

Computability, Complexity

M269 Tutorial

Phil Molyneux

26 April 2026

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Agenda, Aims and Topics

1 Agenda, Aims and Topics

- ▶ Overview of aims of tutorial
- ▶ Note selection of topics
- ▶ Points about my own background and preferences
- ▶ Adobe Connect slides for reference
- ▶ Note that the Computability notes are here mainly for reference since the Complexity notes refer to them
- ▶ This session is mainly on the Complexity topics

Computability, Complexity Tutorial

Agenda

- ▶ Welcome & Introductions
- ▶ Computability topics:
 - ▶ Ideas of Computation and Algorithms
 - ▶ Problem Reduction
 - ▶ Turing Machines
 - ▶ Undecidable, Semi-decidable and decidable problems
 - ▶ Effective Computability: Turing machines, Lambda Calculus, μ -recursive functions
 - ▶ *Optional topic* Lambda Calculus introduction
- ▶ Complexity topics
 - ▶ Complexity classes **P** and **NP**
 - ▶ Demonstrating membership of class **NP**
 - ▶ **NP-complete** class
 - ▶ Boolean satisfiability — first NP-complete problemhow to overcome them.
- ▶ *Adobe Connect* — if you or I get cut off, wait till we reconnect (or send you an email)
- ▶ **Recording** Meeting Record Meeting... ✓

M269 Tutorial

Introductions — Me

- ▶ *Name* Phil Molyneux
- ▶ *Background* Physics and Maths, Operational Research, Computer Science
- ▶ *First programming languages* [Fortran](#), [BASIC](#), [Pascal](#)
- ▶ *Favourite Software*
 - ▶ [Haskell](#) — pure functional programming language
 - ▶ Text editors [TextMate](#), [Sublime Text](#) — previously [Emacs](#)
 - ▶ Word processing and presentation slides in [L^AT_EX](#)
 - ▶ [Mac OS X](#)
- ▶ *Learning style* — I read the manual before using the software (really)

M269 Tutorial

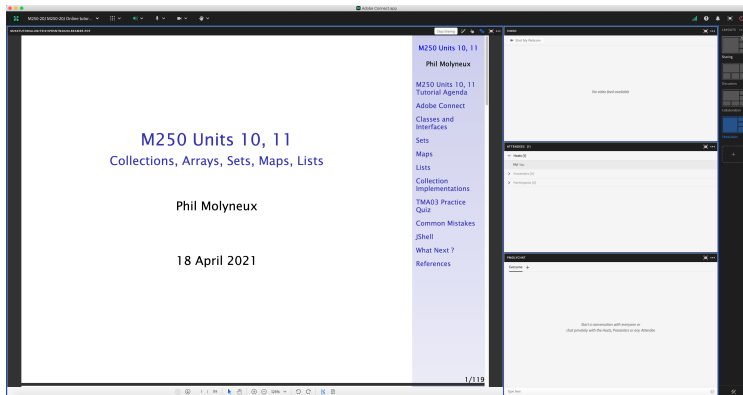
Introductions — You

- ▶ *Name?*
- ▶ *Position in M269?* Which part of which Units and/or Reader have you read?
- ▶ *Particular topics you want to look at?*
- ▶ *Learning Style?*

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Adobe Connect

Interface — Host View



Computability,
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Phil Molyneux

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Interface — Participant View

Computability,
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M250 Units 10, 11 Tutorial
Introductions

- ▶ Introductions
 - ▶ Name *Phil Molyneux*
 - ▶ Learning Style: *Reads the manual*
 - ▶ Learnt last month *Framework for Teaching Recursion* and wrote notes on *Recursion Teaching*
 - ▶ You ?

M250 Units 10, 11 Tutorial Agenda
Phil Molyneux

Adobe Connect
Classes and Interfaces

Sets

Maps

Lists

Collection Implementations

TMA03 Practice Quiz

Common Mistakes

JShell

What Next ?

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Settings

- ▶ **Everybody** *Menu bar* *Meeting* *Speaker & Microphone Setup*
- ▶ *Menu bar* *Microphone* *Allow Participants to Use Microphone* ✓
- ▶ Check Participants see the entire slide **Workaround**
 - ▶ *Disable Draw* *Share pod* *Menu bar* *Draw icon*
 - ▶ *Fit Width* *Share pod* *Bottom bar* *Fit Width icon* ✓
- ▶ *Meeting* *Preferences* *General* *Host Cursor* *Show to all attendees*
- ▶ *Menu bar* *Video* *Enable Webcam for Participants* ✓
- ▶ Do not *Enable single speaker mode*
- ▶ Cancel hand tool
- ▶ Do not enable green pointer
- ▶ **Recording** *Meeting* *Record Session* ✓
- ▶ **Documents** Upload PDF with drag and drop to share pod
- ▶ Delete *Meeting* *Manage Meeting Information* *Uploaded Content*
and *check filename* *click on delete*

▶ Tutor Access

TutorHome > M269 Website > Tutorials

Cluster Tutorials > M269 Online tutorial room

Tutor Groups > M269 Online tutor group room

Module-wide Tutorials > M269 Online module-wide room

▶ Attendance

TutorHome > Students > View your tutorial timetables

▶ Beamer Slide Scaling 440% (422 x 563 mm)

▶ Clear Everyone's Status

Attendee Pod > Menu > Clear Everyone's Status

▶ Grant Access and send link via email

Meeting > Manage Access & Entry > Invite Participants. . .

▶ Presenter Only Area

Meeting > Enable/Disable Presenter Only Area

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Adobe Connect

Keystroke Shortcuts

- ▶ **Keyboard shortcuts in Adobe Connect**
- ▶ **Toggle Mic**  + **M** (Mac), **Ctrl** + **M** (Win) (On/Disconnect)
- ▶ **Toggle Raise-Hand status**  + **E**
- ▶ **Close dialog box**  (Mac), **Esc** (Win)
- ▶ **End meeting**  + ****

Adobe Connect Interface

Sharing Screen & Applications

- ▶ **Share My Screen** > **Application tab** > **Terminal** for **Terminal**
- ▶ **Share menu** > **Change View** > **Zoom in** for mismatch of screen size/resolution (Participants)
- ▶ (Presenter) Change to 75% and back to 100% (solves participants with smaller screen image overlap)
- ▶ Leave the application on the original display
- ▶ Beware blue hatched rectangles — from other (hidden) windows or contextual menus
- ▶ Presenter screen pointer affects viewer display — beware of moving the pointer away from the application
- ▶ First time: **System Preferences** > **Security & Privacy** > **Privacy** > **Accessibility**

Adobe Connect

Ending a Meeting

- ▶ *Notes for the tutor only*
- ▶ **Student:** Meeting > Exit Adobe Connect
- ▶ **Tutor:**
- ▶ **Recording** Meeting > Stop Recording ✓
- ▶ **Remove Participants** Meeting > End Meeting... ✓
 - ▶ Dialog box allows for message with default message:
 - ▶ *The host has ended this meeting. Thank you for attending.*
- ▶ **Recording availability** *In course Web site for joining the room, click on the eye icon in the list of recordings under your recording* — edit description and name
- ▶ **Meeting Information** Meeting > Manage Meeting Information — can access a range of information in Web page.
- ▶ **Delete File Upload** Meeting > Manage Meeting Information > Uploaded Content tab select file(s) and click Delete
- ▶ **Attendance Report** see course Web site for joining room

Adobe Connect


Invite Attendees

- ▶ **Provide Meeting URL** Menu > Meeting > Manage Access & Entry > Invite Participants...
- ▶ **Allow Access without Dialog** Menu > Meeting > Manage Meeting Information provides new browser window with *Meeting Information* Tab bar > Edit Information
- ▶ Check *Anyone who has the URL for the meeting can enter the room*
- ▶ Default *Only registered users and accepted guests may enter the room*
- ▶ **Reverts to default next session but URL is fixed**
- ▶ Guests have blue icon top, registered participants have yellow icon top — same icon if URL is open
- ▶ See [Start, attend, and manage Adobe Connect meetings and sessions](#)

Adobe Connect

Entering a Room as a Guest (1)

- ▶ Click on the link sent in email from the Host
- ▶ Get the following on a Web page
- ▶ As *Guest* enter your name and click on **Enter Room**

 **Adobe Connect**

M269-21J Online tutorial room
London/SE (1,13) CG [2311] (M269-21J)
(1)

Guest Registered User

Name
Guest Name

By entering a Name & clicking "Enter Room", you agree that you have read and accept the [Terms of Use & Privacy Policy](#).

Enter Room

Adobe Connect

Entering a Room as a Guest (2)

- ▶ See the *Waiting for Entry Access* for *Host* to give permission



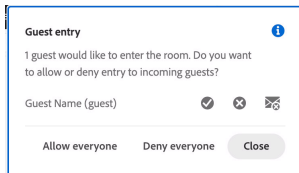
Waiting for Entry Access

This is a private meeting. Your request to enter has been sent to the host. Please wait for a response.

Adobe Connect

Entering a Room as a Guest (3)

- ▶ *Host* sees the following dialog in *Adobe Connect* and grants access



Adobe Connect

Layouts


- ▶ **Creating new layouts** example *Sharing* layout
 - ▶ **Menu** > **Layouts** > **Create New Layout...** > **Create a New Layout dialog** > **Create a new blank layout** and name it *PMolyMain*
- ▶ New layout has no Pods but does have Layouts Bar open (see Layouts menu)
- ▶ **Pods**
 - ▶ **Menu** > **Pods** > **Share** > **Add New Share** and resize/position — initial name is *Share n* — rename *PMolyShare*
 - ▶ **Rename Pod** **Menu** > **Pods** > **Manage Pods...** > **Manage Pods** > **Select** > **Rename** or **Double-click & rename**
- ▶ Add Video pod and resize/reposition
- ▶ Add Attendance pod and resize/reposition
- ▶ Add Chat pod — rename it *PMolyChat* — and resize/reposition

- ▶ Dimensions of **Sharing** layout (on 27-inch iMac)
 - ▶ Width of Video, Attendees, Chat column 14 cm
 - ▶ Height of Video pod 9 cm
 - ▶ Height of Attendees pod 12 cm
 - ▶ Height of Chat pod 8 cm
- ▶ **Duplicating Layouts** does *not* give new instances of the Pods and is probably not a good idea (apart from local use to avoid delay in reloading Pods)
- ▶ **Auxiliary Layouts** name *PMolyAuxOn*
 - ▶ Create new Share pod
 - ▶ Use existing Chat pod
 - ▶ Use same Video and Attendance pods

Adobe Connect

Chat Pods

- ▶ **Format Chat text**

- ▶ 




- ▶ Choices: Red, Orange, Green, Brown, Purple, Pink, Blue, Black

- ▶ Note: Color reverts to Black if you switch layouts

- ▶ 

Graphics Conversion

PDF to PNG/JPG

- ▶ Conversion of the screen snaps for the installation of Anaconda on 1 May 2020
- ▶ Using GraphicConverter 1.1
- ▶ 
- ▶ Select files to convert and destination folder
- ▶ Click on  or 

