbach’s conjecture. If we could decide whether a partial computing function is defined (which we can’t), we could decide Goldbach’s conjecture.
Partial Recursive Functions

- The functions, which can define in the same way as the primitive-recursive functions
  - i.e. being defined from zero, succ, proj \(_k^i\) by using composition (\(\circ\)) and primitive recursion (\(\text{primrec}\))
  - but by additionally closing them under \(\mu\), are called the \text{partial recursive functions}.

- The partial recursive functions will be studied more in detail in Sect. 6.
  - There we will see that the partial recursive functions form a Turing complete model of computation.
Next Step

- We are going to show that the URM computable functions are closed under the operations introduced above.

- In order to show this we need to be able to modify URM programs, so that they
  - have some other specified input and output registers,
  - and conserve the content of certain other registers.

- The following lemma shows that such a modification is possible.
Lemma and Definition 3.2

Assume $f : \mathbb{N}^k \xrightarrow{\sim} \mathbb{N}$ is URM-computable.
Assume $x_0, \ldots, x_{k-1}, y, z_0, \ldots, z_l$ are different variables.
Then one can define a URM program, which, computes $f(x_0, \ldots, x_{k-1})$ and stores the result in $y$ in the following sense:

- If $f(x_0, \ldots, x_{k-1}) \downarrow$, the program terminates at the first instruction following this program, and stores the result in $y$.
- If $f(x_0, \ldots, x_{k-1}) \uparrow$, the program never terminates.

The program can be defined so that it doesn’t change $x_0, \ldots, x_{k-1}, z_0, \ldots, z_l$.

For $\mathcal{U}$ we say it is a URM program which computes $y \xrightarrow{\sim} f(x_0, \ldots, x_{k-1})$ and preserves $z_0, \ldots, z_l$. 
Intuition behind Lem. 3.2

Lemma 3.2 means that if $f$ is URM-computable then we can define a URM-program in such a way that
- it takes the arguments from registers we have chosen,
- and stores the result in a register we have chosen,
- and does this in such a way that the content of the input registers and of some other registers we have chosen are not modified.
- This is possible as long as the input registers and the output register are all different.
Idea of the proof

- First copy the arguments in some other registers, so that the arguments are preserved.
- Then compute the function on those auxiliary registers and make sure that the computation doesn’t affect the registers to be preserved.
- Then move the result into the register chosen as output register.

Omit Proof.
Proof

Let $U$ be a URM program s.t. $U^{(k)} = f$.
Let $u_0, \ldots, u_{k-1}$ be registers different from the above.
By renumbering of registers and of jump addresses, we obtain a program $U'$, which computes the result of $f(u_0, \ldots, u_{k-1})$ in $u_0$
leaves the registers mentioned in the lemma unchanged, and which, if it terminates, terminates in the first instruction following $U'$.
The following is a program as intended:

\[
\begin{align*}
  u_0 &:= x_0; \\
  \ldots \\
  u_{k-1} &:= x_{k-1}; \\
  U' & \\
  y &:= u_0;
\end{align*}
\]
Lemma 3.3

(a) zero, succ and \( \text{proj}_i^n \) are URM-computable.

(b) If \( f : \mathbb{N}^n \rightsquigarrow \mathbb{N}, g_i : \mathbb{N}^k \rightsquigarrow \mathbb{N} \) are URM-computable, so is \( f \circ (g_0, \ldots, g_{n-1}) \).

(c) If \( g : \mathbb{N}^n \rightsquigarrow \mathbb{N} \), and \( h : \mathbb{N}^{n+2} \rightsquigarrow \mathbb{N} \) are URM-computable, so is the function \( f := \text{primrec}(g, h) \) defined by primitive recursion from \( g \) and \( h \).

(d) If \( g : \mathbb{N}^{n+1} \rightsquigarrow \mathbb{N} \) is URM-computable, so is \( \mu(g) \).
Remark

- The Lemma is very powerful:
  - It shows that many functions are URM-computable.
  - This shows that for instance the exponential function is URM computable.
    - This follows since addition, multiplication and exponentiation can be defined by primitive recursion from the basic functions.
  - Writing a URM program directly which computes the exponential function would be very difficult.

Omit Proof.
Proof of Lemma 3.3 (a)

Let $x_i$ denote register $R_i$.

