Lecture
Models of Computation
(DIT310, TDA184)

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Today

- Representing Turing machines.
- A self-interpreter (a universal Turing machine).
- The halting problem.
- A Turing machine that is a χ interpreter.
- The Post correspondence problem.

Representing Turing machines

States

Assume that $S = \{ s_0, ..., s_n \}$.
Note that S is always non-empty.

$$\ulcorner S \urcorner = \ulcorner n \urcorner$$
$$\ulcorner s_k \urcorner = \ulcorner k \urcorner$$

Alphabets

Assume that $\Sigma = \{ c_1, ..., c_m \}$ and $\Gamma = \{ \sqcup \} \cup \{ c_1, ..., c_{m+n} \}$.

$$\ulcorner \Sigma \urcorner = \ulcorner m \urcorner$$
$$\ulcorner \Gamma \urcorner = \ulcorner n \urcorner$$
$$\ulcorner \sqcup \urcorner = \ulcorner 0 \urcorner$$
$$\ulcorner c_k \urcorner = \ulcorner k \urcorner$$

Directions

$$\ulcorner \mathsf{L} \urcorner = [0]$$
$$\ulcorner \mathsf{R} \urcorner = [1]$$

The transition function

- A rule $\delta\,(s, x) = (s', x', d)$ is represented by

$$\ulcorner s \urcorner +\!\!+ \ulcorner x \urcorner +\!\!+ \ulcorner s' \urcorner +\!\!+ \ulcorner x' \urcorner +\!\!+ \ulcorner d \urcorner.$$

- The transition function is represented by the representation of a list containing all of its rules (ordered in some way).

Turing machines and strings

- A Turing machine $(S, s_{initial}, \Sigma, \Gamma, \delta) \in TM$ is represented by

$$\ulcorner S \urcorner +\!\!+ \ulcorner s_{initial} \urcorner +\!\!+ \ulcorner \Sigma \urcorner +\!\!+ \ulcorner \Gamma \urcorner +\!\!+ \ulcorner \delta \urcorner.$$

- A pair consisting of a Turing machine tm and a corresponding input string xs is represented by

$$\ulcorner tm \urcorner +\!\!+ \ulcorner xs \urcorner.$$

- Note that this encoding only uses two non-blank symbols, 0 and 1.

Quiz

What Turing machine does $001010010011101010110001110101010001$ represent?

- None
- $S = \{s_0\}$, $\Sigma = \{c_1\}$, $\Gamma = \{c_1, c_2, \sqcup\}$, $\delta(s_0, c_1) = (s_0, c_1, \mathsf{L})$
- $S = \{s_0\}$, $\Sigma = \{c_1, c_2\}$, $\Gamma = \{c_1, c_2, \sqcup\}$, $\delta(s_0, c_1) = (s_0, c_2, \mathsf{R})$

Self-interpreter

Self-interpreter

A self-interpreter or *universal Turing machine* $eval$ can simulate arbitrary Turing machines with arbitrary input:

$$\Sigma_{eval} = \{0, 1\}$$

$$\forall\ tm \in TM.\ \forall\ xs \in List\ \Sigma_{tm}.$$
$$[\![eval]\!]\ \ulcorner (tm, xs) \urcorner = \ulcorner [\![tm]\!]\ xs \urcorner$$

Implementation sketch

Possibly buggy:

- Let us use three tapes in the implementation. Can convert to a one-tape machine later.
- Mark the left end of the input tape.
- Move the input string to the second tape. Mark the left end and the head's position.
- Write the initial state to the third tape. Mark the left end.

Implementation sketch

- Simulate the input TM,
  using the rules on the first tape.
- If the simulation halts,
  write the result to the first tape and halt.

The halting problem

The halting problem

$$halts \in \{(tm, xs) \mid tm \in TM, xs \in List\ \Sigma_{tm}\} \to Bool$$

$$halts\ (tm, xs) =$$

$\quad$ **if** $[\![tm]\!]\ xs$ is defined **then**

$\qquad$ true

$\quad$ **else**

$\qquad$ false

This function is not Turing-computable.

The halting problem

The halting problem can also be viewed as a language:

$$\{ \ulcorner (tm, xs) \urcorner \mid tm \in TM, xs \in List\ \Sigma_{tm}, \llbracket tm \rrbracket\ xs \text{ is defined} \}$$

This language is Turing-undecidable.

(Note the difference between this definition and the previous one.)

The halting problem (with self-application)

$$\{ \ulcorner tm \urcorner \mid tm \in TM, [\![tm]\!] \ulcorner tm \urcorner \text{ is defined} \}$$

This language is Turing-undecidable. Proof sketch:

- Assume that the TM $halts$ decides it.
- Define a TM $terminv$ in the following way:
  - Simulate $halts$ with $terminv$'s input.
  - If $halts$ accepts, loop forever.
  - If $halts$ rejects, halt.
- Note that $terminv$ applied to $\ulcorner terminv \urcorner$ halts iff it does not halt.

The halting problem is undecidable

$$\{ \ulcorner (tm, xs) \urcorner \mid tm \in TM, xs \in List\ \Sigma_{tm}, \\ \llbracket tm \rrbracket\ xs \text{ is defined} \}$$

Proof sketch:

- Assume that the TM *halts* decides it.
- We can then implement a TM for the halting problem with self-application:
  - If the input is not $\ulcorner tm \urcorner$ for some $tm \in TM$, reject.
  - If it is $\ulcorner tm \urcorner$, write ??? on the tape.
  - Run *halts*.

