The halting problem

Definition. A register machine H decides the Halting Problem if for all $e, a_1, \ldots, a_n \in \mathbb{N}$, starting H with

$$\mathrm{R}_0 = 0 \qquad \mathrm{R}_1 = e \qquad \mathrm{R}_2 = \ulcorner [a_1, \ldots, a_n] \urcorner$$

and all other registers zeroed, the computation of H always halts with R_0 containing 0 or 1; moreover when the computation halts, $\mathrm{R}_0 = 1$ if and only if

> the register machine program with index e eventually halts when started with $\mathrm{R}_0 = 0, \mathrm{R}_1 = a_1, \ldots, \mathrm{R}_n = a_n$ and all other registers zeroed.

Definition. A register machine H decides the Halting Problem if for all $e, a_1, \ldots, a_n \in \mathbb{N}$, starting H with

$$\mathrm{R}_0 = 0 \qquad \mathrm{R}_1 = e \qquad \mathrm{R}_2 = \ulcorner [a_1, \ldots, a_n] \urcorner$$

and all other registers zeroed, the computation of H always halts with R_0 containing 0 or 1; moreover when the computation halts, $\mathrm{R}_0 = 1$ if and only if

> the register machine program with index e eventually halts when started with $\mathrm{R}_0 = 0, \mathrm{R}_1 = a_1, \ldots, \mathrm{R}_n = a_n$ and all other registers zeroed.

Theorem. No such register machine H can exist.

Proof of the theorem

Assume we have a RM $\boldsymbol{H}$ that decides the Halting Problem and derive a contradiction, as follows:

- Let $\boldsymbol{H'}$ be obtained from $\boldsymbol{H}$ by replacing $\mathtt{START}\!\longrightarrow$ by

  $$\mathtt{START}\!\longrightarrow\boxed{\mathtt{Z} ::= \mathtt{R}_1}\longrightarrow\boxed{\begin{array}{c}\textit{push } \mathtt{Z} \\ \textit{to } \mathtt{R}_2\end{array}}\longrightarrow$$

  (where $\mathtt{Z}$ is a register not mentioned in $\boldsymbol{H}$'s program).

- Let $\boldsymbol{C}$ be obtained from $\boldsymbol{H'}$ by replacing each $\mathtt{HALT}$ (& each erroneous halt) by

  $$\begin{tikzcd} {} \arrow[r] & \mathtt{R}_{\mathbf{0}}^{-} \arrow[r, bend left] \arrow[d] & \mathtt{R}_{\mathbf{0}}^{+} \arrow[l, bend left] \\ & \mathtt{HALT} & \end{tikzcd}.$$

- Let $c \in \mathbb{N}$ be the index of $\boldsymbol{C}$'s program.

Proof of the theorem

Assume we have a RM $\boldsymbol{H}$ that decides the Halting Problem and derive a contradiction, as follows:

$$\boldsymbol{C} \text{ started with } \mathtt{R}_1 = \boldsymbol{c} \text{ eventually halts}$$

if & only if

$$\boldsymbol{H'} \text{ started with } \mathtt{R}_1 = \boldsymbol{c} \text{ halts with } \mathtt{R}_0 = \mathbf{0}$$

Proof of the theorem

Assume we have a RM H that decides the Halting Problem and derive a contradiction, as follows:

C started with $\mathtt{R}_1 = c$ eventually halts

if & only if

H' started with $\mathtt{R}_1 = c$ halts with $\mathtt{R}_0 = 0$

if & only if

H started with $\mathtt{R}_1 = c, \mathtt{R}_2 = \ulcorner [c] \urcorner$ halts with $\mathtt{R}_0 = 0$

Proof of the theorem

Assume we have a RM H that decides the Halting Problem and derive a contradiction, as follows:

C started with $\mathtt{R}_1 = c$ eventually halts

if & only if

H' started with $\mathtt{R}_1 = c$ halts with $\mathtt{R}_0 = 0$

if & only if

H started with $\mathtt{R}_1 = c, \mathtt{R}_2 = \ulcorner [c] \urcorner$ halts with $\mathtt{R}_0 = 0$

if & only if

$prog(c)$ started with $\mathtt{R}_1 = c$ does not halt

Proof of the theorem

Assume we have a RM H that decides the Halting Problem and derive a contradiction, as follows:

