

# Operating Systems: Memory and File System

*DS 5110: Big Data Systems (Spring 2023)*

Lecture 2c

Yue Cheng



Some material taken/derived from:

- Wisconsin CS301 by Tyler Harter.

@ 2023 released for use under a [CC BY-SA](https://creativecommons.org/licenses/by-sa/4.0/) license.

# The memory hierarchy

# Recap: How fast can a CPU run a program?

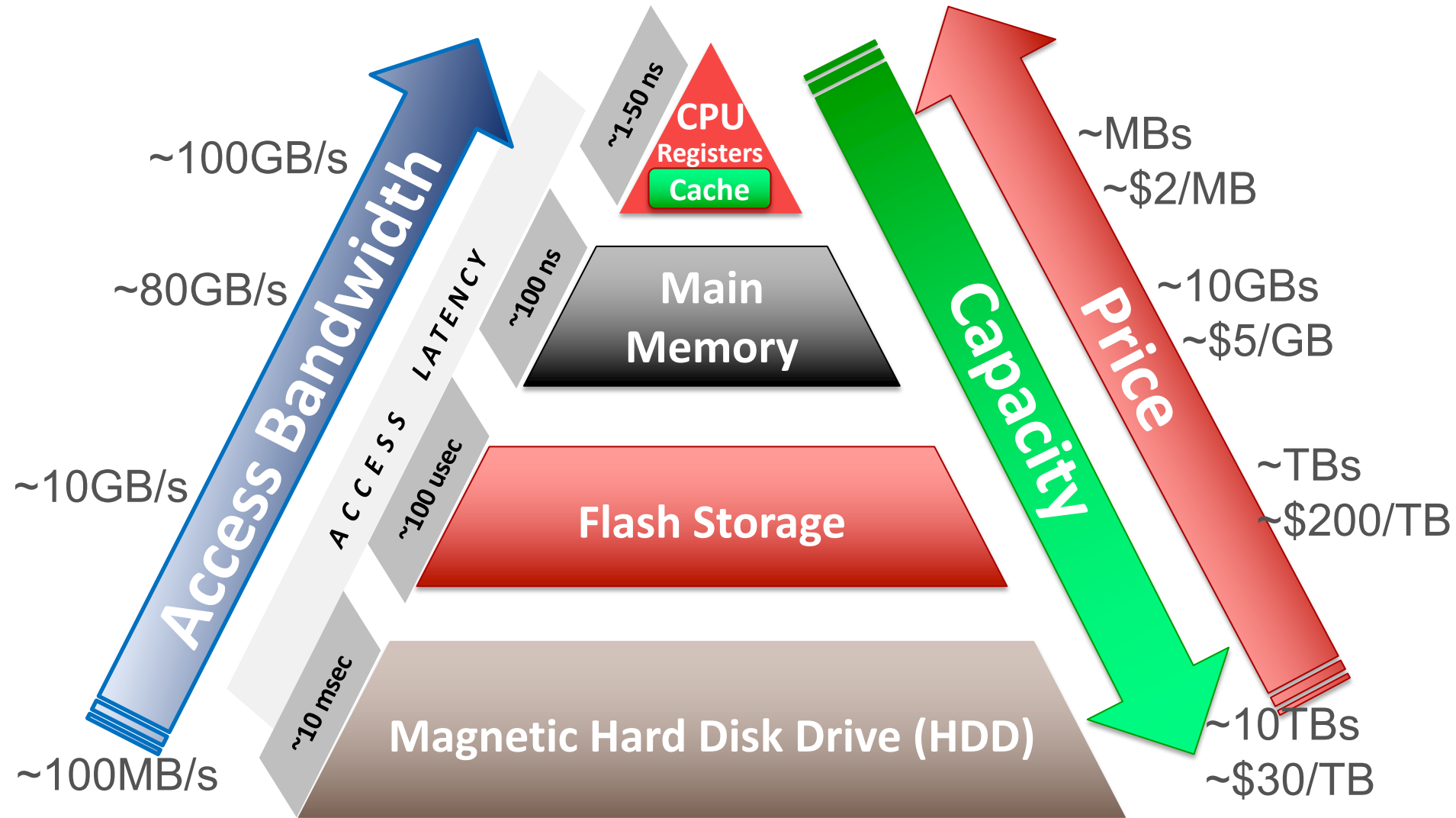
- Most programs do not keep CPU always busy
  - Memory access instructions stall the CPU: i.e., ALU & CU idle during DRAM-register transfer
  - Worse, data may not be in DRAM – wait for disk I/O!
  - Actual runtime of a program may be 10-100x higher than what clock rate calculation model suggests

# Recap: How fast can a CPU run a program?

- Most programs do not keep CPU always busy
  - Memory access instructions stall the CPU: i.e., ALU & CU idle during DRAM-register transfer
  - Worse, data may not be in DRAM – wait for disk I/O!
  - Actual runtime of a program may be 10-100x higher than what clock rate calculation model suggests

**Key principle:** Optimizing use of CPU caches (and faster storage) is critical for processor performance!

# Memory-storage hierarchy



# Workload characteristics

## Application A

```
sum = 0
for i in range(0,1024):
    sum += a[i]
```

# Workload characteristics

## Application A

```
sum = 0
for i in range(0,1024):
    sum += a[i]
```

## Application B

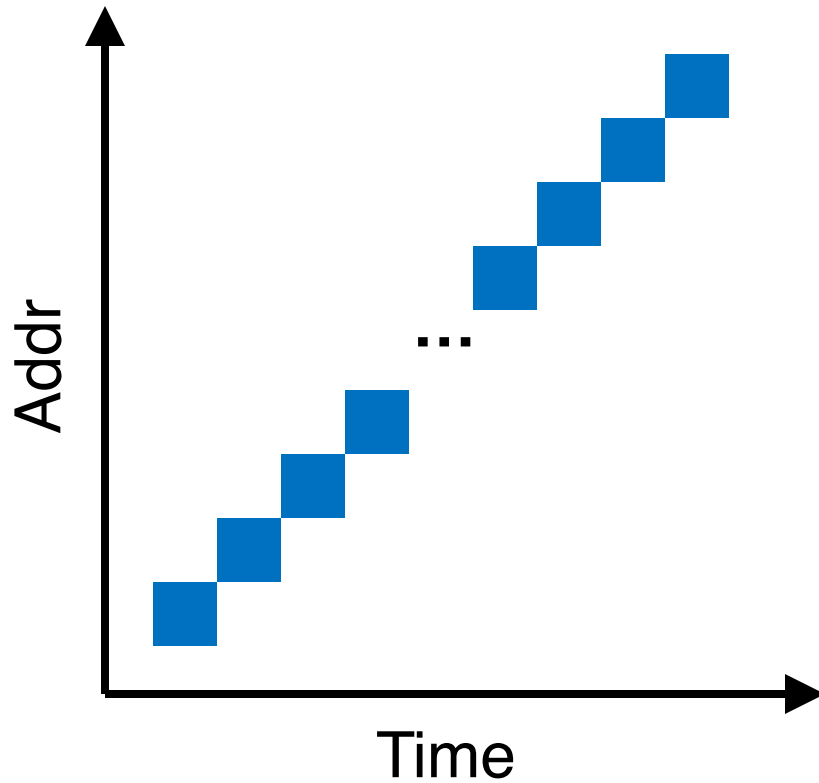
```
import random

sum = 0
random.seed(1234)
for i in range(0,512):
    sum += a[random.randint(0,1023)]

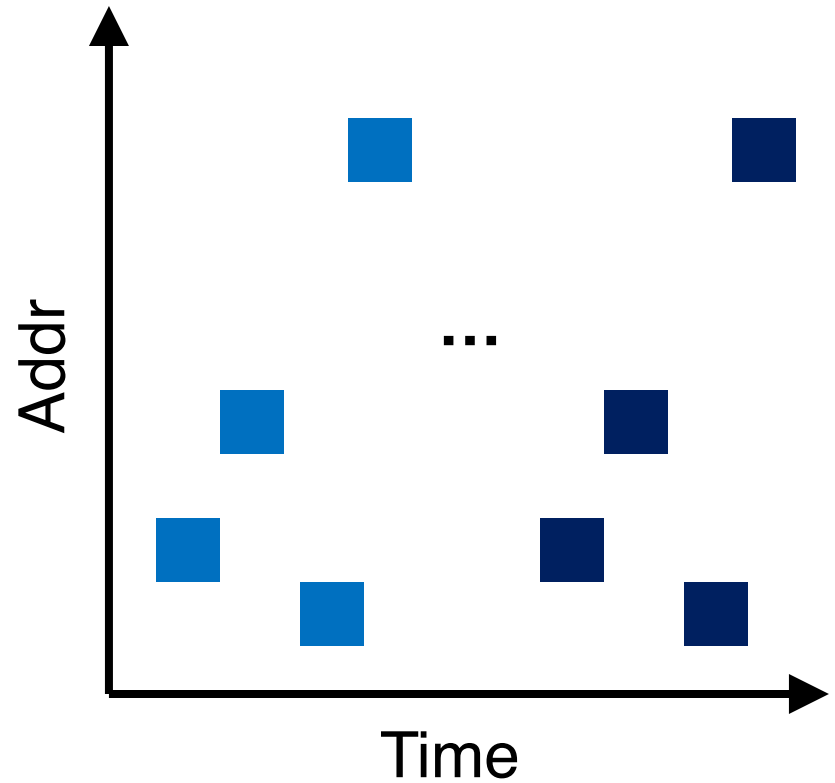
random.seed(1234) # same seed
for i in range(0,512):
    sum += a[random.randint(0,1023)]
```

