

Mathematics 3670: Computer Systems Introduction

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Course administrivia

Course website	www.eiu.edu/~mathcs/mat3670
My email	waslough@eiu.edu
Office hours	10:00 – 11:00 MW, 9:00 – 11:00 F and by appointment
Macintosh accounts	match your EIU e-mail id
Lectures	9:00 – 9:50, Monday and Wednesday
Labs	9:00 – 10:40, Thursday
Exam 1	Wednesday, September 28
Exam 2	Wednesday, November 9
Final	Tuesday, December 13, 8:00–10:00

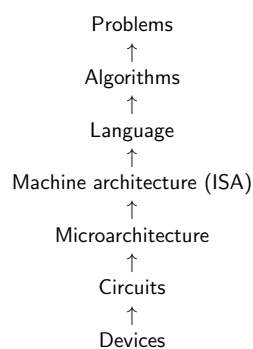
Week 1: to do

What	When
Read Chapter 1	this week
Read Lab 1 handout	before Thursday
Determine Lab 1 Turing machine snapshots	before Thursday
Design Turing machine for halving	before Thursday
Complete Lab 1	this Thursday
Submit Lab 1 work	on/before next Thursday

The big picture

- Complex systems can be organized as a hierarchy of **abstractions**
- Bottom level is most basic; upper levels appear most complex
- We will study this hierarchy from the **bottom up**
- Key idea: how is level $N + 1$ implemented given level N ?
- Ultimate aim – understand how the top level is achieved: **no magic allowed!**

A hierarchy



Problem solving with computers

- Begin with a **problem statement**
 - What are the inputs?
 - What are the desired outputs?
 - What is the relationship between inputs and outputs?
- Design an **algorithm**, which will transform inputs to outputs
- How do we express the algorithm?
Ultimately, we want the algorithm to become a well-defined pattern of electrons flowing within a physical computer

A simple problem

- Input: A non-negative integer n
- Output: $n \bmod 3$

To design an algorithm for this problem, we need to know:

- what **primitive operations** are available
- what **abstraction level** is appropriate

Depending on the abstraction level, we may also need to be aware of **data representation**

The Turing machine

- Proposed in 1936 by English mathematician Alan Turing
- Can be used to formalize the idea of algorithm
- Is simple to describe
- Like modern computers, operates at a very basic level: any one step within a computation doesn't do very much

The Turing machine: basic ingredients

- A **tape**, divided into squares – infinite in both directions
- A **read/write head** which can inspect and change the contents of one square on the tape
- A **finite control unit** which remembers the “state”
- An **initial state**
- A **finite table of actions** which controls how the machine makes one computational step

Turing machine actions

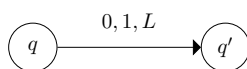
Any one action of the Turing machine is described by five components:

- current state
- current symbol
- symbol to write
- next state
- direction to move read/write head: left, right, stay

For example, $(q, 0, 1, q', L)$ tells the machine “if in state q the read/write head is scanning the symbol 0 , then overwrite it with the symbol 1 , switch to state q' and move the read/write head one step to the left”

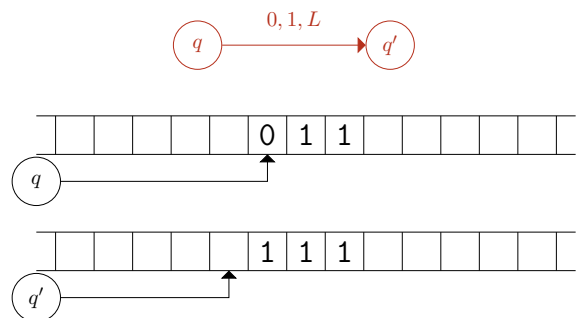
Turing machine actions

The action $(q, 0, 1, q', L)$ can be viewed as an edge in a directed graph:

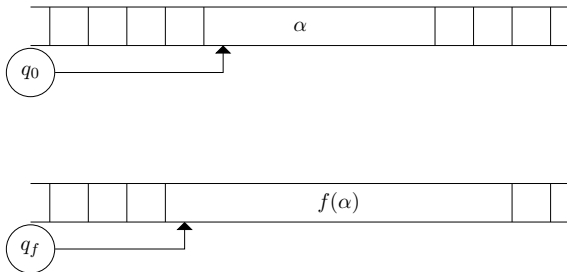


We can describe a Turing machine with a collection of actions like these, giving us a labeled, directed graph

Turing machines: one computation step



Computing functions with Turing machines

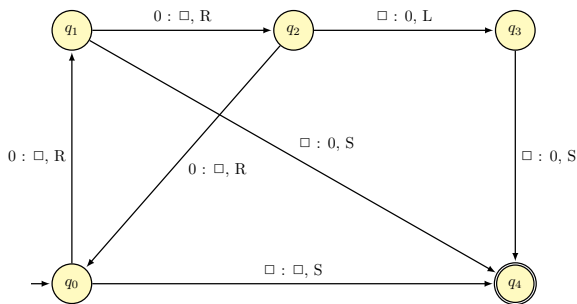


Back to the mod 3 problem

- We will represent n in **unary**
For input 35, place 35 consecutive 0's on the tape
We want to end up with $35 \bmod 3 = 2$, i.e., 2 consecutive 0's
- Division by 3 can be accomplished by repeated subtraction
- Challenge: what states and transitions are needed?