C started with $R_1 = c$ eventually halts

if & only if

H' started with $R_1 = c$ halts with $R_0 = 0$

if & only if

H started with $R_1 = c, R_2 = \ulcorner [c] \urcorner$ halts with $R_0 = 0$

if & only if

$prog(c)$ started with $R_1 = c$ does not halt

if & only if

C started with $R_1 = c$ does not halt

Proof of the theorem

Assume we have a RM H that decides the Halting Problem and derive a contradiction, as follows:

C started with $R_1 = c$ eventually halts

if & only if

H' started with $R_1 = c$ halts with $R_0 = 0$

if & only if

H started with $R_1 = c, R_2 = \ulcorner[c]\urcorner$ halts with $R_0 = 0$

if & only if

$prog(c)$ started with $R_1 = c$ does not halt

if & only if

C started with $R_1 = c$ does not halt

—contradiction!

Computable functions

Recall:

Definition. $f \in \mathbb{N}^n \rightharpoonup \mathbb{N}$ is (register machine) computable if there is a register machine M with at least $n+1$ registers $R_0, R_1, \ldots, R_n$ (and maybe more) such that for all $(x_1, \ldots, x_n) \in \mathbb{N}^n$ and all $y \in \mathbb{N}$,

> the computation of M starting with $R_0 = 0$, $R_1 = x_1, \ldots, R_n = x_n$ and all other registers set to 0, halts with $R_0 = y$

if and only if $f(x_1, \ldots, x_n) = y$.

Note that the same RM M could be used to compute a unary function ($n = 1$), or a binary function ($n = 2$), etc. From now on we will concentrate on the unary case. . .

Enumerating computable functions

For each $e \in \mathbb{N}$, let $\varphi_e \in \mathbb{N} \rightharpoonup \mathbb{N}$ be the unary partial function computed by the RM with program $prog(e)$. So for all $x, y \in \mathbb{N}$:

$\varphi_e(x) = y$ holds iff the computation of $prog(e)$ started with $R_0 = 0, R_1 = x$ and all other registers zeroed eventually halts with $R_0 = y$.

Thus

$$e \mapsto \varphi_e$$

defines an <u>onto</u> function from $\mathbb{N}$ to the collection of all computable partial functions from $\mathbb{N}$ to $\mathbb{N}$.

Enumerating computable functions

For each $e \in \mathbb{N}$, let $\varphi_e \in \mathbb{N} \rightharpoonup \mathbb{N}$ be the unary partial function computed by the RM with program $prog(e)$. So for all $x, y \in \mathbb{N}$:

> $\varphi_e(x) = y$ holds iff the computation of $prog(e)$ started with $R_0 = 0, R_1 = x$ and all other registers zeroed eventually halts with $R_0 = y$.

Thus

So this is countable

$$e \mapsto \varphi_e$$

defines an onto function from $\mathbb{N}$ to the collection of all computable partial functions from $\mathbb{N}$ to $\mathbb{N}$.

So $\mathbb{N} \rightharpoonup \mathbb{N}$ (uncountable, by Cantor) contains uncomputable functions

An uncomputable function

Let $f \in \mathbb{N} \rightharpoonup \mathbb{N}$ be the partial function with graph $\{(x, 0) \mid \varphi_x(x)\uparrow\}$.

Thus $f(x) = \begin{cases} 0 & \text{if } \varphi_x(x)\uparrow \\ \textit{undefined} & \text{if } \varphi_x(x)\downarrow \end{cases}$

An uncomputable function

Let $f \in \mathbb{N} \rightharpoonup \mathbb{N}$ be the partial function with graph $\{(x, 0) \mid \varphi_x(x)\uparrow\}$.

Thus $f(x) = \begin{cases} 0 & \text{if } \varphi_x(x)\uparrow \\ \mathit{undefined} & \text{if } \varphi_x(x)\downarrow \end{cases}$

f is not computable, because if it were, then $f = \varphi_e$ for some $e \in \mathbb{N}$ and hence

- if $\varphi_e(e)\uparrow$, then $f(e) = 0$ (by def. of f); so $\varphi_e(e) = 0$ (since $f = \varphi_e$), hence $\varphi_e(e)\downarrow$
- if $\varphi_e(e)\downarrow$, then $f(e)\downarrow$ (since $f = \varphi_e$); so $\varphi_e(e)\uparrow$ (by def. of f)

—contradiction! So f cannot be computable.

