# Basic Data Structures

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## Primitive!

The most basic data types:

| | |
|---|---|
| - Integers | 1, 2, 3, 1234, -5 |
| - Floating Point Decimals | 1.23, 2.34, -5.0 |
| - Character | ‘a’, ‘b’, ‘c’ |
| - Boolean | True, False |
| | |
| - Strings | “abc” |

## Complexity Increased

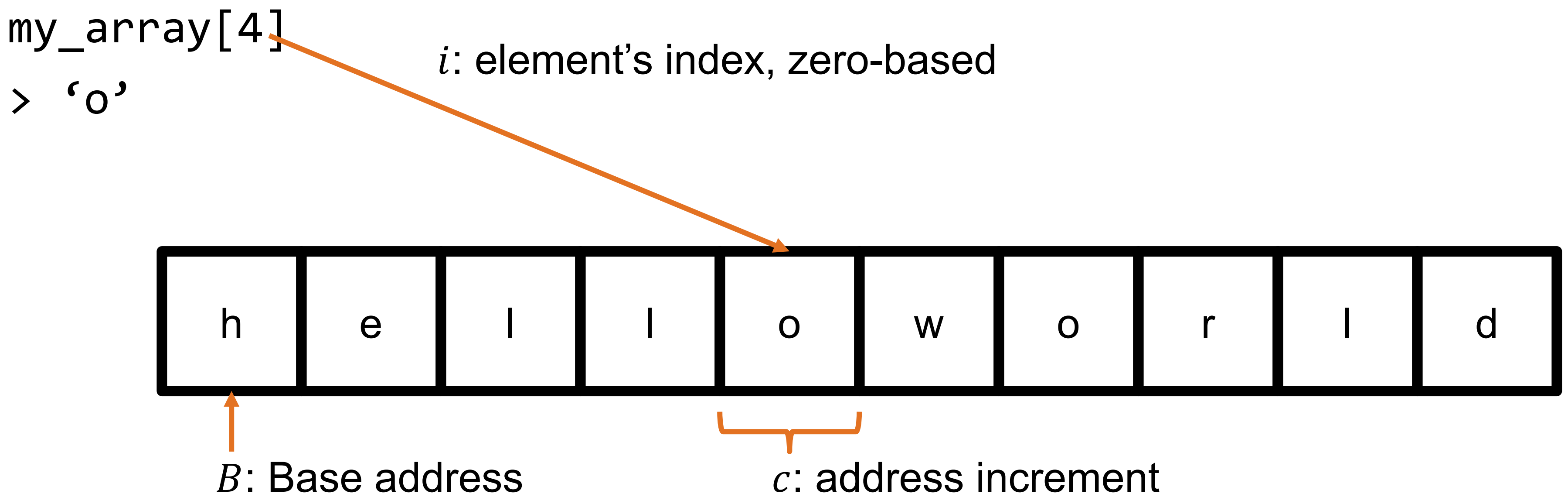
Complex data types can be constructed out of primitive data types.

Example: a date.
2020-11-24

More complex data structures can be constructed out of basic structures

# Array, one-dimensional

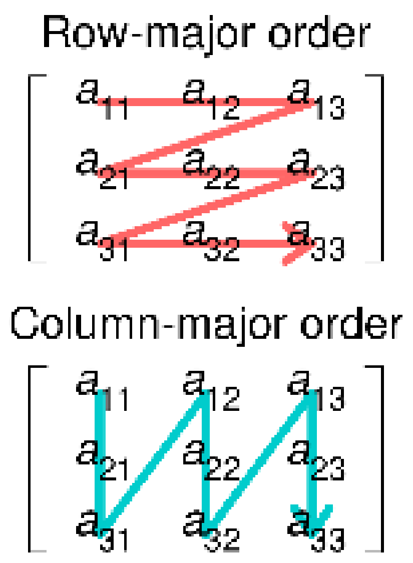
- One of the oldest and most important data structures:
  Almost every program uses arrays at some point.
- Mostly some consecutive space in memory.
- Used to implement a lot of other data structures.
- Accessing elements requires a single subscript.
  Indices are restricted to a consecutive range of integers: $B + c \times i$



```
my_array[4]
> ‘o’
```

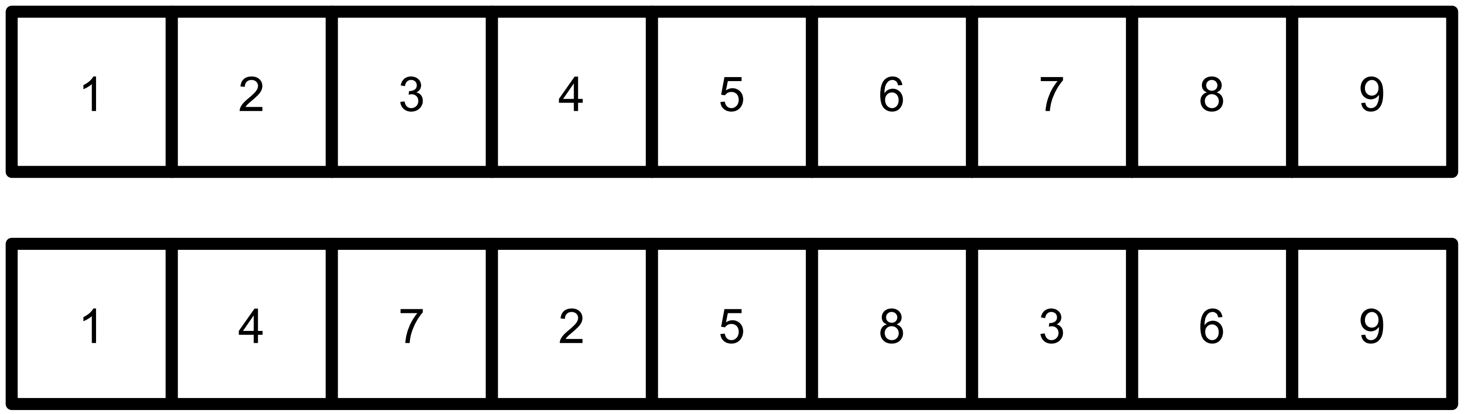
## Array, multi-dimensional

- Used to model a notion of matrices
- Still some consecutive space in memory
- Order either row-major or column-major


Row-major order
$a_{11}$ $a_{12}$ $a_{13}$
$a_{21}$ $a_{22}$ $a_{23}$
$a_{31}$ $a_{32}$ $a_{33}$
Column-major order
$a_{11}$ $a_{12}$ $a_{13}$
$a_{21}$ $a_{22}$ $a_{23}$
$a_{31}$ $a_{32}$ $a_{33}$

$$my\_matrix = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{bmatrix}$$

```
my_matrix[1][2]
> 6
```

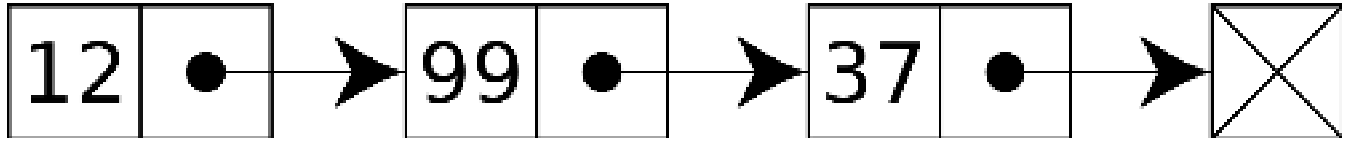


Row-major order

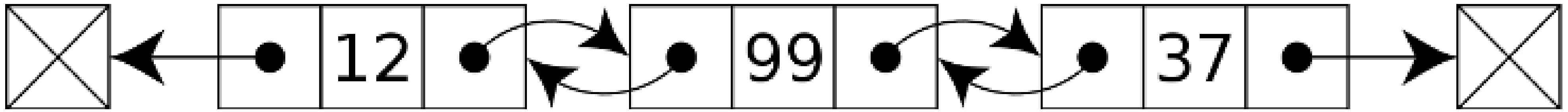
Column-major order

# Lists

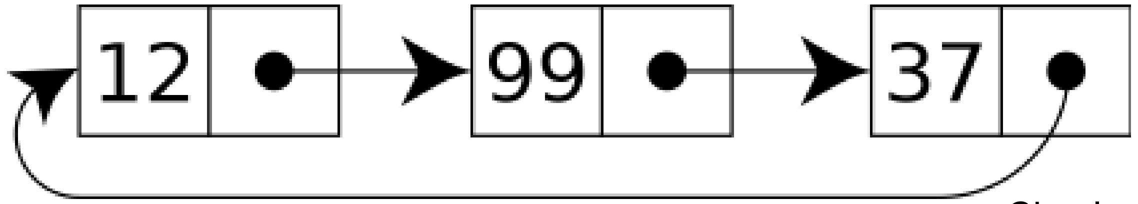
- A problem with arrays: Their consecutive space in memory is fixed.
  That makes insertion and deletion of elements a “costly operation” – sometimes the whole array has to be copied to a larger or smaller space in memory.
- Linked lists allow insertion and deletion at any point in the list