Proof of (a)

- **zero** is computed by the following program:
  $$x_0 := 0.$$

- **succ** is computed by the following program:
  $$x_0 := x_0 + 1.$$

- **proj** is computed by the following program:
  $$x_0 := x_k.$$

  Especially, if $k = 0$ then $\text{proj}^n_k$ is the empty program
  (i.e. the program with no instructions this is since we defined $x_0 := x_0$ to be the empty program.)
Proof of Lemma 3.3 (b)

Assume $f : \mathbb{N}^n \sim \mathbb{N}$, $g_i : \mathbb{N}^k \sim \mathbb{N}$ are URM-computable. Show $f \circ (g_0, \ldots, g_{n-1})$ is computable.

A plan for the program is as follows:

- Input is stored in registers $x_0, \ldots, x_{k-1}$.
  Let $\bar{x} := x_0, \ldots, x_{k-1}$.
- First we compute $g_i(\bar{x})$ for $i = 0, \ldots, n - 1$, store result in registers $y_i$.
  By Lemma 3.2 we can do this in such a way that $x_0, \ldots, x_{k-1}$ and the previously computed values $g_i(\bar{x})$, which are stored in $y_j$ for $j < i$ are not destroyed.
- Then compute $f(y_0, \ldots, y_{n-1})$, and store result in $x_0$.
- Then $x_0$ contains $f(g_0(\bar{x}), \ldots, g_{n-1}(\bar{x}))$. 
Proof of Lemma 3.3 (b)

Let therefore $U_i$ be a URM program $(i = 0, \ldots, n - 1)$, which computes $y_i \simeq g_i(\vec{x})$ and preserves $y_j$ for $j \neq i$.

Let $V$ be a URM program, which computes $x_0 \simeq f(y_0, \ldots, y_{n-1})$. 
Proof of Lemma 3.3 (b)

Let $U'$ be defined as follows:

$U_0$

$\ldots$

$U_{n-1}$

$V$

We show $U'(k)(\bar{x}) \simeq (f \circ (g_0(\bar{x}), \ldots, g_{n-1}(\bar{x})))$.

Omit rest of proof.
Proof of Lemma 3.3 (b)

$U'$ is the program

$U_0$

$\ldots$

$U_{n-1}$

$V$

- **Case 1**: For one $i$ $g_i(\vec{x}) \uparrow$.
  The program will loop in program $U_i$ for the first such $i$.

- **Case 2**: For all $i$ $g_i(\vec{x}) \downarrow$.
  The program executes $U_i$, sets $y_i \simeq g_i(x_0, \ldots, x_{k-1})$ and reaches beginning of $V$. 
Proof of Lemma 3.3 (b)

$U'$ is the program

$U_0$

$\ldots$

$U_{n-1}$

$V$

**Case 2.1:** $f(g_0(\vec{x}), \ldots, g_{n-1}(\vec{x})) \uparrow$.

$V$ will loop, $U'^{(k)}(\vec{x}) \uparrow$, $f \circ (g_0, \ldots, g_{n-1})(\vec{x}) \uparrow$.

**Case 2.2:** Otherwise.

The program reaches the end of program $V$ and result in $x_0 \simeq f(g_0(\vec{x}), \ldots, g_{n-1}(\vec{x}))$.

So $U'^{(k)}(\vec{x}) \simeq (f \circ (g_0, \ldots, g_{n-1}))(\vec{x})$.
Proof of Lemma 3.3 (b)

In all cases

\[ U'(k) (\vec{x}) \simeq (f \circ (g_0, \ldots, g_{n-1}))(\vec{x}). \]
Proof of Lemma 3.3 (c)

Assume
\[ g : \mathbb{N}^n \rightarrow \mathbb{N}, \quad h : \mathbb{N}^{n+2} \rightarrow \mathbb{N} \]
are URM-computable.
Let
\[ f := \text{primrec}(g, h). \]

Show \( f \) is URM-computable.
Defining equations for \( f \) are as follows
(let \( \vec{n} := n_0, \ldots, n_{n-1} \)):

- \( f(\vec{n}, 0) \simeq g(\vec{n}) \),
- \( f(\vec{n}, k + 1) \simeq h(\vec{n}, k, f(\vec{n}, k)) \).
Proof of Lemma 3.3 (c)

