

GEM 1501 Problem Solving With Computers

Lecture 9:

Universality

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Summary of Previous Lecture

- Certain things are not only slow but just impossible
- Unbounded Puzzles, Post's Correspondence Problem
- The Halting-Problem
- Recursively Enumerable Sets
- Rice's Theorem

General Picture

- In general, problems are just sets of texts.
- Recursive functions and recursively enumerable sets: recursive functions are those which can be specified using a Java Script program. A recursively enumerable set is the range of a recursive function (or is empty).
- Decidable Problems: An algorithm, although perhaps slow, can decide the membership.
A problem is decideable iff the problem itself and its complement are both recursively enumerable.
All the problems from Lecture 7 are decidable.
- Highly undecidable problems.
Example: Set of all texts T such that T is the text of a Java Script program which terminates on all possible inputs.

Hierarchy of Recursively Enumerable Sets

- **Complete recursively enumerable problems**

A recursively enumerable set A is complete iff for every r.e. set B there is a computable function F with $\forall x [x \in B \Leftrightarrow F(x) \in A]$.

Examples: Halting Problem, Post's Correspondence problem.

Most natural undecidable recursively enumerable sets are complete.

- **Incomplete but undecidable problems**

Most examples of these are not natural and difficult to construct.

Problem of compressible texts is one which is most easy to understand: T is compressible iff there is a Java Script program P outputting T such that P needs no input and is shorter than T .

- **Decidable problems**

A problem A is decidable iff there is an algorithm (computable function) which, for any input x , outputs "YES" if $x \in A$ and "NO" if $x \notin A$.

Presburger arithmetic is an example of a decidable problem (although it is intractible).

Proof Techniques

- Diagonalization:
Origin of proof method is Set Theory;
Create new problem D such that $D(P)$ differs from $P(P)$ for all total programs P with input being P itself;
The halting problem is undecidable.
- Translation and Simulation:
Every recursively enumerable set can be translated into the halting problem;
Rice's Theorem: The halting problem can be translated into many problems dealing with program behaviour;
Most undecidability results are obtained that way.

Today: Are all computers the same?

- Computers differ in their speed, architecture and design.
- Obvious question: Is every problem solvable by computer A also solvable by computer B?
- In practice: no; — In theory: yes.
- Given enough time and memory, any computer can “simulate” any other computer.
- Emphasis will be on easy computers and mechanisms able to simulate all other computing machinery.

Overview

- **Turing Machines**
- Multiple Stack Machines
- Church's Thesis
- Numerical Computation:
Counter Programs
- Restricted Models:
One Stack Machines and Finite Automata

Simplifications

- Data: All data are strings!
- Control: Tape, gearbox, narrow eye.
- Operations: Change the symbol under the eye and move left or right.
- Result: The Turing Machine.

The Turing Machine

- Finite set of states
- Finite alphabet of symbols
- Infinite tape
- Head that can read and write symbols on the tape
- State-transition table (“Turing Table”)

`http://www.comp.nus.edu.sg/~gem1501/turingmachine.html`

`http://www.comp.nus.edu.sg/~gem1501/interactiveturing.html`

Changing Symbols

Task: Nonempty input, exchange 0 and 1 everywhere.

States: st, ri, ch. Commands: Write #,0,1,2,3,4; Right; Left; Halt.

Turing Table maps old state * symbol to new state and action.

Old State	#	0	1	2	3	4
st	st R	ri 1	ri 0	ch R	ch R	ch R
ri	----	ch R	ch R	----	----	----
ch	ch H	ri 1	ri 0	ch R	ch R	ch R

Algorithm:

```
st: if symbol == # then right and goto st;
    if symbol == 0 or symbol == 1, then change symbol and goto ri;
    if symbol == 2 or symbol == 3 or symbol == 4, then right and goto ch;
ri: right and goto ch;
ch: if symbol == # then halt;
    if symbol == 0 or symbol == 1, then change symbol and goto ri;
    if symbol == 2 or symbol == 3 or symbol == 4, then right and goto ch.
```

Runtime Example

Old State	#	0	1	2	3	4
st	st R	ri 1	ri 0	ch R	ch R	ch R
ri	----	ch R	ch R	----	----	----
ch	ch H	ri 1	ri 0	ch R	ch R	ch R

State	Position	Symbol	String	Action	New State
st	0	#	#00231#	Right	st
st	1	0	#00231#	Write 1	ri
ri	1	1	#10231#	Right	ch
ch	2	0	#10231#	Write 1	ri
ri	2	1	#11231#	Right	ch
ch	3	2	#11231#	Right	ch
ch	4	3	#11231#	Right	ch
ch	5	1	#11231#	Write 0	ri
ri	5	0	#11230#	Right	ch
ch	6	#	#11230#	Halt	ch

Appending Symbol

Task: Nonempty input, append first symbol at end.

