



FALMOUTH
UNIVERSITY



COMP110: Principles of Computing

5: Complexity

Research Journal



Research journal presentations

- ▶ Presentation sessions in **week 7** (week after next)
- ▶ Prepare a **10 minute** presentation
- ▶ Discussing your chosen paper, its context and influence
- ▶ Use any presentation software to prepare slides (e.g. Beamer, PowerPoint, Google Slides)

Research journal presentations — Why?

- ▶ Assessed on a **threshold** basis
- ▶ A chance to share insights on what you've been reading
- ▶ A chance for informal feedback

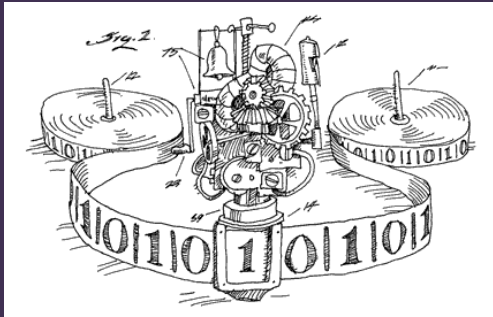
Research journal

- ▶ You should also be working on the journal itself!
- ▶ Peer review (draft needed) in **week 8**
- ▶ This week's worksheet is the last one for a while, to give you time to work on your research journal

Turing machines



Turing machines



- ▶ Introduced in 1936 by Alan Turing
- ▶ Theoretical model of a “computer”
 - ▶ I.e. a machine that carries out computations (calculations)

Turing machine

- ▶ Has a finite number of **states**
- ▶ Has an infinite **tape**
- ▶ Each space on the tape holds a **symbol** from a finite **alphabet**
- ▶ Has a **tape head** pointing at one space on the tape
- ▶ Has a transition table which, given:
 - ▶ The current state
 - ▶ The symbol under the tape headspecifies:
 - ▶ A new state
 - ▶ A new symbol to write to the tape, overwriting the current symbol
 - ▶ Where to move the tape head: one space to the left, or one space to the right

The Church-Turing Thesis

- ▶ If a calculation can be carried out by a mechanical process at all, then it can be carried out by a Turing machine
- ▶ I.e. a Turing machine is the most “powerful” computer possible, in terms of what is possible or impossible to compute
- ▶ A machine, language or system is **Turing complete** if it can simulate a Turing machine
- ▶ (In practice, nothing can simulate an infinite tape, so we just assume a large enough tape)

Examples of Turing complete systems

- ▶ All general-purpose CPUs and programming languages
- ▶ Esoteric programming languages (e.g. Brainf*ck)
- ▶ NAND gate circuits
- ▶ Cellular automata
- ▶ Minecraft redstone circuits
- ▶ Factorio circuit networks
- ▶ Magic: The Gathering cards
- ▶ ...

Computability



Computability theory

- ▶ Let A and B be **sets** of elements
 - ▶ NB: A may be **infinite**
- ▶ A function $f : A \rightarrow B$ is **computable** if there exists a Turing machine which computes f
 - ▶ I.e. given an encoding of $a \in A$ as input, the Turing machine outputs an encoding of $f(a)$

An uncomputable function

The **halting problem**

- ▶ A = the set of all Turing machines (encoded as transition tables)
- ▶ $B = \{\text{true}, \text{false}\}$
- ▶
$$f(a) = \begin{cases} \text{true} & \text{if } a \text{ halts in finite time on all inputs} \\ \text{false} & \text{otherwise} \end{cases}$$
- ▶ There is **no** Turing machine that computes f
- ▶ f is **uncomputable**

Computability and the Church-Turing Thesis

- ▶ Church-Turing tells us that Turing machines are as powerful as any other computer
- ▶ Therefore if a function is uncomputable, there is **no conceivable machine** that can compute it

The halting problem

- ▶ Write a software tool that, given a C# program, predicts whether that program can go into an infinite loop
- ▶ Your tool must work for **all** C# programs, considering **all** possible inputs to the program
- ▶ This task is impossible!

Search



Search

- ▶ We have a list of names, each with some data associated
- ▶ We want to find one of them

Linear search

```
procedure FIND(name, list)
  for each item in list do
    if item.name = name then
      return item
    end if
  end for
  raise error "Not found"
end procedure
```

How long does it take?