# Access patterns

Application A



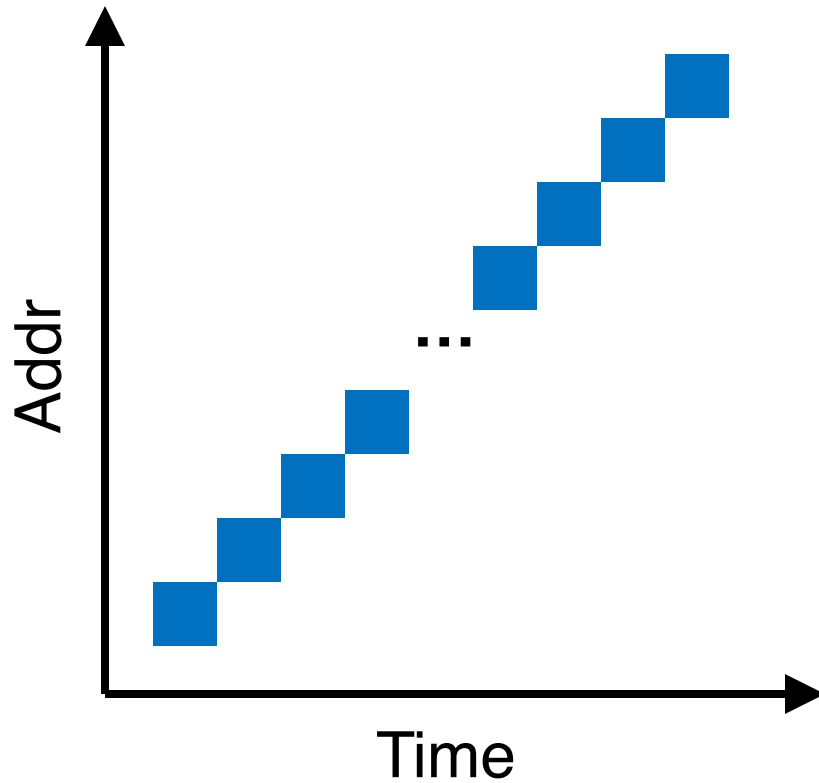
Application B





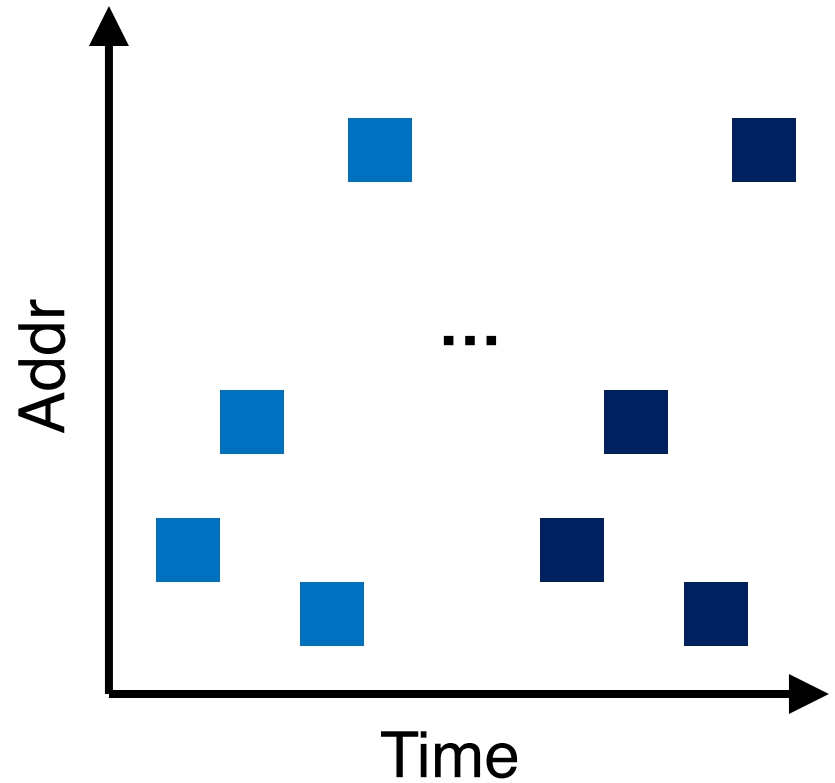
# Access patterns

Application A



**Spatial Locality**

Application B



**Temporal Locality**

# Locality of data accesses

- **Spatial locality:**
  - Future access will be to nearby addresses
- **Temporal locality:**
  - Future access will be repeated to the same data

# Locality of data accesses

- **Spatial locality:**
  - Future access will be to nearby addresses
- **Temporal locality:**
  - Future access will be repeated to the same data
- Q: What is the **implication of data locality** to Data Science applications?

# Locality optimization in Data Science

- Consider a tensor (matrix) named `data` with  $128 * 128$  elements
- Each row is of size 128 words and **prefetching+caching** means full row of accessed data item is brought to CPU cache

# Locality optimization in Data Science

- Consider a tensor (matrix) named `data` with  $128 \times 128$  elements
- Each row is of size 128 words and **prefetching+caching** means full row of accessed data item is brought to CPU cache
- **Program 1**

```
for j in range(0,128):  
    for i in range(0,128):  
        data[i][j] = 0
```

$128 \times 128 = 16,384$  CPU cache misses

Not too hardware-efficient (not able to exploit prefetching+caching)

# Locality optimization in Data Science

- Consider a tensor (matrix) named `data` with  $128 \times 128$  elements
- Each row is of size 128 words and **prefetching+caching** means full row of accessed data item is brought to CPU cache

- **Program 1**

```
for j in range(0,128):  
    for i in range(0,128):  
        data[i][j] = 0
```

$128 \times 128 = 16,384$  CPU cache misses

Not too hardware-efficient (not able to exploit prefetching+caching)

---

- **Program 2**

```
for i in range(0,128):  
    for j in range(0,128):  
        data[i][j] = 0
```

Only **128** CPU cache misses

Row `data[i]` is prefetched to cache so subsequent accesses are hits!

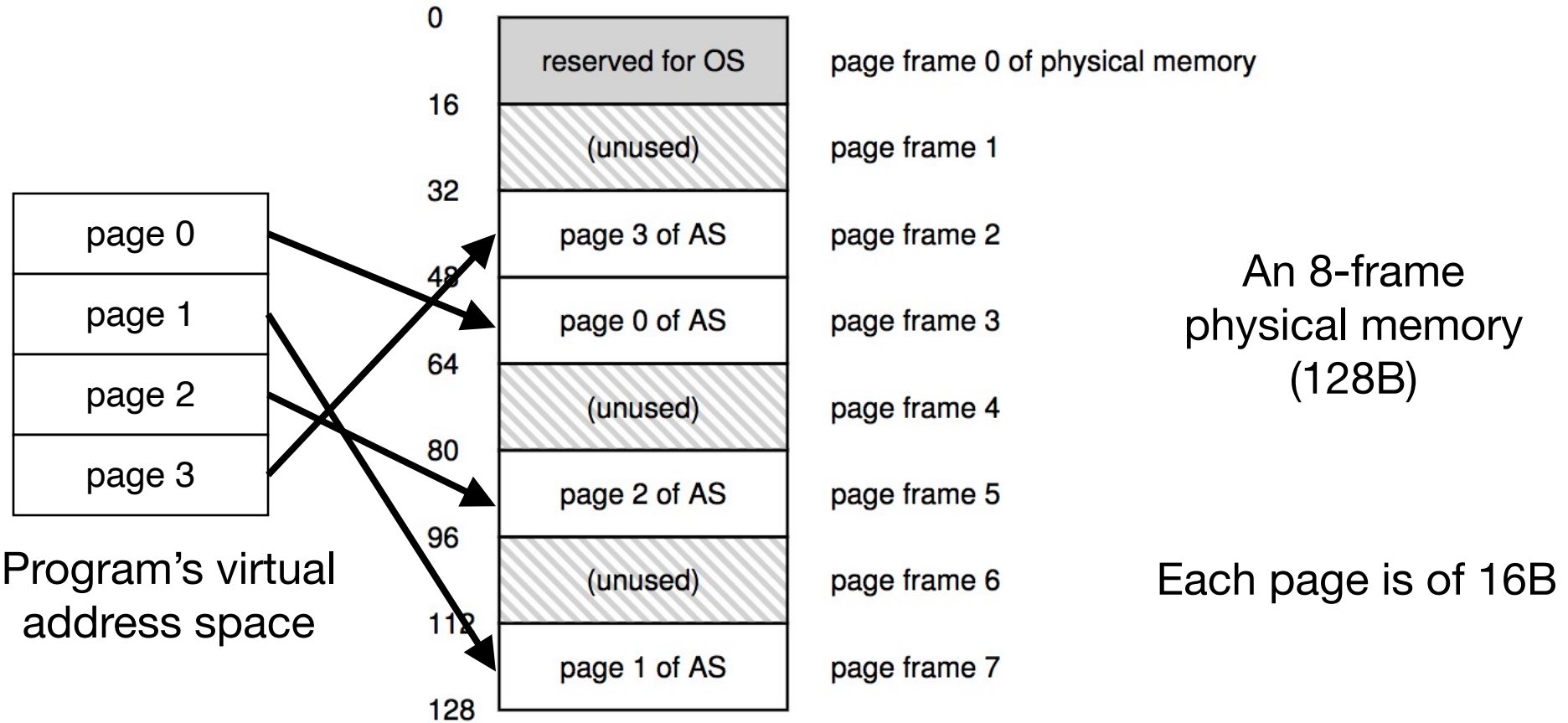
# Virtualizing (sharing) memory

# OS memory management: Paging

- Paging is a memory management scheme that allows the physical address space of a process to be **non-contiguous**
- Divide **physical memory** into fixed-sized blocks called **frames**
- Divide a program's **virtual memory** into blocks of same size called **pages**
- Flexible mapping: Any page can go to any free frame
- Scalability: To run a program of size  $n$  pages, need to find  $n$  free frames and load program
  - **Grow memory segments wherever we please!**



# A toy example



# File system abstraction

# What is a **File**?

- File: Array of bytes on a disk
  - Ranges of bytes can be read/written
- File system (FS) is an on-disk data structure that consists of many files
- Files need names so programs can choose the right one

# File names

- Three types of names (abstractions)
  - **inode** (low-level names)
  - **path** (human readable)
  - **file descriptor** (runtime state)

