Formal Languages

A Universal Turing Machine

A limitation of Turing Machines:

Turing Machines are "hardwired"

$\underbrace{\hphantom{\text{hardwired}}}_{\text{they execute only one program}}$

they execute
only one program

Real Computers are re-programmable

Solution: Universal Turing Machine

Attributes:

- Reprogrammable machine

- Simulates any other Turing Machine

Universal Turing Machine

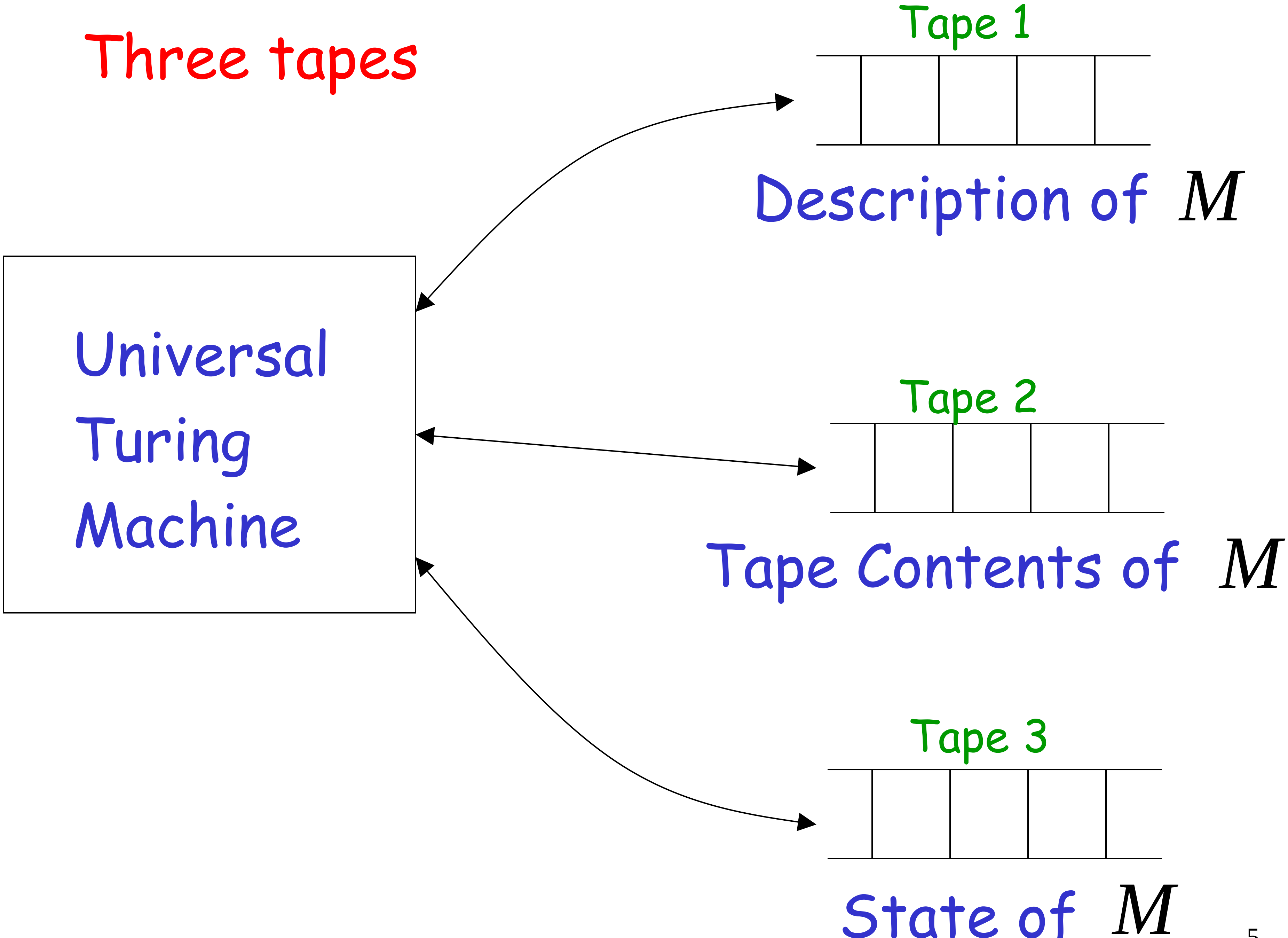
simulates any other Turing Machine M

Input of Universal Turing Machine:

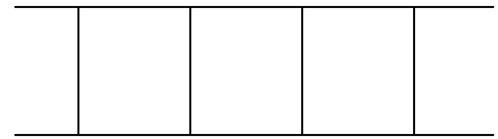
Description of transitions of M

Initial tape contents of M

Three tapes


Universal
Turing
Machine
Tape 1
Description of M
Tape 2
Tape Contents of M
Tape 3
State of M