States: st,q0,...,q4,ha. Commands: Write #,0,1,2,3,4; Right; Left; Halt.

Turing Table maps old state * symbol to new state and action.

Old State	#	0	1	2	3	4
st	st R	q0 R	q1 R	q2 R	q3 R	q4 R
q0	ha 0	q0 R	q0 R	q0 R	q0 R	q0 R
q1	ha 1	q1 R	q1 R	q1 R	q1 R	q1 R
q2	ha 2	q2 R	q2 R	q2 R	q2 R	q2 R
q3	ha 3	q3 R	q3 R	q3 R	q3 R	q3 R
q4	ha 4	q4 R	q4 R	q4 R	q4 R	q4 R
ha	ha H	ha H	ha H	ha H	ha H	ha H

Algorithm (with k in {0,1,2,3,4}):

```
st: while (symbol == #) { right; }
```

```
    k = symbol; right; goto qk;
```

```
qk: while (symbol != #) { right; } write k; goto ha;
```

```
ha: halt;
```

Runtime Example

Algorithm

```
st: while (symbol == #) { right; }  
    k = symbol; right; goto qk;  
qk: while (symbol != #) { right; } write k; goto ha;  
ha: halt;
```

Machine uses state to remember first symbol k in $\{0,1,2,3,4\}$.

State	Position	Symbol	String	Action	New State
st	0	#	#400231##	Right	st
st	1	4	#400231##	Right	q4
q4	2	0	#400231##	Right	q4
q4	3	0	#400231##	Right	q4
q4	4	2	#400231##	Right	q4
q4	5	3	#400231##	Right	q4
q4	6	1	#400231##	Right	q4
q4	7	#	#400231##	Write 4	ha
ha	7	4	#4002314#	Halt	ha

Detecting Palindromes

- Input tape: `...##010##...`
- Ideas:
 - For each digit at the beginning, find the corresponding digit at the end.
 - If equal, replace corresponding digits by #.
 - Write 1 if the entire string has been replaced by #.
 - Erase string and write 0 if at some time corresponding digits are different.

Turing Table for 2 digits

Situations which cannot come up are marked by "-----"

st: start, br: branch, zk: zero, ok: one,

bk: back, ek: erase, ha: halt.

Old State	#	0	1
st	br R	-----	-----
br	ha 1	z1 R	o1 R
z1	z2 L	z1 R	z1 R
z2	-----	b1 #	e1 1
o1	o2 L	o1 R	o1 R
o2	-----	e1 0	b1 #
b1	b2 L	-----	-----
b2	b3 R	b2 L	b2 L
b3	ha 1	st #	st #
e1	ha 0	e2 #	e2 #
e2	e1 L	-----	-----
ha	-----	ha H	ha H

Runtime Example 010 - Part 1

State	Position	Symbol	String	Action	New State
st	0	#	#010#	Right	br
br	1	0	#010#	Right	z1
z1	2	1	#010#	Right	z1
z1	3	0	#010#	Right	z1
z1	4	#	#010#	Left	z2
z2	3	0	#010#	Write #	b1
b1	3	#	#01##	Left	b2
b2	2	1	#01##	Left	b2
b2	1	0	#01##	Left	b2
b2	0	#	#01##	Right	b3
b3	1	0	#01##	Write #	st

Runtime Example 010 - Part 2

State	Position	Symbol	String	Action	New State
st	1	#	##1##	Right	br
br	2	1	##1##	Right	o1
o1	3	#	##1##	Left	o2
o2	2	1	##1##	Write #	b1
b1	2	#	#####	Left	b2
b2	1	#	#####	Right	b3
b3	2	#	##1##	Write 1	ha
ha	2	1	##1##	Halt	ha

There is no requirement where exactly the output appears on the tape.
It must only be unique in the sense that no other digits are on the tape.

Runtime Examples 011

State	Position	Symbol	String	Action	New State
st	0	#	#011#	Right	br
br	1	0	#011#	Right	z1
z1	2	1	#011#	Right	z1
z1	3	1	#011#	Right	z1
z1	4	#	#011#	Left	z2
z2	3	1	#011#	Write 1	e1
e1	3	1	#011#	Write #	e2
e2	3	#	#01##	Left	e1
e1	2	1	#01##	Write #	e2
e2	2	#	#0###	Left	e1
e1	1	0	#0###	Write #	e2
e2	1	#	#####	Left	e1
e1	0	#	#####	Write 0	ha
ha	0	0	0#####	Halt	ha

<http://www.comp.nus.edu.sg/~gem1501/assignment18.html>

Variants of Turing Machines

- Turing Machines might use additional symbols on the tape.
- Turing Machines might by the same command write a symbol and then move the head (as in Harel's book).
- Turing Machines might compute $\{0, 1\}$ -valued functions by having states for “Halt with output 1” and a “Halt with output 0” (as in Harel's book).
- All these models are equivalent.