Computation of $f(\vec{n}, l)$ for $l > 0$ is as follows:

- Compute $f(\vec{n}, 0)$ as $g(\vec{n})$.
- Compute $f(\vec{n}, 1)$ as $h(\vec{n}, 0, f(\vec{n}, 0))$, using the previous result.
- Compute $f(\vec{n}, 2)$ as $h(\vec{n}, 1, f(\vec{n}, 1))$, using the previous result.
- \ldots
- Compute $f(\vec{n}, l)$ as $h(\vec{n}, l - 1, f(\vec{n}, l - 1))$, using the previous result.
Proof of Lemma 3.3 (c)

Plan for the program:

- Let $\vec{x} := x_0, \ldots, x_{n-1}$.
- Let $y, z, u$ be new registers.
- Compute $f(\vec{x}, y)$ for $y = 0, 1, 2, \ldots, x_n$, and store result in $z$.
- Initially we have $y = 0$ (holds for all registers except $x_0, \ldots, x_n$ initially).

We compute $z \simeq g(\vec{x}) \ (\simeq f(\vec{x}, 0))$.
Then $y = 0, z \simeq f(\vec{x}, 0)$. 
Proof of Lemma 3.3 (c)

In step from \( y \) to \( y + 1 \):
- Assume that we have \( z \simeq f(\vec{x}, y) \).
- We want that after increasing \( y \) by 1 the loop invariant \( z \simeq f(\vec{x}, y) \) still holds.

Obtained as follows
- Compute \( u \simeq h(\vec{x}, y, z) \)
  \( (\simeq h(\vec{x}, y, f(\vec{x}, y)) \simeq f(\vec{x}, y + 1)) \).
- Execute \( z := u \simeq f(\vec{x}, y + 1) \).
- Execute \( y := y + 1 \).
- At the end, \( z \simeq f(\vec{x}, y) \) for the new value of \( y \).

Repeat this until \( y = x_n \).

Once \( y \) has reached \( x_n \), \( z \) contains \( f(\vec{x}, y) \simeq f(\vec{x}, x_n) \).

Execute \( x_0 := z \).
Proof of Lemma 3.3 (c)

Let

- \( U \) be a URM program, which computes \( z \simeq g(\vec{x}) \) and preserves \( y \) (by definition 3.2, it doesn’t modify the arguments \( \vec{x} \) of \( g \));

- \( V \) be a program, which computes \( u \simeq h(\vec{x}, y, z) \). (by definition 3.2, it doesn’t change \( \vec{x}, y, z \).)
Proof of Lemma 3.3 (c)

Let $U'$ be as follows:

\[
\begin{align*}
U & \quad \text{Compute } z \simeq g(\vec{x})(\simeq f(\vec{x}, 0)) \\
\text{while } x_n \neq y & \text{ do } \\
V & \quad \text{Compute } u \simeq h(\vec{x}, y, z) \\
& \quad \text{will be } \simeq h(\vec{x}, y, f(\vec{x}, y)) \simeq f(\vec{x}, y + 1) \\
z & := u; \\
y & := y + 1; \\
x_0 & := z;
\end{align*}
\]
Proof of Lemma 3.3 (c)

Correctness of this program:

- When $U$ has terminated, we have $y = 0$ and $z \simeq g(\vec{x}) \simeq f(\vec{x}, y)$.

- After each iteration of the while loop, we have $y := y' + 1$ and $z \simeq h(\vec{x}, y', z')$.
  ($y'$, $z'$ are the previous values of $y$, $z$, respectively.)

- Therefore we have $z \simeq f(\vec{x}, y)$.

- The loop terminates, when $y$ has reached $x_n$. Then $z$ contains $f(\vec{x}, y)$.
  This is stored in $x_0$. 
Proof of Lemma 3.3 (c)

If $U$ loops for ever, or in one of the iterations $V$ loops for ever, then:

- $U'$ loops, $U''^{(n+1)}(\vec{x}, x_n) \uparrow$.
- $f(\vec{x}, k) \uparrow$ for some $k < x_n$,
- subsequently $f(\vec{x}, l) \uparrow$ for all $l > k$.
- Especially, $f(\vec{x}, x_n) \uparrow$.
- Therefore $f(\vec{x}, x_n) \simeq U''^{(n+1)}(\vec{x}, x_n)$.
Proof of Lemma 3.3 (d)