Tape 1



Description of M

We describe Turing machine M
as a string of symbols:

We encode M as a string of symbols

Alphabet Encoding

Symbols:	a	b	c	d	$\cdots$
	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	
Encoding:	1	11	111	1111	

State Encoding

States:	q_1	q_2	q_3	q_4	$\cdots$
	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	
Encoding:	1	11	111	1111	

Head Move Encoding

Move:	L	R
	$\downarrow$	$\downarrow$
Encoding:	1	11

Transition Encoding

Transition: $\delta(q_1, a) = (q_2, b, L)$

Encoding: $1\,0\,1\,0\,11\,0\,11\,0\,1$

separator

Machine Encoding

Transitions:

$$\delta(q_1, a) = (q_2, b, L) \qquad \delta(q_2, b) = (q_3, c, R)$$

Encoding:

$$10101101101 \quad 00 \quad 1101101110111011$$

separator

Tape 1 contents of Universal Turing Machine:

encoding of the simulated machine M
as a binary string of 0's and 1's

A Turing Machine is described with a binary string of 0's and 1's

Therefore:

The set of Turing machines forms a language:

each string of the language is the binary encoding of a Turing Machine

Language of Turing Machines

L = { 010100101, (Turing Machine 1)

00100100101111, (Turing Machine 2)

111010011110010101, ……

…… }

Countable Sets

Infinite sets are either:

Countable

or

Uncountable

Countable set:

Any finite set

or

Any *Countably infinite set*:

There is a one to one correspondence

between

elements of the set

and

Natural numbers

Example: The set of even integers is countable

Even integers: $0, \ 2, \ 4, \ 6, \ \ldots$

Correspondence: $\downarrow \ \downarrow \ \downarrow \ \downarrow$

Positive integers: $1, \ 2, \ 3, \ 4, \ \ldots$

$2n$ corresponds to $n+1$

Example: The set of rational numbers is countable

Rational numbers: $$\frac{1}{2},\ \frac{3}{4},\ \frac{7}{8},\ \ldots$$

Naïve Proof

Rational numbers: $\frac{1}{1}, \frac{1}{2}, \frac{1}{3}, \ldots$

Correspondence: $\downarrow \quad \downarrow \quad \downarrow$

Positive integers: $1, \; 2, \; 3, \; \ldots$

Doesn't work:

we will never count
numbers with nominator 2: $\frac{2}{1}, \frac{2}{2}, \frac{2}{3}, \ldots$

Better Approach

$$\frac{1}{1} \quad \frac{1}{2} \quad \frac{1}{3} \quad \frac{1}{4} \quad \cdots$$

$$\frac{2}{1} \quad \frac{2}{2} \quad \frac{2}{3} \quad \cdots$$

$$\frac{3}{1} \quad \frac{3}{2} \quad \cdots$$

$$\frac{4}{1} \quad \cdots$$

$$
\begin{array}{ccccc}
\dfrac{1}{1} \longrightarrow & \dfrac{1}{2} & \dfrac{1}{3} & \dfrac{1}{4} & \cdots \\[2em]
\dfrac{2}{1} & \dfrac{2}{2} & \dfrac{2}{3} & \cdots & \\[2em]
\dfrac{3}{1} & \dfrac{3}{2} & \cdots & & \\[2em]
\dfrac{4}{1} & \cdots & & &
\end{array}
$$

$$
\begin{array}{ccccc}
\frac{1}{1} & \to \frac{1}{2} & \frac{1}{3} & \frac{1}{4} & \cdots \\[2em]
\frac{2}{1} & \frac{2}{2} & \frac{2}{3} & \cdots & \\[2em]
\frac{3}{1} & \frac{3}{2} & \cdots & & \\[2em]
\frac{4}{1} & \cdots & & &
\end{array}
$$

$$\begin{array}{ccccc}
\frac{1}{1} & \frac{1}{2} & \frac{1}{3} & \frac{1}{4} & \cdots \\
\frac{2}{1} & \frac{2}{2} & \frac{2}{3} & \cdots & \\
\frac{3}{1} & \frac{3}{2} & \cdots & & \\
\frac{4}{1} & \cdots & & &
\end{array}$$

$$
\begin{array}{cccccc}
\frac{1}{1} & \frac{1}{2} & \frac{1}{3} & \frac{1}{4} & \cdots \\[2em]
\frac{2}{1} & \frac{2}{2} & \frac{2}{3} & \cdots & \\[2em]
\frac{3}{1} & \frac{3}{2} & \cdots & & \\[2em]
\frac{4}{1} & \cdots & & &
\end{array}
$$

$$
\begin{tikzcd}[column sep=large, row sep=large]
\frac{1}{1} \arrow[r] & \frac{1}{2} \arrow[dl] & \frac{1}{3} \arrow[dl] & \frac{1}{4} \arrow[dl] & \cdots \\
\frac{2}{1} \arrow[urr] & \frac{2}{2} \arrow[dl] & \frac{2}{3} \arrow[dl] & \cdots & \\
\frac{3}{1} \arrow[uurrr] & \frac{3}{2} \arrow[dl] & \cdots & & \\
\frac{4}{1} & \cdots & & &
\end{tikzcd}
$$