Quiz

What does ??? stand for?

- tm
- $\ulcorner tm \urcorner$
- $\ulcorner \ulcorner tm \urcorner \urcorner$
- $tm \mathbin{+\!\!+} \ulcorner tm \urcorner$
- $\ulcorner tm \urcorner \mathbin{+\!\!+} \ulcorner \ulcorner tm \urcorner \urcorner$
- $tm \mathbin{+\!\!+} \ulcorner tm \urcorner \mathbin{+\!\!+} \ulcorner \ulcorner tm \urcorner \urcorner$

X interpreter

A χ interpreter

The χ semantics is Turing-computable:

- X programs can be represented as strings in some finite alphabet Σ:

$$\ulcorner \_ \urcorner^{\mathsf{TM}} \in \mathit{CExp} \to \mathit{List}\ \Sigma$$

- There is a TM chi satisfying the following properties:

$$\Sigma_{\mathit{chi}} = \Sigma$$

$$\forall\ e \in \mathit{CExp}.\ [\![\mathit{chi}]\!]_{\mathsf{TM}}\ \ulcorner e \urcorner^{\mathsf{TM}} = \ulcorner [\![e]\!]_{\chi} \urcorner^{\mathsf{TM}}$$

Recursion

- How can recursion be implemented?
- One idea: An explicit stack on a separate tape.

Implementation sketch

- Come up with a small-step semantics for χ.
- Use small steps also for substitution.
- Make sure that every small step can be simulated on a TM.
- The design can be based on some abstract machine for the λ-calculus, perhaps the CEK machine.

Every χ-computable partial function in $\mathbb{N} \rightharpoonup \mathbb{N}$ is Turing-computable

Proof sketch:

- If $f \in \mathbb{N} \rightharpoonup \mathbb{N}$ is χ-computable, then

  $$\forall\, m \in \mathbb{N}.\, [\![e \ulcorner m \urcorner^{\chi}]\!]_{\chi} = \ulcorner f\ m \urcorner^{\chi}$$

  for some $e \in CExp$.
- The following TM implements f:
  - Convert input: $\ulcorner m \urcorner^{\mathsf{TM}} \mapsto \ulcorner e \ulcorner m \urcorner^{\chi} \urcorner^{\mathsf{TM}}$.
  - Simulate the χ interpreter.
  - Convert output: $\ulcorner \ulcorner n \urcorner^{\chi} \urcorner^{\mathsf{TM}} \mapsto \ulcorner n \urcorner^{\mathsf{TM}}$.

The Post correspondence problem

The Post correspondence problem

Definition (for a set Σ with at least two members):

- Given: $x_1, \ldots, x_n \in \mathit{List}\ \Sigma \times \mathit{List}\ \Sigma$.
- Goal: Find $k \geq 1$ and $i_1, \ldots, i_k \in \{1, \ldots, n\}$ such that

$$\begin{aligned} &\mathit{fst}\ x_{i_1} \mathbin{+\!\!+} \cdots \mathbin{+\!\!+} \mathit{fst}\ x_{i_k} = \\ &\mathit{snd}\ x_{i_1} \mathbin{+\!\!+} \cdots \mathbin{+\!\!+} \mathit{snd}\ x_{i_k}. \end{aligned}$$

Examples on Wikipedia.

Quiz

Is the Post correspondence problem solvable for the given pairs of strings?

- A: $(001, 00)$, $(01, 10)$.
- B: $(01, 001)$, $(010, 01)$.

The Post correspondence problem

- Undecidable.
- Note that there is no reference to Turing machines (or χ expressions) in the statement of the problem.
- Proof idea:
  - Construct pairs such that a TM halts iff the problem is solvable.
  - The resulting string (if any) encodes the TM's computation history.
- Sipser's *Introduction to the Theory of Computation* (available online via Chalmers' library) contains a readable proof.

Ambiguity

- Undecidable:
  Is a context-free grammar ambiguous?
- The Post correspondence problem can be reduced to this one.

Ambiguity

Proof sketch (taken from Sipser):

- Given: Pairs $(t_1, b_1), \ldots, (t_n, b_n)$.
- Define a CFG with three non-terminals, and Start as the starting non-terminal:

$$
\begin{array}{lllllll}
\mathit{Start} & ::= & \mathit{Top} \mid \mathit{Bottom} & & & & \\
\mathit{Top} & ::= & t_1 \ \mathit{Top} & \mathtt{1} \mid \ldots \mid & t_n \ \mathit{Top} & \mathtt{n} \\
 & \mid & t_1 & \mathtt{1} \mid \ldots \mid & t_n & \mathtt{n} \\
\mathit{Bottom} & ::= & b_1 \ \mathit{Bottom} & \mathtt{1} \mid \ldots \mid & b_n \ \mathit{Bottom} & \mathtt{n} \\
 & \mid & b_1 & \mathtt{1} \mid \ldots \mid & b_n & \mathtt{n}
\end{array}
$$

(Here $\mathtt{1}, \ldots, \mathtt{n}$ are fresh terminals.)

- This grammar is ambiguous iff the given instance of the Post correspondence problem has a solution.

Summary

- Representing Turing machines.
- A self-interpreter (a universal Turing machine).
- The halting problem.
- A Turing machine that is a χ interpreter.
- The Post correspondence problem.

Next week

- Summary of the course.
- Old exam questions.

Any questions?

- I expect plenty of spare time at the end of this lecture.
- Feel free to ask questions about, say, things that are difficult, or things you want to know more about.