# Inodes

- Each file has exactly one inode number
- Inodes are unique (at a given time) within a FS
- Numbers may be recycled after deletes

# Inodes

- Each file has exactly one inode number
- Inodes are unique (at a given time) within a FS
- Numbers may be recycled after deletes
- Show inodes via `stat`
  - `$ stat <file or dir>`

# stat example

```
PROMPT>: stat test.dat
```

```
File: 'test.dat'  Size: 5      Blocks: 8      IO Block: 4096   regular  
file
```

```
Device: 803h/2051d      Inode: 119341128   Links: 1
```

```
Access: (0664/-rw-rw-r--)  Uid: ( 1001/      yue)   Gid: ( 1001/      yue)
```

```
Context: unconfined_u:object_r:user_home_t:s0
```

```
Access: 2015-12-17 04:12:47.935716294 -0500
```

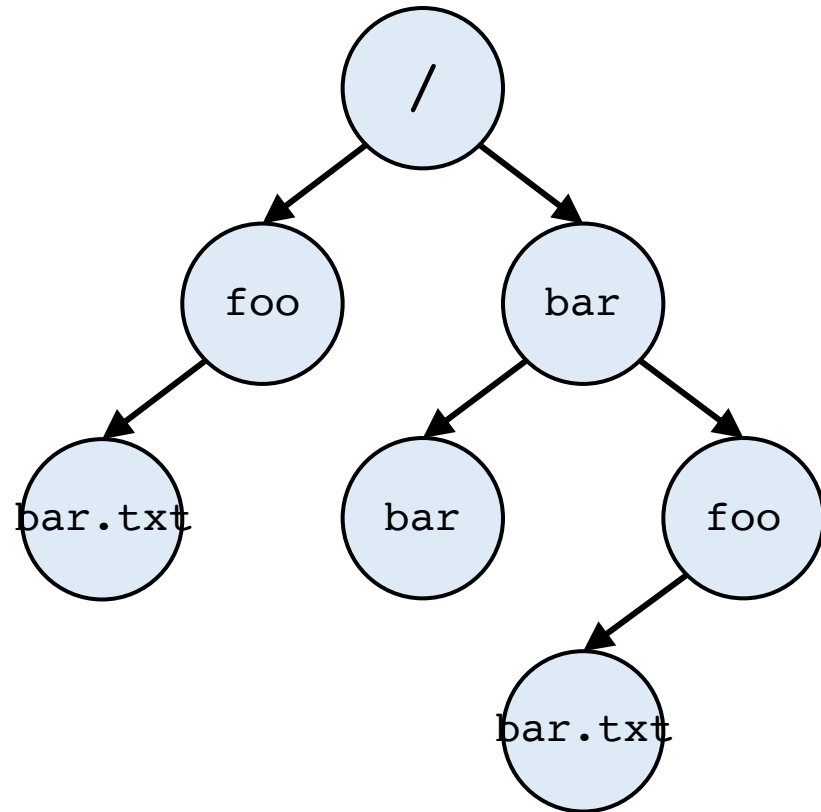
```
Modify: 2014-12-12 19:25:32.669625220 -0500
```

```
Change: 2014-12-12 19:25:32.669625220 -0500
```

```
Birth: -
```

# Path (multiple directories)

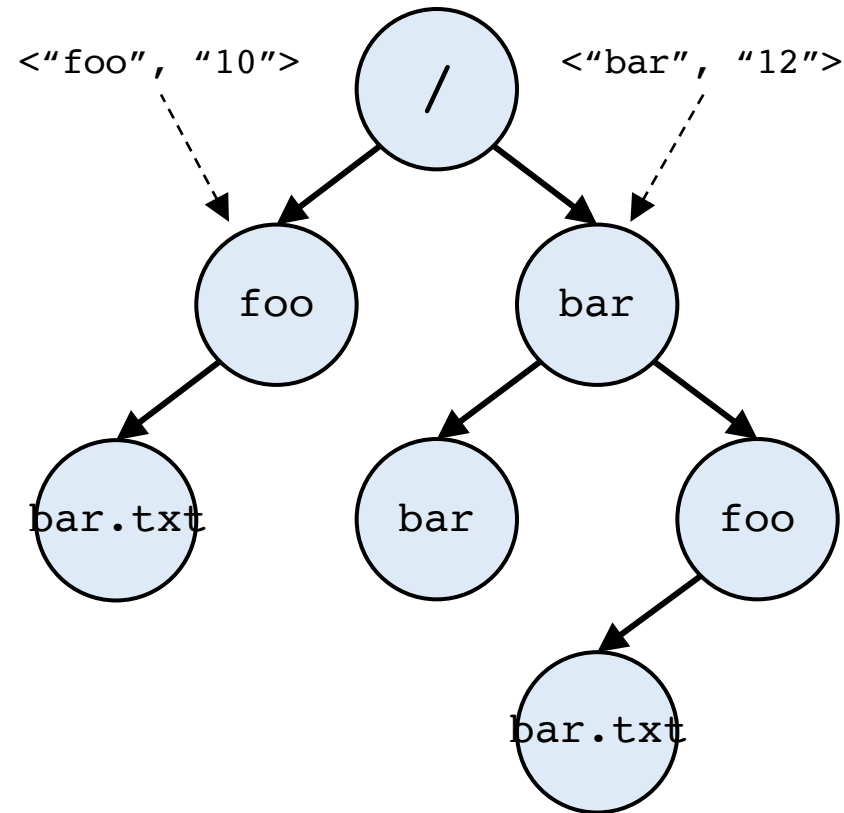
- A directory is a file
  - Associated with an inode
- Contains a list of <user-readable name, low-level name> pairs





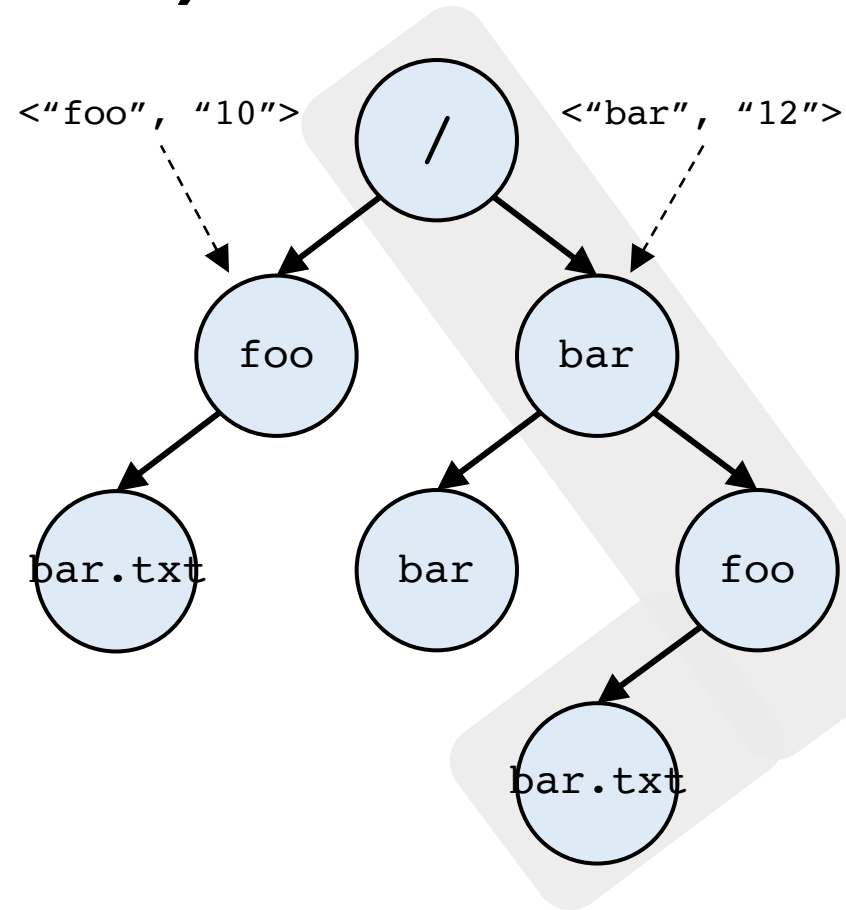
# Path (multiple directories)

- A directory is a file
  - Associated with an inode
- Contains a list of `<user-readable name, low-level name>` pairs



# Path (multiple directories)

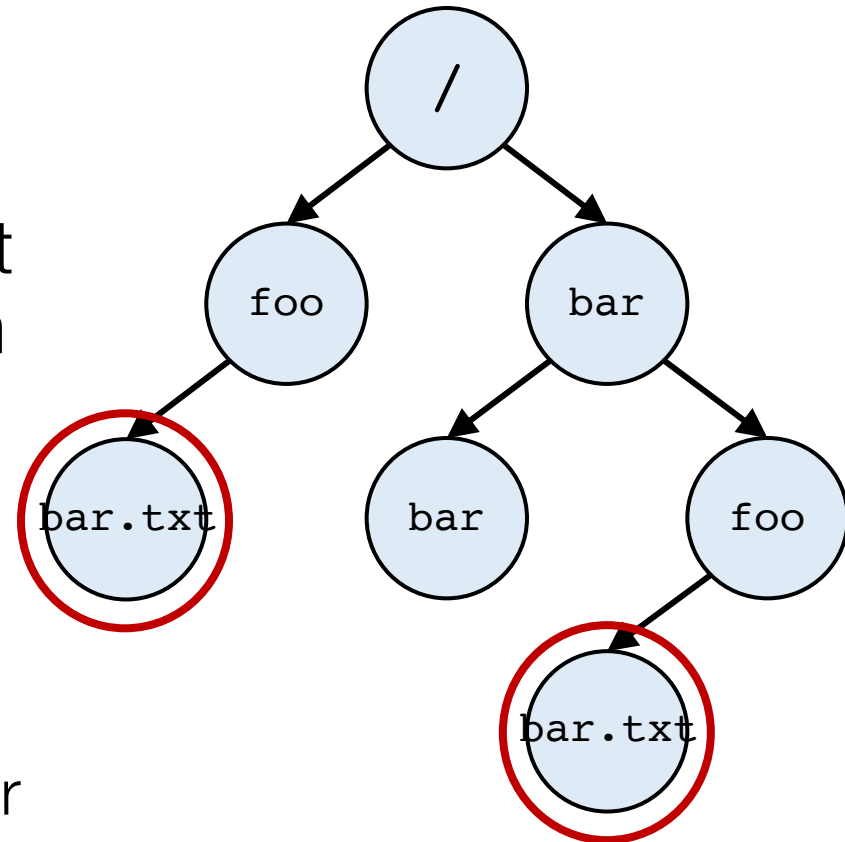
- A directory is a file
  - Associated with an inode
- Contains a list of `<user-readable name, low-level name>` pairs
- Directory tree: reads for getting final inode called **traversal**