Linked list



Double-linked list



Circular-linked list

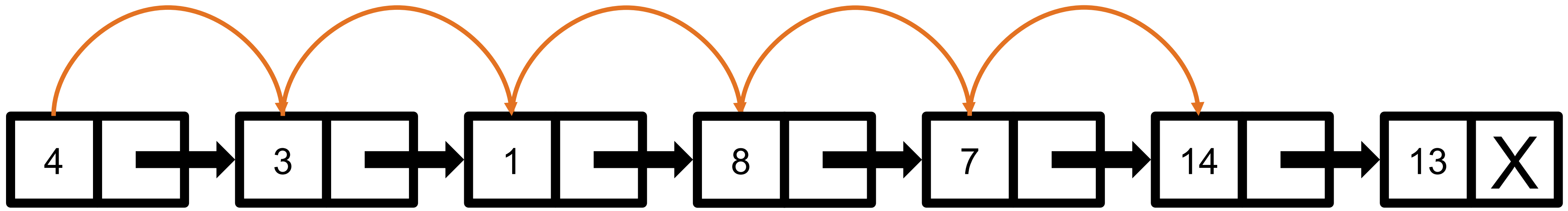
https://en.wikipedia.org/wiki/Linked_list

## Why should we care?

## Data structures make a difference

Choosing an appropriate data structure for your task will make a difference!

Example: Find the element ‘14’!

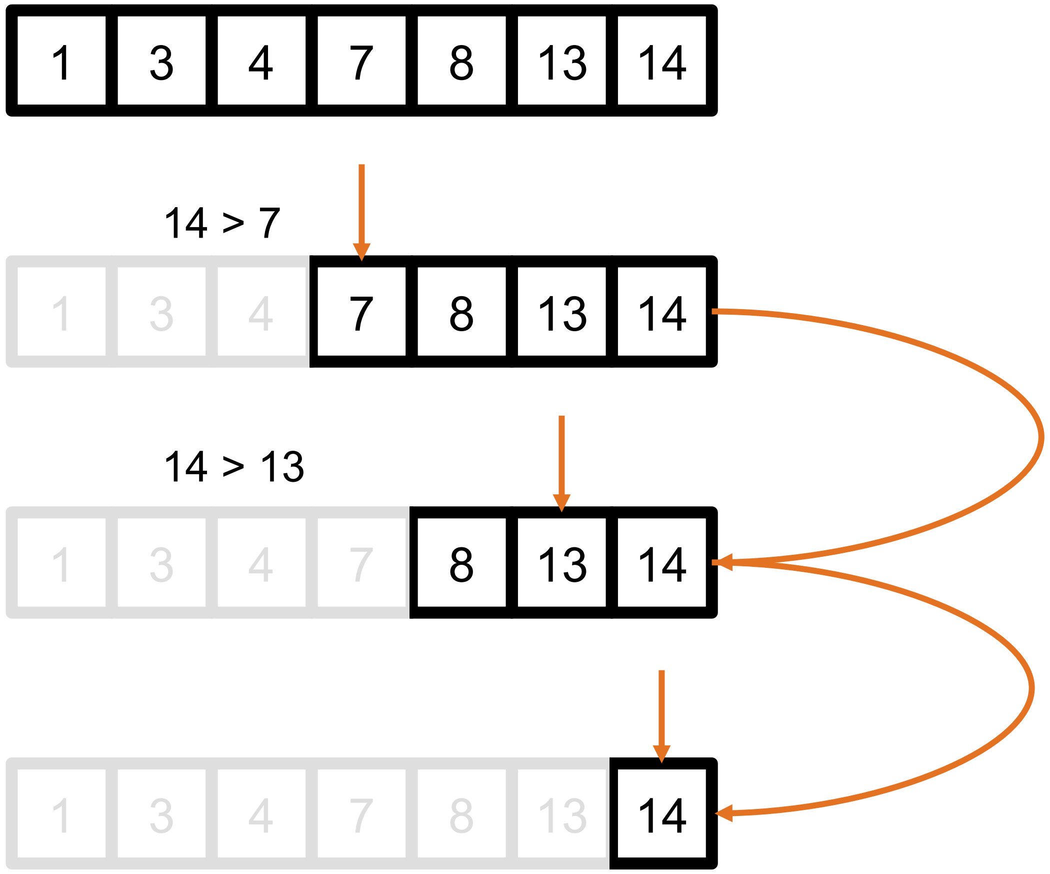


Data structure supports only to proceed to next element like a linked list.
Linear search – in worst case we have to visit all elements of the list!
Sorting the list first doesn’t increase lookup speed.

## Data structures make a difference

Choosing an appropriate data structure for your task will make a difference!

Example: Find the element ‘14’!



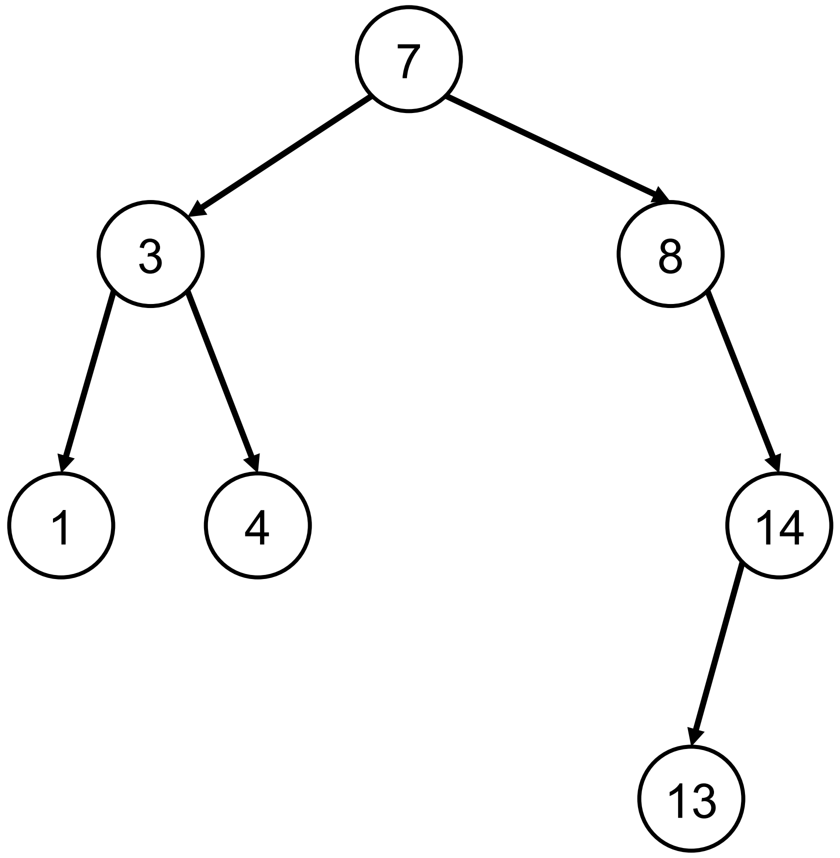
Data structure supports accessing specific positions of the list like an array. This boils down to binary search. With each operation we can eliminate half of the remaining list. Even in worst case, we don’t have to visit all elements in the list.

## Data structures make a difference

Choosing an appropriate data structure for your task will make a difference!

Example: Find the element ‘14’!

For binary search, the array has to be sorted. The logical structure represented within the array is a binary search tree.



A binary search tree is a rooted binary tree data structure whose internal nodes each store a key greater than all the keys in the node’s left subtree and less than those in its right subtree.

As a binary tree, each node has at most two children.

