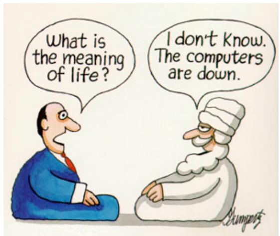
Duality, Universality, and Computability



Fundamental Questions

Q. What is a general-purpose computer?
Q. Are there limits on the power of digital computers?
Q. Are there limits on the power of machines we can build?

Pioneering work in the 1930s.
- Princeton == center of universe.
- Hilbert, Gödel, Turing, Church, von Neumann.
- Automata, languages, computability, universality, complexity, logic.


David Hilbert


Kurt Gödel


Alan Turing


Alonzo Church


John von Neumann

7.5 Turing Machines


Alan Turing (1912-1954)

Turing Machine

Desiderata. Simple model of computation that is "as powerful" as conventional computers.

Intuition. Simulate how humans calculate.

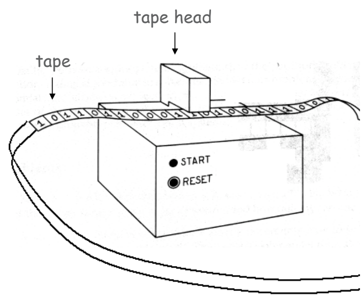
Ex. Addition.

			1	2	3	4	5	6		
		+	3	1	4	1	5	9		

Turing Machine: Tape

Tape.
- Stores input, output, and intermediate results.
- One arbitrarily long strip, divided into cells.
- Finite alphabet of symbols.

Tape head.
- Points to one cell of tape.
- Reads a symbol from active cell.
- Writes a symbol to active cell.
- Moves left or right one cell at a time.

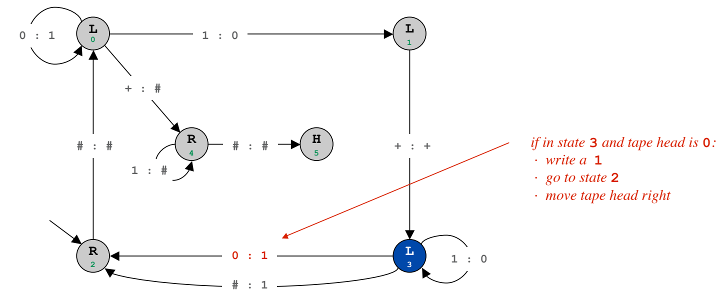


tape head

tape	...	#	1	1	0	0	+	1	0	1	1	#	...

Turing Machine: States

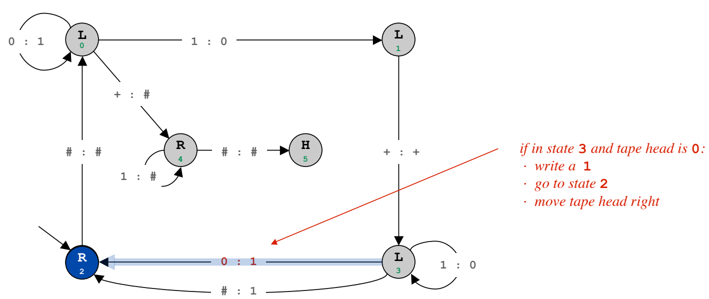
State. What machine remembers.
State transition diagram. Complete description of what machine will do.



tape (before)	...	#	1	1	0	0	+	1	0	1	1	#	...

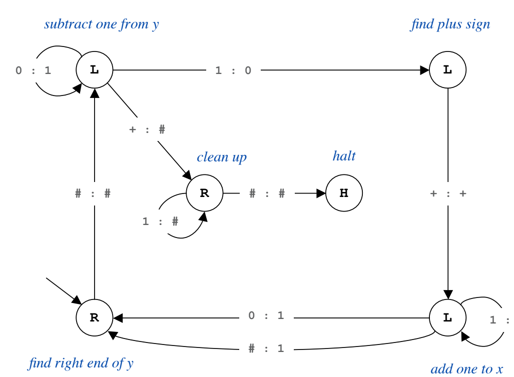
Turing Machine: States

State. What machine remembers.
State transition diagram. Complete description of what machine will do.



tape (after)	...	#	1	1	1	0	+	1	0	1	1	#	...