Assume

\[ g : \mathbb{N}^{n+1} \rightarrow \mathbb{N} \]

is URM-computable. Show

\[ \mu(g) \]

is URM-computable as well. Note \( \mu(g)(x_0, \ldots, x_{k-1}) \) is the minimal \( z \) s.t.

\[ g(x_0, \ldots, x_{k-1}, z) \simeq 0 \ . \]

Let \( \vec{x} := x_0, \ldots, x_{k-1} \) and let \( y, z \) be registers different from \( \vec{x} \).
Proof of Lemma 3.3 (d)

Plan for the program:

- Compute \( g(\overline{x}, 0) \), \( g(\overline{x}, 1) \), . . . until we find a \( k \) s.t. \( g(\overline{x}, k) \simeq 0 \).
  Then return \( k \).

- This is carried out by executing

\[
z \simeq g(\overline{x}, y)
\]

and successively increasing \( y \) by 1 until we have \( z = 0 \).
Proof of Lemma 3.3 (d)

Let $U$ compute

$$z \simeq g(x_0, \ldots, x_{k-1}, y),$$

(and preserve the arguments $x_0, \ldots, x_{k-1}, y$.)
Let $V$ be as follows:

```plaintext
repeat{
    U
    $y := y + 1$;
} until ($z = 0$);
$y := y - 1$;
$x_0 := y$;
```

Omit rest of proof.
Proof of Lemma 3.3 (d)

V is \( \text{repeat}\{U; y := y + 1;\} \) until \((z = 0)\);
\[
y := y \cdot 1; x_0 := y;
\]

Initially \( y = 0 \).
After each iteration of the repeat loop, we have
\[
y := y' + 1, z \simeq g(x_0, \ldots, x_{k-1}, y')
\]

\((y' \text{ is the value of } y \text{ before this iteration}).\)
If the loop terminates, we have
\[
z \simeq 0 \quad y = y' + 1
\]

where \( y' \) is the first value, such that \( g(x_0, \ldots, x_{k-1}, y') \simeq 0 \).
Proof of Lemma 3.3 (d)

Finally \( y \) is decreased by one.

Then \( y \) is the least \( y \) s.t.

\[
g(x_0, \ldots, x_{k-1}, y) \simeq 0.
\]

\( x_0 \) is then set to that value.
(d) Configurations of URMs

We will later simulate URMs by Turing machines.

For this we need to describe the state of a URM finitely.

**Definition 3.4**

The configuration of an intermediate state of a URM is given by

\[ \pi(\text{PC}, \langle R_0, \ldots, R_{N-1} \rangle) \]

where

- \( N \) is minimal s.t. \( R_n \) contains zero for \( n \geq N \),
- \( \text{PC}, R_i \) more precisely denote the content of the PC and register \( R_i \) respectively.
Configurations

Note that during the execution of a URM program starting in a state where initially only finitely many registers are non-zero, at any time only finitely many registers are non zero.

Therefore, a configuration exists and describes completely the state of a URM.

Especially, this holds during a run computing $U^{(n)}(a_0, \ldots, a_{n-1})$. 

\[ U^{(n)}(a_0, \ldots, a_{n-1}) \]
Undecidability of the Halting Problem first proved 1936 by Alan Turing.

We present this in context of URMs.

In this Section, we will identify computable with URM-computable.

This will later be justified by the Church-Turing thesis.
History of Computability Theory

Alan Mathison Turing (1912 – 1954)
Introduced the Turing machine.
Proved the undecidability of the Turing-Halting problem.
Definition 3.5

(a) A problem is an $n$-ary predicate $M(\vec{x})$ of natural numbers, i.e. a property of $n$-tuples of natural numbers.

(b) A problem (or predicate) $M$ is **decidable**, if the characteristic function $\chi_M$ of $M$ is computable.
Characteristic function

Reminder:

\[ \chi_M(\vec{x}) := \begin{cases} 
1 & \text{if } M(\vec{x}) \text{ holds}, \\
0 & \text{otherwise} 
\end{cases} \]

If we treat true as 1 and false as 0, then the characteristic function is nothing but the Boolean valued function which decides whether \( M(\vec{x}) \) holds or not:

\[ \chi_M(\vec{x}) = \begin{cases} 
\text{true} & \text{if } M(\vec{x}) \text{ holds}, \\
\text{false} & \text{otherwise} 
\end{cases} \]
Example of Decidable Problems

The binary predicate

\[
\text{Multiple}(x, y) :\iff x \text{ is a multiple of } y
\]

is a predicate and therefore a problem.