Rational Numbers: $\frac{1}{1}, \frac{1}{2}, \frac{2}{1}, \frac{1}{3}, \frac{2}{2}, \ldots$

Correspondence:

Positive Integers: $1, 2, 3, 4, 5, \ldots$

We proved:

the set of rational numbers is countable
by describing an enumeration procedure

Definition

Let S be a set of strings

An **enumeration procedure** for S is a Turing Machine that generates all strings of S one by one

and

Each string is generated in finite time

strings $s_1, s_2, s_3, \ldots \in S$

Enumeration Machine for S

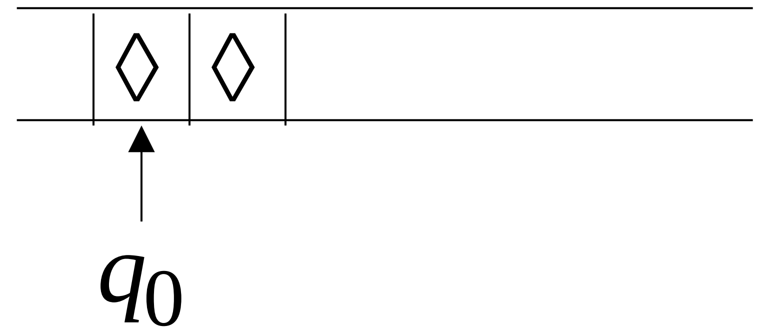
$\xrightarrow[\text{(on tape)}]{\text{output}}$ $s_1, s_2, s_3, \ldots$

Finite time: $t_1, t_2, t_3, \ldots$

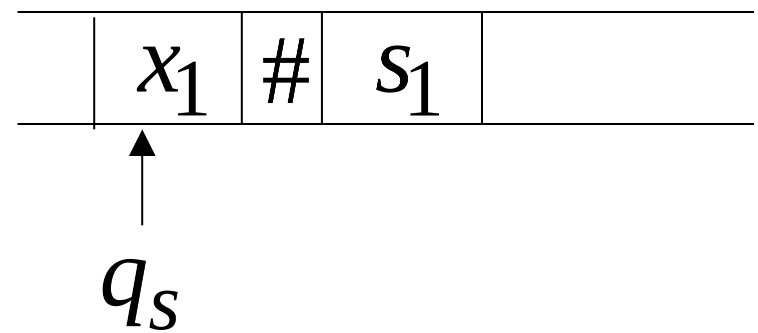
Enumeration Machine

Configuration

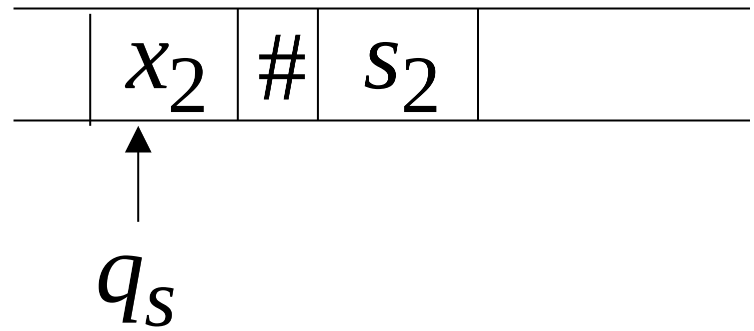
Time 0



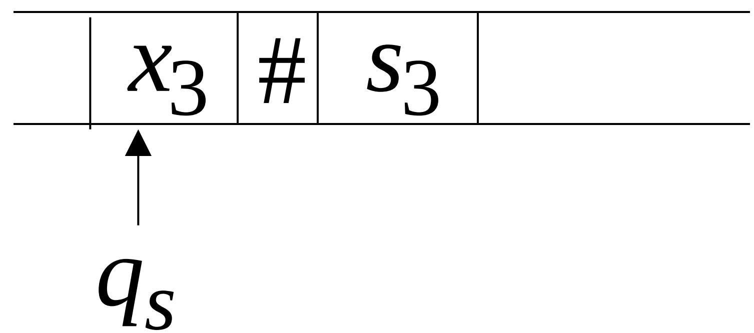
Time t_1



Time t_2



Time t_3



Observation:

If for a set there is an enumeration procedure, then the set is countable

Example:

The set of all strings $\{a,b,c\}^+$ is countable

Proof:

We will describe an enumeration procedure

Naive procedure:

Produce the strings in lexicographic order:

a

aa

aaa

$aaaa$

$\ldots\ldots$

Doesn't work:

strings starting with b

will never be produced

Better procedure: **Proper Order**

1. Produce all strings of length 1

2. Produce all strings of length 2

3. Produce all strings of length 3

4. Produce all strings of length 4

....