Binary Adder



...	#	1	0	1	0	+	1	1	1	1	#	...

$\underbrace{1\ 0\ 1\ 0}_{x}$ $\underbrace{1\ 1\ 1\ 1}_{y}$

Turing Machine: Initialization and Termination

Initialization. Set input on some portion of tape; set tape head.

tape head

tape	...	#	1	0	1	0	+	1	1	1	1	#	...

Termination. Stop if enter `yes`, `no`, or `halt` state.

infinite loop possible

Duality

Duality of Program and Data

Data. Sequence of symbols (interpreted one way).
Program. Sequence of symbols (interpreted another way).

Program and data are interchangeable.

Ex 1. A compiler is a program that takes a program in one language as input and outputs a program in another language.

Java

machine language

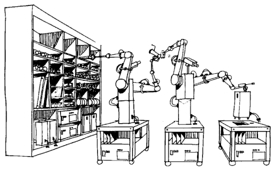
Duality of Program and Data

Data. Sequence of symbols (interpreted one way).
Program. Sequence of symbols (interpreted another way).

Program and data are interchangeable.

Ex 2. Self-replication. [von Neumann 1940s]

> Print the following statement twice, the second time in quotes.
> "Print the following statement twice, the second time in quotes."



Duality of Program and Data

Data. Sequence of symbols (interpreted one way).
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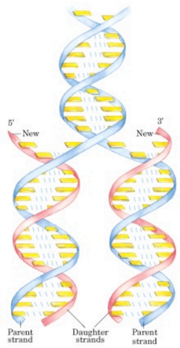
Ex 3. Self-replication. [Watson-Crick 1953]



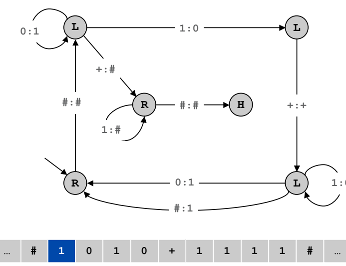
self-replicating DNA

Duality of Program and Data

Data. Sequence of symbols (interpreted one way).
Program. Sequence of symbols (interpreted another way).

Program and data are interchangeable.

Ex 4. Turing machine.



graphical representation

```
% more adder.tur
vertices
2 R
0 L
1 L
3 L
4 R
5 H

edges
0 0 0 1
0 1 1 0
0 4 + #
1 3 + +
2 0 # #
3 2 # 1
3 2 0 1
3 3 1 0
4 4 1 #
4 5 # #

tape
[1] 0 1 0 + 1 1 1 1
```

text representation

Universality

Universal Machines and Technologies

Cray

Dell PC

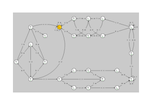
iMac

iPod

Printer

Xbox

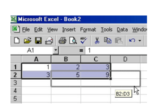
Tivo



Turing machine

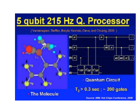
TOY

Java language



MS Excel

Blackberry



Quantum computer

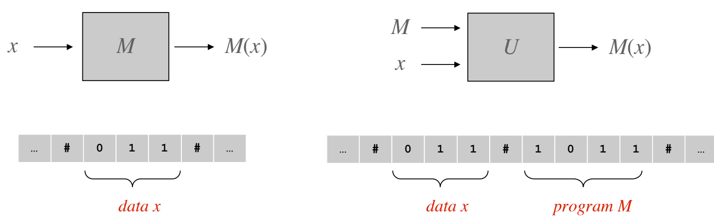
DNA computer

Python language

Universal Turing Machine

Turing machine M. Given input x, Turing machine M outputs $M(x)$.

Universal Turing machine U. Given input M and x, universal Turing machine U outputs $M(x)$.



TM intuition. Software program that solves one particular problem.
UTM intuition. Hardware platform that can implement any algorithm.