Universal Turing Machines

There is a Turing machine M with two inputs interpreting the first input e as a program. M has the following properties:

- For every two inputs e and x , the function f_e given by e is computable where $f_e(x) = y$ if M with input e, x halts with output y and $f_e(x)$ be undefined if M with input e, x does not halt.
- Whenever g is a computable partial function then there is an e with $g = f_e$;
- Whenever N is a Turing machine with one input then one can compute from the description of N an index e such that f_e is the function computed by N .

The power of Turing Machines

- Turing machines can detect palindromes, add, multiply and so on.
- What other problems can they solve?
- Answer: Turing machines can solve any effectively solvable algorithmic problem!
- A function is recursive iff there is a Turing machine computing it; thus recursive functions are also just called computable functions.

Characterizing Recursively Enumerable Sets

- A nonempty set A is recursively enumerable iff there is a Turing machine which computes a total function f with range A .
- A set A is recursively enumerable iff there is a Turing machine which halts iff the input is from A .
- The same could be done with Java Script programs in place of Turing machines.
- Are there other simple machine models?

Overview

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- **Multiple Stack Machines**
- Church's Thesis
- Numerical Computation:
Counter Programs
- Restricted Models:
One Stack Machines and Finite Automata

Example: Multiple Stack Machines

- Machine with k stacks, k a constant.
- Machine can pop top symbol of some stack.
- Machine can push a symbol onto some stack.
- Besides that, machine has finitely many states and variables holding one symbol to store current information.
- Input either read step by step from a source or in one stack.

Detecting Palindromes

Machine with three stacks u, v, w and two character variables a, b .
Initially input in stack u , stacks v and w are empty.

Algorithm:

```
function ispalindrome(u)
  { while (u not empty) // copying and
    { a = pop(u); push(v,a); push(w,a); } // reverting u to v,w
  while (v not empty) // copying and
    { a = pop(v); push(u,a); } // reverting v to u
  b = a; // copying a to b
  while ((u not empty) and (a == b)) // comparing u,w
    { a = pop(u); b = pop(w); }
  if (a == b) { return(true); } else { return(false); } }
```

Runtime Example

stacks	u	v	w	variables	a	b	
Input 1	10201	-	-	-	-	-	
u -> v,w	-	10201	10201	1	-		
v -> u	10201	-	10201	1	-		
a -> b	10201	-	10201	1	1		
comparing	1020	-	1020	1	1		
	102	-	102	0	0		
	10	-	10	2	2		
	1	-	1	0	0		
	-	-	-	1	1		>> a palindrome
Input 2	1011201	-	-	-	-	-	
u -> v,w	-	1021101	1021101	1	-		
v -> u	1011201	-	1021101	1	-		
a -> b	1011201	-	1021101	1	1		
comparing	101120	-	102110	1	1		
	10112	-	10211	0	0		
	1011	-	1021	2	1		>> not a palindrome

Detecting Palindromes, Summary

- Multi Stack Machines can also detect palindromes.
- They are even faster and need time $O(n)$.
- Turing Machine cannot detect palindromes in time $O(n)$.
- Can Multi Stack Machines do the same operations as Turing machines?

Simulating Turing Machines

2 Stack Machines can simulate Turing machines.

Popping an empty stack gives the symbol #.

stack v	var a	stack w	var b
left part of tape	head	right part of tape	state

Initialization

v is empty, a = #, b = st, w = input word.

Operations simulated as follows:

Left Push a onto stack w, Pop a from stack v

Right Push a onto stack v, Pop a from stack w

Write c Let a = c

Halt Halt the stack machine

Update of state:

b = Turing Table Entry for (old value of b, old value of a)

Equivalence

- Just seen: Multi Stack machines can simulate Turing machines
- Turing machines can also simulate Multi Stack machines.
- The models for computation given by Turing machines and Multi Stack machines are equivalent.