[traverse /bar/foo/bar.txt]

# File naming

- Directories and files can have the same name as long as they are in different locations of the file-system tree
- .txt, .c, etc.
  - Naming convention
  - In Linux, no enforcement for extension name



# Special directory entries

```
prompt> ls -al
```

```
total 216
```

```
drwxr-xr-x 19 yue staff 646 Nov 23 16:28 .  
drwxr-xr-x+ 40 yue staff 1360 Nov 15 01:41 ..
```

```
-rw-r--r--@ 1 yue staff 1064 Aug 29 21:48 common.h
```

```
-rwxr-xr-x 1 yue staff 9356 Aug 30 14:03 cpu
```

```
-rw-r--r--@ 1 yue staff 258 Aug 29 21:48 cpu.c
```

```
-rwxr-xr-x 1 yue staff 9348 Sep 6 12:12 cpu_bound
```

```
-rw-r--r-- 1 yue staff 245 Sep 5 13:10 cpu_bound.c
```

```
...
```

# Basic file interactions

# Basic file interactions

- Basic file system operations
  - opening/closing
  - reading/writing
- OS-related module
  - listdir, mkdir, exists, join

# Basic file interactions

- Basic file system operations
  - opening/closing
  - reading/writing
- OS-related module
  - listdir, mkdir, exists, join

# File objects

```
f = open(path)

# read data from f
# OR
# write data to f

f.close()
```



# File objects

Built-in open function

```
f = open(path)
```

File object

File path

```
# read data from f
```

```
# OR
```

```
# write data to f
```

```
f.close()
```

# File objects

main.py Built-in open function

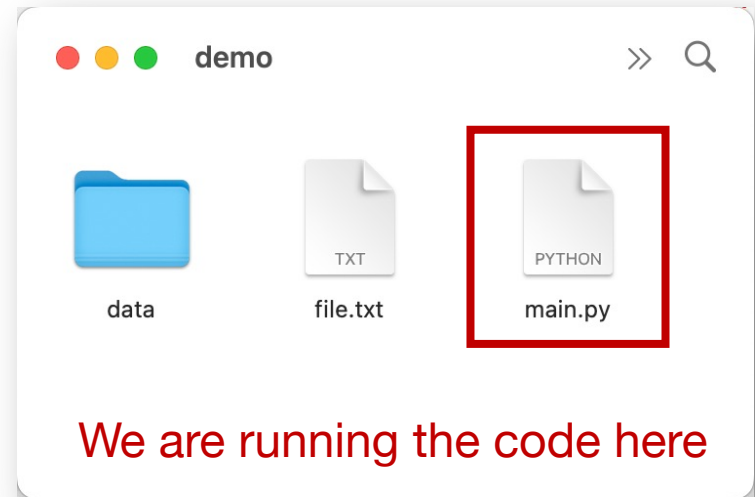
```
f = open(path)
```

File object

File path

```
# read data from f  
# OR  
# write data to f
```

```
f.close()
```



# File objects

main.py Built-in open function

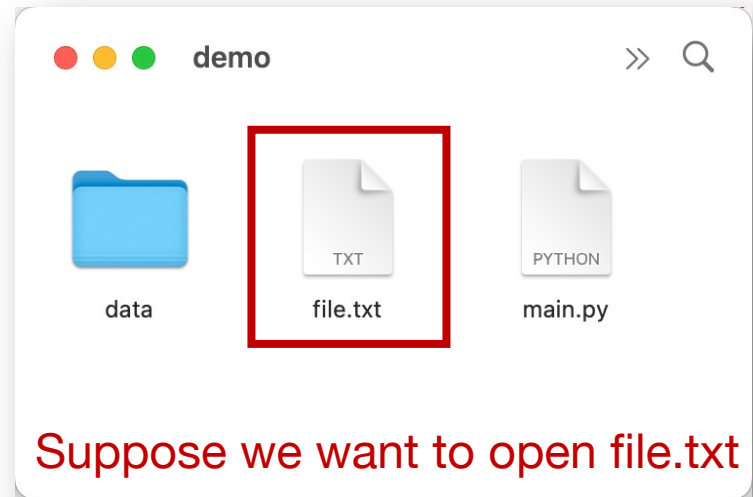
```
f = open(path)
```

File object

File path

```
# read data from f  
# OR  
# write data to f
```

```
f.close()
```



# File objects

main.py Built-in open function

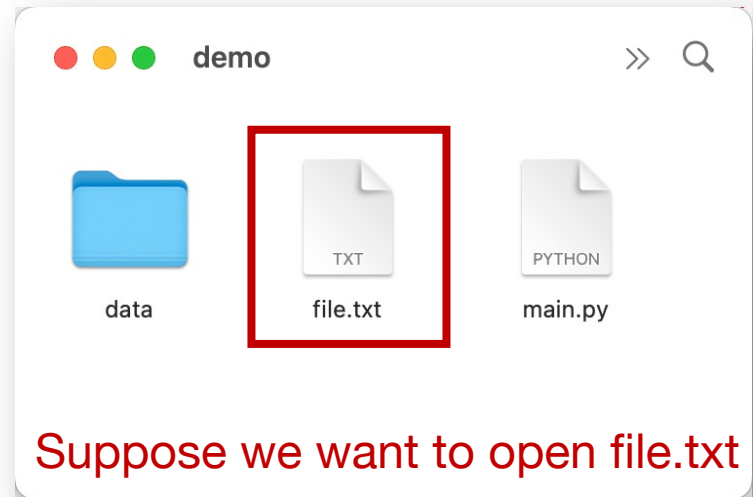
```
f = open("file.txt")
```

File object

File path

```
# read data from f  
# OR  
# write data to f
```

```
f.close()
```



# File objects

main.py Built-in open function

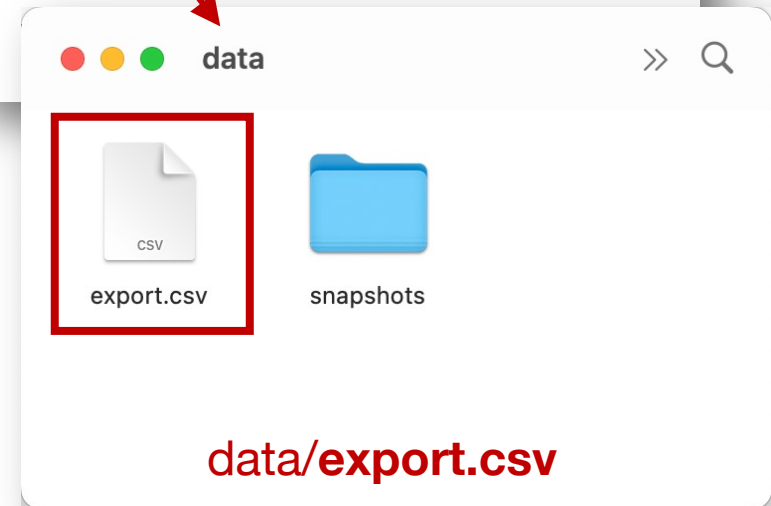
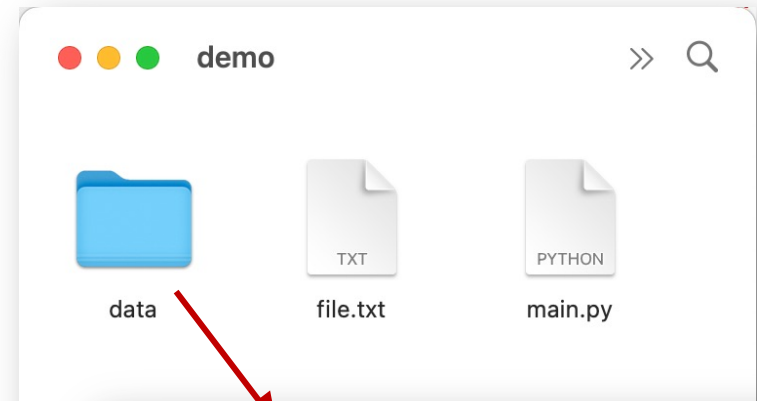
```
f = open(
    "data/export.csv")
```