Socrative room code: FALCOMPED

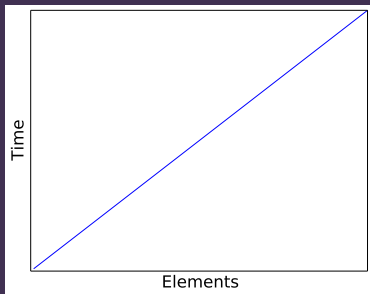
- ▶ Suppose there are 25 items in the list
- ▶ In the **best case**, how many items do we need to visit before finding the one we want?
- ▶ How about in the **worst case**?

How long does it take?

Socrative room code: FALCOMPED

- ▶ If there are 25 items in the list, the **worst case** number of items visited is 25
- ▶ How about if there are 50 items?
- ▶ How about 100 items?
- ▶ If the number of items **doubles**, what happens to the amount of time the search takes?

Linear time



- ▶ The running time of linear search is **proportional** to the size n of the list
- ▶ Linear search is said to have **linear time complexity**
- ▶ Also written as $O(n)$ **time complexity**

Searching a sorted list

- ▶ If the list is **sorted** in alphabetical order, we can do better than linear...

Binary search

```
procedure FIND(name, list)
  if list is empty then
    raise error "Not found"
  end if
  mid  $\leftarrow$  the "middle" item of the list
  if name = mid.name then
    return mid
  else if name < mid.name then
    return FIND(name, first half of list)
  else if name > mid.name then
    return FIND(name, second half of list)
  end if
end procedure
```

Find “Lopez, Jeffrey”

Anderson, Martha
Baker, Theresa
Brown, Janet
Clark, Stephanie
Collins, Jane
Cox, Shirley
Davis, Marilyn
Diaz, Harold
Gonzalez, Adam
Henderson, Lawrence
Hughes, Aaron
Kelly, Phillip
→ Lewis, Rose
Lopez, Jeffrey
Miller, Jeremy
Parker, Debra
Perez, Diana
Russell, Mildred
Sanders, Phillip
Scott, Michelle
Stewart, Howard
Ward, Jessica
White, Amanda
Williams, Billy
Young, Frank

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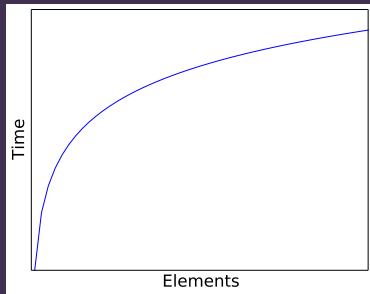
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How long does it take?

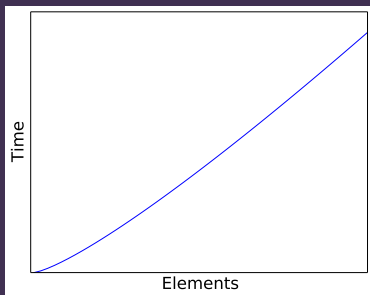
Socrative room code: FALCOMPED

- ▶ Each iteration cuts the list in **half**
- ▶ Worst case: we have to keep halving until we get down to a single element
- ▶ If the size of the list is **doubled**, what happens to the worst-case **number of iterations** required?
- ▶ **Answer:** it increases by 1
- ▶ The running time is **logarithmic** or $O(\log n)$



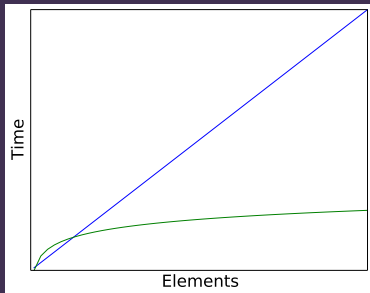
Hidden complexity

```
if name < mid.name then  
    return FIND(name, first half of list)  
else if name > mid.name then  
    return FIND(name, second half of list)  
end if
```



- ▶ Careful how you implement this!
- ▶ **Copying** (half of) a list is **linear** $O(n)$
- ▶ The actual running time would be $O(n \log n)$
- ▶ Use **pointers** into the list instead of copying

Binary search vs linear search



- So binary search is better than linear search... right?