Let's think about it...

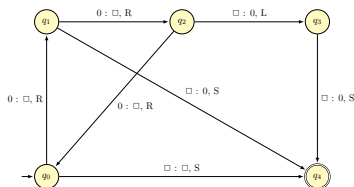
A Turing machine solution for the mod 3 problem



Simulating a Turing machine

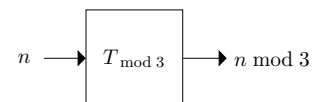
Live demo of JFLAP

Understanding the mod 3 Turing machine



- The q_0, q_1, q_2 cycle subtracts 3 on each complete loop
- q_0 – so far, we have removed $3t$ zeros
- q_1 – so far, we have removed $3t + 1$ zeros
- q_2 – so far, we have removed $3t + 2$ zeros
- $q_2 \rightarrow q_3 \rightarrow q_4$ writes 00, then halts
- $q_1 \rightarrow q_4$ writes 0, then halts
- $q_0 \rightarrow q_4$ writes \square , then halts

Turing machines as black boxes

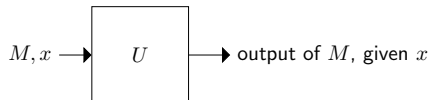


Black box view is an essential **abstraction**:

- Hides inessential detail
- Allows for understanding of "big picture"

Universal computational device (Turing, 1936)

- $T_{\text{mod } 3}$ does one task and one task only
- If you want to perform some other task, you need a different machine
- Could we design **one** machine that can do the work of **any** other machine?
- Yes! This is the machine we call U — the **universal** machine



- U simulates what M would do — a **programmable computer!**

Turing's thesis

If an algorithm exists for some problem, there is an equivalent Turing machine

Turing's work provides a foundation for understanding the limits of computation — what is possible to compute and what is impossible to compute

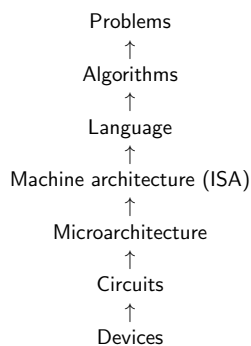
Important idea #1 (textbook)

All computers (big, small, fast, slow, ...) are capable of computing exactly the same things, given enough time and enough memory

Important idea #2 (textbook)

Problems we wish to solve with a computer are stated in some natural language, such as English. Ultimately, these problems are solved by electrons running around inside the computer. To achieve this, a sequence of systematic transformations takes place. At the lowest levels, very simple tasks are being performed.

The hierarchy, revisited



Problem statement

- Stated in a natural language, like English
- We must avoid any ambiguity
- Misunderstandings at this level will cause many issues later in the development, increasing development cost, delaying completion
- Obtaining an accurate specification of the problem is often difficult

The algorithm: essential ingredients

- Some number of **inputs**
- Some number of **outputs**
- **Definiteness** property: each step must be precisely defined
- **Effectiveness** property: each step must be something that can be carried out by a person in a finite amount of time
- **Finiteness** property: the algorithm, when followed, must terminate after a finite number of steps

Definiteness – you be the judge

- Suppose m and n are two arbitrary integers; positive, zero, or negative
- We are devising an algorithm that uses “integer” division, with quotient and remainder; one step is:
let k be the remainder of $m \div n$
- For **definiteness**, we need a precise definition of the action
- Do we have that?

Effectiveness – you be the judge

- Suppose we are devising an algorithm which uses floating point arithmetic; one step is:
if there are 7 consecutive 3's in the decimal expansion of π then ...
- For **effectiveness**, each step must be something that can be
 - basic enough to be carried out by a person
 - completed in a finite amount of time
- Do we have that?

Finiteness – you be the judge

- Suppose we are computing with exact, rational arithmetic
Let x be $1/7$
Determine m and d_1, d_2, \dots, d_m so that $0.d_1d_2\dots d_m = x$
- For **finiteness**, each step must terminate after some finite number of steps
- Do we have that?

From algorithms to programs

- To implement an algorithm, we need a programming language
 - High level: Java, C++, C, COBOL, FORTRAN, Python, Perl, Prolog, etc.
 - Low level: Assembly language
- High level – machine independent
- Low level – tied to a specific architecture

The ISA – Instruction Set Architecture

- Ultimately, programs are expressed as patterns of 0's and 1's: machine language
- **Translators** (compilers and assemblers) perform conversion, producing machine language from higher levels
- ISA specifies:
 - instruction set (what operations are possible?)
 - data types (e.g., integer vs. floating point, range and precision)
 - addressing modes (how is an operand located in the memory?)
- Typical ISAs: Intel x86, HP PA-RISC, Sun Sparc, ARM, Motorola 68k, etc.

Microarchitecture

- microarchitecture: implementation of an ISA
- To add x to y requires lower level details, register transfers, etc.
- There can be multiple implementations of an ISA

Logic circuits

- Fundamental building blocks: AND, OR, NOT
- Very simple: one bit operands
- Use these building blocks to create ALUs, memories, etc.

Device level

- Technologies: CMOS, NMOS, GaAs, etc.
- Solid-state physics, electrical engineering