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Adobe Connect Recordings

Exporting Recordings

- ▶ *Menu bar* > *Meeting* > *Preferences* > *Video*
- ▶ *Aspect ratio* > *Standard (4:3)* (not *Wide screen (16:9)* default)
- ▶ *Video quality* > *Full HD* (1080p not *High* default 480p)
- ▶ **Recording** *Menu bar* > *Meeting* > *Record Session* ✓
- ▶ **Export Recording**
- ▶ *Menu bar* > *Meeting* > *Manage Meeting Information*
- ▶ *New window* > *Recordings* > *check Tutorial* > *Access Type button*
- ▶ *check Public* > *check Allow viewers to download*
- ▶ **Download Recording**
- ▶ *New window* > *Recordings* > *check Tutorial* > *Actions* > *Download File*

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Commentary 2

Computability

2 Computability

- ▶ Description of Turing Machine
- ▶ Turing Machine examples
- ▶ Computability, Decidability and Algorithms
- ▶ Non-computability — Halting Problem
- ▶ Reductions and non-computability
- ▶ Lambda Calculus (optional)
- ▶ Note that the Computability notes are here mainly for reference since the Complexity notes refer to them
- ▶ This session is mainly on the Complexity topics

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Computability

Ideas of Computation

- ▶ The idea of an algorithm and what is effectively computable
- ▶ **Church-Turing thesis** Every function that would naturally be regarded as computable can be computed by a deterministic Turing Machine. (Unit 7 Section 4)
- ▶ See [Phil Wadler on computability theory](#) performed as part of the Bright Club at The Strand in Edinburgh, Tuesday 28 April 2015

Computability

Models of Computation

- ▶ In automata theory, a *problem* is the question of deciding whether a given string is a member of some particular language
- ▶ If Σ is an alphabet, and L is a language over Σ , that is $L \subseteq \Sigma^*$, where Σ^* is the set of all strings over the alphabet Σ then we have a more formal definition of *decision problem*
- ▶ Given a string $w \in \Sigma^*$, decide whether $w \in L$
- ▶ Example: Testing for a prime number — can be expressed as the language L_p consisting of all binary strings whose value as a binary number is a prime number (only divisible by 1 or itself)
- ▶ See Hopcroft (2007, section 1.5.4)

Automate Theory

Alphabets, Strings

- ▶ An **Alphabet**, Σ , is a finite, non-empty set of symbols.
- ▶ Binary alphabet $\Sigma = \{0, 1\}$
- ▶ Lower case letters $\Sigma = \{a, b, \dots, z\}$
- ▶ A **String** is a finite sequence of symbols from some alphabet
- ▶ 01101 is a string from the Binary alphabet $\Sigma = \{0, 1\}$
- ▶ The **Empty string**, ϵ , contains no symbols
- ▶ **Powers**: Σ^k is the set of strings of length k with symbols from Σ
- ▶ The set of all strings over an alphabet Σ is denoted Σ^*
- ▶ $\Sigma^* = \Sigma^0 \cup \Sigma^1 \cup \Sigma^2 \cup \dots$
- ▶ **Question** Does $\Sigma^0 = \emptyset$? (\emptyset is the empty set)

Automata Theory

Languages

- ▶ An **Language**, L , is a subset of Σ^*
- ▶ The set of binary numerals whose value is a prime
 $\{10, 11, 101, 111, 1011, \dots\}$
- ▶ The set of binary numerals whose value is a square
 $\{100, 1001, 10000, 11001, \dots\}$

Computability

Church-Turing Thesis & Quantum Computing

- ▶ **Church-Turing thesis** Every function that would naturally be regarded as computable can be computed by a deterministic Turing Machine.
- ▶ **physical Church-Turing thesis** Any finite physical system can be simulated (to any degree of approximation) by a Universal Turing Machine.
- ▶ **strong Church-Turing thesis** Any finite physical system can be simulated (to any degree of approximation) with polynomial slowdown by a Universal Turing Machine.
- ▶ **Shor's algorithm** (1994) — quantum algorithm for factoring integers — an NP problem that is not known to be P — also not known to be NP-complete and we have no proof that it is not in P
- ▶ Reference: Section 4 of Unit 6 & 7 Reader

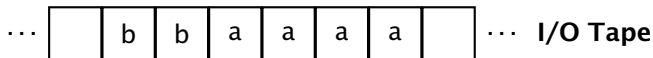
Computability

Turing Machine

- ▶ **Finite control** which can be in any of a finite number of *states*
- ▶ **Tape** divided into cells, each of which can hold one of a finite number of symbols
- ▶ Initially, the **input**, which is a finite-length string of symbols in the *input alphabet*, is placed on the tape
- ▶ All other tape cells (extending unbounded left and right) hold a special symbol called *blank*
- ▶ A **tape head** which initially is over the leftmost input symbol
- ▶ A **move** of the Turing Machine depends on the state and the tape symbol scanned
- ▶ A move can change state, write a symbol in the current cell, move left, right or stay
- ▶ References: Hopcroft (2007, page 326), Unit 6 & 7 Reader (section 5.3)

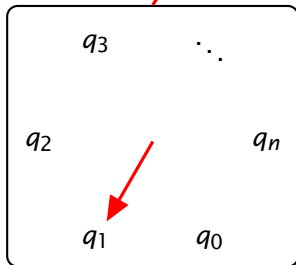
Turing Machine Diagram

Turing Machine Diagram



Reading and Writing Head

(moves in both directions)



Finite Control

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Computability

Turing Machine notation

- ▶ Q finite set of states of the finite control
- ▶ Σ finite set of *input symbols* (M269 S)
- ▶ Γ complete set of *tape symbols* $\Sigma \subset \Gamma$
- ▶ δ Transition function (M269 instructions, l)
 $\delta :: Q \times \Gamma \rightarrow Q \times \Gamma \times \{L, R, S\}$
 $\delta(q, X) \mapsto (p, Y, D)$
- ▶ $\delta(q, X)$ takes a state, q and a tape symbol, X and returns (p, Y, D) where p is a state, Y is a tape symbol to overwrite the current cell, D is a direction, Left, Right or Stay
- ▶ q_0 start state $q_0 \in Q$
- ▶ B blank symbol $B \in \Gamma$ and $B \notin \Sigma$
- ▶ F set of *final or accepting states* $F \subseteq Q$

Turing Machine Examples

Turing Machine Simulators

- ▶ [Morphett's Turing machine simulator](#) — the examples below are adapted from here
- ▶ [Ugarte's Turing machine simulator](#)
- ▶ [XKCD A Bunch of Rocks](#) — [XKCD Explanation](#)
Image below (will need expanding to be readable)
- ▶ The term *state* is used in two different ways:
The value of the *Finite Control*
The overall configuration of *Finite Control* and current contents of the tape
See [Turing Machine: State](#)
will lead to some confusion

Turing Machine Examples

XKCD A Bunch of Rocks

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Turing Machine Examples

Meta-Exercise

- ▶ For each of the Turing Machine Examples below, identify

$(Q, \Sigma, \Gamma, \delta, q_0, B, F)$

Turing Machine Examples

The Successor Function

- ▶ **Input** binary representation of numeral n
- ▶ **Output** binary representation of $n + 1$
- ▶ Example $1010 \mapsto 1011$ and $1011 \mapsto 1100$
- ▶ Initial cell: leftmost symbol of n
- ▶ **Strategy**
- ▶ **Stage A** make the rightmost cell the current cell
- ▶ **Stage B** Add 1 to the current cell.
- ▶ If the current cell is 0 then replace it with 1 and go to stage C
- ▶ If the current cell is 1 replace it with 0 and go to stage B and move Left
- ▶ If the current cell is blank, replace it by 1 and go to stage C
- ▶ **Stage C** Finish up by making the leftmost cell current

Turing Machine Examples

The Successor Function (2)

- ▶ Represent the Turing Machine program as a list of quintuples (q, X, p, Y, D)

- ▶ **Stage A**

$(q_0, 0, q_0, 0, R)$

$(q_0, 1, q_0, 1, R)$

(q_0, B, q_1, B, L)

- ▶ **Stage B**

$(q_1, 0, q_2, 1, S)$

$(q_1, 1, q_1, 0, L)$

$(q_1, B, q_2, 1, S)$

- ▶ **Stage C**

$(q_2, 0, q_2, 0, L)$

$(q_2, 1, q_2, 1, L)$

(q_2, B, q_h, B, R)

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Turing Machine Examples

The Successor Function (2a)

- ▶ **Exercise** Translate the quintuples (q, X, p, Y, D) into English and check they are the same as the specification

- ▶ **Stage A** make the rightmost cell the current cell

$(q_0, 0, q_0, 0, R)$

If state q_0 and read symbol 0 then stay in state q_0 write 0, move R

$(q_0, 1, q_0, 1, R)$

If state q_0 and read symbol 1 then stay in state q_0 write 1, move R

(q_0, B, q_1, B, L)

If state q_0 and read symbol B then state q_1 write B , move L

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Turing Machine Examples

The Successor Function (2b)

► **Exercise** Translate the quintuples (q, X, p, Y, D) into English

► **Stage B** Add 1 to the current cell.

$(q_1, 0, q_2, 1, S)$

If state q_1 and read symbol 0 then state q_2 write 1, stay

$(q_1, 1, q_1, 0, L)$

If state q_1 and read symbol 1 then state q_1 write 0, move L

$(q_1, B, q_2, 1, S)$

If state q_1 and read symbol B then state q_2 write 1, stay

Turing Machine Examples

The Successor Function (2c)

- ▶ **Exercise** Translate the quintuples (q, X, p, Y, D) into English
- ▶ **Stage C** Finish up by making the leftmost cell current
 $(q_2, 0, q_2, 0, L)$
If state q_2 and read symbol 0 then state q_2 write 0, move L
 $(q_2, 1, q_2, 1, L)$
If state q_2 and read symbol 1 then state q_2 write 0, move L
 (q_2, B, q_h, B, R)
If state q_2 and read symbol B then state q_h write B , move R HALT
- ▶ Notice that the Turing Machine feels like a series of **if ... then** or **case** statements inside a **while** loop

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Turing Machine Examples

The Successor Function (2d) — Meta-Exercise

- ▶ Identify $(Q, \Sigma, \Gamma, \delta, q_0, B, F)$

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Turing Machine Examples

The Successor Function (2e) — Meta-Exercise

- ▶ Identify $(Q, \Sigma, \Gamma, \delta, q_0, B, F)$
- ▶ $Q = \{q_0, q_1, q_2, q_h\}$
- ▶ q_0 finding the rightmost symbol
- ▶ q_1 add 1 to current cell
- ▶ q_2 move to leftmost cell
- ▶ q_h finish
- ▶ $\Sigma = \{0, 1\}$
- ▶ $\Gamma = \Sigma \cup \{B\}$
- ▶ $\delta :: Q \times \Gamma \rightarrow Q \times \Gamma \times \{L, R, S\}$
 $\delta(q, X) \mapsto (p, Y, D)$
 δ is represented as $\{(q, X, p, Y, D)\}$
 equivalent to $\{((q, X), (p, Y, D))\}$ *set of pairs*
- ▶ q_0 start with leftmost symbol under head, state moving to rightmost symbol
- ▶ B is \sqcup a visible space
- ▶ $F = \{q_h\}$