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Church's Thesis

- Named after Alonzo Church (and sometimes also after Alan Turing).
- **Thesis:** A function is computable in the intuitive sense iff it is computable by a Turing machine.
- More precisely, any reasonable formalization of the notion “computable function” will lead to a concept equivalent to being computable by a Turing machine.
- The same applies for the notions of “decidable (or recursive) set” and “recursively enumerable set”.
- Furthermore, computation can be formalized in the numerical framework as well as in the symbolic one (by manipulating strings). Both frameworks are transformable into each other.

Some Evidence for Church's Thesis

- Multi Stack machines and Turing machines can simulate each other.
- Furthermore, a function is polynomial time computable iff this holds for one of the following models:
 - Turing machines;
 - Multi Stack machines;
 - Java Script programs.
- The notions of computation and even of polynomial time computation are independent of the chosen machine model.

Why “Thesis” ?

- **Theorem**

A function is computable by a Turing machine iff it is computable by a Multi Stack machine.

- **Thesis**

A function is computable by a Turing machine iff it is computable by any reasonable model of computation.

- **Remark**

The words “reasonable model” or “intuition” used in Church’s Thesis are not formally defined.

Thus “Thesis” and not “Theorem”.

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A numerical model: Counter programs

- Variables can hold any natural number
- Operations: $x = 0$, $x = y$, $x = y + 1$, $x = y - 1$
- Control statement: `if $x == 0$ goto line g`

Also unconditional Goto Statements permitted

Adding numbers

```
function add(x,y) // counter machine format
```

```
  1: z = 0;
  2: if x == 0 goto 6;
  3: x = x-1;
  4: z = z+1;
  5: goto 2;
  6: if y == 0 goto 10;
  7: y = y-1;
  8: z = z+1;
  9: goto 6;
10: return(z);
```

```
function add(x,y) // normal Java Script format for same program
```

```
{ var z; z = 0;
  while (x>0) { x = x-1; z = z+1; }
  while (y>0) { y = y-1; z = z+1; }
  return(z); }
```

Multiplying numbers

```
function mult(x,y)
```

```
  1: z = 0;
  2: v = x;
  3: if v == 0 then goto 11;
  4: w = y;
  5: if w == 0 then goto 9;
  6: w = w-1;
  7: z = z+1;
  8: goto 5;
  9: v = v-1;
 10: goto 3;
 11: return(z);
```

```
function mult(x,y)
```

```
  { var z; var v; var w; z = 0; v = x;
    while (v>0) { w = y; v = v-1;
                  while (w>0) { z = z+1; w = w-1; } }
    return(z); }
```

Counter Programs

- Counter programs and Turing machines are equivalent.
- One can always translate one to the other, they can simulate each other.
- Counter programs are slower than Turing machines: adding n -digit numbers is polynomial in n for Turing machines and exponential in n for counter programs.
- As very simple models, Turing machines are used in lower-bound proofs on computation speed.
- One can speed up counter programs by permitting them to add, subtract or compare variables in one step. For these programs, the notion of polynomial time computable function is the same as for Turing machines.

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One Stack machines

- Exactly one stack permitted;
- Input is read from separate source from left to right;
- Furthermore finite control (finitely many variables for one symbol, finitely many states)
- Some states are accepting and some rejecting.
- Input word in set A iff last state of computation is “accepting” .

Brackets

Algorithm to check correctness of bracket-expression

```
var stack = new Array("#"); var a; var b;
loop { a = next input symbol;
      switch(a)
        { case "(", case "[": stack.push(a); break;
          case ")": b = stack.pop();
                    if (b != "(") { reject; abort; } break;
          case "]": b = stack.pop();
                    if (b != "[") { reject; abort; } break;
          default: break; }
      if (stack == "#") then accept else reject; }
```

Algorithm accepts iff it is not aborted and the state is accepting after processing all input symbols.

Runtime Example

Input	Stack after current input	Accept / Reject / Reject forever (current) (aborted case)
(2+3*(5+8)+[10	#([Reject
-25*3]-18)*12	#	Accept
*x*y+23*(235+	#(Reject
[[[(12+3)*5+7*	#([[Reject
234567]-13]+2*(#([Reject
12-17)]*3+5)+8*	#	Accept
[[*17-3))+((5*2	#[Aborted, Reject forever
.....	#[Aborted, Reject forever

A more sophisticated version of this algorithm is implemented in syntax-checkers of compilers and browsers.