File object

File path

```
# read data from f
# OR
# write data to f
```

```
f.close()
```



# File objects

main.py Built-in open function

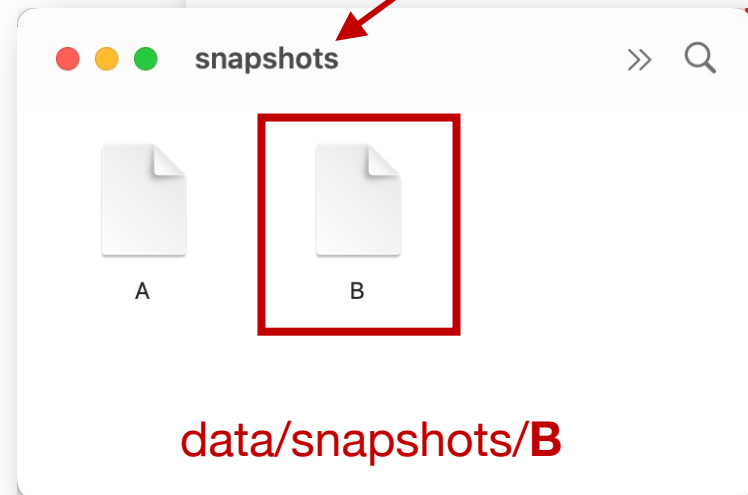
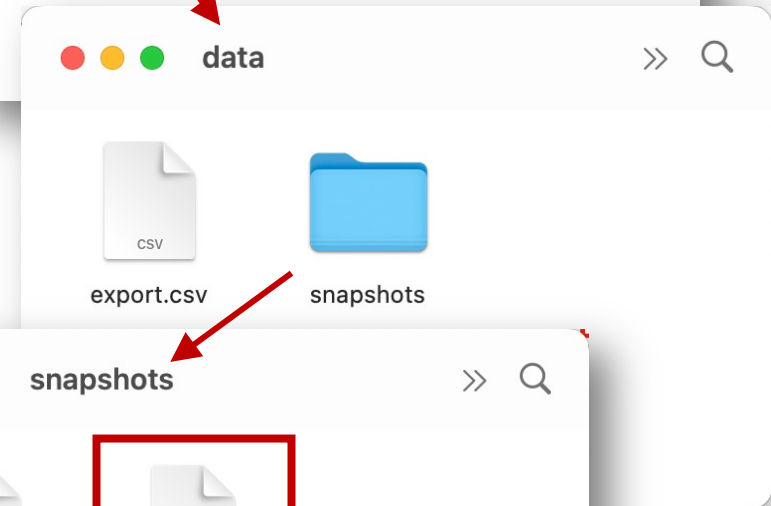
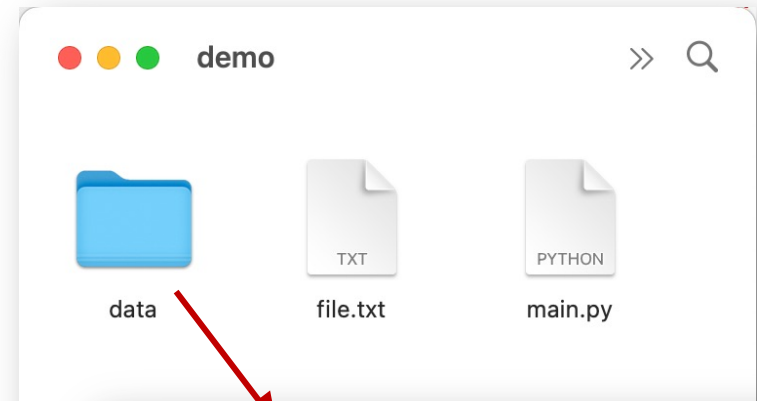
```
f = open(  
"data/snapshots/B")
```

File object

File path

```
# read data from f  
# OR  
# write data to f
```

```
f.close()
```



# File objects

main.py

```
f = open("file.txt")
```

```
# read data from f
```

```
# OR
```

```
# write data to f
```

```
f.close()
```

# File objects

main.py

```
f = open("file.txt")
```

```
# read data from f  
# OR  
# write data to f
```

Using file

```
f.close()
```



# File objects

main.py

```
f = open("file.txt")
```

```
# read data from f  
# OR  
# write data to f
```

Using file

```
f.close()
```

Cleanup

Imagine a file object as a sandwich ...

# File objects

main.py

```
f = open("file.txt")
```

```
# read data from f  
# OR  
# write data to f
```

```
f.close()
```

`f = open(...)`

Using file...

`f.close()`

Reasons for **closing**:

- Avoid data loss
- Limited number of open files

Using file

Cleanup

# Basic file interactions

- Basic file system operations
  - opening/closing
  - **reading/writing**
- OS-related module
  - listdir, mkdir, exists, join

# Reading a file

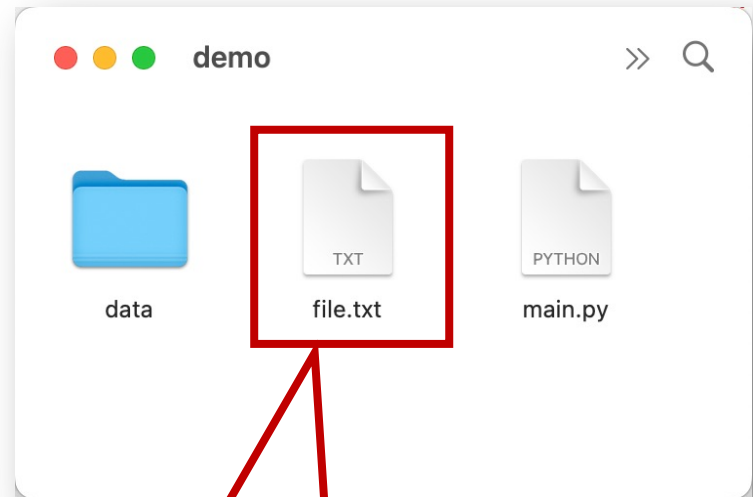
```
f = open("file.txt")
```

```
# read data from f
```

```
# OR
```

```
# write data to f
```

```
f.close()
```



I promise to always close my files

# Reading a file

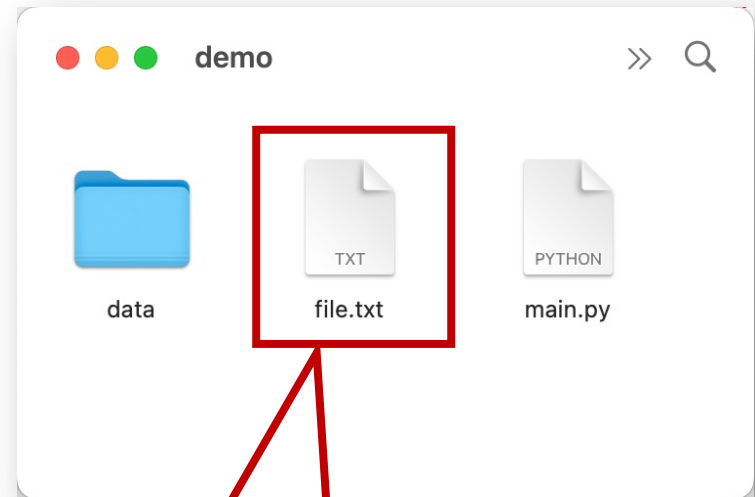
```
f = open("file.txt")
```

```
data = f.read()
```

```
print(data)
```

data is: "I promise to always\nnclose my files"

```
f.close()
```



I promise to always  
close my files

read() method

- Fetch entire content
- Return as a string

# Writing a file

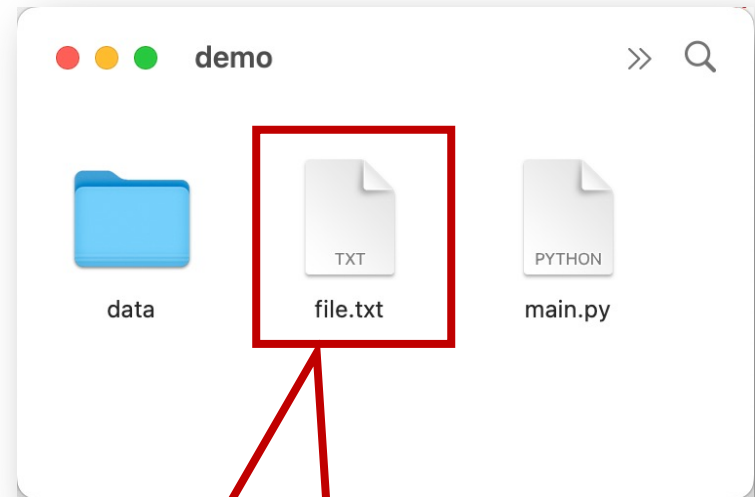
```
f = open("file.txt")
```

```
# read data from f
```

```
# OR
```

```
# write data to f
```

```
f.close()
```



I promise to always  
close my files

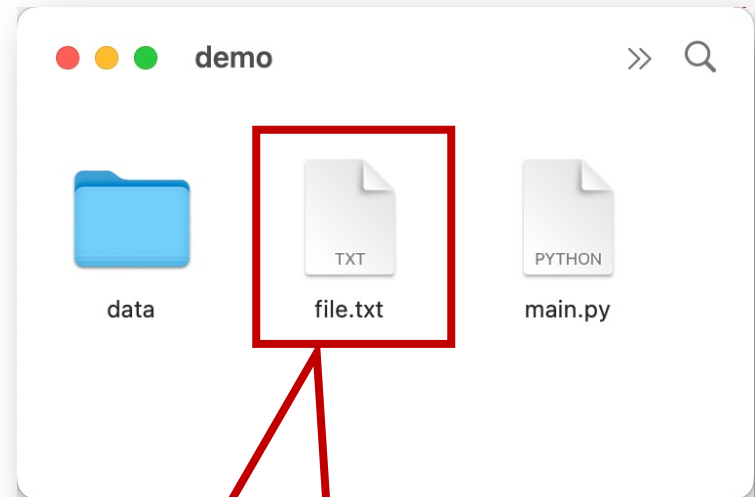
# Writing a file

```
f = open("file.txt",  
        "w")
```

"w" mode indicates  
to write to this file

```
# read data from f  
# OR  
# write data to f
```

```
f.close()
```



I promise to always  
close my files

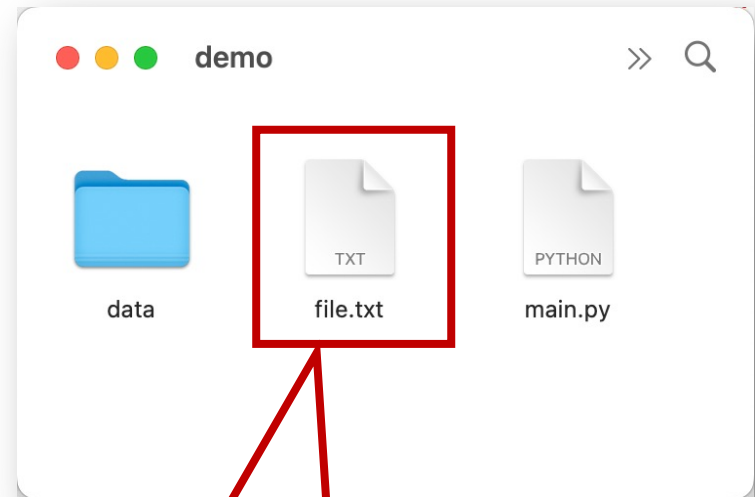
# Writing a file

```
f = open("file.txt",  
        "w")
```