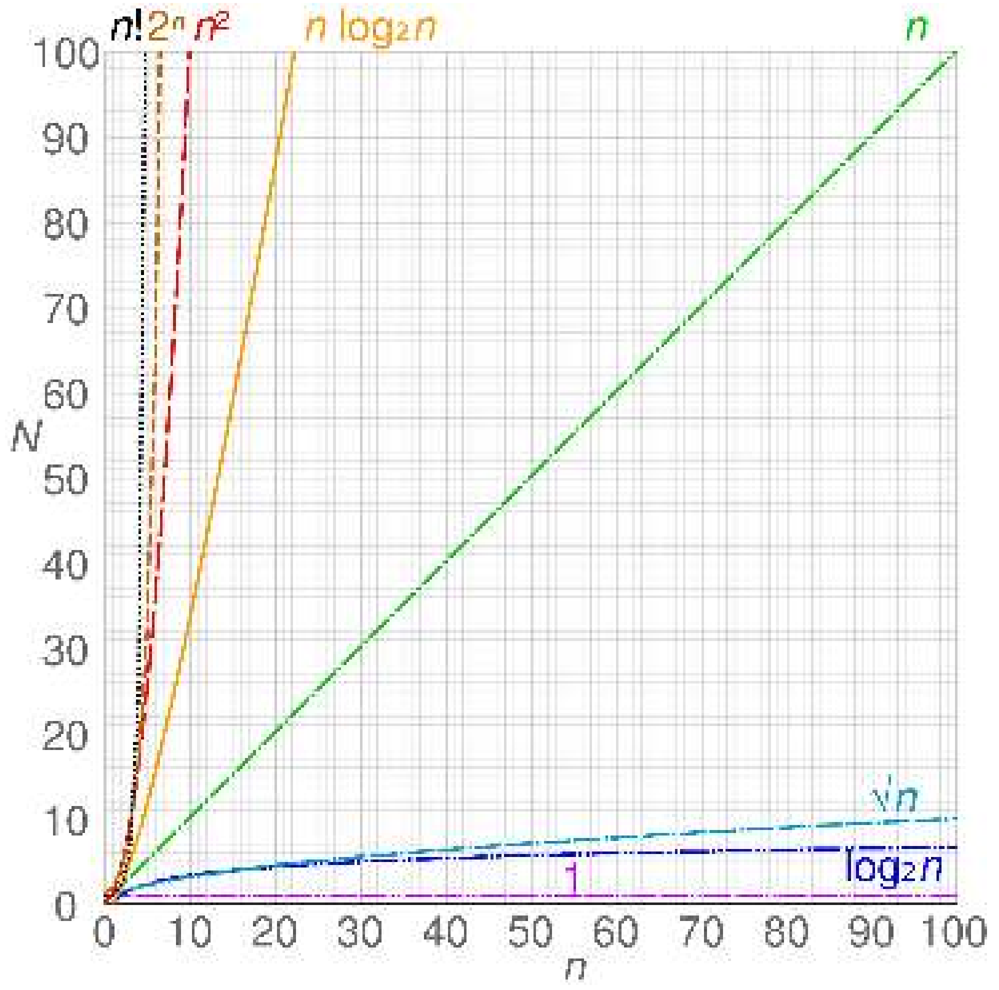
## Do we even notice?

Classification of

- Linear search: O(n)
- Binary search: O(log n)

Big-O-Notation

- Classifies algorithms according to how runtime grows with growing input size
- Usually provides an upper bound on the growth rate
- Picture shows some important classes
- O(1) means “in constant time”, i.e. not depending on input size at all



## Do we even notice?

Let’s assume $n = 100$ elements

- O(n): 100 operations required to find an element
- O(log n): 10 operations required

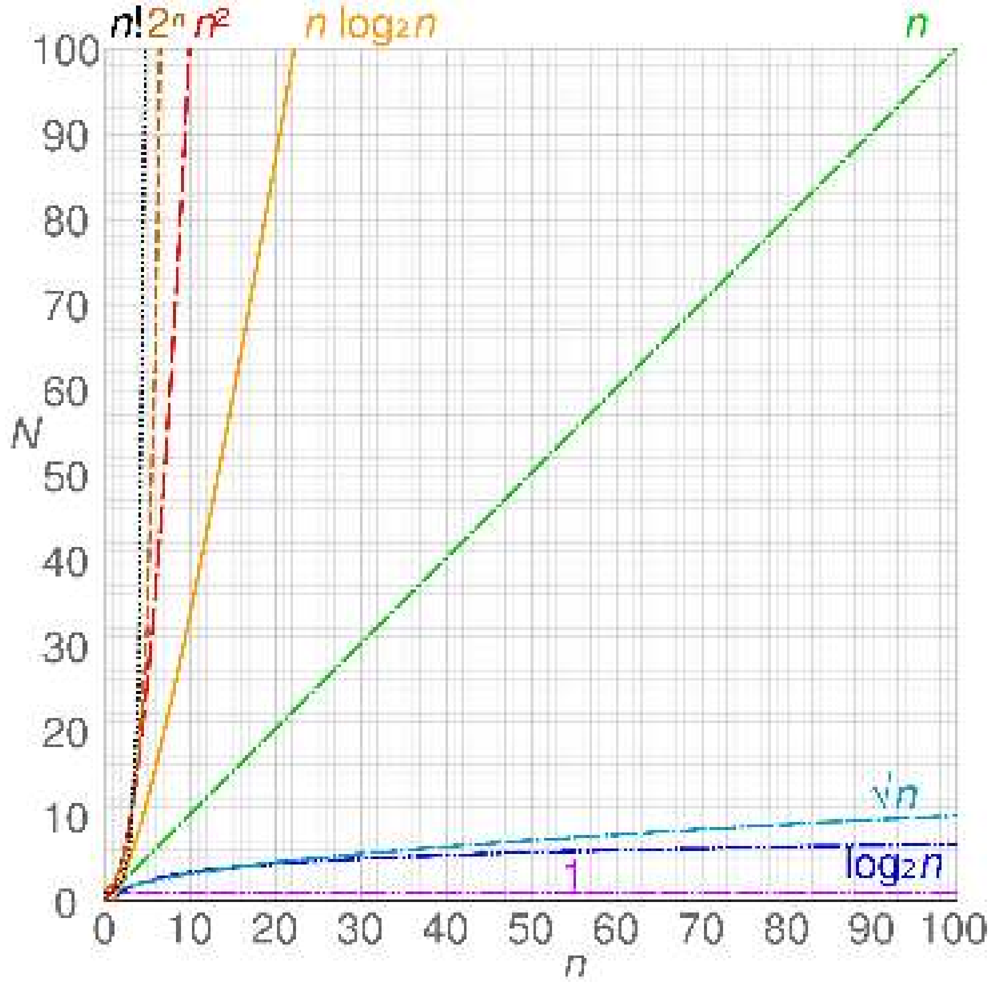
And for $n = 10.000.000$ (i.e. a factor of 100.000)?

- O(n): 10.000.000 operations required
- O(log n): ~24 operations required.
  That’s a factor of ~2,4!

And now imagine each operation takes one second to finish…

10.000.000 sec ~ 2777,78 hours ~ 115,74 days

Google wouldn’t be your friend anymore…



## More on data structures

## Sets

- Arrays maintain the order among elements but elements are not necessarily unique
- Sets store unique values without particular order
- Usually used to test a value for membership in a set

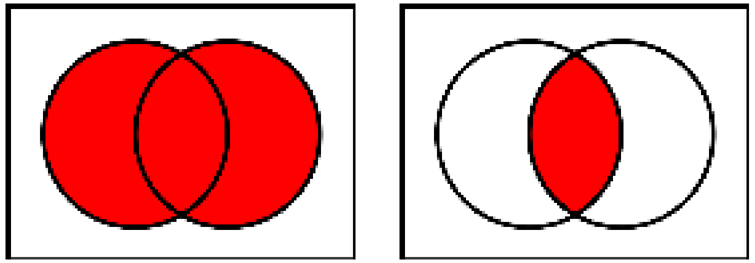
A poem as an array:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| a | rose | is | a | rose | is | a | rose |

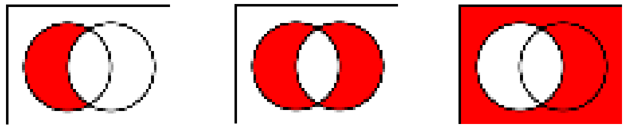
and as a set:

{ a, rose, is }

Sets allow fundamental operations to create new sets from given sets, e.g. the union of two sets and their intersection

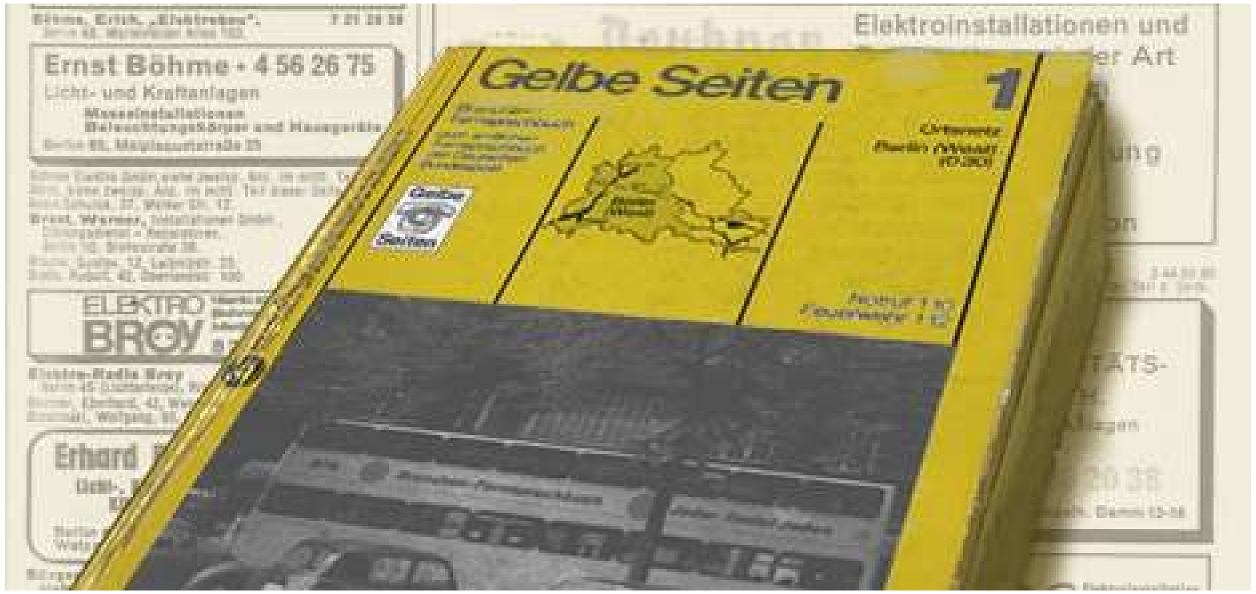


and more complex ones…



## Keys and values

- Arrays allow accessing elements by index, i.e. their position in the list.
- Accessing elements by a semantically meaningful key requires dictionaries a.k.a. associative arrays
- Keys must be unique
- Can be implemented such that finding elements is possible in O(1)