Universal Turing Machine

Consequences. Your laptop (a UTM) can do any computational task.

even tasks not yet contemplated when laptop was purchased

- Java programming.
- Pictures, music, movies, games.
- Email, browsing, downloading files, telephony.
- Word-processing, finance, scientific computing.
- …

> *Again, it [the Analytical Engine] might act upon other things besides numbers… the engine might compose elaborate and scientific pieces of music of any degree of complexity or extent.* — Ada Lovelace

Church-Turing Thesis

Church Turing thesis (1936). Turing machines can do anything that can be described by any physically harnessable process of this universe.

Remark. "Thesis" and not a mathematical theorem because it's a statement about the physical world and not subject to proof.

but can be falsified

Implications.
- No need to seek more powerful machines or languages.
- Enables rigorous study of computation (in this universe).

Bottom line. Turing machine is a simple and universal model of computation.

Church-Turing Thesis: Evidence

Evidence.
- 7 decades without a counterexample.
- Many, many models of computation that turned out to be equivalent.

"universal"

model of computation	description
enhanced Turing machines	multiple heads, multiple tapes, 2D tape, nondeterminism
untyped lambda calculus	method to define and manipulate functions
recursive functions	functions dealing with computation on integers
unrestricted grammars	iterative string replacement rules used by linguists
extended L-systems	parallel string replacement rules that model plant growth
programming languages	Java, C, C++, Perl, Python, PHP, Lisp, PostScript, Excel
random access machines	registers plus main memory, e.g., TOY, Pentium
cellular automata	cells which change state based on local interactions
quantum computer	compute using superposition of quantum states
DNA computer	compute using biological operations on DNA

7.7 Computability

Halting Problem

Halting problem. Write a Java function that reads in a Java function `f` and its input `x`, and decides whether `f(x)` results in an infinite loop.

relates to famous open math conjecture

Ex. Does `f(x)` terminate?

```
public void f(int x) {
   while (x != 1) {
      if  (x % 2 == 0)  x = x / 2;
      else              x = 3*x + 1;
   }
}
```

- `f(6)`: 6 3 10 5 16 8 4 2 1
- `f(27)`: 27 82 41 124 62 31 94 47 142 71 214 107 322 … 4 2 1
- `f(-17)`: -17 -50 -25 -74 -37 -110 -55 -164 -82 -41 -122 … -17 …

Undecidable Problem

A yes-no problem is undecidable if no Turing machine exists to solve it.

and (by universality) no Java program either

Theorem. [Turing 1937] The halting problem is undecidable.

Proof intuition: lying paradox.
- Divide all statements into two categories: truths and lies.
- How do we classify the statement: *I am lying*.

Key element of lying paradox and halting proof: self-reference.

Halting Problem Proof

Assume the existence of `halt(f,x)`:
- Input: a function `f` and its input `x`.
- Output: `true` if `f(x)` halts, and `false` otherwise.
- Note: `halt(f,x)` does not go into infinite loop.

We prove by contradiction that `halt(f,x)` does not exist.
- *Reductio ad absurdum* : if any logical argument based on an assumption leads to an absurd statement, then assumption is false.

encode f and x as strings

```
public boolean halt(String f, String x) {
   if ( something terribly clever ) return true;
   else                             return false;
}
```

hypothetical halting function

Halting Problem Proof

Assume the existence of `halt(f,x)`:
- Input: a function `f` and its input `x`.
- Output: `true` if `f(x)` halts, and `false` otherwise.

Construct function `strange(f)` as follows:
- If `halt(f,f)` returns `true`, then `strange(f)` goes into an infinite loop.
- If `halt(f,f)` returns `false`, then `strange(f)` halts.

f is a string so legal (if perverse)
to use for second input

```
public void strange(String f) {
   if (halt(f, f)) {
      // an infinite loop
      while (true) { }
   }
}
```


Halting Problem Proof

Assume the existence of `halt(f,x)`:
- Input: a function `f` and its input `x`.
- Output: `true` if `f(x)` halts, and `false` otherwise.

Construct function `strange(f)` as follows:
- If `halt(f,f)` returns `true`, then `strange(f)` goes into an infinite loop.
- If `halt(f,f)` returns `false`, then `strange(f)` halts.