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Turing Machine Examples

The Successor Function (3)

- ▶ **Sample Evaluation** $11 \mapsto 100$
- ▶ **Representation** $\dots BX_1 X_2 \dots X_{i-1} q X_i X_{i+1} \dots X_n B \dots$

$q_0 11$

$1 q_0 1$

$11 q_0 B$

$1 q_1 1$

$q_1 10$

$q_1 B00$

$q_2 100$

$q_2 B100$

$q_h 100$

- ▶ **Exercise** evaluate $1011 \mapsto 1100$

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Turing Machine Examples

Instantaneous Description

- ▶ **Representation** $\cdots BX_1 X_2 \cdots X_{i-1} qX_i X_{i+1} \cdots X_n B \cdots$
- ▶ q is the state of the TM
- ▶ The head is scanning the symbol X_i
- ▶ Leading or trailing blanks B are (usually) not shown unless the head is scanning them
- ▶ \vdash_M denotes one move of the TM M
- ▶ \vdash_M^* denotes zero or more moves
- ▶ \vdash will be used if the TM M is understood
- ▶ If (q, X_i, p, Y, L) denotes a TM move then

$$X_1 \cdots X_{i-1} qX_i \cdots X_n \vdash_M X_1 \cdots X_{i-2} pX_{i-1} Y \cdots X_n$$

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Turing Machine Examples

The Binary Palindrome Function

- ▶ **Input** binary string s
- ▶ **Output** YES if palindrome, NO otherwise
- ▶ Example $1010 \mapsto \text{NO}$ and $1001 \mapsto \text{YES}$
- ▶ Initial cell: leftmost symbol of s
- ▶ **Strategy**
- ▶ **Stage A** read the leftmost symbol
- ▶ If blank then accept it and go to stage D otherwise erase it
- ▶ **Stage B** find the rightmost symbol
- ▶ If the current cell matches leftmost recently read then erase it and go to stage C
- ▶ Otherwise reject it and go to stage E
- ▶ **Stage C** return to the leftmost symbol and stage A
- ▶ **Stage D** print YES and halt
- ▶ **Stage E** erase the remaining string and print NO

Turing Machine Examples

The Binary Palindrome Function (2)

- ▶ Represent the Turing Machine program as a list of quintuples (q, X, p, Y, D)

- ▶ **Stage A** read the leftmost symbol

$(q_0, 0, q_{1_o}, B, R)$

$(q_0, 1, q_{1_i}, B, R)$

(q_0, B, q_5, B, S)

- ▶ **Stage B** find rightmost symbol

$(q_{1_o}, B, q_{2_o}, B, L)$

$(q_{1_o}, *, q_{1_o}, *, R)$ * is a wild card, matches anything

$(q_{1_i}, B, q_{2_i}, B, L)$

$(q_{1_i}, *, q_{1_i}, *, R)$

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Turing Machine Examples

The Binary Palindrome Function (3)

► **Stage B** check

$(q_{2_0}, 0, q_3, B, L)$

(q_{2_0}, B, q_5, B, S)

$(q_{2_0}, *, q_6, *, S)$

$(q_{2_i}, 1, q_3, B, L)$

(q_{2_i}, B, q_5, B, S)

$(q_{2_i}, *, q_6, *, S)$

► **Stage C** return to the leftmost symbol and stage A

(q_3, B, q_5, B, S)

$(q_3, *, q_4, *, L)$

(q_4, B, q_0, B, R)

$(q_4, *, q_4, *, L)$

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Turing Machine Examples

The Binary Palindrome Function (4)

- ▶ **Stage D** accept and print YES

$(q_5, *, q_{5a}, Y, R)$

$(q_{5a}, *, q_{5b}, E, R)$

$(q_{5b}, *, q_7, S, S)$

- ▶ **Stage E** erase the remaining string and print NO

(q_6, B, q_{6a}, N, R)

$(q_6, *, q_6, B, L)$

$(q_{6a}, *, q_7, O, S)$

- ▶ **Finish**

(q_7, B, q_h, B, R)

$(q_7, *, q_7, *, L)$

Turing Machine Examples

The Binary Palindrome Function (3a) — Meta-Exercise

- ▶ Identify $(Q, \Sigma, \Gamma, \delta, q_0, B, F)$

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Turing Machine Examples

The Binary Palindrome Function (3b) — Meta-Exercise

- ▶ Identify $(Q, \Sigma, \Gamma, \delta, q_0, B, F)$
- ▶ $Q = \{q_0, q_{1_o}, q_{1_i}, q_{2_o}, q_{2_i}, q_3, q_4, q_5, q_{5_a}, q_{5_b}, q_6, q_{6_a}, q_7, q_h\}$
- ▶ q_0 read leftmost symbol
- ▶ q_{1_o}, q_{1_i} find rightmost symbol looking for 0 or 1
- ▶ q_{2_o}, q_{2_i} check, confirm or reject
- ▶ q_3, q_4 check finish or move to start
- ▶ q_5, q_6, q_7 print YES or NO and finish
- ▶ q_h finish
- ▶ $\Sigma = \{0, 1\}$
- ▶ $\Gamma = \Sigma \cup \{B, Y, E, S, N, O\}$
- ▶ $\delta :: Q \times \Gamma \rightarrow Q \times \Gamma \times \{L, R, S\}$
 $\delta(q, X) \mapsto (p, Y, D)$
 δ is represented as $\{(q, X, p, Y, D)\}$
 equivalent to $\{(q, X), (p, Y, D)\}$ *set of pairs*
- ▶ Start with leftmost symbol under head, state q_0
- ▶ B is \sqcup a visible space
- ▶ $F = \{q_h\}$

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Turing Machine Examples

The Binary Palindrome Function (4)

► **Sample Evaluation** 101 \mapsto YES

$q_0 101 \vdash Bq_{1_i} 01 \vdash B0q_{1_i} 1 \vdash B01q_{1_i} B$

$\vdash B0q_{2_i} 1$

$\vdash Bq_3 0B \vdash q_4 B0B$

$\vdash Bq_0 0B \vdash BBq_{1_o} B$

$\vdash Bq_{2_o} BB$

$\vdash Bq_5 BB \vdash Yq_{5_a} B \vdash YEq_{5_b} B \vdash YEq_7 S$

$\vdash Yq_7 ES \vdash Bq_7 YES \vdash q_7 BYES \vdash q_h YES$

► **Exercise** Evaluate 110 \mapsto NO

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Turing Machine Examples

Binary Addition Example

- ▶ **Input** two binary numerals separated by a single space $n1\ n2$
- ▶ **Output** binary numeral which is the sum of the inputs
- ▶ Example $110110 + 101011 \mapsto 1100001$
- ▶ Initial cell: leftmost symbol of $n1\ n2$
- ▶ **Insight** look at the arithmetic algorithm

$$\begin{array}{r}
 \\
 \\
 \hline
 1 \\
 \hline
 \end{array}$$

- ▶ **Discussion** how can we overwrite the first number with the result and remember how far we have gone ?

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Turing Machine Examples

Binary Addition Example — Arithmetic Reinvented

⌊	1	1	0	1	1	0
⌊	1	0	1	0	1	1
<hr/>						
⌊	1	1	0	1	1	y
⌊	1	0	1	0	1	⌊
<hr/>						
⌊	1	1	1	0	x	y
⌊	1	0	1	0	⌊	⌊
<hr/>						
⌊	1	1	1	x	x	y
⌊	1	0	1	⌊	⌊	⌊
<hr/>						
1	0	x	x	x	x	y
⌊	1	⌊	⌊	⌊	⌊	⌊
<hr/>						
1	y	x	x	x	x	y
⌊	⌊	⌊	⌊	⌊	⌊	⌊
<hr/>						
1	1	0	0	0	0	1

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Turing Machine Examples

Binary Addition Example (2)

- ▶ **Input** two binary numerals separated by a single space $n1\ n2$
- ▶ **Output** binary numeral which is the sum of the inputs
- ▶ Example $110110 + 101011 \mapsto 1100001$
- ▶ Initial cell: leftmost symbol of $n1\ n2$
- ▶ **Strategy**
- ▶ **Stage A** find the rightmost symbol
If the symbol is 0 erase and go to stage Bx
If the symbol is 1 erase go to stage By
If the symbol is blank go to stage F
dealing with each digit in $n2$
if no further digits in $n2$ go to final stage
- ▶ **Stage Bx** Move left to a blank go to stage Cx
- ▶ **Stage By** Move left to a blank go to stage Cy
moving to $n1$

Turing Machine Examples

Binary Addition Example (3)

- ▶ **Stage Cx** Move left to find first 0, 1 or B
Turn 0 or B to X, turn 1 to Y and go to stage A
adding 0 to a digit finalises the result (no *carry one*)
- ▶ **Stage Cy** Move left to find first 0, 1 or B
Turn 0 or B to 1 and go to stage D
Turn 1 to 0, move left and go to stage Cy
dealing with the *carry one* in school arithmetic
- ▶ **Stage D** move right to X, Y or B and go to stage E
- ▶ **Stage E** replace 0 by X, 1 by Y, move right and go to Stage A
finalising the value of a digit resulting from a *carry*
- ▶ **Stage F** move left and replace X by 0, Y by 1 and at B halt

Turing Machine Examples

Binary Addition Example (4)

- ▶ Represent the Turing Machine program as a list of quintuples (q, X, p, Y, D)
- ▶ **Stage A** find the rightmost symbol

(q_0, B, q_1, B, R)

$(q_0, *, q_0, *, R)$ * is a wild card, matches anything

(q_1, B, q_2, B, L)

$(q_1, *, q_1, *, R)$

$(q_2, 0, q_{3_x}, B, L)$

$(q_2, 1, q_{3_y}, B, L)$

(q_2, B, q_7, B, L)

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Turing Machine Examples

Binary Addition Example (5)

- ▶ **Stage Bx** move left to blank
 $(q_{3_x}, B, q_{4_x}, B, L)$
 $(q_{3_x}, *, q_{3_x}, *, L)$
- ▶ **Stage By** move left to blank
 $(q_{3_y}, B, q_{4_y}, B, L)$
 $(q_{3_y}, *, q_{3_y}, *, L)$
- ▶ **Stage Cx** move left to 0, 1, or blank
 $(q_{4_x}, 0, q_0, x, R)$
 $(q_{4_x}, 1, q_0, y, R)$
 (q_{4_x}, B, q_0, x, R)
 $(q_{4_x}, *, q_{4_x}, *, L)$

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Turing Machine Examples

Binary Addition Example (6)

- ▶ **Stage C_y** move left to 0, 1, or blank

$(q_{4y}, 0, q_5, 1, S)$

$(q_{4y}, 1, q_{4y}, 0, L)$

$(q_{4y}, B, q_5, 1, S)$

$(q_{4y}, *, q_{4y}, *, L)$

- ▶ **Stage D** move right to x, y or B

(q_5, x, q_6, x, L)

(q_5, y, q_6, y, L)

(q_5, B, q_6, B, L)

$(q_5, *, q_5, *, R)$

- ▶ **Stage E** replace 0 by x, 1 by y

$(q_6, 0, q_0, x, R)$

$(q_6, 1, q_0, y, R)$

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Turing Machine Examples

Binary Addition Example (7)