Ancient key-value-store in paperback. ~1900

## Keys and values

Most high-level programming languages offer dictionaries as a primitive, built-in data structure:

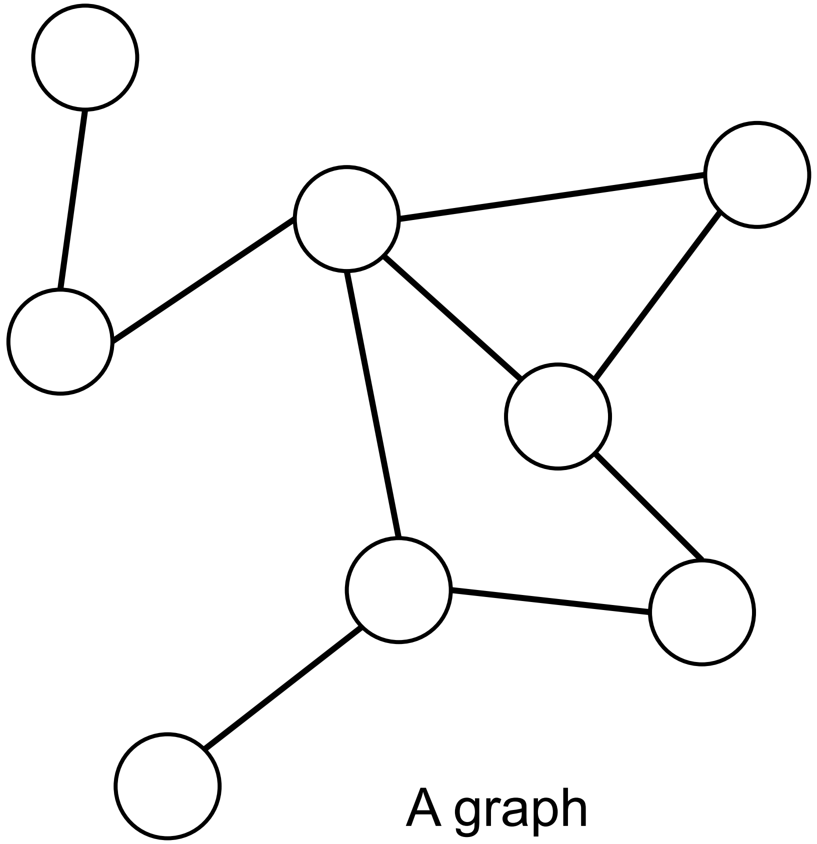
- dict (Python)
- dataframe (R)
- Map (Java)
- std::map (C++)

Differences in syntax, but functionality is basically the same

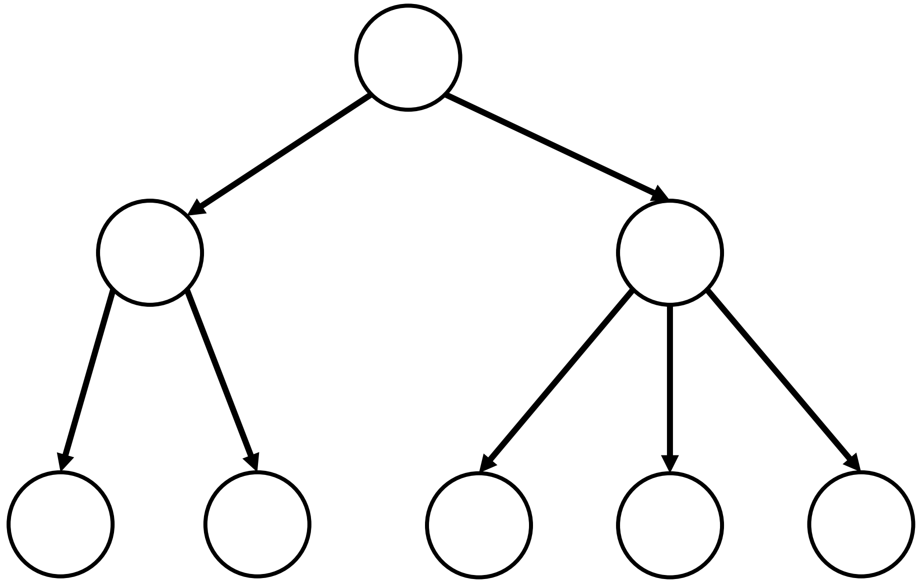
```
capitals = {
        "France"  :  "Paris",
        "Germany" :  "Berlin",
        "Brazil"  :  "Brasilia"
}
capitals["France"]
> "Paris"

capitals["Mexico"] = "Mexico City"
```

## Graphs & Trees

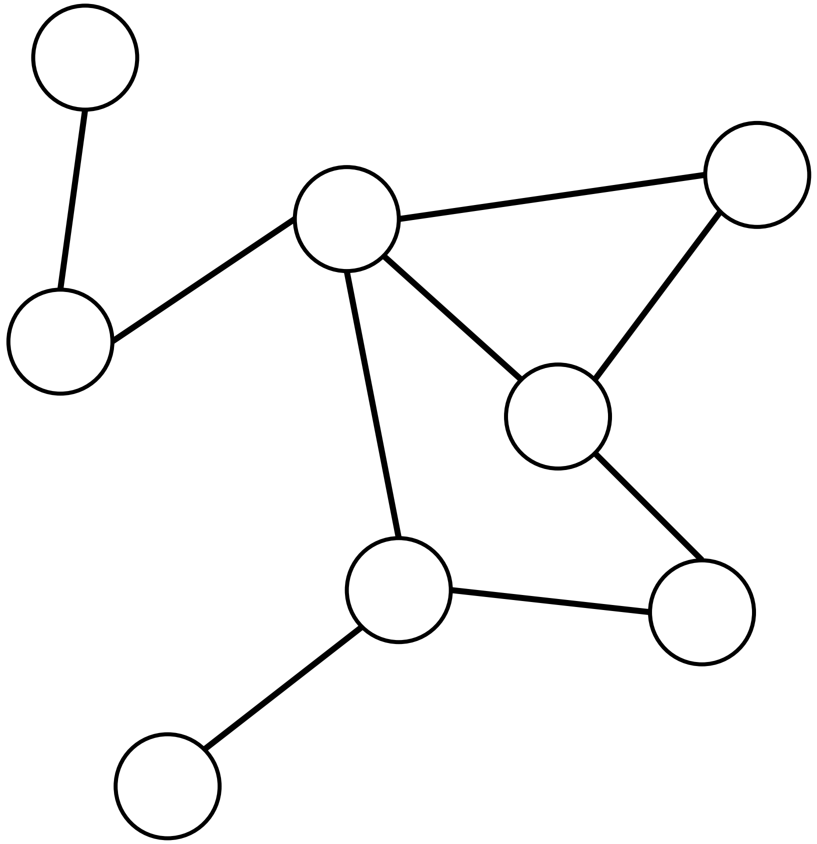


A graph



A tree

## Graphs



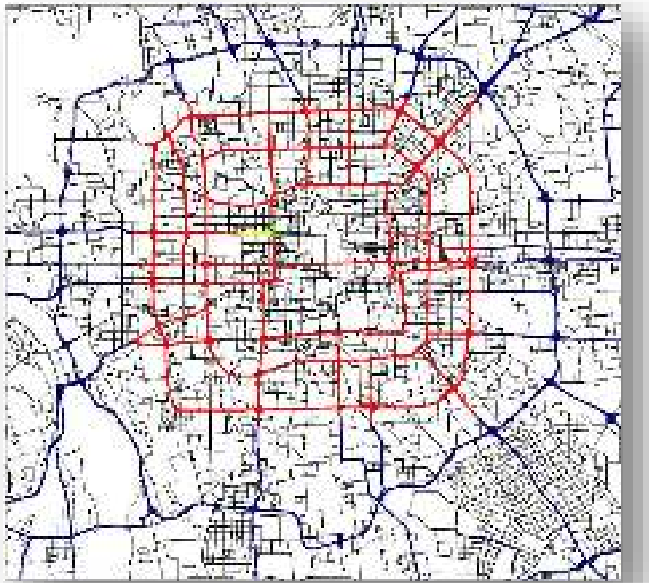
A graph in graph theory is a mathematical structure used to model pairwise relations between objects.