\(\chi_{\text{Multiple}}(x, y)\) decides, whether \(\text{Multiple}(x, y)\) holds (then it returns 1 for yes), or not:

\[
\chi_{\text{Multiple}}(x, y) = \begin{cases} 
1 & \text{if } x \text{ is a multiple of } y, \\
0 & \text{if } x \text{ is not a multiple of } y.
\end{cases}
\]

\(\chi_{\text{Multiple}}\) is intuitively computable, therefore \(\text{Multiple}\) is decidable.
URM programs

- URM-programs can be written as a string of ASCII-symbols.

⇒ URM programs can be represented as elements of $A^*$, where $A = \text{set of ASCII-symbols}$. Of course more efficient encoding exist.

⇒ URM programs can be encoded as natural numbers. Let for a URM program $U$, $\text{encode}(U) \in \mathbb{N}$ be its code.

It is intuitively decidable, whether a string of ASCII symbols is a URM-program. One can show that this can be decided by a URM.

⇒ It is intuitively decidable, whether $n = \text{encode}(U)$ for a URM-program $U$. 

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Assume $e \in \mathbb{N}$. We define a partial function $\{e\}' : \mathbb{N} \leadsto \mathbb{N}$, by

$$\{e\}'(n) \simeq \begin{cases} m & \text{if } e = \text{encode}(U) \text{ for some URM } U \\ \text{and } U^{(1)}(n) \simeq m, \\ \bot & \text{otherwise.} \end{cases}$$

So if $e = \text{encode}(U)$, $\{e\}' = U^{(1)}$.

Roughly speaking, $\{e\}'$ is the function computed by the $e$th URM.

So for every computable (more precisely URM-computable) function $f : \mathbb{N} \leadsto \mathbb{N}$ there exists an $e$ s.t. $f = \{e\}'$. 
The notation $\{e\}'$ is due to Stephen Kleene.  

$\{\}'$ are called **Kleene-Brackets**.  

We will introduce them later more precisely in the context of Turing Machines.  

There we write $\{e\}^n$ for the corresponding notation.  

We write here $\{e\}'$ in order to distinguish this notation from $\{e\}^n$. 
Stephen Cole Kleene

Probably the most influential computability theorist up to now. Introduced the partial recursive functions.
The Halting Problem

Definition 3.6

The **Halting Problem** is the following binary predicate:

\[
\text{Halt}(e, n) :\Leftrightarrow \{e\}'(n)\downarrow
\]

We will show that Halt is undecidable.
Example

Let \( e = \text{encode}(U) \), where \( U \) is the URM program \( U \)

\[ I_0 = \text{ifzero}(0, 0) \]

If input is \( > 0 \), the program terminates immediately, and \( R_0 \) remains unchanged, so

\[ \{e\}'(k) \simeq U^{(1)}(k) \simeq k \]

for \( k > 0 \).

If input is \( = 0 \), the program loops for ever.

Therefore

\[ \{e\}'(0) \simeq U^{(1)}(0) \uparrow \]

Therefore \( \text{Halt}(e, k) \) holds for \( k > 0 \) and does not hold for \( k = 0 \).
Remark

Below we will see: $\text{Halt}$ is undecideable.

However, the following function $\text{WeakHalt}$ is computable:

$$\text{WeakHalt}(e, n) : \sim \begin{cases} 1 & \text{if } \{e\}'(n) \downarrow \\ \perp & \text{otherwise} \end{cases}$$

Computed as follows:
First check whether $e = \text{encode}(U)$ for some URM program $U$.
If not, enter an infinite loop.
Otherwise, simulate $U$ with input $n$.
If simulation stops, output 1, otherwise the program loops for ever.
Question

What is $\text{WeakHalt}(e, n)$, where $e$ is a code for the URM program

$$I_0 = \text{ifzero}(0, 0)$$
Theorem 3.7

Theorem 3.7 The halting problem is undecidable. Proof:

Assume the Halting problem is decidable i.e. assume that we can decide using a URM whether \( \{e\}'(n) \downarrow \) holds.