- ▶ **Stage F** replace x by 0 , y by 1
 - $(q_7, x, q_7, 0, L)$
 - $(q_7, y, q_7, 1, L)$
 - (q_7, B, q_h, B, R)
 - $(q_7, *, q_7, *, L)$
- ▶ **Exercise** Evaluate $11 + 10 \mapsto 101$

Turing Machine Examples

The Binary Addition Function (7a) — Meta-Exercise

- ▶ Identify $(Q, \Sigma, \Gamma, \delta, q_0, B, F)$

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Turing Machine Examples

The Binary Addition Function (7b) — Meta-Exercise

- ▶ Identify $(Q, \Sigma, \Gamma, \delta, q_0, B, F)$
- ▶ $Q = \{q_0, q_1, q_2, q_{3x}, q_{3y}, q_{4x}, q_{4y}, q_5, q_6, q_7, q_h\}$
- ▶ q_0, q_1, q_2 find rightmost symbol of second number
- ▶ q_{3x}, q_{3y} move left to inter-number blank
- ▶ q_{4x}, q_{4y} move left to 0, 1 or blank
- ▶ q_5 move right to x, y or B
- ▶ q_6 replace 0 by $x, 1$ by y and move right
- ▶ q_7 replace x by 0, y by 1 and move left
- ▶ q_h finish
- ▶ $\Sigma = \{0, 1\}$
- ▶ $\Gamma = \Sigma \cup \{B, x, y\}$
- ▶ $\delta :: Q \times \Gamma \rightarrow Q \times \Gamma \times \{L, R, S\}$
 $\delta(q, X) \mapsto (p, Y, D)$
 δ is represented as $\{(q, X, p, Y, D)\}$
 equivalent to $\{((q, X), (p, Y, D))\}$ *set of pairs*
- ▶ Start with leftmost symbol under head, state q_0
- ▶ B is $_$ a visible space
- ▶ $F = \{q_h\}$

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Turing Machine Examples

Binary Addition Example (8a)

▶ **Exercise** Evaluate $11 + 10 \mapsto 101$

▶ **Stage A** find the rightmost symbol

$BBq_011B10B$ Note space symbols B at start and end

⊢ $BB1q_01B10B$

⊢ $BB11q_0B10B$

⊢ $BB11Bq_110B$

⊢ $BB11B1q_10B$

⊢ $BB11B10q_1B$

⊢ $BB11B1q_20B$

⊢ $BB11Bq_{3_x}1BB$

▶ **Stage B_x** move left to blank

⊢ $B11q_{3_x}B1BB$

▶ **Stage C_x** move left to 0, 1, or blank

⊢ $BB1q_{4_x}1B1BB$

⊢ $BB1Yq_0B1BB$

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Turing Machine Examples

Binary Addition Example (8b)

- ▶ **Exercise** Evaluate $11 + 10 \mapsto 101$ (contd)
- ▶ **Stage A** find the rightmost symbol
 - ⊢ $BB1BYBq_11BB$
 - ⊢ $BB1YB1q_1BB$
 - ⊢ $BB1YBq_21BB$
 - ⊢ $BB1Yq_3yBBBB$
- ▶ **Stage C_y** move left to 0, 1, or blank
 - ⊢ $BB1q_4yYBBBB$
 - ⊢ $BBq_4y1YBBBB$
 - ⊢ $Bq_4yB0YBBBB$
 - ⊢ $Bq_510YBBBB$
- ▶ **Stage D** move right to x, y or B
 - ⊢ $Bq_50YBBBB$
 - ⊢ $B0q_5YBBBB$
 - ⊢ $Bq_60YBBBB$
- ▶ **Stage E** replace 0 by x, 1 by y
 - ⊢ $B1Xq_0YBBBB$

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Turing Machine Examples

Binary Addition Example (8c)

- ▶ **Exercise** Evaluate $11 + 10 \mapsto 101$ (contd)
- ▶ **Stage A** find the rightmost symbol
 - ⊢ $B1XYq_0BBBB$
 - ⊢ $B1XYBq_1BBB$
 - ⊢ $B1XYq_2BBBB$
 - ⊢ $B1Xq_7YBBBB$
- ▶ **Stage F** replace x by 0, y by 1
 - ⊢ $B1q_7X1BBBB$
 - ⊢ $Bq_7101BBBB$
 - ⊢ $Bq_7B101BBBB$
 - ⊢ $Bq_h101BBBB$
- ▶ This is mimicking what you learnt to do on paper as a child! Real *step-by-step* instructions
- ▶ See [Morphett's Turing machine simulator](#) for more examples (takes too long by hand!)

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Computability

Universal Turing Machine

- ▶ **Universal Turing Machine**, U , is a **Turing Machine** that can simulate any arbitrary Turing machine, M
- ▶ Achieves this by encoding the transition function of M in some standard way
- ▶ The input to U is the encoding for M followed by the data for M
- ▶ See **Turing machine examples**

Computability

Decidability

- ▶ **Decidable** — there is a TM that will halt with yes/no for a decision problem — that is, given a string w over the alphabet of P the TM will halt and return yes/no if the string is in the language P (same as *recursive* in [Recursion theory](#) — old use of the word)
- ▶ **Semi-decidable** — there is a TM that will halt with yes if some string is in P but may loop forever on some inputs (same as *recursively enumerable*) — *Halting Problem*
- ▶ **Highly-undecidable** — no outcome for any input — *Totality, Equivalence Problems*

Computability

Undecidable Problems

- ▶ **Halting problem** — the problem of deciding, given a program and an input, whether the program will eventually halt with that input, or will run forever — term first used by Martin Davis 1952
- ▶ **Entscheidungsproblem** — the problem of deciding whether a given statement is provable from the axioms using the rules of logic — shown to be undecidable by Turing (1936) by reduction from the *Halting problem* to it
- ▶ **Type inference and type checking** in the second-order lambda calculus (important for functional programmers, Haskell, GHC implementation)
- ▶ **Undecidable problem** — see link to list

Computability

Halting Problem — Sketch Proof (1)

- ▶ **Halting problem** — is there a program that can determine if any arbitrary program will halt or continue forever ?
- ▶ Assume we have such a program (Turing Machine) $h(f, x)$ that takes a program f and input x and determines if it halts or not

```
h(f, x)
= if f(x) runs forever
  return True
  else
  return False
```

- ▶ We shall prove this cannot exist by contradiction

Computability

Halting Problem — Sketch Proof (2)

- ▶ Now invent two further programs:
- ▶ $q(f)$ that takes a program f and runs h with the input to f being a copy of f
- ▶ $r(f)$ that runs $q(f)$ and halts if $q(f)$ returns **True**, otherwise it loops

```
q(f)
= h(f, f)
```

```
r(f)
= if q(f)
    return
    else
    while True: continue
```

- ▶ What happens if we run $r(r)$?
- ▶ If it loops, $q(r)$ returns **True** and it does not loop — contradiction.
- ▶ **Scoping theLoop Snooper: A proof that the Halting Problem is undecidable** Geoffrey K Pullum (21 May 2024)

Computability

Why undecidable problems must exist

- ▶ A *problem* is really membership of a string in some language
- ▶ The number of different languages over any alphabet of more than one symbol is uncountable
- ▶ Programs are finite strings over a finite alphabet (ASCII or Unicode) and hence countable.
- ▶ There must be an infinity (big) of problems more than programs.
- ▶ **Computational problem** — defined by a function
- ▶ **Computational problem is computable** if there is a Turing machine that will calculate the function.

Computability

Computability and Terminology (1)

- ▶ The idea of an *algorithm* dates back 3000 years to Euclid, Babylonians. . .
- ▶ In the 1930s the idea was made more formal: which *functions are computable*?
- ▶ A *function* is a set of pairs $f = \{(x, f(x)) : x \in X \wedge f(x) \in Y\}$ with the *function property*
- ▶ *Function property*: $(a, b) \in f \wedge (a, c) \in f \Rightarrow b == c$
- ▶ *Function property*: Same input implies same output
- ▶ Note that maths notation is deeply inconsistent here — see [Function](#) and [History of the function concept](#)
- ▶ *What do we mean by computing a function — an algorithm?*

Functions

Relation and Rule

- ▶ The idea of function as a set of pairs (**Binary relation**) with the function property (each element of the domain has at most one element in the co-domain) is fairly recent — see **History of the function concept**
- ▶ School maths presents us with function as rule to get from the input to the output
- ▶ Example: the **square** function: **square** $x = x \times x$
- ▶ But lots of rules (or algorithms) can implement the same function
- ▶ **square1** $x = x^2$
- ▶ **square2** $x = \overbrace{x + \dots + x}^{x \text{ times}}$ if x is integer

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Computability

Computability and Terminology (2)

- ▶ In the 1930s three definitions:
- ▶ λ -Calculus, simple semantics for computation — [Alonzo Church](#)
- ▶ General recursive functions — [Kurt Gödel](#)
- ▶ Universal (Turing) machine — [Alan Turing](#)
- ▶ Terminology:
 - ▶ Recursive, recursively enumerable — Church, [Kleene](#)
 - ▶ Computable, computably enumerable — Gödel, Turing
 - ▶ Decidable, semi-decidable, highly undecidable
 - ▶ In the 1930s, *computers were human*
 - ▶ Unfortunate choice of terminology
- ▶ Turing and Church showed that the above three were equivalent
- ▶ [Church-Turing thesis](#) — function is intuitively computable if and only if Turing machine computable

Computability

Reducing one problem to another

- ▶ To reduce problem P_1 to P_2 , invent a construction that converts instances of P_1 to P_2 that have the same answer. That is:
 - ▶ any string in the language P_1 is converted to some string in the language P_2
 - ▶ any string over the alphabet of P_1 that is not in the language of P_1 is converted to a string that is not in the language P_2
- ▶ With this construction we can solve P_1
 - ▶ Given an instance of P_1 , that is, given a string w that may be in the language P_1 , apply the construction algorithm to produce a string x
 - ▶ Test whether x is in P_2 and give the same answer for w in P_1

Computability

Problem Reduction

- ▶ **Problem Reduction — Ordinary Example**
- ▶ Want to phone Alice but don't have her number
- ▶ You know that Bill has her number
- ▶ So *reduce* the problem of finding Alice's number to the problem of getting hold of Bill

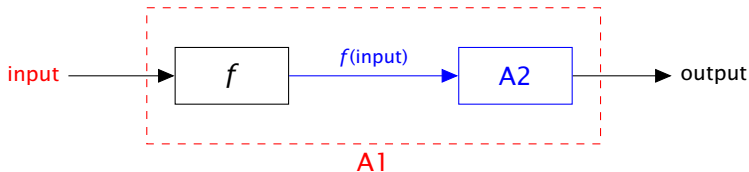
Computability

Direction of Reduction

- ▶ The direction of reduction is important
- ▶ If we can reduce P_1 to P_2 then (in some sense) P_2 is at least as hard as P_1 (since a solution to P_2 will give us a solution to P_1)
- ▶ So, if P_2 is decidable then P_1 is decidable
- ▶ To show a problem is undecidable we have to reduce from an known undecidable problem to it
- ▶ $\forall x(dp_{P_1}(x) = dp_{P_2}(\text{reduce}(x)))$
- ▶ Since, if P_1 is undecidable then P_2 is undecidable