(Un)decidable sets of numbers

Given a subset $S \subseteq \mathbb{N}$, its characteristic function $\chi_S \in \mathbb{N} \to \mathbb{N}$ is given by: $\chi_S(x) \triangleq \begin{cases} \mathbf{1} & \text{if } x \in S \\ \mathbf{0} & \text{if } x \notin S. \end{cases}$

(Un)decidable sets of numbers

Definition. $S \subseteq \mathbb{N}$ is called (register machine) decidable if its characteristic function $\chi_S \in \mathbb{N} \to \mathbb{N}$ is a register machine computable function. Otherwise it is called undecidable.

So S is decidable iff there is a RM M with the property: for all $x \in \mathbb{N}$, M started with $R_0 = 0, R_1 = x$ and all other registers zeroed eventually halts with R_0 containing 1 or 0; and $R_0 = 1$ on halting iff $x \in S$.

(Un)decidable sets of numbers

Definition. $S \subseteq \mathbb{N}$ is called (register machine) decidable if its characteristic function $\chi_S \in \mathbb{N} \rightarrow \mathbb{N}$ is a register machine computable function. Otherwise it is called undecidable.

So S is decidable iff there is a RM M with the property: for all $x \in \mathbb{N}$, M started with $R_0 = 0, R_1 = x$ and all other registers zeroed eventually halts with R_0 containing 1 or 0; and $R_0 = 1$ on halting iff $x \in S$.

Basic strategy: to prove $S \subseteq \mathbb{N}$ undecidable, try to show that decidability of S would imply decidability of the Halting Problem.

For example. . .

Claim: $S_0 \triangleq \{e \mid \varphi_e(0)\downarrow\}$ is undecidable.

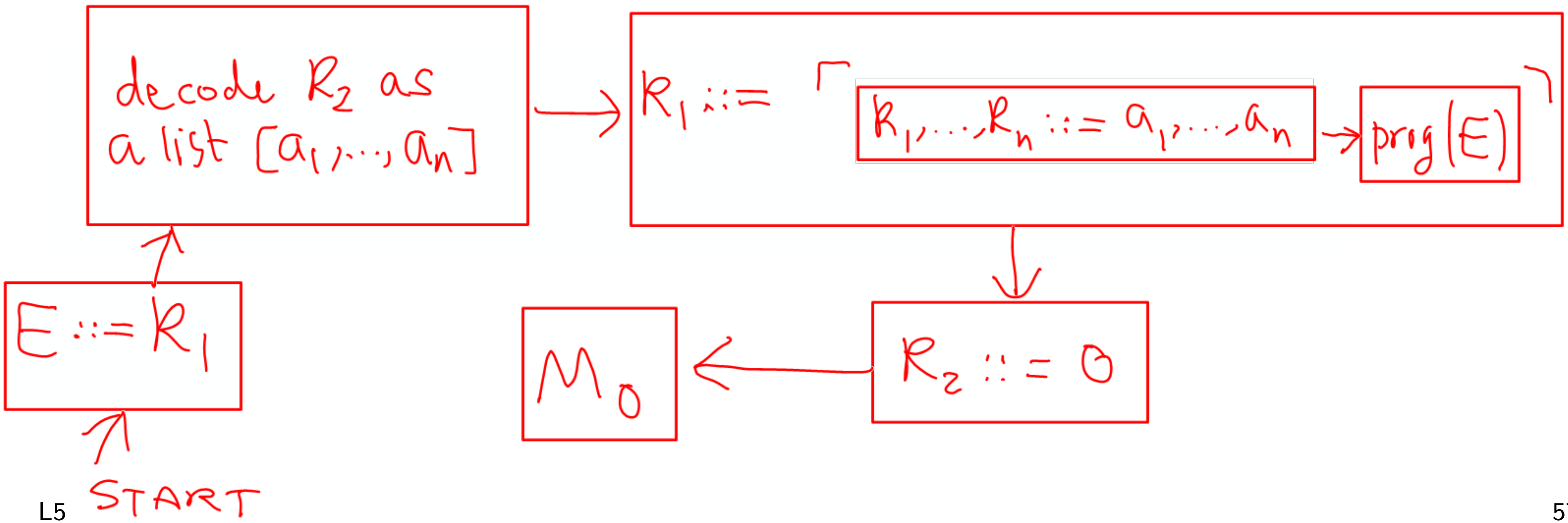
Proof (sketch): Suppose M_0 is a RM computing χ_{S_0}. From M_0's program (using the same techniques as for constructing a universal RM) we can construct a RM H to carry out:

$$
\begin{array}{l}
\mathit{let}\ e = \mathtt{R}_1\ \mathit{and}\ \ulcorner[a_1,\ldots,a_n]\urcorner = \mathtt{R}_2\ \mathit{in} \\
\qquad \mathtt{R}_1 ::= \ulcorner(\mathtt{R}_1 ::= a_1)\,;\cdots;(\mathtt{R}_n ::= a_n)\,;\mathit{prog}(e)\urcorner\,; \\
\mathtt{R}_2 ::= 0\,; \\
\mathit{run}\ M_0
\end{array}
$$

Claim: $S_0 \triangleq \{e \mid \varphi_e(0)\!\downarrow\}$ is undecidable.

Proof (sketch): Suppose M_0 is a RM computing χ_{S_0}. From M_0's program (using the same techniques as for constructing a universal RM) we can construct a RM H to carry out:

$$
\begin{aligned}
&\textit{let } e = \mathrm{R}_1 \textit{ and } \ulcorner[a_1,\ldots,a_n]\urcorner = \mathrm{R}_2 \textit{ in}\\
&\qquad \mathrm{R}_1 ::= \ulcorner(\mathrm{R}_1 ::= a_1)\,;\cdots;(\mathrm{R}_n ::= a_n)\,;\textit{prog}(e)\urcorner\,;\\
&\mathrm{R}_2 ::= 0\,;\\
&\textit{run } M_0
\end{aligned}
$$



Claim: $S_0 \triangleq \{e \mid \varphi_e(0){\downarrow}\}$ is undecidable.

Proof (sketch): Suppose M_0 is a RM computing χ_{S_0}. From M_0's program (using the same techniques as for constructing a universal RM) we can construct a RM H to carry out:

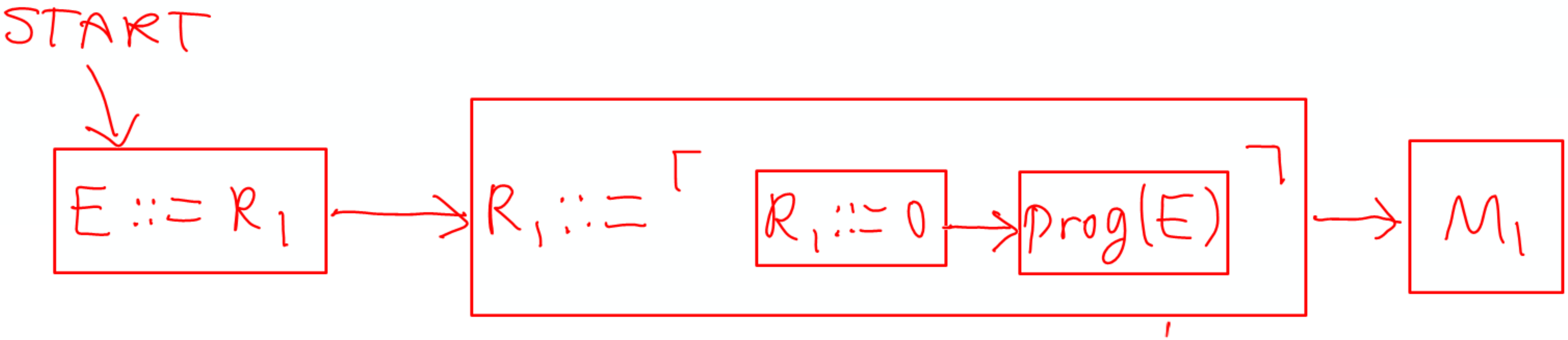
$$
\begin{array}{l}
\textit{let } e = \mathtt{R}_1 \textit{ and } \ulcorner[a_1, \ldots, a_n]\urcorner = \mathtt{R}_2 \textit{ in} \\
\qquad \mathtt{R}_1 ::= \ulcorner(\mathtt{R}_1 ::= a_1)\,;\cdots;(\mathtt{R}_n ::= a_n)\,;\textit{prog}(e)\urcorner\,; \\
\mathtt{R}_2 ::= 0\,; \\
\textit{run } M_0
\end{array}
$$

Then by assumption on M_0, H decides the Halting Problem—contradiction. So no such M_0 exists, i.e. χ_{S_0} is uncomputable, i.e. S_0 is undecidable.