Counting 0's and 1's

Algorithm to check whether 0's and 1's are same quantity

```
var stack = new Array(); var a; var b;
loop { a = next input symbol;
      if ((a == "0") or (a == "1"))
        { if (stack.length == 0) { stack.push(a); }
          else
            { b = stack.pop();
              if (a == b) { stack.push(b); stack.push(a); } } }
      if (stack.length == 0) { accept; } else { reject; } }
```

Assume that n zeroes and m ones have seen:

If $n > m$ then stack has $n-m$ zeroes and state rejecting;

If $n < m$ then stack has $m-n$ ones and state rejecting;

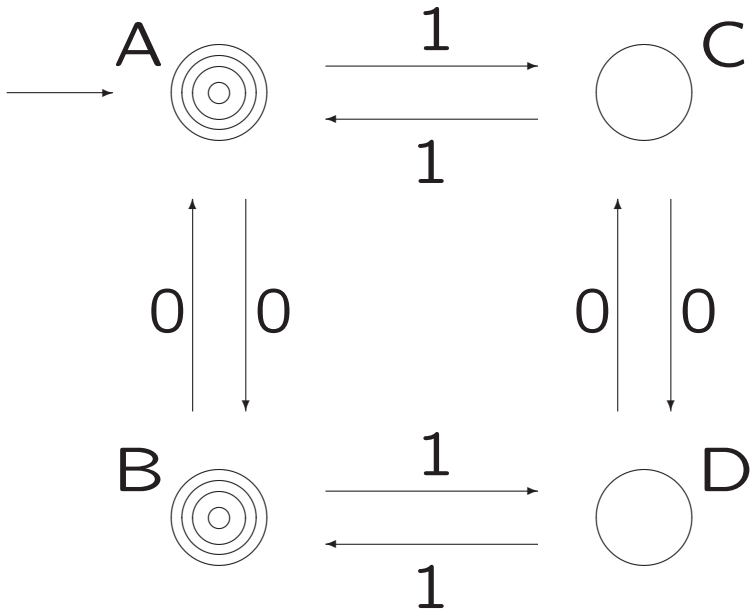
If $n == m$ then stack is empty and state accepting.

So stack is 000 after input 01112020001200.

Limitations

- One stack machines cannot count independently three things: Set of all numbers containing as many 0 as 1 as 2 cannot be accepted.
- One stack machines also cannot check in program-texts whether the names of declared and used variables are the same. This part of a syntax check needs more complicated methods.

Finite Automata



A word is accepted iff it has an even number of 1s.

State:	A	B	C	D	Starting: A
Successor when 0:	B	A	D	C	Accepting: A, B
Successor when 1:	C	D	A	B	Rejecting: C, D

Runtime Example

Input read so far	State
-	A (accepting)
0	B (accepting)
00	A (accepting)
000	B (accepting)
0001	D (rejecting)
00010	C (rejecting)
000101	A (accepting)
0001011	C (rejecting)
00010111	A (accepting)
000101110	A (accepting)

See also <http://www.comp.nus.edu.sg/~gem1501/assignment16.html>

Further Example

This automaton recognizes whether a binary number is the multiple of 5. The empty binary word is accepted and the starting state is q0.

state	successor at 0	successor at 1	acc/rej
q0	q0	q1	accept
q1	q2	q3	reject
q2	q4	q0	reject
q3	q1	q2	reject
q4	q3	q4	reject

Sample run

1010 (ten) 1 0 1 0
q0 -> q1 -> q2 -> q0 -> q0: accept

1100 (twelf) 1 1 0 0
q0 -> q1 -> q3 -> q1 -> q2: reject

Power of Finite Automata

- Cannot count
- Only finite control
- Can easily be modified and analyzed
- Every task has a minimal finite automaton

Finite Automata Cannot Count!

No finite automaton can decide whether its input sequence contains precisely the same number of 0's and 1's.

- There are two different numbers n and m such that automaton is in same state after seeing 0^n and 0^m .
- For any k , automaton is then also in the same state after seeing $0^n 1^k$ and $0^m 1^k$.
- Automaton either accepts both $0^n 1^n$ and $0^m 1^n$ or rejects both.
- Thus automaton does not count 0's and 1's properly, even if all 0's come first and all 1's second.

Application of Finite Automata

- Describing Processes with finitely many states.
- Often used as basic algorithms: In each state, a certain subprogram is activated.
- Example: Drawing Money from Automated Teller Machine
 1. Read Card.
 2. Read PIN.
 3. If PIN incorrect goto 8.
 4. Read amount of money to withdraw.
 5. If money not in account goto 8.
 6. If money not in machine goto 9.
 7. Hand out card, hand out money and goto 1.
 8. Print excuse, hand out card and goto 1.
 9. Print big excuse, hand out card and goto 1.

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Next Week: Parallelism

- Parallel Computing
- Parallel Sorting
- Weighted Averages
- Sequential Polynomial Space, Parallel Polynomial Time
- Nick's Class
- Coordinating Parallelism
- New Models of Computing