Reductions & Non-Computable

Reductions

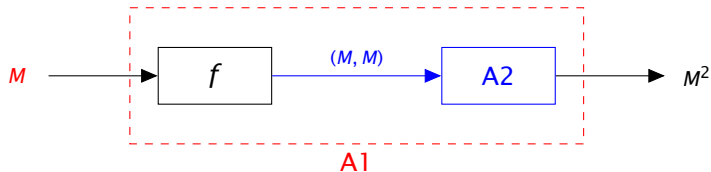


- ▶ A *reduction* of problem P_1 to problem P_2
 - ▶ transforms inputs to P_1 into inputs to P_2
 - ▶ runs algorithm A_2 (which solves P_2) and
 - ▶ interprets the outputs from A_2 as answers to P_1
- ▶ More formally: A problem P_1 is *reducible* to a problem P_2 if there is a function f that takes any input x to P_1 and transforms it to an input $f(x)$ of P_2 such that the solution of P_2 on $f(x)$ is the solution of P_1 on x

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Reductions & Non-Computable

Example: Squaring a Matrix



- ▶ Given an algorithm ($A2$) for matrix multiplication (P_2)
 - ▶ Input: pair of matrices, (M_1, M_2)
 - ▶ Output: matrix result of multiplying M_1 and M_2
- ▶ P_1 is the problem of squaring a matrix
 - ▶ Input: matrix M
 - ▶ Output: matrix M^2
- ▶ Algorithm $A1$ has
 - $f(M) = (M, M)$
 - uses $A2$ to calculate $M \times M = M^2$

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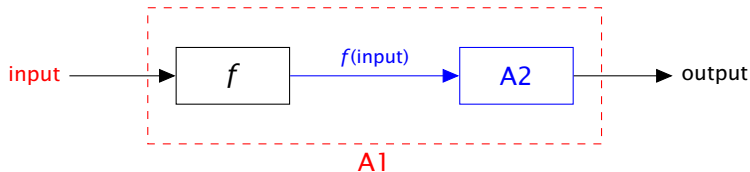
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Reductions & Non-Computable

Non-Computable Problems



- ▶ If P_2 is computable ($A2$ exists) then P_1 is computable (f being simple or polynomial)
- ▶ Equivalently If P_1 is non-computable then P_2 is non-computable
- ▶ **Exercise:** show $B \rightarrow A \equiv \neg A \rightarrow \neg B$

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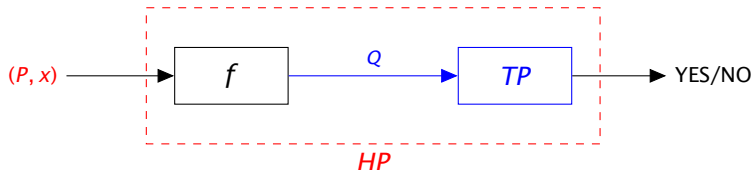
Reductions & Non-Computable

Contrapositive

- ▶ **Proof by Contrapositive**
- ▶ $B \rightarrow A \equiv \neg B \vee A$ by truth table or equivalences
 - $\equiv \neg(\neg A) \vee \neg B$ commutativity and negation laws
 - $\equiv \neg A \rightarrow \neg B$ equivalences
- ▶ Common error: switching the order round

Reductions & Non-Computable

Totality Problem



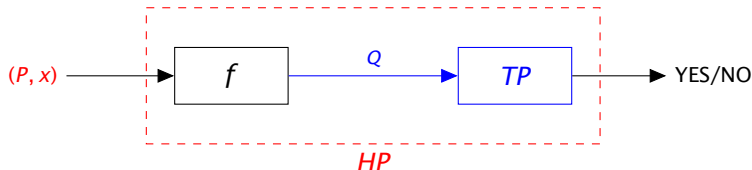
▶ Totality Problem

- ▶ Input: program Q
- ▶ Output: YES if Q terminates for all inputs else NO
- ▶ Assume we have algorithm TP to solve the Totality Problem
- ▶ Now reduce the Halting Problem to the Totality Problem

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Reductions & Non-Computable

Totality Problem



- ▶ Define f to transform inputs to HP to TP **pseudo-Python**

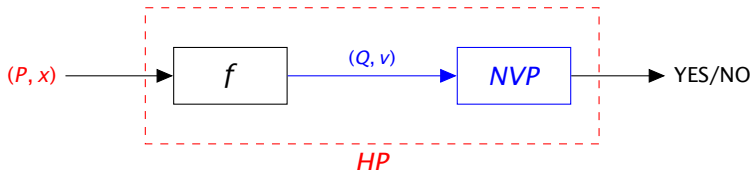
```
def f(P,x) :
    def Q(y):
        # ignore y
        P(x)
    return Q
```

- ▶ Run TP on Q
 - ▶ If TP returns YES then P halts on x
 - ▶ If TP returns NO then P does not halt on x
- ▶ We have *solved* the Halting Problem — contradiction

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Reductions & Non-Computable

Negative Value Problem



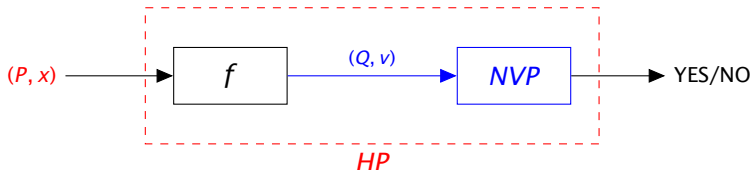
▶ Negative Value Problem

- ▶ Input: program Q which has no input and variable v used in Q
- ▶ Output: YES if v ever gets assigned a negative value else NO
- ▶ Assume we have algorithm NVP to solve the Negative Value Problem
- ▶ Now reduce the Halting Problem to the Negative Value Problem

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Reductions & Non-Computable

Negative Value Problem



- ▶ Define f to transform inputs to HP to NVP **pseudo-Python**

```
def f(P,x) :
    def Q(y):
        # ignore y
        P(x)
        v = -1
    return (Q,var(v))
```

- ▶ Run NVP on $(Q, var(v))$ $var(v)$ gets the variable name
 - ▶ If NVP returns YES then P halts on x
 - ▶ If NVP returns NO then P does not halt on x
- ▶ We have *solved* the Halting Problem — contradiction

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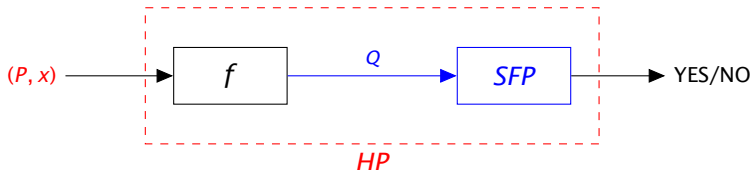
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Squaring Function Problem



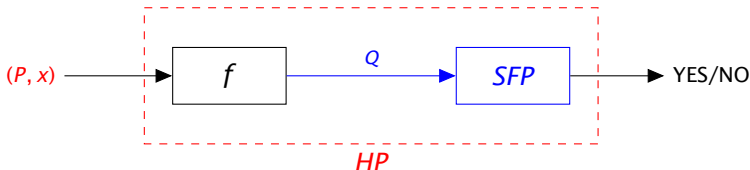
► Squaring Function Problem

- Input: program Q which takes an integer, y
 - Output: YES if Q always returns the square of y else NO
- Assume we have algorithm SFP to solve the Squaring Function Problem
- Now reduce the Halting Problem to the Squaring Function Problem

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Squaring Function Problem



- ▶ Define f to transform inputs to HP to SFP **pseudo-Python**

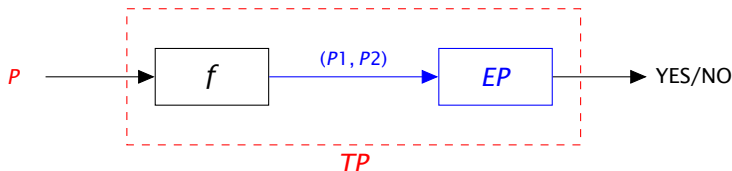
```
def f(P,x) :
    def Q(y):
        P(x)
        return y * y
    return Q
```

- ▶ Run SFP on Q
 - ▶ If SFP returns YES then P halts on x
 - ▶ If SFP returns NO then P does not halt on x
- ▶ We have *solved* the Halting Problem — contradiction

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Reductions & Non-Computable

Equivalence Problem



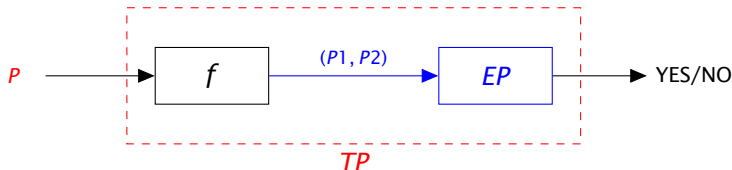
► Equivalence Problem

- Input: two programs $P1$ and $P2$
- Output: YES if $P1$ and $P2$ solve the same problem (same output for same input) else NO
- Assume we have algorithm EP to solve the Equivalence Problem
- Now reduce the Totality Problem to the Equivalence Problem

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Reductions & Non-Computable

Equivalence Problem



- ▶ Define f to transform inputs to TP to EP **pseudo-Python**

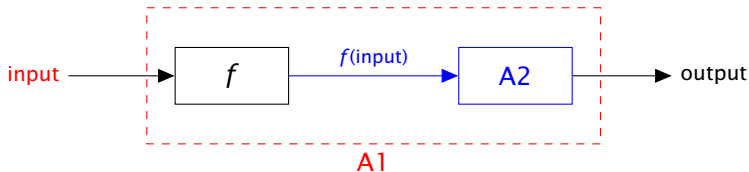
```
def f(P) :
    def P1(x):
        P(x)
        return "Same_string"
    def P2(x)
        return "Same_string"
    return (P1, P2)
```

- ▶ Run EP on $(P1, P2)$
 - ▶ If EP returns YES then P halts on all inputs
 - ▶ If EP returns NO then P does not halt on all inputs
- ▶ We have *solved* the Totality Problem — contradiction

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Reductions & Non-Computable

Rice's Theorem



- ▶ **Rice's Theorem** all non-trivial, semantic properties of programs are undecidable. [H G Rice 1951 PhD Thesis](#)
- ▶ Equivalently: For any non-trivial property of partial functions, no general and effective method can decide whether an algorithm computes a partial function with that property.
- ▶ A property of partial functions is called trivial if it holds for all partial computable functions or for none.

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Reductions & Non-Computable

Rice's Theorem

- ▶ [Rice's Theorem](#) and computability theory
- ▶ Let S be a set of languages that is nontrivial, meaning
 - ▶ there exists a Turing machine that recognizes a language in S
 - ▶ there exists a Turing machine that recognizes a language not in S
- ▶ Then, it is undecidable to determine whether the language recognized by an arbitrary Turing machine lies in S .
- ▶ This has implications for compilers and virus checkers
- ▶ Note that Rice's theorem does not say anything about those properties of machines or programs that are not also properties of functions and languages.
- ▶ For example, whether a machine runs for more than 100 steps on some input is a decidable property, even though it is non-trivial.