Claim: $S_1 \triangleq \{e \mid \varphi_e \text{ a total function}\}$ is undecidable.

Proof (sketch): Suppose M_1 is a RM computing χ_{S_1}. From M_1's program we can construct a RM M_0 to carry out:

$$\begin{array}{l} let\ e = \mathrm{R}_1\ in\ \mathrm{R}_1 ::= \ulcorner \mathrm{R}_1 ::= 0\,; prog(e) \urcorner\,; \\ run\ M_1 \end{array}$$



Claim: $S_1 \triangleq \{e \mid \varphi_e \textit{ a total function}\}$ is undecidable.

Proof (sketch): Suppose M_1 is a RM computing χ_{S_1}. From M_1's program we can construct a RM M_0 to carry out:

$$\begin{array}{l} \textit{let } e = \mathtt{R}_1 \textit{ in } \mathtt{R}_1 ::= \ulcorner \mathtt{R}_1 ::= 0\,; \textit{prog}(e) \urcorner\,; \\ \textit{run } M_1 \end{array}$$

Then by assumption on M_1, M_0 decides membership of S_0 from previous example (i.e. computes χ_{S_0})—contradiction. So no such M_1 exists, i.e. χ_{S_1} is uncomputable, i.e. S_1 is undecidable.

Exercise 5 If $f : \mathbb{N} \to \mathbb{N}$ is a RM computable function, $S_0 \subseteq \mathbb{N}$ & $S_1 \subseteq \mathbb{N}$ satisfy

$$\boxed{\forall e \in \mathbb{N}.\ e \in S_0 \Leftrightarrow f(e) \in S_1}$$

then if S_1 is decidable, then so is S_0

Exercise 5 If $f : \mathbb{N} \to \mathbb{N}$ is a RM computable function, $S_0 \subseteq \mathbb{N}$ & $S_1 \subseteq \mathbb{N}$ satisfy

$$\boxed{\forall e \in \mathbb{N}.\ e \in S_0 \Leftrightarrow f(e) \in S_1}$$

then if S_1 is decidable, then so is S_0

For S_1 & S_2 as on Slides 57 & 58 we have:

$$e \in S_0 \Leftrightarrow \varphi_e(0)\downarrow$$

$$f(e) \in S_1 \Leftrightarrow \forall x \in \mathbb{N}.\ \varphi_{f(e)}(x)\downarrow$$

Exercise 5 If $f : \mathbb{N} \to \mathbb{N}$ is a RM computable function, $S_0 \subseteq \mathbb{N}$ & $S_1 \subseteq \mathbb{N}$ satisfy

$$\boxed{\forall e \in \mathbb{N}.\ e \in S_0 \Leftrightarrow f(e) \in S_1}$$

then if S_1 is decidable, then so is S_0

For S_1 & S_2 as on Slides 57 & 58 we have:

$$e \in S_0 \Leftrightarrow \varphi_e(0)\downarrow$$

$$f(e) \in S_1 \Leftrightarrow \forall x \in \mathbb{N}.\ \varphi_{f(e)}(x)\downarrow$$

So can apply the Exercise to deduce <u>un</u>decidability of S_1 from <u>un</u>decidability of S_0 by finding RM computable $f : \mathbb{N} \to \mathbb{N}$ with

$$\forall e, x.\ \varphi_{f(e)}(x) \equiv \varphi_e(0)$$

Exercise 5 If $f : \mathbb{N} \to \mathbb{N}$ is a RM computable function, $S_0 \subseteq \mathbb{N}$ & $S_1 \subseteq \mathbb{N}$ satisfy

$$\boxed{\forall e \in \mathbb{N}.\ e \in S_0 \Leftrightarrow f(e) \in S_1}$$

then if S_1 is decidable, then so is S_0

For S_1 & S_2 as on Slides 57 & 58 we have:

$$e \in S_0 \Leftrightarrow \varphi_e(0)\downarrow$$

$$f(e) \in S_1 \Leftrightarrow \forall x \in \mathbb{N}.\ \varphi_{f(e)}(x)\downarrow$$

So can apply the Exercise to deduce undecidability of S_1 from undecidability of S_0 by finding RM computable $f : \mathbb{N} \to \mathbb{N}$ with

$$\forall e, x.\ \varphi_{f(e)}(x) \equiv \varphi_e(0)$$

"Kleene equivalence" (p 82): either LHS & RHS are undefined, or both are defined and equal