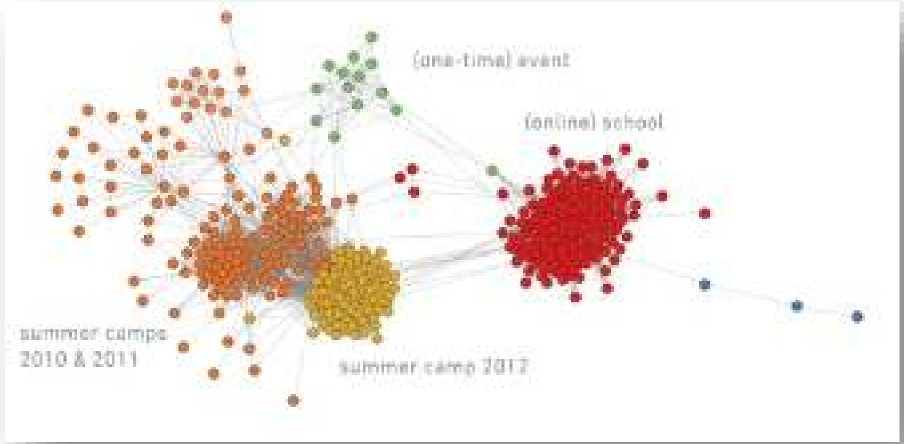
A graph consists of *vertices* (or *nodes*) and connecting *edges* (or *links*)

There is a large variety of types of graphs

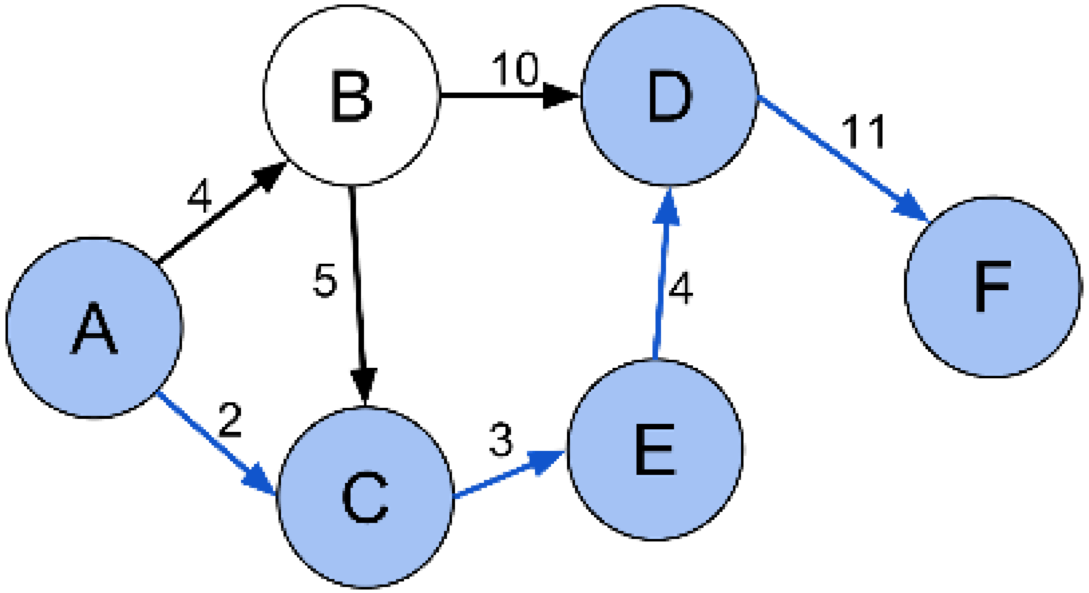
- Directed / Undirected / Mixed
- Connected / Disconnected
- Bipartite
- Weighted
- Attributed
- Tree

## Graphs

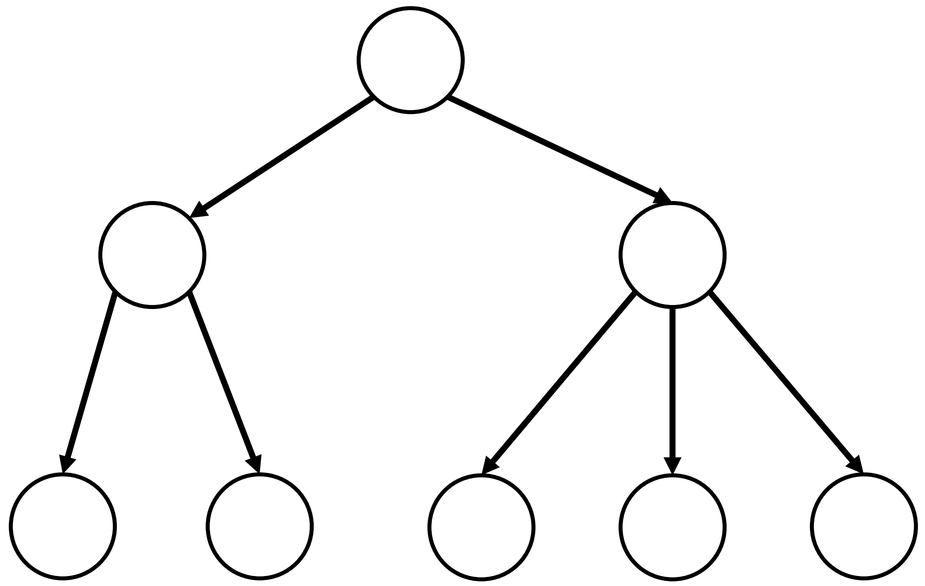



(one-time) event
(online) school
summer camps 2010 & 2011
summer camp 2012

名古屋市営地下鉄 路線図
Nagoya Subway Network


A
B
C
D
E
F
4
10
5
2
3
4
11

## Trees



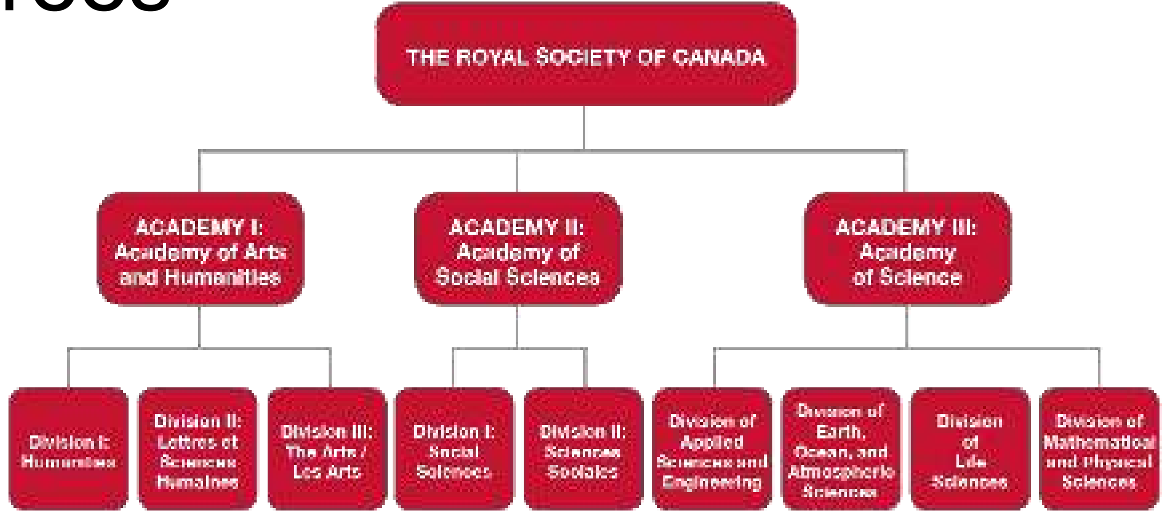
A tree in graph theory is an undirected graph in which any two vertices are connected by exactly one path, or equivalently a connected acyclic undirected graph.

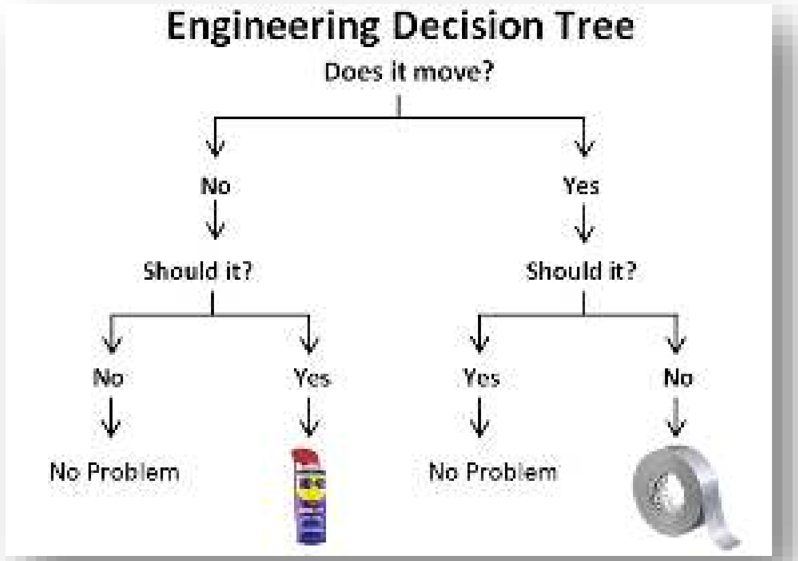
A tree as an abstract data type simulates a hierarchical tree structure, with a root value and subtrees of children with a parent node.