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Lambda Calculus

Motivation

- ▶ **Lambda Calculus** is a **formal system** in **mathematical logic** for expressing **computation** based on function abstraction and application using variable **binding** and **substitution**
- ▶ Lambda calculus is **Turing complete** — it can simulate any Turing machine
- ▶ Introduced by Alonzo Church in 1930s
- ▶ Basis of functional programming languages — **Lisp**, **Scheme**, **ISWIM**, **ML**, **SASL**, **KRC**, **Miranda**, **Haskell**, **Scala**, **F#**...
- ▶ **Note** this is not part of M269 but may help understand ideas of computability

Functions

Binding and Substitution

- ▶ School maths introduces functions as

$$f(x) = 3x^2 + 4x + 5$$

- ▶ Substitution: $f(2) = 3 \times 2^2 + 4 \times 2 + 5 = 25$

- ▶ Generalise: $f(x) = ax^2 + bx + c$

- ▶ What is wrong with the following:

- ▶ $f(a) = a \times a^2 + b \times a + c$

- ▶ The ideas of free and bound variables and substitution

Expressions

Evaluation Strategies (a)

- ▶ In evaluating an expression we have choices about the order in which we evaluate subterms
- ▶ Some choices may involve more work than others but the [Church-Rosser theorem](#) ensures that if the evaluation terminates then all choices get to the same answer
- ▶ The second edition of a famous book on [Functional programming](#) — Bird (1998, Ex 1.2.2, page 6) *Introduction to Functional Programming using Haskell* — had the following exercise:
 - ▶ How many ways can you evaluate $(3 + 7)^2$
List the evaluations and assumptions
- ▶ The first edition — Bird and Wadler (1988, Ex 1.2.1, page 6) *Introduction to Functional Programming* — had the exercise:
 - ▶ How many ways can you evaluate $((3 + 7)^2)^2$

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Expressions

Evaluation Strategies (b)

- ▶ How many ways can you evaluate $(3 + 7)^2$
List the evaluations and assumptions

- ▶ **Answer** 3 ways

- ▶ **Reducible expressions** (redexes)

$x^2 \rightarrow x \times x$ where x is a term

$a + b$ where a and b are numbers

$x \times y$ where x and y are numbers

- 1 [sqr (3+7), ((3+7)*(3+7)), ((3+7)*10), (10*10), 100]
- 2 [sqr (3+7), ((3+7)*(3+7)), (10*(3+7)), (10*10), 100]
- 3 [sqr (3+7), sqr 10, (10*10), 100]

- ▶ The assumed redexes do not include **distributive laws**

$(a + b) \times (x + y) \rightarrow a \times x + a \times y + b \times x + b \times y$

- ▶ This would increase the number of different evaluations

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Expressions

Evaluation Strategies (d)

- ▶ The actual **Evaluation strategy** used by a particular programming language implementation may have optimisations which make an evaluation which looks costly to be somewhat cheaper
- ▶ For example, the **Haskell** implementation **GHC** **optimises** the evaluation of common subexpressions so that **(3+7)** will be evaluated only once

```
1 [sqr sqr (3+7), (sqr (3+7)*sqr (3+7)), (sqr (3+7)*((3+7)*(3+7))), (sqr (3+7))*((3+7)*(3+7))*10]
2 [sqr sqr (3+7), (sqr (3+7)*sqr (3+7)), (sqr(3+7)*((3+7)*(3+7))), (sqr (3+7))*((3+7))*10]
```

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Lambda Calculus

Optional Topic

- ▶ M269 Unit 6/7 Reader *Logic and the Limits of Computation* alludes to other formalisations with equal power to a Turing Machine (pages 81 and 87)
- ▶ The *Reader* mentions Alonzo Church and his 1930s formalism (page 87, but does not give any detail)
- ▶ The notes in this section are optional and for comparison with the Turing Machine material
- ▶ Turing machine: explicit memory, state and implicit loop and case/if statement
- ▶ Lambda Calculus: function definition and application, explicit rules for evaluation (and transformation) of expressions, explicit rules for substitution (for function application)
- ▶ [Lambda calculus reduction workbench](#)
- ▶ [Lambda Calculus Calculator](#)

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Lambda Calculus

Lambda Terms

- ▶ A **variable**, x , is a lambda term
- ▶ If M is a lambda term and x is a variable, then $(\lambda x.M)$ is a lambda term — a **lambda abstraction** or function definition
- ▶ If M and N are lambda terms, the $(M N)$ is lambda term — an **application**
- ▶ Nothing else is a lambda term

Lambda Calculus

Lambda Terms — Notational Conveniences

- ▶ Outermost parentheses are omitted $(M N) \equiv M N$
- ▶ Application is left associative $((M N) P) \equiv M N P$
- ▶ The body of an abstraction extends as far right as possible, subject to scope limited by parentheses
- ▶ $\lambda x.M N \equiv \lambda x.(M N)$ and not $(\lambda x.M) N$
- ▶ $\lambda x.\lambda y.\lambda z.M \equiv \lambda x y z.M$

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Lambda Calculus

Lambda Calculus Semantics

- ▶ What do we mean by *evaluating an expression*?
- ▶ To evaluate $(\lambda x.M)N$
- ▶ Evaluate M with x replaced by N
- ▶ This rule is called β -reduction
- ▶ $(\lambda x.M)N \xrightarrow{\beta} M[x := N]$
- ▶ $M[x := N]$ is M with occurrences of x replaced by N
- ▶ This operation is called *substitution* — see rules below

Lambda Calculus

β -Reduction Examples

▶ $(\lambda x.x)z \rightarrow z$

▶ $(\lambda x.y)z \rightarrow y$

▶ $(\lambda x.x y)z \rightarrow z y$

a function that applies its argument to y

▶ $(\lambda x.x y)(\lambda z.z) \rightarrow (\lambda z.z)y \rightarrow y$

▶ $(\lambda x.\lambda y.x y)z \rightarrow \lambda y.z y$

A *curried* function of two arguments — applies first argument to second

▶ *currying* replaces $f(x, y)$ with $(f x)y$ — nice notational convenience — gives *partial application* for free

Lambda Calculus

Substitution

- ▶ To define *substitution* use recursion on the structure of terms
- ▶ $x[x := N] \equiv N$
- ▶ $y[x := N] \equiv y$
- ▶ $(P Q)[x := N] \equiv (P[x := N]) (Q[x := N])$
- ▶ $(\lambda x.M)[x := N] = \lambda x.M$

In $(\lambda x.M)$, the x is a formal parameter and thus a local variable, different to any other
- ▶ $(\lambda y.M)[x := N] = \text{what?}$
- ▶ Look back at the school maths example above — a subtle point

Lambda Calculus

Substitution (2)

- ▶ Renaming *bound variables consistently is allowed*
- ▶ $\lambda x.x \equiv \lambda y.y \equiv \lambda z.z$
- ▶ $\lambda y.\lambda x.y \equiv \lambda z.\lambda x.z$
- ▶ This is called α -conversion
- ▶ $(\lambda x.\lambda y.x y) y \rightarrow (\lambda x.\lambda z.x z) y \rightarrow \lambda z.y z$

► **Bound and Free Variables**

► $BV(x) = \emptyset$

► $BV(\lambda x.M) = BV(M) \cup \{x\}$

► $BV(MN) = BV(M) \cup BV(N)$

► $FV(x) = \{x\}$

► $FV(\lambda x.M) = FV(M) - \{x\}$

► $FV(MN) = FV(M) \cup FV(N)$

► The above is a formalisation of school maths

► A Lambda term with no free variables is said to be *closed* — such terms are also called **combinators** — see [Combinator](#) and [Combinatory logic](#) (Hankin, 2004, page 10)

► **α -conversion**

► $\lambda x.M \xrightarrow{\alpha} \lambda y.M[x := y]$ if $y \notin FV(M)$

Lambda Calculus

Substitution (4)

- ▶ β -reduction final rule
- ▶ $(\lambda y.M)[x := N] = \lambda y.M$ if $x \notin FV(M)$
- ▶ $(\lambda y.M)[x := N] = \lambda y.M[x := N]$
if $x \in FV(M)$ and $y \notin FV(N)$
- ▶ $(\lambda y.M)[x := N] = \lambda z.M[y := z][x := N]$
if $x \in FV(M)$ and $y \in FV(N)$
 z is chosen to be first variable $z \notin FV(NM)$
- ▶ This is why you cannot go $f(a)$ when given
- ▶ $f(x) = ax^2 + bx + c$
- ▶ School maths — but made formal

Lambda Calculus

Rules Summary — Conversion

- ▶ **α -conversion** renaming bound variables
- ▶ $\lambda x.M \xrightarrow{\alpha} \lambda y.M[x := y]$ if $y \notin FV(M)$
- ▶ **β -conversion** function application
- ▶ $(\lambda x.M)N \xrightarrow{\beta} M[x := N]$
- ▶ **η -conversion** extensionality
- ▶ $\lambda x.F x \xrightarrow{\eta} F$ if $x \notin FV(F)$

Lambda Calculus

Rules Summary — Substitution

1. $x[x := N] \equiv N$
2. $y[x := N] \equiv y$
3. $(P Q)[x := N] \equiv (P[x := N]) (Q[x := N])$
4. $(\lambda x.M)[x := N] = \lambda x.M$
5. $(\lambda y.M)[x := N] = \lambda y.M$ if $x \notin FV(M)$
6. $(\lambda y.M)[x := N] = \lambda y.M[x := N]$
if $x \in FV(M)$ and $y \notin FV(N)$
7. $(\lambda y.M)[x := N] = \lambda z.M[y := z][x := N]$
if $x \in FV(M)$ and $y \in FV(N)$
 z is chosen to be first variable $z \notin FV(NM)$

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Lambda Calculus

Lambda Calculus Encodings

- ▶ So what does this formalism get us ?
- ▶ The Lambda Calculus is Turing complete
- ▶ We can encode any computation (if we are clever enough)
- ▶ Booleans and propositional logic
- ▶ Pairs
- ▶ Natural numbers and arithmetic
- ▶ Looping and recursion

Lambda Calculus Encodings

Booleans and Propositional Logic

- ▶ True = $\lambda x.\lambda y.x$
- ▶ False = $\lambda x.\lambda y.y$
- ▶ IF a THEN b ELSE $c \equiv a b c$
- ▶ IF True THEN b ELSE $c \rightarrow (\lambda x.\lambda y.x) b c$
- ▶ $\rightarrow (\lambda y.b) c \rightarrow b$
- ▶ IF False THEN b ELSE $c \rightarrow (\lambda x.\lambda y.y) b c$
- ▶ $\rightarrow (\lambda y.y) c \rightarrow c$

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Lambda Calculus Encodings

Booleans and Propositional Logic (2)