Produce strings in **Proper Order:**

$$\left.\begin{matrix} a \\ b \\ c \end{matrix}\right\} \text{length 1}$$

$$\left.\begin{matrix} aa \\ ab \\ ac \\ ba \\ bb \\ bc \\ ca \\ cb \\ cc \end{matrix}\right\} \text{length 2}$$

$$\left.\begin{matrix} aaa \\ aab \\ aac \\ \ldots\ldots \end{matrix}\right\} \text{length 3}$$

Theorem: The set of all Turing Machines is countable

Proof: Any Turing Machine can be encoded with a binary string of 0's and 1's

Find an enumeration procedure for the set of Turing Machine strings

Enumeration Procedure:

Repeat

1. Generate the next binary string of 0's and 1's in proper order

2. Check if the string describes a Turing Machine

   if **YES:** print string on output tape

   if **NO:** ignore string

Uncountable Sets

Definition: A set is uncountable if it is not countable

Theorem:

Let S be an infinite countable set

The powerset 2^S of S is uncountable

Proof:

Since S is countable, we can write

$$S = \{s_1, s_2, s_3, \ldots\}$$

Elements of S

Elements of the powerset have the form:

$$\{s_1, s_3\}$$

$$\{s_5, s_7, s_9, s_{10}\}$$

$$\ldots\ldots$$

We encode each element of the power set with a binary string of 0's and 1's

Powerset element	Encoding s_1	s_2	s_3	s_4	$\cdots$
$\{s_1\}$	1	0	0	0	$\cdots$
$\{s_2, s_3\}$	0	1	1	0	$\cdots$
$\{s_1, s_3, s_4\}$	1	0	1	1	$\cdots$

Let's assume (for contradiction) that the powerset is countable.

Then: we can enumerate the elements of the powerset

Powerset element	Encoding					
t_1	1	0	0	0	0	$\cdots$
t_2	1	1	0	0	0	$\cdots$
t_3	1	1	0	1	0	$\cdots$
t_4	1	1	0	0	1	$\cdots$
$\cdots$						

Take the powerset element whose bits are the complements of the bits in the diagonal

$$
\begin{array}{llllll}
t_1 & 1 & 0 & 0 & 0 & 0 \;\cdots \\
t_2 & 1 & 1 & 0 & 0 & 0 \;\cdots \\
t_3 & 1 & 1 & 0 & 1 & 0 \;\cdots \\
t_4 & 1 & 1 & 0 & 0 & 1 \;\cdots
\end{array}
$$

New element: $0011\ldots$

(binary complement of diagonal)

The new element must be some t_i of the powerset

However, that's impossible:

from definition of t_i

the i-th bit of t_i must be the complement of itself

Contradiction!!!

Since we have a contradiction:

The powerset 2^S of S is uncountable

An Application: Languages

Example Alphabet : $\{a, b\}$

The set of all Strings:

$$S = \{a, b\}^* = \{\lambda, a, b, aa, ab, ba, bb, aaa, aab, \ldots\}$$

infinite and countable

Example Alphabet : $\{a,b\}$

The set of all Strings:

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infinite and countable

A language is a subset of S :

$$L = \{aa, ab, aab\}$$

Example Alphabet : $\{a,b\}$

The set of all Strings:

$$S=\{a,b\}^{*}=\{\lambda,a,b,aa,ab,ba,bb,aaa,aab,\ldots\}$$

infinite and countable

The powerset of S contains all languages:

$$2^{S}=\{\underbrace{\{\lambda\}}_{L_1},\underbrace{\{a\}}_{L_2},\underbrace{\{a,b\}}_{L_3}\underbrace{\{aa,ab,aab\}}_{L_4},\ldots\}$$

uncountable

Languages: uncountable

L_1 $\quad$ L_2 $\quad$ L_3 $\quad \cdots \quad$ L_k $\quad \cdots$

$\downarrow$ $\quad$ $\downarrow$ $\quad$ $\downarrow$ $\quad\quad\quad$ $\downarrow$

M_1 $\quad$ M_2 $\quad$ M_3 $\quad\quad\quad$?

Turing machines: countable

There are more languages than Turing Machines

Conclusion:

There are some languages not accepted by Turing Machines

(These languages cannot be described by algorithms)

Languages not accepted by Turing Machines