"w" mode indicates  
to write to this file

```
f.write("hello")  
f.write(" world\n")  
f.write("!!!\n")
```

```
f.close()
```



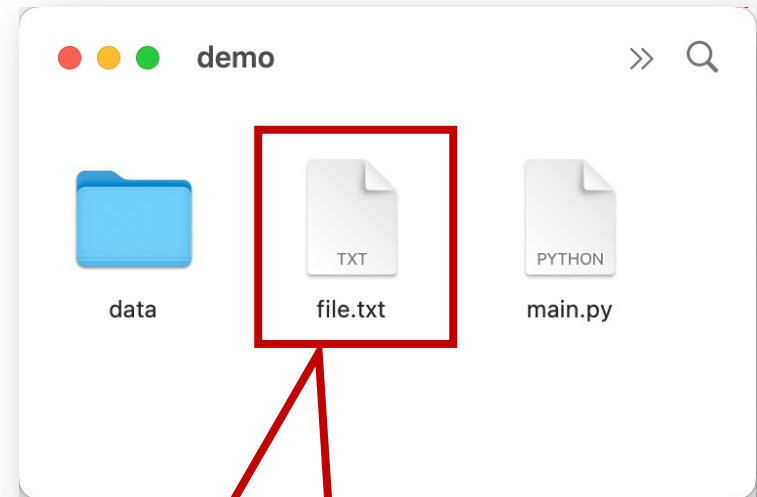
I promise to always  
close my files



# Writing a file

```
→ f = open("file.txt",  
           "w")  
    f.write("hello")  
    f.write(" world\n")  
    f.write("!!!\n")  
  
f.close()
```

"w" mode indicates  
to write to this file



I promise to always  
close my files

Let's run it!

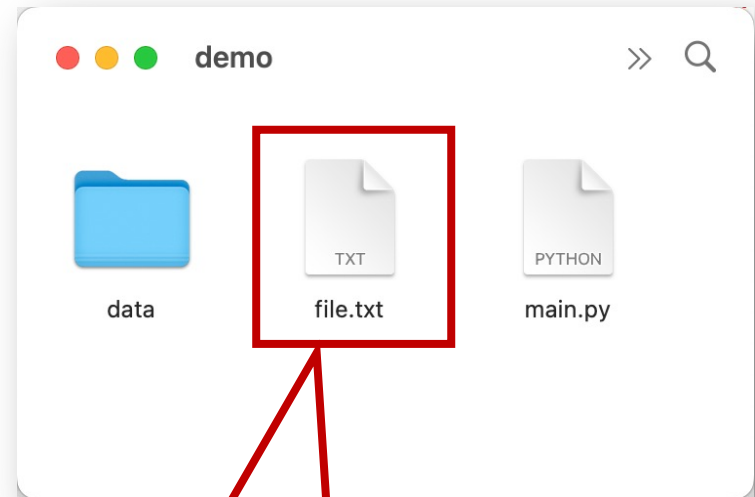
# Writing a file

```
f = open("file.txt",  
        "w")
```

"w" mode indicates  
to write to this file

```
f.write("hello")  
f.write(" world\n")  
f.write("!!!\n")
```

```
f.close()
```



Open with "w" is dangerous.  
It immediately wipes out  
your file

(Or create a new one if there  
isn't already a file.txt)

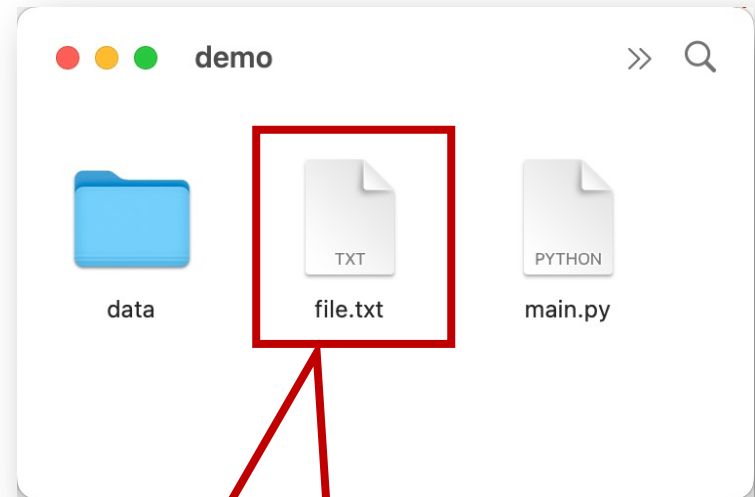
# Writing a file

```
f = open("file.txt",  
        "w")
```

"w" mode indicates  
to write to this file

```
f.write("hello")  
f.write(" world\n")  
f.write("!!!\n")
```

```
f.close()
```



hello

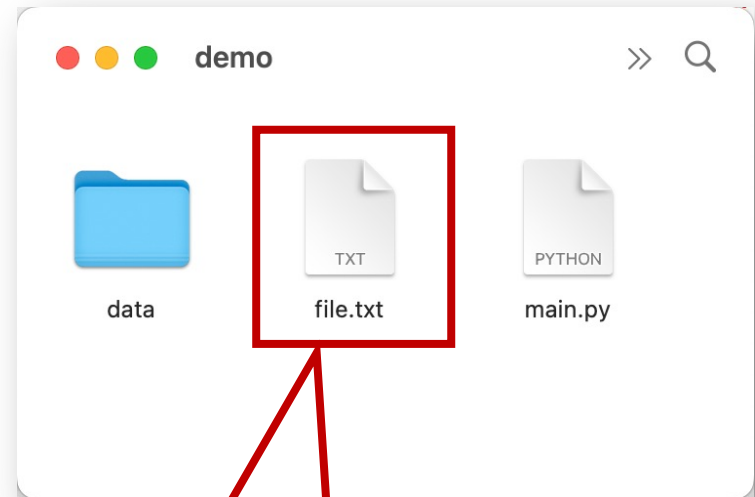
# Writing a file

```
f = open("file.txt",  
        "w")
```

"w" mode indicates  
to write to this file

```
f.write("hello")  
f.write(" world\n")  
f.write("!!!\n")
```

```
f.close()
```



hello world

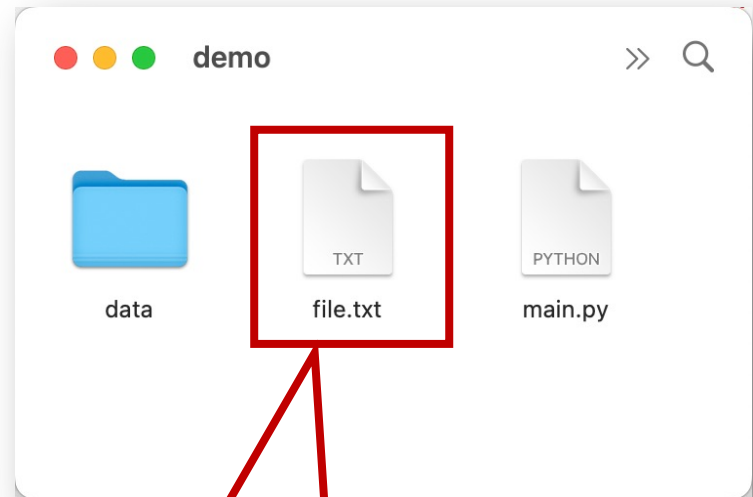
# Writing a file

```
f = open("file.txt",  
        "w")
```

"w" mode indicates  
to write to this file

```
f.write("hello")  
f.write(" world\n")  
f.write("!!!\n")
```

→ `f.close()`



```
hello world  
!!!
```

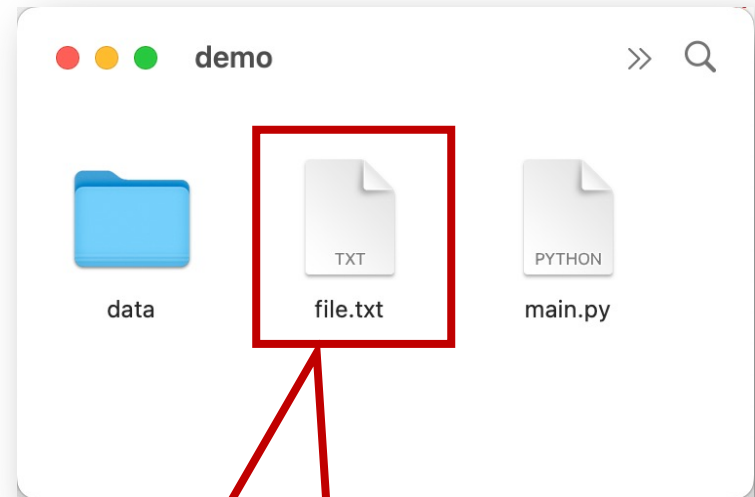
# Writing a file

```
f = open("file.txt",  
        "w")
```

"w" mode indicates  
to write to this file

```
f.write("hello")  
f.write(" world\n")  
f.write("!!!\n")
```

```
f.close()
```



```
hello world  
!!!
```

Be careful with newlines  
(write doesn't add them like print does)

# Basic file interactions

- Basic file system operations
  - opening/closing
  - reading/writing
- OS-related module
  - **listdir, mkdir, exists, join**

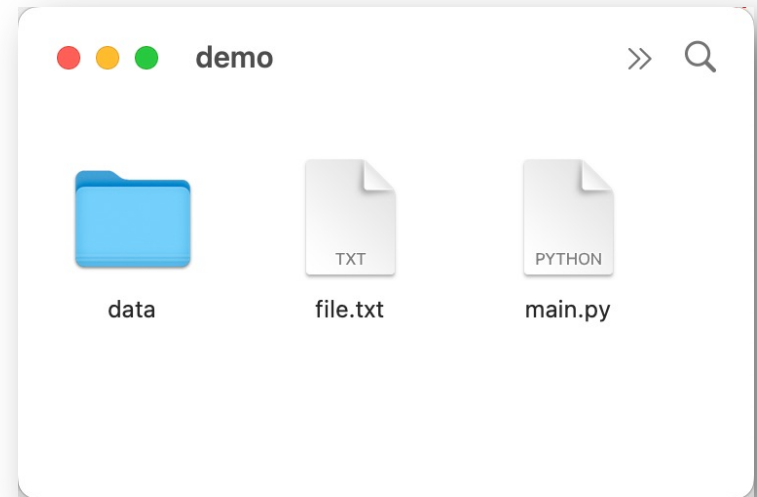
# OS module

- Many functions in `os` and `os.path` for working w/ files
  - `os.listdir`
  - `os.mkdir`
  - `os.path.exists`
  - `os.path.join`
  - ...