Hashing

- ▶ Come up with a **hashing function** which maps elements to numbers
- ▶ Example: assign $A = 1, B = 2, C = 3$ etc, and add them together
- ▶ Use these numbers to assign each element to a “bin” where it can be found

:	:
:	:
112	Ward, Jessica
113	Baker, Theresa
114	Collins, Jane
115	—
116	—
117	Hughes, Aaron
118	—
119	—
120	—
121	—
122	Brown, Janet
123	—
124	—
125	Gonzalez, Adam Lewis, Rose
126	—
127	—
128	—
129	—
130	—
131	—
132	Young, Frank
:	:
:	:

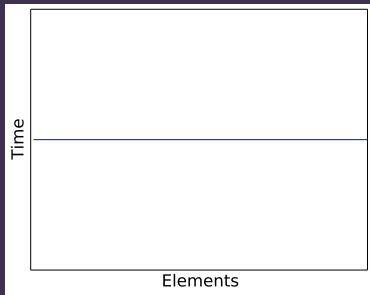
Hash look-up

98	Diaz, Harold
99	Parker, Debra Perez, Diana White, Amanda
112	Ward, Jessica
113	Baker, Theresa
114	Collins, Jane
117	Hughes, Aaron
122	Brown, Janet
125	Gonzalez, Adam Lewis, Rose
132	Young, Frank
135	Kelly, Philip
138	Cox, Shirley
142	Clark, Stephanie
144	Scott, Michelle
145	Miller, Jeremy
147	Davis, Marilyn
149	Lopez, Jeffrey
151	Anderson, Martha
158	Williams, Billy
162	Sanders, Phillip
171	Russell, Mildred
175	Stewart, Howard
183	Henderson, Lawrence

“Lopez, Jeffrey”

$$12 + 15 + 16 + 5 + 26 + 10 + 5 + 6 + 6 + 18 + 5 + 25 = 149$$

How long does it take?



- ▶ If there are no “collisions”, look-up time is **constant** or $O(1)$
 - ▶ (NB: constant **with respect to** n)
- ▶ I.e. doubling the size of the list **does not change** the look-up time
- ▶ When there are collisions, need to fall back on something like linear or binary search within each bin

Don't reinvent the wheel!

- ▶ We are using search as an **example**, to learn the **principles** — in practice you should hardly ever implement your own search
- ▶ Linear search in C#:
 - ▶ `List<T>.IndexOf()`
- ▶ Binary search in C#:
 - ▶ `List<T>.BinarySearch()`
- ▶ Hash tables in C#:
 - ▶ `Dictionary<TKey, TValue>`
 - ▶ `GetHashCode()` is used to specify hash function

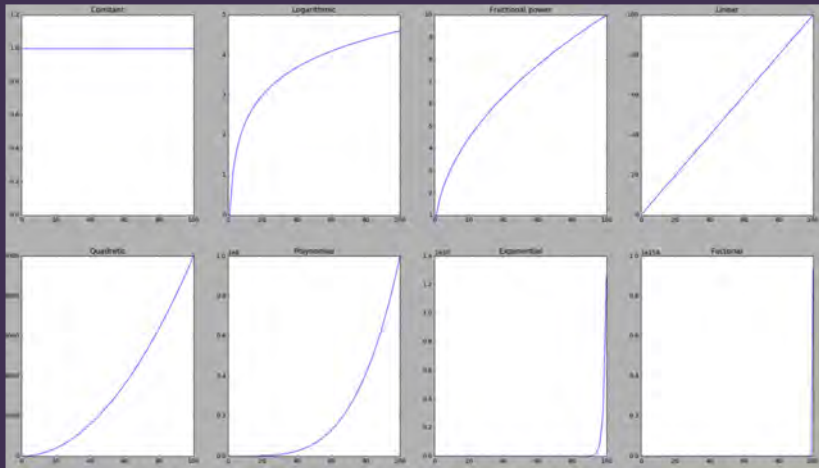
More on complexity



Common complexity classes

"Faster"	Constant	$O(1)$
↑	Logarithmic	$O(\log n)$
	Fractional power	$O(n^k), k < 1$
	Linear	$O(n)$
	Quadratic	$O(n^2)$
	Polynomial	$O(n^k), k > 1$
↓	Exponential	$O(e^n)$
"Slower"	Factorial	$O(n!)$