We will define below a computable function \( f : \mathbb{N} \rightarrow \mathbb{N} \), s.t. \( f \neq \{e\}' \).

Therefore \( f \) cannot be computed by the URM with code \( e \) for any \( e \), i.e. \( f \) is noncomputable.

Therefore we obtain a contradiction.
Proof of Theorem 3.7

We argue similarly as in the $\mathbb{N} \not\approx \mathcal{P}(\mathbb{N})$

- We define $f(e)$ in such a way that $f = \{e\}'$ is violated by having $f(e) \not\approx \{e\}'(e)$.

- If $\{e\}'(e) \downarrow$, then we let $f(e) \uparrow$.

- If $\{e\}'(e) \uparrow$, we let $f(e) \downarrow$, e.g. by defining $f(e) \simeq 0$ (any other defined result would be appropriate as well).

So we define

$$f(e) \simeq \begin{cases} 
\bot, & \text{if } \{e\}'(e) \downarrow \\
0, & \text{if } \{e\}'(e) \uparrow 
\end{cases}$$
Proof of Theorem 3.7

\[ f(e) \simeq \begin{cases} \bot, & \text{if } \{e\}'(e) \downarrow \\ 0, & \text{if } \{e\}'(e) \uparrow \end{cases} \]

We obtain \( f(e) \downarrow \iff \{e\}'(e) \uparrow \).  

Since \( \text{Halt} \) is decidable, \( f \) is computable (Exercise: show that \( f \) is computable by a URM program, assuming a URM-program for \( \text{Halt} \)).

Therefore \( f = \{e\}' \) for some \( e \).

But then by (*)&

\[ f(e) \downarrow \iff \{e\}'(e) \uparrow \iff f = \{e\}' \iff f(e) \uparrow \]

a contradiction.
Proof of Theorem 3.7

The complete proof on one slide is as follows:

- Assume \texttt{Halt} were decidable.
- Define

\[
f(e) \simeq \begin{cases} 
\bot, & \text{if } \{e\}'(e) \downarrow \\
0, & \text{if } \{e\}'(e) \uparrow 
\end{cases}
\]

- By \texttt{Halt} decidable, we obtain \( f \) is computable, so \( f = \{e\}' \) for some \( e \).
- But then

\[
f(e) \downarrow \iff f \{e\}'(e) \uparrow \iff f = \{e\}' \iff f(e) \uparrow
\]
Remark

The above proof can easily be adapted to any reasonable programming language, in which one can define all intuitively computable functions.

Such programming languages are called **Turing-complete** languages.

Babbage’s machine was, if one removes the restriction to finite memory, Turing-complete, since it had a conditional jump.

For standard Turing complete languages, the unsolvability of the Turing-halting problem means: it is not possible to write a program, which checks, whether a program on given input terminates.
Theorem 3.8: It is undecidable, whether a URM with empty input (i.e. initially all registers containing 0) holds.

Proof:

Let

\[ \text{Halt}'(e) \iff e \text{ is a code for a URM } U \text{ and } U \text{ started with registers initially } 0 \text{ terminates} \]

Assume Halt' were decidable.
Halting Problem with no Inputs

Then we can decide $\text{Halt}(e, n)$ as follows:

- Assume inputs $e, n$.
- If $e$ is not a code for a URM, we return 0.
- Otherwise, let $\text{encode}(U) = e$.

Define a URM program $V$ as follows:

- $V$ first increments $n$-times register 0 by 1.
- Then it executes the URM program $U$.

We have

- $V$, run with all registers initially set to 0, terminates iff $U$ run with initially $R_0 = n$ terminates
- iff $U^{(1)}(n) \downarrow$
- iff $\{e\}'(n) \downarrow$. 

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Halting Problem with no Inputs

V, run with all registers initially set to 0, terminates iff \(\{e\}'(n)\downarrow\).

- Let \(\text{encode}(V) = e'\). Then
  \[
  \text{Halt}'(e') \iff \text{Halt}(e, n)
  \]

Therefore using the decidability of \(\text{Halt}'\) we can decide \(\text{Halt}(e, n)\).

So we have decided \(\text{Halt}\), a contradiction.