# OS module

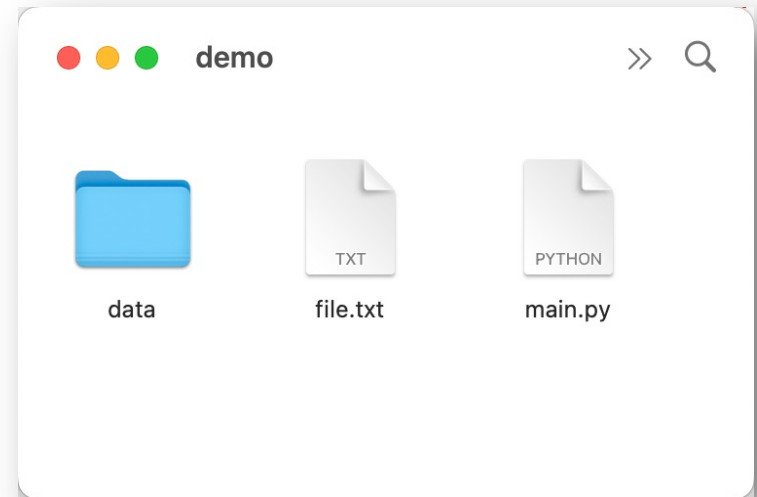
- Many functions in `os` and `os.path` for working w/ files
  - **`os.listdir`**
  - `os.mkdir`
  - `os.path.exists`
  - `os.path.join`
  - ...



```
>>> import os
>>> os.listdir(".")
["file.txt", "main.py", "data"]
```

# OS module

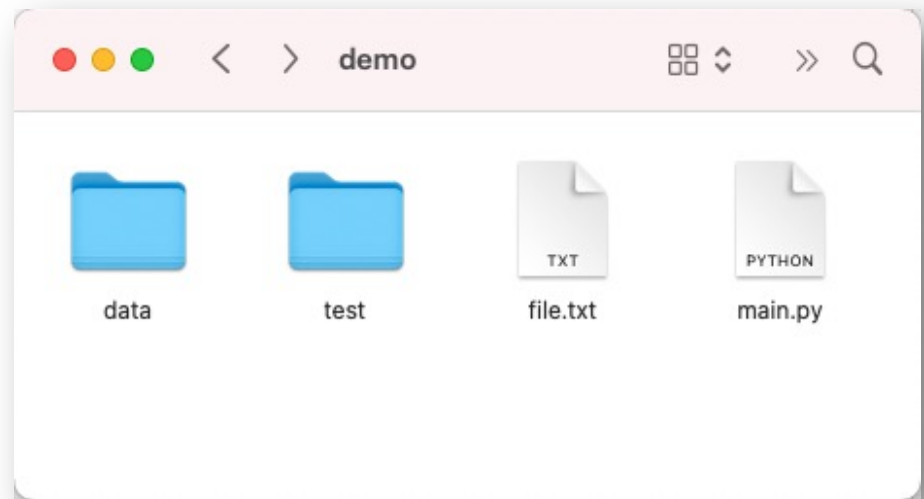
- Many functions in `os` and `os.path` for working w/ files
  - `os.listdir`
  - **`os.mkdir`**
  - `os.path.exists`
  - `os.path.join`
  - ...



```
>>> import os
>>> os.mkdir("test")
```

# OS module

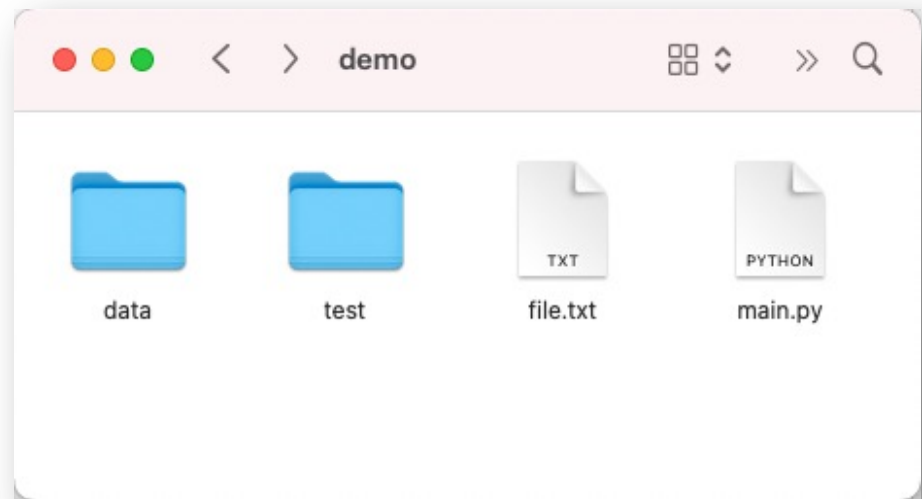
- Many functions in `os` and `os.path` for working w/ files
  - `os.listdir`
  - **`os.mkdir`**
  - `os.path.exists`
  - `os.path.join`
  - ...



```
>>> import os
>>> os.mkdir("test")
```

# OS module

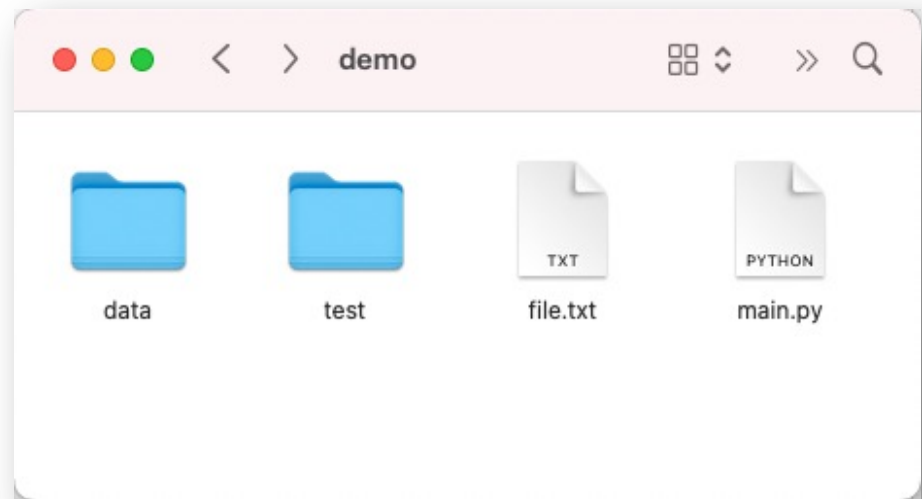
- Many functions in `os` and `os.path` for working w/ files
  - `os.listdir`
  - `os.mkdir`
  - **`os.path.exists`**
  - `os.path.join`
  - ...



```
>>> import os
>>> os.path.exists("file.txt")
True
```

# OS module

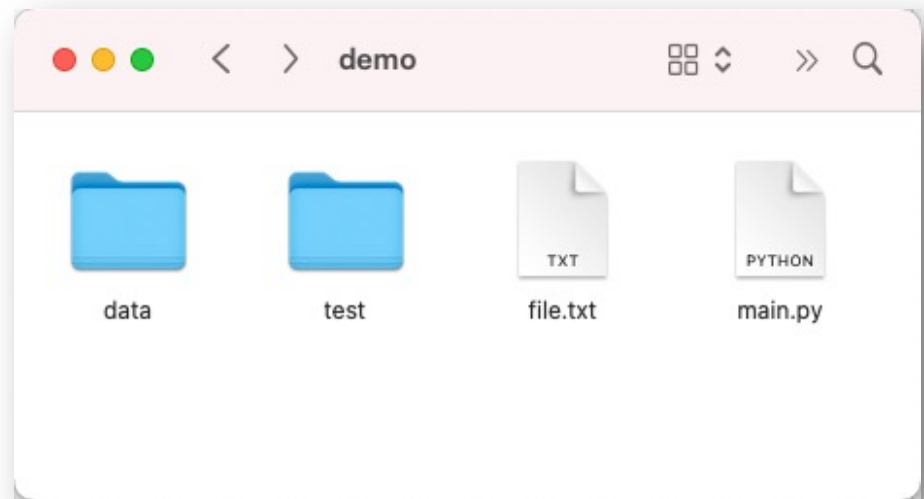
- Many functions in `os` and `os.path` for working w/ files
  - `os.listdir`
  - `os.mkdir`
  - **`os.path.exists`**
  - `os.path.join`
  - ...



```
>>> import os
>>> os.path.exists("haha.txt")
False
```

# OS module

- Many functions in `os` and `os.path` for working w/ files
  - `os.listdir`
  - `os.mkdir`
  - `os.path.exists`
  - **`os.path.join`**
  - ...



```
>>> import os
>>> os.path.join("data", "export.csv")
data/export.csv
```



on Linux/MacOS

on Windows: **data\export.csv**

# Tabular data: CSVs/JSONs vs. Databases

# CSV

State	Capital	Population	Area
VA	Richmond	226,604	42774.2
...	...	...	...