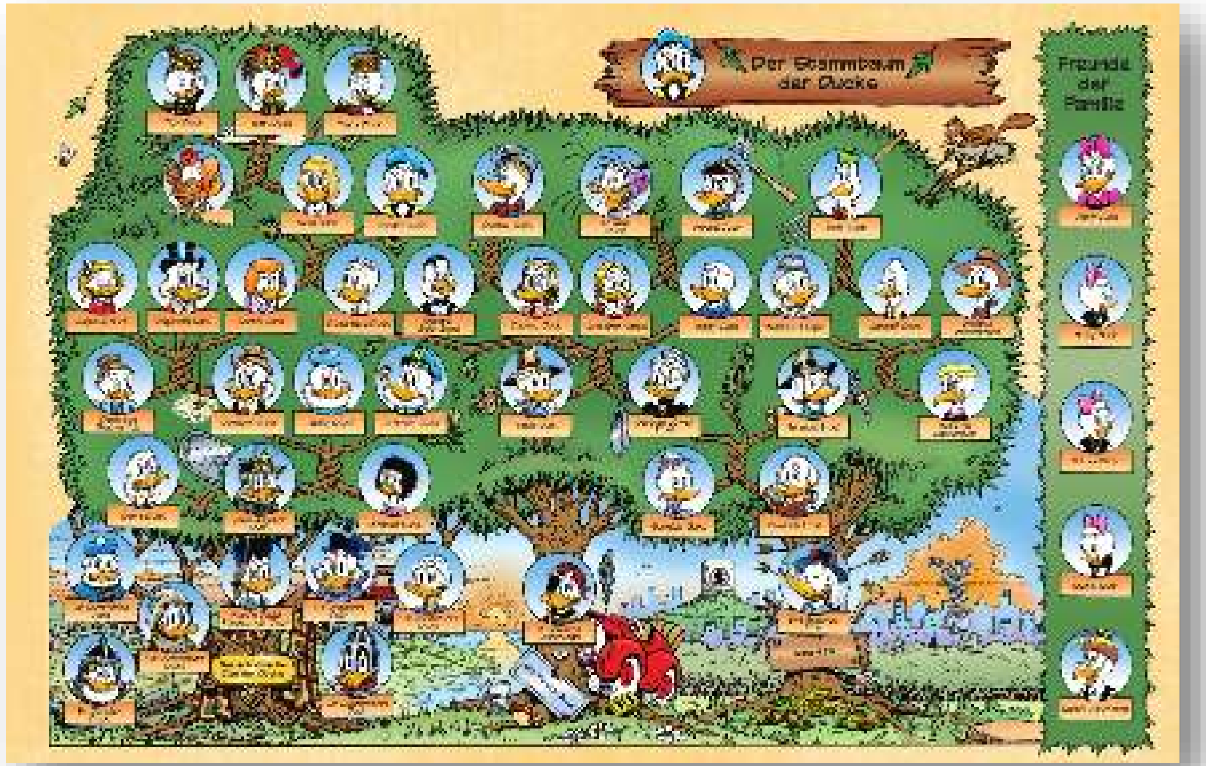
Trees as abstract data types are used to

- Represent hierarchical data (e.g. file systems)
- Represent evolutional data (e.g. in biology, technology, …)
- Represent Document Object Models of XML
- Implement efficient search

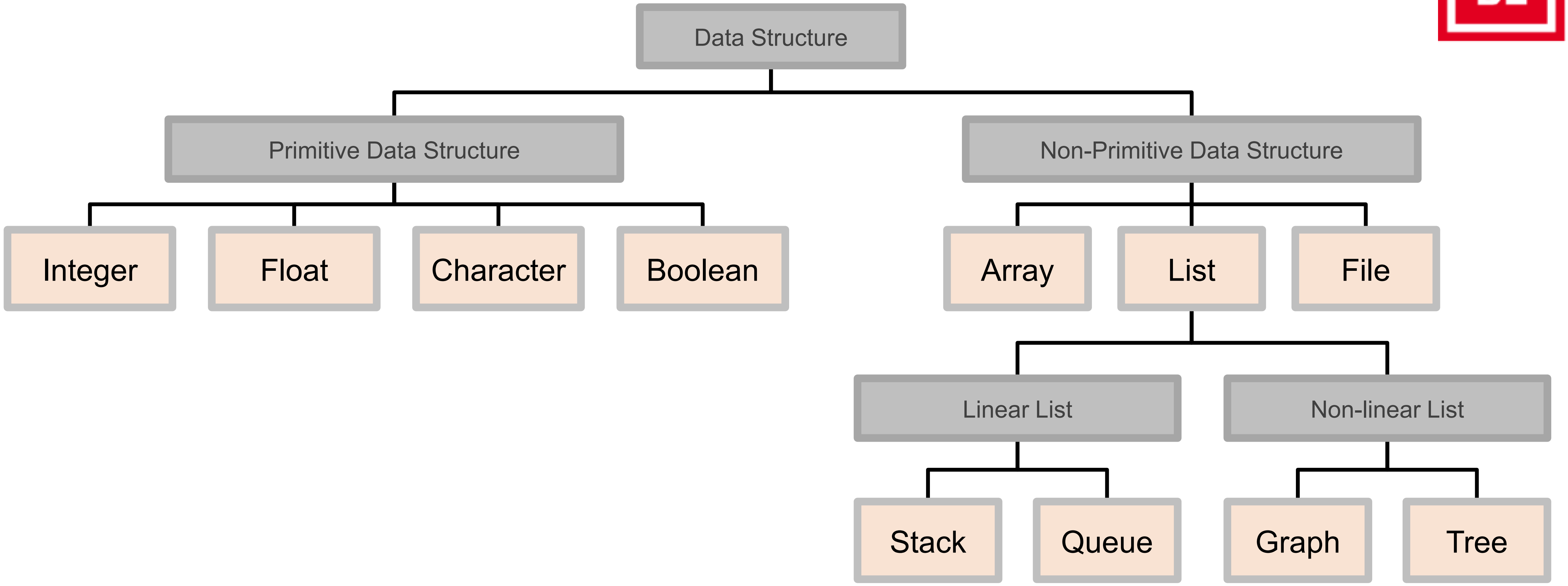
## Trees


THE ROYAL SOCIETY OF CANADA
ACADEMY I: Academy of Arts and Humanities
ACADEMY II: Academy of Social Sciences
ACADEMY III: Academy of Science
Division I: Humanities
Division II: Lettres et Sciences Humaines
Division III: The Arts / Les Arts
Division I: Social Sciences
Division II: Sciences Sociales
Division of Applied Sciences and Engineering
Division of Earth, Ocean, and Atmospheric Sciences
Division of Life Sciences
Division of Mathematical and Physical Sciences


Engineering Decision Tree
Does it move?
No
Yes
Should it?
Should it?
No
Yes
Yes
No
No Problem
No Problem


Der Stammbaum der Ducks
Freunde der Familie

# Data Structures: An Overview



Wait… files are data structures?