In other words:
- If `f(f)` halts, then `strange(f)` goes into an infinite loop.
- If `f(f)` does not halt, then `strange(f)` halts.

Call `strange()` with ITSELF as input.
- If `strange(strange)` halts then `strange(strange)` does not halt.
- If `strange(strange)` does not halt then `strange(strange)` halts.

Either way, a contradiction. Hence `halt(f,x)` cannot exist.

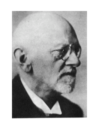
Consequences

Q. Why is debugging hard?
A. All problems below are undecidable.

Halting problem. Give a function f, does it halt on a given input x?
Totality problem. Give a function f, does it halt on every input x?
No input halting problem. Give a function f with no input, does it halt?
Program equivalence. Do two functions f and always return same value?
Uninitialized variables. Is the variable x initialized before it's used?
Dead code elimination. Does this statement ever get executed?

More Undecidable Problems

Hilbert's 10th problem.



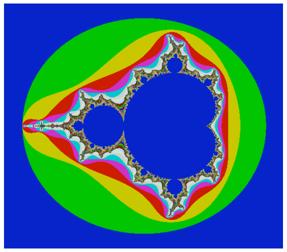
Devise a process according to which it can be determined by a finite number of operations whether a given multivariate polynomial has an integral root.

- $f(x, y, z) = 6x^3 y z^2 + 3xy^2 - x^3 - 10.$ yes : $f(5, 3, 0) = 0.$
- $f(x, y) = x^2 + y^2 - 3.$ no.

Definite integration. Given a rational function $f(x)$ composed of polynomial and trig functions, does $\int_{-\infty}^{+\infty} f(x)\,dx$ exist?
- $g(x) = \cos x\,(1 + x^2)^{-1}$ yes, $\int_{-\infty}^{+\infty} g(x)\,dx = \pi / e.$
- $h(x) = \cos x\,(1 - x^2)^{-1}$ no, $\int_{-\infty}^{+\infty} h(x)\,dx$ undefined.

More Undecidable Problems

Optimal data compression. Find the shortest program to produce a given string or picture.



Mandelbrot set (40 lines of code)

More Undecidable Problems

Virus identification. Is this program a virus?

```
Private Sub AutoOpen()
On Error Resume Next
If System.PrivateProfileString("", CURRENT_USER\Software\Microsoft\Office\9.0\Word\Security",
                               "Level") <> "" Then
CommandBars("Macro").Controls("Security...").Enabled = False
. . .
For oo = 1 To AddyBook.AddressEntries.Count
   Peep = AddyBook.AddressEntries(x)
   BreakUmOffASlice.Recipients.Add Peep
   x = x + 1
   If x > 50 Then oo = AddyBook.AddressEntries.Count
Next oo
. . .
BreakUmOffASlice.Subject = "Important Message From " & Application.UserName
BreakUmOffASlice.Body = "Here is that document you asked for ... don't show anyone else ;-)"
. . .
```

Can write programs in MS Word.
This statement disables security.

Melissa virus
March 28, 1999

Context: Mathematics and Logic

Mathematics. Formal system powerful enough to express arithmetic.

Principia Mathematics
Peano arithmetic
Zermelo-Fraenkel set theory

Complete. Can prove truth or falsity of any arithmetic statement.
Consistent. Can't prove contradictions like 2 + 2 = 5.
Decidable. Algorithm exists to determine truth of every statement.

Q. [Hilbert] Is mathematics complete and consistent?
A. [Gödel's Incompleteness Theorem, 1931] No!!!

Q. [Hilbert's Entscheidungsproblem] Is mathematics decidable?
A. [Church 1936, Turing 1936] No!

Turing's Key Ideas

Turing machine.
formal model of computation

Duality.
encode program and data as sequence of symbols; use interchangeably

Universality.
concept of general-purpose, programmable computers

Church-Turing thesis.
computable at all == computable with a Turing machine

Computability.
inherent limits to computation

Hailed as one of top 10 science papers of 20th century.

Reference: *On Computable Numbers, With an Application to the Entscheidungsproblem* by A. M. Turing. In Proceedings of the London Mathematical Society, ser. 2. vol. 42 (1936-7), pp.230-265.