## Characteristics

- One table

# SQL Database

## Capitals

State	Capital
VA	Richmond
...	...

## Population

State	Population
VA	226,604
...	...

## Areas

State	Area
VA	42774.2
...	...

## Characteristics

- Collections of tables, each named



# CSV

State	Capital	Population	Area
VA	Richmond	226,604	42774.2
...	...	...	...

## Characteristics

- One table
- **Columns sometimes named**

# SQL Database

## Capitals

State	Capital
VA	Richmond
...	...

## Population

State	Population
VA	226,604
...	...

## Areas

State	Area
VA	42774.2
...	...

## Characteristics

- Collections of tables, each named
- **Columns always named**

# CSV

State	Capital	Population	Area
string	string	string	string
string	string	string	string
string	string	string	string
string	string	string	string

## Characteristics

- One table
- Columns sometimes named
- **Everything is a string**

# SQL Database

## Capitals

State	Capital
text	text
text	text
text	text
text	text

## Areas

State	Area
text	real
text	real
text	real
text	real

## Population

State	Population
text	integer
text	integer
text	integer
text	integer



No text allowed

## Characteristics

- Collections of tables, each named
- Columns always named
- **Types per column (enforced)**

# Why use a database?

## 1. More relations

### Database

A	B	C
text	integer	real
text	integer	real
text	integer	real
text	integer	real

Same fields and same types in every column

### CSV

```
A,B,C
string,string,string
string,string,string
string,string,string
string,string,string
```

Everything is a **string**

### JSON

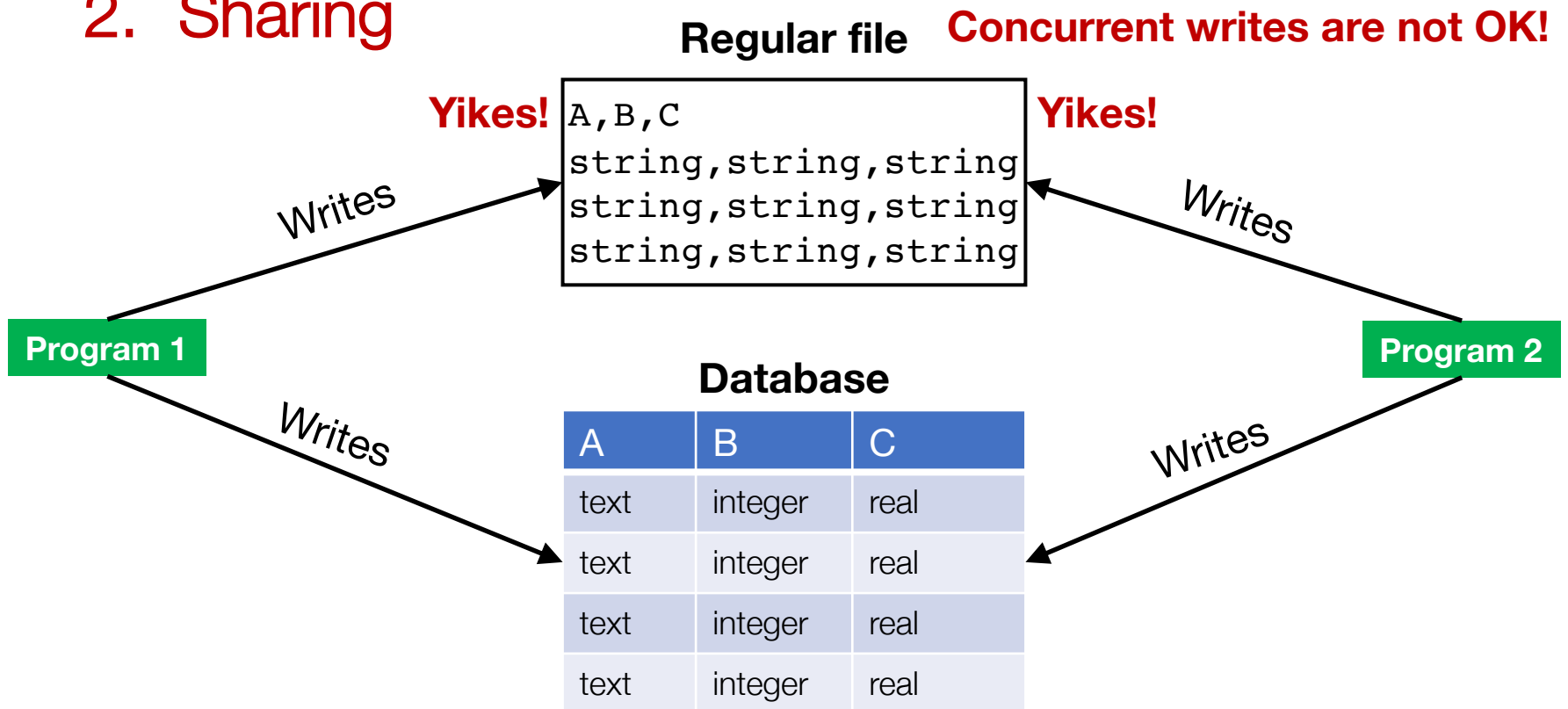
```
[{"A":"val","B":10,"C":2.1},
{"A":"val"},
{"A":"v3","B":2,"C":True}]
```

Types, but...  
**Semi-structured** data  
Missing values  
Types may differ across columns

# Why use a database?

1. More relations

2. Sharing



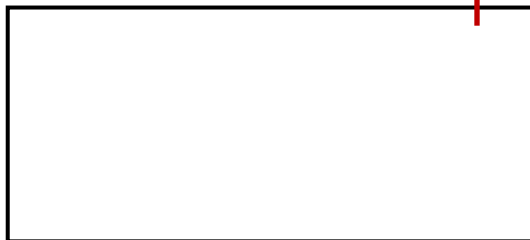
**OK to have multiple programs write to same DB**

# Why use a database?

1. More relations
2. Sharing
3. **Queries**

Python code to find the NBA player who played for the most teams

**Regular file**



Query: which NBA player played for the most teams?

Jim Jackson



**Database**

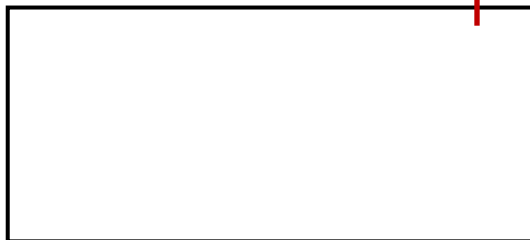
A	B	C
text	integer	real
text	integer	real
text	integer	real
text	integer	real

# Why use a database?

1. More relations
2. Sharing
3. **Queries**

Python code to find the NBA player who played for the most teams

Regular file



Question formulated in **SQL**  
(structured query language)

Jim Jackson



**Database**

A	B	C
text	integer	real
text	integer	real
text	integer	real
text	integer	real

# Why use a database?

1. More relations
2. Sharing
3. Queries
4. Performance

# Why use a database?

1. More relations
2. Sharing
3. Queries
4. Performance

## Exercise:

- I'm going to show a table and ask you **two questions**
- You get out your **stop watch**
- Answer both questions, measuring how long each took you



Name	Age	Score
Parker	26	21
Heidy	22	22
Shirly	27	22
Arla	21	22
Bella	22	22
Bill	28	22
Hollis	26	23
Maurita	22	24
Milda	22	25
Pearline	29	25
Teresa	25	25
Ceola	30	26
Milford	25	26
Alisha	30	27
Antonio	28	28
Ryan	25	28
Karma	23	28
Breana	21	30
Sara	26	30

### Question 1:

How many people are 23 or younger?

### Question 2:

How many people scored 23 or less?

Name	Age	Score
Parker	26	21
Heidy	22	22
Shirly	27	22
Arla	21	22
Bella	22	22
Bill	28	22
Hollis	26	23
Maurita	22	24
Milda	22	25
Pearline	29	25
Teresa	25	25
Ceola	30	26
Milford	25	26
Alisha	30	27
Antonio	28	28
Ryan	25	28
Karma	23	28
Breana	21	30
Sara	26	30

### Question 1:

How many people are 23 or younger?

### Question 2:

How many people scored 23 or less?

*Which question took longer? Why?*

Name	Age	Score
Parker	26	21
Heidy	22	22
Shirly	27	22
Arla	21	22
Bella	22	22
Bill	28	22
Hollis	26	23
Maurita	22	24
Milda	22	25
Pearline	29	25
Teresa	25	25
Ceola	30	26
Milford	25	26
Alisha	30	27
Antonio	28	28
Ryan	25	28
Karma	23	28
Breana	21	30
Sara	26	30

DBs can keep **multiple copies** of the same data

- Which copy to use is **automatically determined** based on the question (query) being asked

Name	Age	Score
Arla	21	22
Breana	21	30
Heidy	22	22
Bella	22	22
Maurita	22	24
Milda	22	25
Karma	23	28
Teresa	25	25
Milford	25	26
Ryan	25	28
Parker	26	21
Hollis	26	23
Sara	26	30
Shirly	27	22
Bill	28	22
Antonio	28	28
Pearline	29	25
Ceola	30	26
Alisha	30	27

**Copy 1**

Name	Age	Score
Parker	26	21
Heidy	22	22
Shirly	27	22
Arla	21	22
Bella	22	22
Bill	28	22
Hollis	26	23
Maurita	22	24
Milda	22	25
Pearline	29	25
Teresa	25	25
Ceola	30	26
Milford	25	26
Alisha	30	27
Antonio	28	28
Ryan	25	28
Karma	23	28
Breana	21	30
Sara	26	30

**Copy 2**

# Why use a database?

1. More relations
2. Sharing
3. Queries
4. Performance

# Why use a database?

1. More relations
2. Sharing
3. Queries
4. Performance

# Why not use a database?

1. It's often an **overkill** and too **heavyweight**
2. For many situations, writing ad-hoc Python code on a simple CSV/JSON file is easier to use

# Next step...

- Assignment 1 is out today!
- Next week: GFS, MapReduce