- ▶ Not = $\lambda x.((x \text{ False})\text{True})$
- ▶ Not x = IF x THEN False ELSE True
- ▶ Exercise: evaluate Not True
- ▶ And = $\lambda x.\lambda y.((x \ y) \text{ False})$
- ▶ And $x \ y$ = IF x THEN y ELSE False
- ▶ Exercise: evaluate And True False
- ▶ Or = $\lambda x.\lambda y.((x \ \text{True}) \ y)$
- ▶ Or $x \ y$ = IF x THEN True ELSE y
- ▶ Exercise: evaluate Or False True

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Lambda Calculus Encodings

Booleans and Propositional Logic (2) — Exercises

- ▶ Exercise: evaluate Not True
- ▶ $\rightarrow (\lambda x.((x \text{ False}) \text{ True})) \text{ True}$
- ▶ $\rightarrow (\text{True False}) \text{ True}$
- ▶ Could go straight to False from here, but we shall fill in the detail
- ▶ $\rightarrow ((\lambda x.\lambda y.x) (\lambda x.\lambda y.y)) (\lambda x.\lambda y.x)$
- ▶ $\rightarrow (\lambda y.(\lambda x.\lambda y.y)) (\lambda x.\lambda y.x)$
- ▶ $\rightarrow (\lambda x.\lambda y.y) \equiv \text{False}$
- ▶ Exercise: evaluate And True False
- ▶ $\rightarrow (\text{IF } x \text{ THEN } y \text{ ELSE False}) \text{ True False}$
- ▶ $\rightarrow (\text{IF True THEN False ELSE False}) \rightarrow \text{False}$
- ▶ Exercise: evaluate Or False True
- ▶ $\rightarrow (\text{IF } x \text{ THEN True ELSE } y) \text{ False True}$
- ▶ $\rightarrow (\text{IF False THEN True ELSE True}) \rightarrow \text{True}$

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Lambda Calculus Encodings

Natural Numbers — Church Numerals

- ▶ Encoding of natural numbers
- ▶ $0 = \lambda f. \lambda y. y$
- ▶ $1 = \lambda f. \lambda y. f y$
- ▶ $2 = \lambda f. \lambda y. f (f y)$
- ▶ $3 = \lambda f. \lambda y. f (f (f y))$
- ▶ Successor $\text{Succ} = \lambda z. \lambda f. \lambda y. f (z f y)$
- ▶ $\text{Succ } 0 = (\lambda z. \lambda f. \lambda y. f (z f y)) (\lambda f. \lambda y. y)$
- ▶ $\rightarrow \lambda f. \lambda y. f ((\lambda f. \lambda y. y) f y)$
- ▶ $\rightarrow \lambda f. \lambda y. f ((\lambda y. y) y)$
- ▶ $\rightarrow \lambda f. \lambda y. f y = 1$

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Lambda Calculus Encodings

Natural Numbers — Operations

- ▶ $\text{isZero} = \lambda z.z(\lambda y. \text{False}) \text{True}$
- ▶ Exercise: evaluate $\text{isZero } 0$
- ▶ If M and N are numerals (as λ expressions)
- ▶ Add $MN = \lambda x.\lambda y.(Mx)((Ny) y)$
- ▶ Mult $MN = \lambda x.(M(Nx))$
- ▶ Exercise: show $1 + 1 = 2$

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Lambda Calculus Encodings

Pairs

- ▶ Encoding of a pair a, b
- ▶ $(a, b) = \lambda x. \text{IF } x \text{ THEN } a \text{ ELSE } b$
- ▶ $\text{FST} = \lambda f.f \text{ True}$
- ▶ $\text{SND} = \lambda f.f \text{ False}$
- ▶ Exercise: evaluate $\text{FST } (a, b)$
- ▶ Exercise: evaluate $\text{SND } (a, b)$

Lambda Calculus Encodings

The Fixpoint Combinator

- ▶ $Y = \lambda f.(\lambda x.f(x x))(\lambda x.f(x x))$
- ▶ $Y F = \lambda f.(\lambda x.f(x x))(\lambda x.f(x x)) F$
- ▶ $\rightarrow (\lambda x.F(x x))(\lambda x.F(x x))$
- ▶ $F((\lambda x.F(x x))(\lambda x.F(x x))) = F(Y F)$
- ▶ $(Y F)$ is a **fixed point** of F
- ▶ We can use Y to achieve recursion for F

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Lambda Calculus Encodings

The Fixpoint Combinator — Recursion

- ▶ **Recursion implementation — Factorial**
- ▶ $\text{Fact} = \lambda f. \lambda n. \text{IF } n = 0 \text{ THEN } 1 \text{ ELSE } n * (f(n - 1))$
- ▶ $(Y \text{ Fact})1 = (\text{Fact } (Y \text{ Fact}))1$
- ▶ $\rightarrow \text{IF } 1 = 0 \text{ THEN } 1 \text{ ELSE } 1 * ((Y \text{ Fact}) 0)$
- ▶ $\rightarrow 1 * ((Y \text{ Fact}) 0)$
- ▶ $\rightarrow 1 * (\text{Fact } (Y \text{ Fact}) 0)$
- ▶ $\rightarrow 1 * \text{IF } 0 = 0 \text{ THEN } 1 \text{ ELSE } 0 * ((Y \text{ Fact}) (0 - 1))$
- ▶ $\rightarrow 1 * 1 \rightarrow 1$
- ▶ Factorial $n = (Y \text{ Fact}) n$
- ▶ Recursion implemented with a non-recursive function Y

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Computability

Turing Machines, Lambda Calculus and Programming Languages

- ▶ Anything computable can be represented as TM or Lambda Calculus
- ▶ But programs would be slow, large and hard to read
- ▶ In practice use the ideas to create more expressive languages which include built-in primitives
- ▶ Also leads to ideas on data types
- ▶ Polymorphic data types
- ▶ Algebraic data types
- ▶ Also leads on to ideas on higher order functions — functions that take functions as arguments or returns functions as results.

Commentary 3

Complexity

3 Complexity

- ▶ Complexity Classes **P** and **NP**
- ▶ Class **NP**
- ▶ NP-completeness
- ▶ NP-completeness and Boolean Satisfiability

Complexity

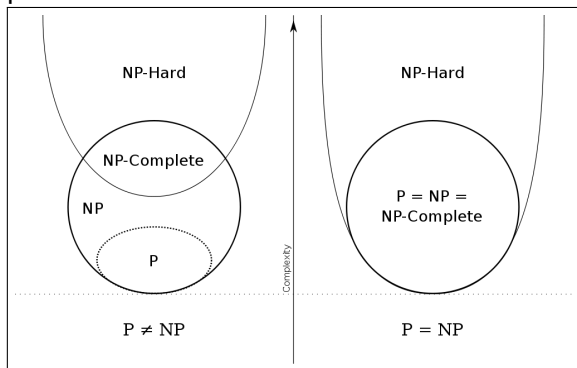
P and NP

- ▶ **P**, the set of all decision problems that can be solved in polynomial time on a deterministic Turing machine
- ▶ **NP**, the set of all decision problems whose solutions can be verified (certificate) in polynomial time
- ▶ Equivalently, **NP**, the set of all decision problems that can be solved in polynomial time on a non-deterministic Turing machine
- ▶ A *decision problem*, dp is **NP-complete** if
 1. dp is in NP and
 2. Every problem in NP is reducible to dp in polynomial time
- ▶ **NP-hard** — a problem satisfying the second condition, whether or not it satisfies the first condition. Class of problems which are at least as hard as the hardest problems in NP. NP-hard problems do not have to be in NP and may not be decision problems

Complexity

P and NP — Diagram

Euler diagram for P, NP, NP-complete and NP-hard set of problems



Source: [Wikipedia NP-complete entry](#)

Class NP

Certificate and Verifier

- ▶ To formalise the definition of the **class NP**, we need to formalise the idea of checking a candidate solution
- ▶ Define a *certificate* for each problem input that would return Yes
- ▶ Describe the *verifier* algorithm
- ▶ Demonstrate the *verifier* algorithm has polynomial complexity
- ▶ The terms *certificate* and *verifier* have technical definitions in terms of languages and Turing Machines but can be thought of as *candidate solution* and *checker algorithm*

Class NP

Example Decision Problems (1)

- ▶ **Composite Numbers** Given a number N decide if N is a composite (i.e. non-prime) number
Certificate factorization of N
- ▶ **Connectivity** Given a graph G and two vertices s, t in G , decide if s is connected to t in G .
Certificate path from s to t
- ▶ **Linear Programming** Given a list of m linear inequalities with rational coefficients over n variables u_1, \dots, u_n (a linear inequality has the form $a_1 u_1 + a_2 u_2 + \dots + a_n u_n \leq b$ for some coefficients a_1, \dots, a_n, b), decide if there is an assignment of rational numbers to the variables u_1, \dots, u_n which satisfies all the inequalities
Certificate is the assignment

Class NP

Example Decision Problems (2)

- ▶ The above are in **P**
- ▶ *Composite Numbers*, *Connectivity* and *Linear programming* are in **P**
- ▶ *Composite Numbers* follows from **Integer factorization** and the **AKS primality test** from 2004
- ▶ *Connectivity* follows from the breadth-first search algorithm
- ▶ *Linear programming* shown to be in **P** by the **Ellipsoid method**

Class NP

Example Decision Problems (3)

- ▶ **Integer Programming** some or all variables are restricted to be integers
- ▶ **Travelling Salesperson** Given a set of nodes and distances between all pairs of nodes and a number k , decide if there is a closed circuit that visits every node exactly once and has total length at most k
Certificate sequence of nodes in such a tour
- ▶ **Subset sum** Given a list of numbers and a number T , decide if there is a subset that adds up to T
Certificate list of members of such a subset
- ▶ **Independent set (graph theory)** A subgraph of G with of at least k vertices which have no edges between them
Certificate the list of k vertices
- ▶ **Clique problem** Given a graph and a number k , decide if there is a complete subgraph (clique) of size k
Certificate list of nodes. For explanation see [Prove Clique is NP](#)

Class NP

Example Decision Problems (4)

- ▶ The above are **NP-complete** — see [List of NP-complete problems](#)
 - ▶ The following two are not known to be **P** nor **NP-complete**
 - ▶ **Graph Isomorphism** Given two $n \times n$ adjacency matrices M_1, M_2 , decide if M_1 and M_2 define the same graph (up to renaming of the vertices)
Certificate the permutation $\pi : [n] \rightarrow [n]$ such that M_2 is equal to M_1 after reordering the indices of M_1 according to π
 - ▶ **Integer factorization** Given three numbers N, L, U decide if N has a prime factor p in the interval $[L, U]$
Certificate is the factorization of N
- Source Arora and Barak (2009, page 49) *Computational Complexity: A Modern Approach* and contained links

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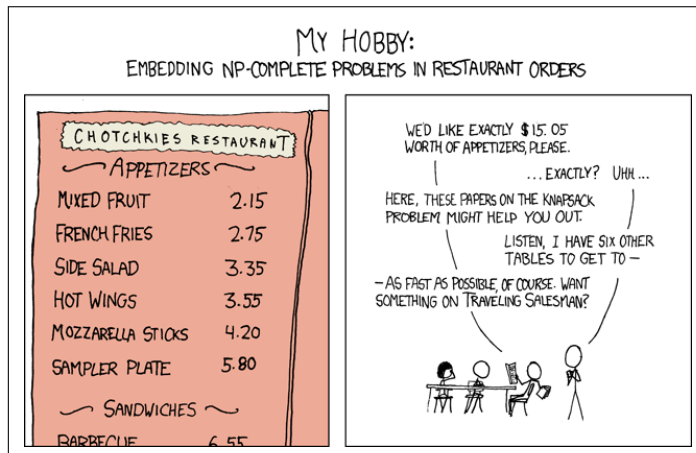
Complexity

NP-complete problems

- ▶ Boolean satisfiability (SAT) Cook-Levin theorem
- ▶ Conjunctive Normal Form 3SAT
- ▶ Hamiltonian path problem
- ▶ Travelling salesman problem
- ▶ NP-complete — see list of problems

Complexity

Knapsack Problem



Source & Explanation: [XKCD 287](#)

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NP-Completeness and Boolean Satisfiability

Points on Notes

- ▶ The *Boolean satisfiability problem (SAT)* was the first decision problem shown to be *NP-Complete*
- ▶ This section gives a sketch of an explanation
- ▶ **Health Warning** different texts have different notations and there will be some inconsistency in these notes
- ▶ **Health warning** these notes use some formal notation *to make the ideas more precise* — computation requires precise notation and is about manipulating strings according to precise rules.