## Important file types

Popular file types for exchanging data

- csv / tsv
- JSON
- XML
- GraphML

All of the above choices are essentially text files

Proprietary binary formats are bad choices for exchanging data

## Why text files?

- Human-readable
- Require no proprietary software to view / edit
- Work well with version control systems
- Can easily be fed into algorithms
- Command-line tools are great in processing text files
  - Tools are available by default on Unix/Linux platforms
  - Individual tools are simple but powerful in combination
  - Allow to examine and explore data without any code

Examples:

- `wc` count word & line numbers
- `grep` filter & search files based on their content
- `sort` sort files
- `shuf` pick random lines out of files
- `uniq` handling duplicates
- `cut` access columns in tables
- `join` combine files
- `sed` modify files
- `awk` execute programs on every line of input

## csv/tsv: Comma Separated Values

```
Sherlock Holmes,221B Baker Street,Detective
James Moriarty,Reichenbach Falls,Villain
```

- Simple format
- Human-readable
- Widely used
- Problems if separator is part of a data field
- Separator customizable. **Strong recommendation:** use tsv (tab separated values)!

```
Sherlock Holmes     221B Baker Street    Detective
James Moriarty      Reichenbach Falls    Villain
```

https://www.datafix.com.au/cookbook/tables1.html

## json: JavaScript Object Notation

```
[{"name":"Sherlock Holmes", "address":"221B Baker Street", "job":"Detective"},
{"name":"James Moriarty", "address":"Reichenbach Falls", "job":"Villain"}]
```

- Format more standardized than csv/tsv
- Suitable for nested data and composited data
- Fairly easy to write
- Quite popular

## xml: eXtensible Markup Language

```
<characters>
<person name="Sherlock Holmes" address="221B Baker Street" job="Detective"/>
<person name="James Moriarty" address="Reichenbach Falls" job="Villain"/>
</characters>
```

- Format standardized
- Not too friendly to write
- Very verbose, can be very complex
- Advanced features like DTD, XML Schema, XSL, … (rarely used)

## GraphML

```
<?xml version="1.0" encoding="UTF-8"?>
<graphml xmlns="http://graphml.graphdrawing.org/xmlns"
    xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
    xsi:schemaLocation="http://graphml.graphdrawing.org/xmlns/1.0/graphml.xsd">
  <graph id="G" edgedefault="undirected">
    <node id="n0"/>
    <node id="n1"/>
    <edge id="e1" source="n0" target="n1"/>
  </graph>
</graphml>
```

- XML-based definition of graphs
- Supports the entire range of possible graph structure constellations
- Supports attributes on graphs, nodes, and edges

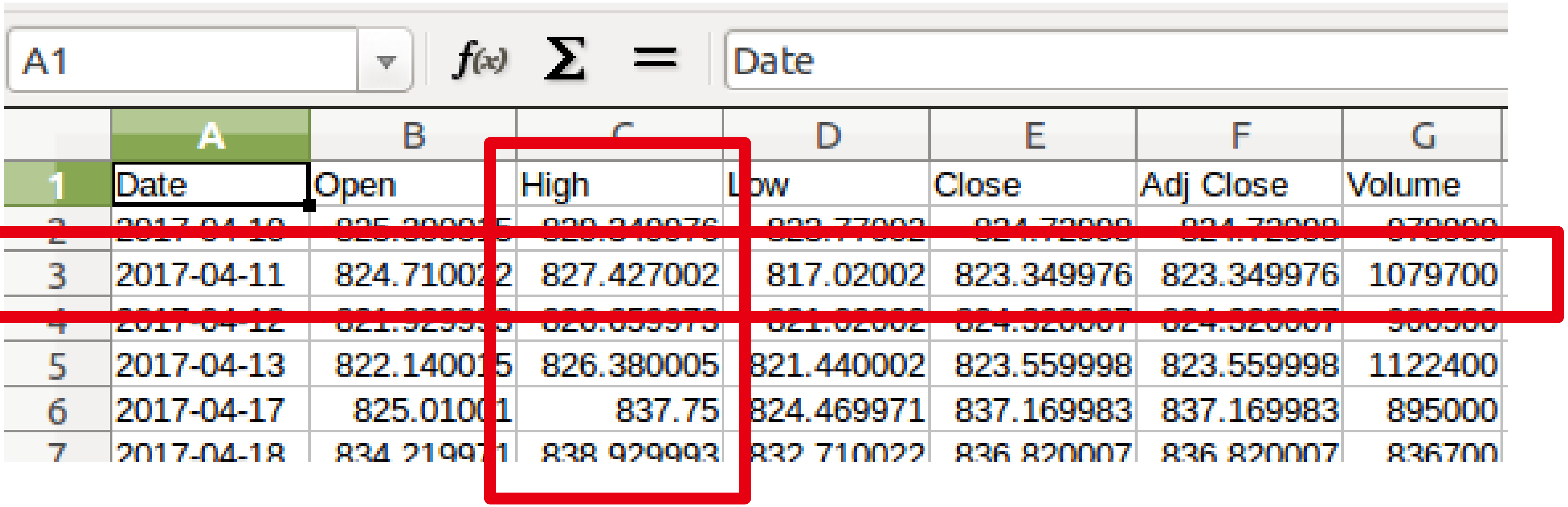
## So… What is a data structure?

## What is a Data Structure?

- Specialized format for organizing, processing, retrieving, and storing data.
- Designed to arrange data to suit a specific purpose
  e.g. working with the data using an algorithm
- Contains information about data values, relationships between the data, and functions that can be applied to the data
- Maintains logical relationships between individual data elements
- Different operations on data structures:
  - Insertions
  - Deletions
  - Searching
  - Traversing

## Tables

## What are tables?



A1 | Date

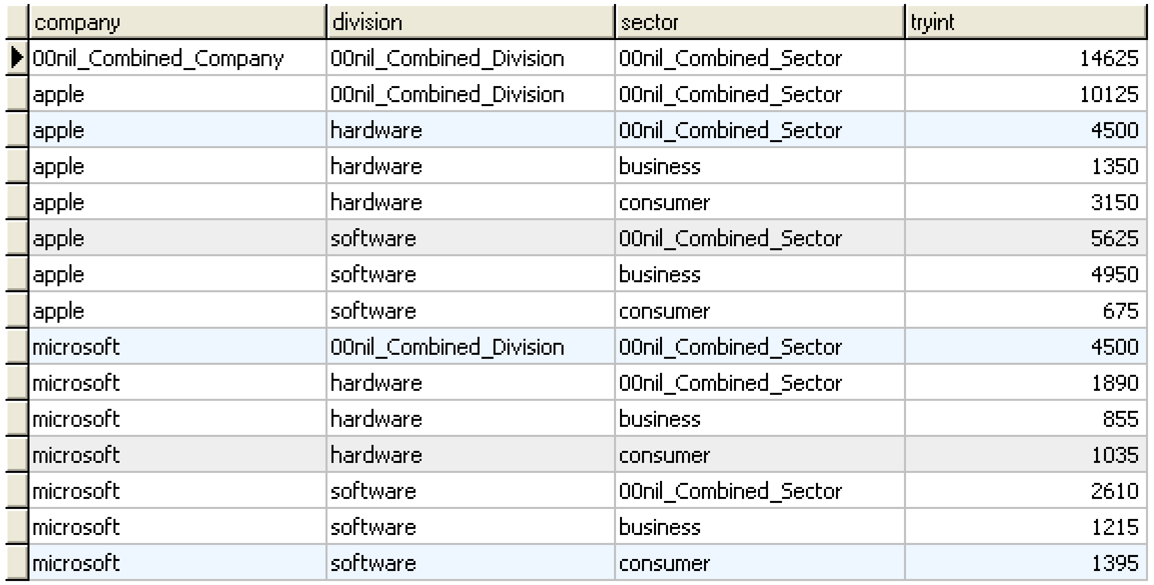
|  | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 1 | Date | Open | High | Low | Close | Adj Close | Volume |
| 2 | 2017-04-10 | 825.390015 | 829.349976 | 823.77002 | 824.72998 | 824.72998 | 978900 |
| 3 | 2017-04-11 | 824.710022 | 827.427002 | 817.02002 | 823.349976 | 823.349976 | 1079700 |
| 4 | 2017-04-12 | 821.929993 | 826.659973 | 821.02002 | 824.320007 | 824.320007 | 900500 |
| 5 | 2017-04-13 | 822.140015 | 826.380005 | 821.440002 | 823.559998 | 823.559998 | 1122400 |
| 6 | 2017-04-17 | 825.01001 | 837.75 | 824.469971 | 837.169983 | 837.169983 | 895000 |
| 7 | 2017-04-18 | 834.219971 | 838.929993 | 832.710022 | 836.820007 | 836.820007 | 836700 |