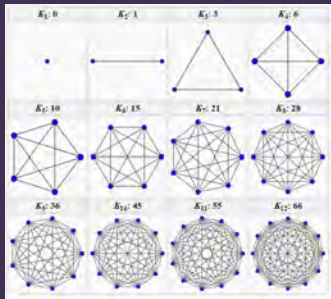
Common complexity classes



Working with big O notation

- ▶ Can ignore **leading constants**
 - ▶ If one algorithm takes n^2 operations, another takes $500n^2$ and a third takes $0.00000001n^2$, all three are $O(n^2)$
- ▶ Take only the **dominant term**
 - ▶ The term that is largest when n is large
 - ▶ If an algorithm takes $0.1n^3 + 300n^2 + 7000$ operations, it is $O(n^3)$
- ▶ Multiply **compound** algorithms
 - ▶ If an algorithm does n “things” and each “thing” is $O(n)$, then the overall algorithm is $O(n^2)$

Quadratic complexity



- ▶ Collision detection between n objects
- ▶ The naïve way: check **each pair** of objects to see whether they have collided
- ▶ This is **quadratic** or $O(n^2)$
- ▶ Doubling the number of objects would **quadruple** the time required!
- ▶ Cleverer methods exist that are more scalable
 - ▶ Further reading: spatial hashing, quadtrees, octrees, Verlet lists

Exponential complexity

- ▶ A prime number is a number that is divisible only by 1 and itself
- ▶ Given an n -bit number $m = pq$ that is a product of two primes p and q , find p and q .

```
for  $p = 2, 3, \dots, m$  do  
     $q \leftarrow m/p$   
    if  $q$  is an integer then  
        return  $p, q$   
    end if  
end for
```

- ▶ Since $m \leq 2^n - 1$, in the worst case this is $O(2^n)$
 - ▶ Actually even slower because division is not $O(1)$
- ▶ Adding 1 to n potentially **doubles** the running time!

Exponential complexity

- ▶ If adding 1 bit **doubles** the running time...
- ▶ Suppose factoring a 16-bit number takes 1 millisecond
- ▶ Factoring a 32-bit number would take 65.5 seconds
- ▶ Factoring a 48-bit number would take 49.7 days
- ▶ Factoring a 64-bit number would take 8919 years
- ▶ Factoring a 96-bit number would take 2800 times the age of the universe

Aside: a famous unanswered question in computing

- ▶ A problem is “in P ” if it can be solved with an algorithm running in $O(n^k)$ time
- ▶ A problem is in NP if a potential solution can be checked in $O(n^k)$ time
 - ▶ Equivalently, it can be solved with an algorithm running in $O(n^k)$ time on an infinitely parallel machine
- ▶ Are there any problems in NP but not in P ?

P versus NP

- ▶ If you can find a **mathematical proof** that either $P = NP$ or $P \neq NP$, there's a \$1 million prize...
- ▶ It is believed that $P \neq NP$, so large instances of *NP*-hard problems are not solvable in a feasible amount of time
 - ▶ Many types of cryptography are based on this assumption
 - ▶ Quantum computers are "infinitely parallel" in a sense so *can* solve some large *NP*-hard problems

Caveats

- ▶ Time complexity only tells us how an algorithm **scales** with the size of the input
 - ▶ If we know the input will always be **small**, time complexity is not so important
 - ▶ Linear search is quicker than binary search if you only ever have 3 elements
 - ▶ Naïve collision detection is fine if your game only ever has 4 objects on screen
 - ▶ Sometimes complexity in terms of other resources (e.g. space, bandwidth) are more important than time
- ▶ Software development is all about choosing **the right tool for the job**
 - ▶ If you need scalability, choose a scalable algorithm
 - ▶ Otherwise, choose simplicity

Summary

- ▶ Time complexity tells us how the running time of an algorithm **scales** with the size of the data it is given
- ▶ Choice of data structures and algorithms can have a large impact on the efficiency of your software
- ▶ ... but only if scalability is actually a factor

Open workshop



Open workshop

- ▶ Use the rest of this session to get on with your **research journal**
- ▶ Post in the chat if you have questions or need help!