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NP-Completeness and Boolean Satisfiability

Alphabets, Strings and Languages

- ▶ Notation:
- ▶ Σ is a set of symbols — the alphabet
- ▶ Σ^k is the set of all string of length k , which each symbol from Σ
- ▶ Example: if $\Sigma = \{0, 1\}$
 - ▶ $\Sigma^1 = \{0, 1\}$
 - ▶ $\Sigma^2 = \{00, 01, 10, 11\}$
- ▶ $\Sigma^0 = \{\epsilon\}$ where ϵ is the empty string
- ▶ Σ^* is the set of all possible strings over Σ
- ▶ $\Sigma^* = \Sigma^0 \cup \Sigma^1 \cup \Sigma^2 \cup \dots$
- ▶ A *Language*, L , over Σ is a subset of Σ^*
- ▶ $L \subseteq \Sigma^*$

NP-Completeness and Boolean Satisfiability

Language Accepted by a Turing Machine

- ▶ Language accepted by Turing Machine, M denoted by $L(M)$
- ▶ $L(M)$ is the set of strings $w \in \Sigma^*$ accepted by M
- ▶ For *Final States* $F = \{Y, N\}$, a string $w \in \Sigma^*$ is accepted by $M \Leftrightarrow$ (if and only if) M starting in q_0 with w on the tape halts in state Y
- ▶ Calculating a function (**function problem**) can be turned into a **decision problem** by asking whether $f(x) = y$

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NP-Completeness and Boolean Satisfiability

The NP-Complete Class

- ▶ If we do not know if $P \neq NP$, what can we say ?
- ▶ A language L is *NP-Complete* if:
 - ▶ $L \in NP$ and
 - ▶ for all other $L' \in NP$ there is a *polynomial time transformation* (Karp reducible, reduction) from L' to L
- ▶ Problem P_1 *polynomially reduces* (Karp reduces, transforms) to P_2 , written $P_1 \propto P_2$ or $P_1 \leq_p P_2$, iff $\exists f : dp_{P_1} \rightarrow dp_{P_2}$ such that
 - ▶ $\forall I \in dp_{P_1} [I \in Y_{P_1} \Leftrightarrow f(I) \in Y_{P_2}]$
 - ▶ f can be computed in polynomial time

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NP-Completeness and Boolean Satisfiability

The NP-Complete Class (2)

- ▶ More formally, $L_1 \subseteq \Sigma_1^*$ polynomially transforms to $L_2 \subseteq \Sigma_2^*$, written $L_1 \propto L_2$ or $L_1 \leq_p L_2$, iff $\exists f : \Sigma_1^* \rightarrow \Sigma_2^*$ such that
 - ▶ $\forall x \in \Sigma_1^* [x \in L_1 \Leftrightarrow f(x) \in L_2]$
 - ▶ There is a polynomial time TM that computes f
- ▶ *Transitivity* If $L_1 \propto L_2$ and $L_2 \propto L_3$ then $L_1 \propto L_3$
- ▶ If L is NP-Hard and $L \in P$ then $P = NP$
- ▶ If L is NP-Complete, then $L \in P$ if and only if $P = NP$
- ▶ If L_0 is NP-Complete and $L \in NP$ and $L_0 \propto L$ then L is NP-Complete
- ▶ Hence if we find one NP-Complete problem, it may become easier to find more
- ▶ In 1971/1973 [Cook-Levin](#) showed that the [Boolean satisfiability problem \(SAT\)](#) is NP-Complete

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NP-Completeness and Boolean Satisfiability

The Boolean Satisfiability Problem

- ▶ A propositional logic formula or Boolean expression is built from variables, operators: AND (conjunction, \wedge), OR (disjunction, \vee), NOT (negation, \neg)
- ▶ A formula is said to be *satisfiable* if it can be made True by some assignment to its variables.
- ▶ *The Boolean Satisfiability Problem* is, given a formula, check if it is satisfiable.
 - ▶ *Instance*: a finite set U of Boolean variables and a finite set C of clauses over U
 - ▶ *Question*: Is there a satisfying truth assignment for C ?
- ▶ A *clause* is a disjunction of variables or negations of variables
- ▶ *Conjunctive normal form (CNF)* is a conjunction of clauses
- ▶ Any Boolean expression can be transformed to CNF

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NP-Completeness and Boolean Satisfiability

The Boolean Satisfiability Problem (2)

- ▶ Given a set of Boolean variable $U = \{u_1, u_2, \dots, u_n\}$
- ▶ A literal from U is either any u_i or the negation of some u_i (written $\overline{u_i}$)
- ▶ A clause is denoted as a subset of literals from U — $\{u_2, \overline{u_4}, u_5\}$
- ▶ A clause is satisfied by an assignment to the variables if at least one of the literals evaluates to True (just like disjunction of the literals)
- ▶ Let C be a set of clauses over U — C is satisfiable iff there is some assignment of truth values to the variables so that every clause is satisfied (just like CNF)
- ▶ $C = \{\{u_1, u_2, u_3\}, \{\overline{u_2}, \overline{u_3}\}, \{u_2, \overline{u_3}\}\}$ is satisfiable
- ▶ $C = \{\{u_1, u_2\}, \{u_1, \overline{u_2}\}, \{\overline{u_1}\}\}$ is not satisfiable

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NP-Completeness and Boolean Satisfiability

The Boolean Satisfiability Problem (3)

- ▶ Proof that SAT is NP-Complete looks at the structure of NDTMs and shows you can transform any NDTM to SAT in polynomial time (in fact logarithmic space suffices)
- ▶ SAT is in NP since you can check a solution in polynomial time
- ▶ To show that $\forall L \in \text{NP} : L \leq \text{SAT}$ invent a polynomial time algorithm for each polynomial time NDTM, M , which takes as input a string x and produces a Boolean formula E_x which is satisfiable iff M accepts x
- ▶ See [Cook-Levin theorem](#)

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NP-Completeness and Boolean Satisfiability

Coping with NP-Completeness

- ▶ What does it mean if a problem is NP-Complete ?
 - ▶ There is a P time verification algorithm.
 - ▶ There is a P time algorithm to solve it iff $P = NP$ (?)
 - ▶ No one has yet found a P time algorithm to solve any NP-Complete problem
 - ▶ So what do we do ?
- ▶ Improved exhaustive search — Dynamic Programming; Branch and Bound
- ▶ Heuristic methods — *acceptable* solutions in *acceptable* time — compromise on optimality
- ▶ Average time analysis — look for an algorithm with good average time — compromise on generality (see [Big-O Algorithm Complexity Cheatsheet](#))
- ▶ Probabilistic or Randomized algorithms — compromise on correctness

Commentary 4

Future Work, Other Examples, References

Computability,
Complexity

Phil Molyneux

4 Future Work, Other Examples, References

- ▶ Future work — Tutorials and TMAs
- ▶ Other examples
- ▶ References and other sources
- ▶ **Colophon**
- ▶ LaTeX with Beamer, Listings and other packages
- ▶ Index of Python code and diagrams
- ▶ PGF/TikZ for the diagrams
- ▶ External copies of the diagrams as PDF with tight bounding boxes are available

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What Next ?

Programming, Debugging, Psychology

Although programming techniques have improved immensely since the early days, the process of finding and correcting errors in programming — known graphically if inelegantly as *debugging* — still remains a most difficult, confused and unsatisfactory operation. The chief impact of this state of affairs is psychological. Although we are happy to pay lip-service to the adage that to err is human, most of us like to make a small private reservation about our own performance on special occasions when we really try. It is somewhat deflating to be shown publicly and incontrovertibly by a machine that even when we do try, we in fact make just as many mistakes as other people. If your pride cannot recover from this blow, you will never make a programmer.

Christopher Strachey, Scientific American 1966 vol 215 (3) September pp112-124

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What Next ?

To err is human ?

- ▶ To err is human, to really foul things up requires a computer.
- ▶ Attributed to [Paul R. Ehrlich](#) in [101 Great Programming Quotes](#)
- ▶ Attributed to [Bill Vaughn](#) in [Quote Investigator](#)
- ▶ Derived from [Alexander Pope](#) (1711, [An Essay on Criticism](#))
- ▶ *To Err is Humane; to Forgive, Divine*
- ▶ This also contains
 - A little learning is a dangerous thing;
Drink deep, or taste not the [Pierian Spring](#)*
- ▶ In programming, this means you have to *read the fabulous manual* ([RTFM](#))

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Future Work

TMA03 Topics

- ▶ Abstract Data Types
- ▶ Queues, Bags, Binary Trees
- ▶ Logic and SQL
- ▶ Computability, Complexity

Future Work

Dates

- ▶ Sunday, 3 May 2026 online tutorial TMA03 topics
- ▶ Thursday, 28 May 2026 TMA03 due
- ▶ Please email me with any requests for particular topics

Web Sites

Computability

▶ **Logic**

- ▶ [WFF, WFF'N Proof online](#)

▶ **Computability**

- ▶ [Computability](#)
- ▶ [Computable function](#)
- ▶ [Decidability \(logic\)](#)
- ▶ [Turing Machines](#)
- ▶ [Universal Turing Machine](#)
- ▶ [Turing machine simulator](#)
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- ▶ [Von Neumann Architecture](#)
- ▶ [Turing Machine XKCD 205 Candy Button Paper](#)
- ▶ [Turing Machine XKCD 505 A Bunch of Rocks](#)
- ▶ [RIP John Conway Why can Conway's Game of Life be classified as a universal machine?](#)
- ▶ [Phil Wadler Bright Club on Computability](#)
- ▶ [Bridges: Theory of Computation: Halting Problem](#)
- ▶ [Bridges: Theory of Computation: Other Non-computable Problems](#)

Web Sites

Complexity

- ▶ **Complexity**
 - ▶ Complexity class
 - ▶ NP complexity
 - ▶ NP complete
 - ▶ Reduction (complexity)
 - ▶ P versus NP problem
 - ▶ Graph of NP-Complete Problems