## Important aspects of tables

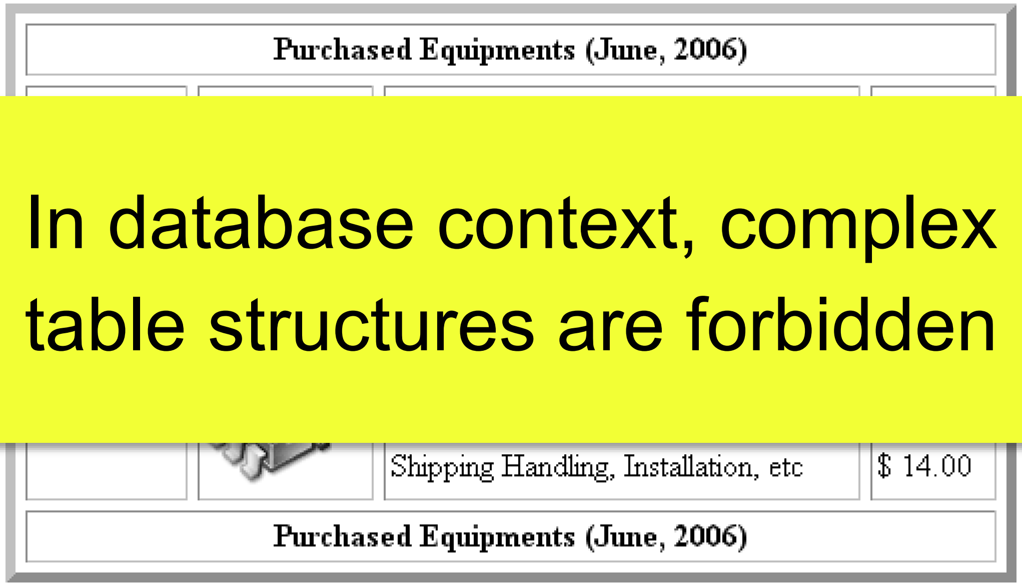
Tables hold *related* data

Consist of rows & columns; their intersections is called cell

Tables have a specified number of columns and any number of rows



| company | division | sector | tryint |
|---|---|---|---|
| 00nil_Combined_Company | 00nil_Combined_Division | 00nil_Combined_Sector | 14625 |
| apple | 00nil_Combined_Division | 00nil_Combined_Sector | 10125 |
| apple | hardware | 00nil_Combined_Sector | 4500 |
| apple | hardware | business | 1350 |
| apple | hardware | consumer | 3150 |
| apple | software | 00nil_Combined_Sector | 5625 |
| apple | software | business | 4950 |
| apple | software | consumer | 675 |
| microsoft | 00nil_Combined_Division | 00nil_Combined_Sector | 4500 |
| microsoft | hardware | 00nil_Combined_Sector | 1890 |
| microsoft | hardware | business | 855 |
| microsoft | hardware | consumer | 1035 |
| microsoft | software | 00nil_Combined_Sector | 2610 |
| microsoft | software | business | 1215 |
| microsoft | software | consumer | 1395 |



Purchased Equipments (June, 2006)

Shipping Handling, Installation, etc $ 14.00

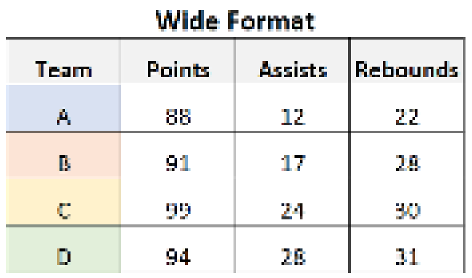
Purchased Equipments (June, 2006)

In database context, complex table structures are forbidden

https://en.wikipedia.org/wiki/File:Rollup_table.png
https://commons.wikimedia.org/wiki/File:Table-sample-appearance-default-params-values-01.gif

# Different table formats

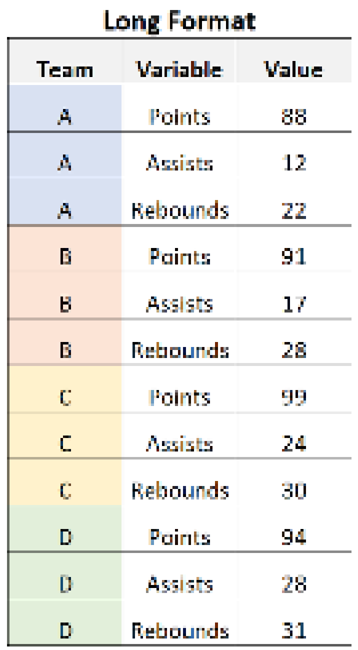
- Expressing data is possible in different formats
- Wide and Long format contain the exact same information
- In the wide format the first column consists of unique values



Wide Format

| Team | Points | Assists | Rebounds |
|---|---|---|---|
| A | 88 | 12 | 22 |
| B | 91 | 17 | 28 |
| C | 99 | 24 | 30 |
| D | 94 | 28 | 31 |

unique



Long Format

| Team | Variable | Value |
|---|---|---|
| A | Points | 88 |
| A | Assists | 12 |
| A | Rebounds | 22 |
| B | Points | 91 |
| B | Assists | 17 |
| B | Rebounds | 28 |
| C | Points | 99 |
| C | Assists | 24 |
| C | Rebounds | 30 |
| D | Points | 94 |
| D | Assists | 28 |
| D | Rebounds | 31 |

Repeated for each variable

When to use?
- Wide Format:
  - Analyzing data
  - Databases
  - Human interpretation is nesessary
- Long Format:
  - Visualizing multiple variables in a plot e.g. in R or Pyphon

## Tables as abstract data structures

### Tables are usually multisets

i.e. duplicate rows are allowed

### How could a table be implemented?

### Difference to a spreadsheet: tables have a schema assigned

Schemes as logical data models specify which data types are allowed in which columns, for example

## Type safety

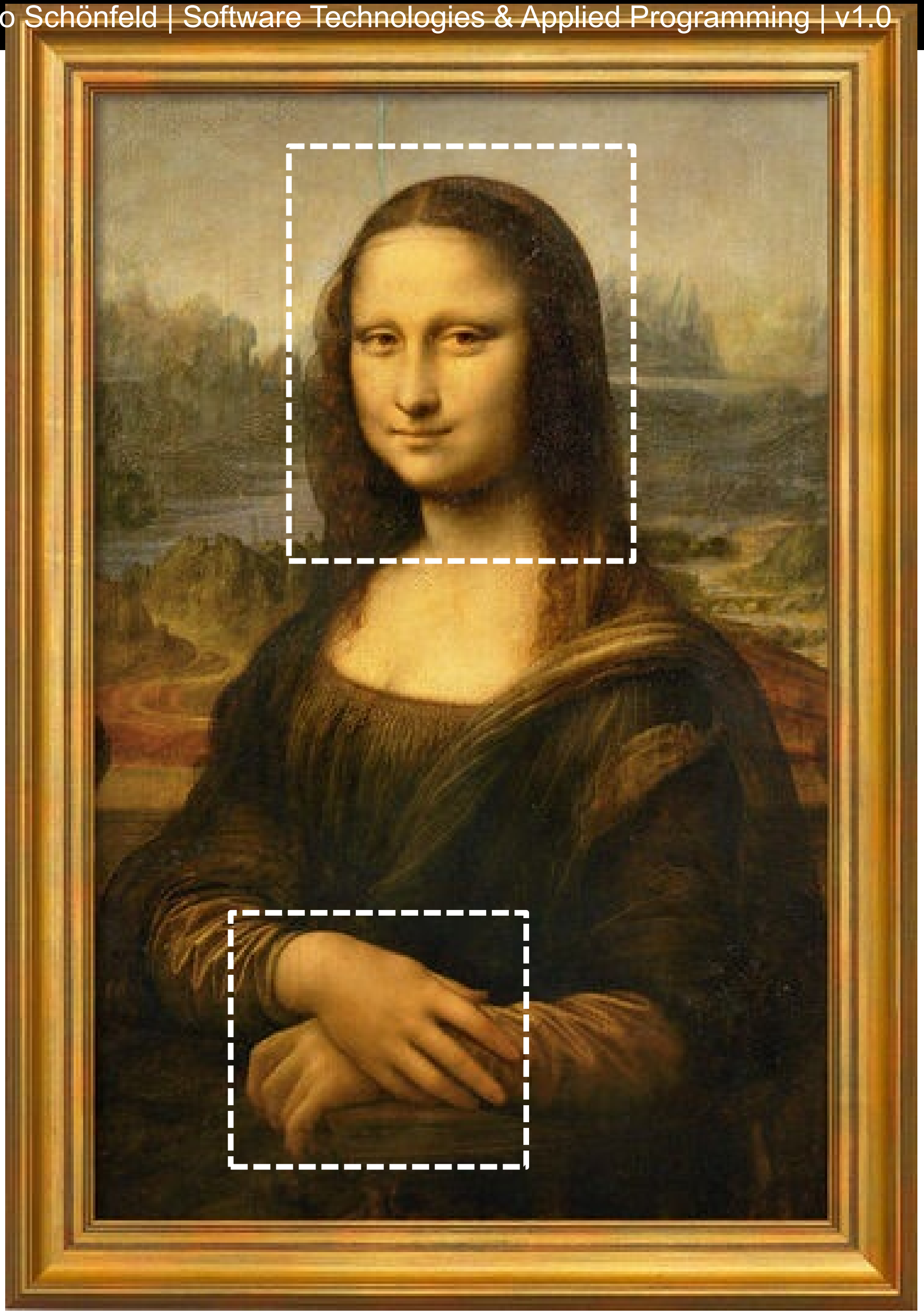
Often, for specific data elements, only certain types are allowed!

| ID | Painter | Year | Title |
|---|---|---|---|
| 124123 | Leonardo da Vinci | 1506 | Mona Lisa |
| 453723 | Peter Paul Rubens | 1606 | The Judgment of Paris |

## Type safety

Often, for specific data elements, only certain types are allowed!

| ID | Upper-left-x | Upper-left-y | Lower-right-x | Lower-right-y | Annotation |
|---|---|---|---|---|---|
| 124123 | 24 | 5 | 57 | 40 | Face |
| 124123 | 17 | 76 | 43 | 87 | Hands |



Thanks.

mirco.schoenfeld@uni-bayreuth.de