Lecture 07: Locality of Reference

COSC 273: Parallel and Distributed Computing

Spring 2023

HW 01 Submission link soon! 1 submission per group

Coming Soon!

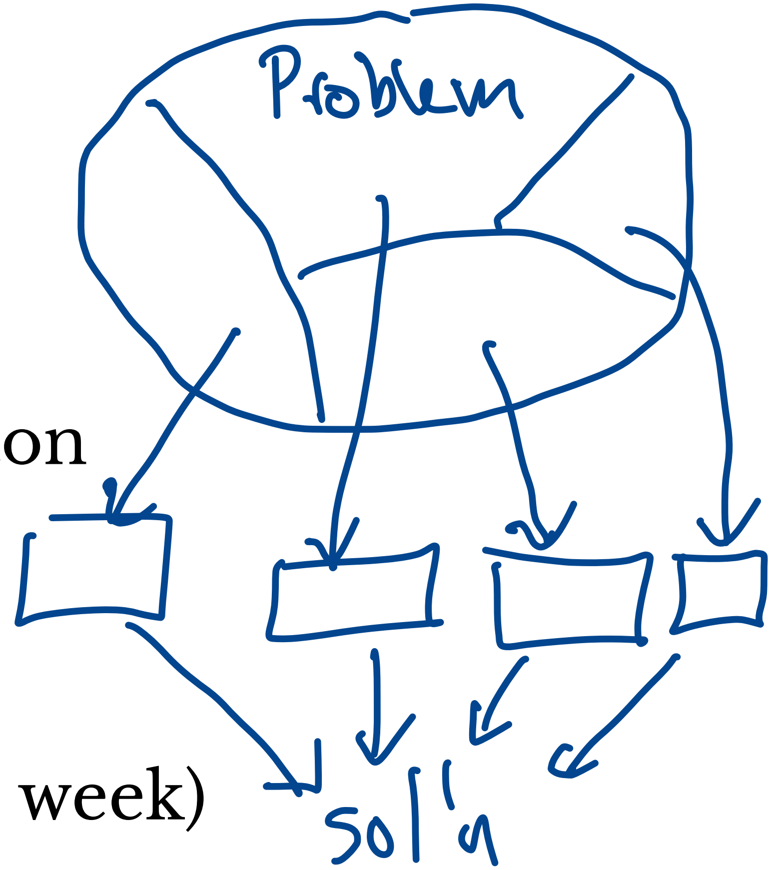
- Lab 02: Computing Shortcuts
- HPC cluster instructions

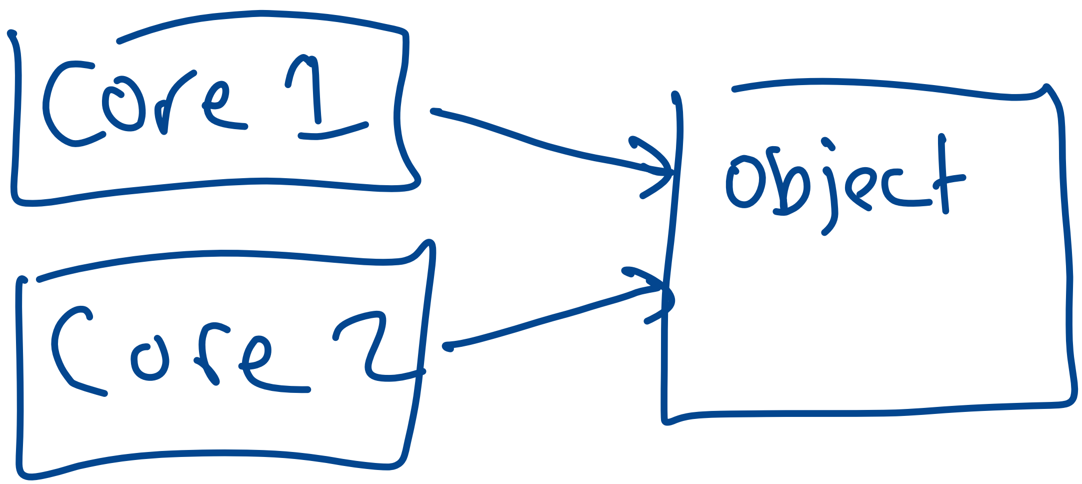
Outline

1. Activity: Locality of Reference
   - download `lec07-locality-of-reference.zip` from website
2. Computer Architecture, less Oversimplified
3. Computing Shortcuts

Two Stories

1. Multithreaded performance
   - embarrassingly parallel computaton
   - e.g., estimating π
2. Multithreaded correctness
   - e.g., `Counter` example
   - mutual exclusion (continued next week)





Two Stories

1. Multithreaded performance
    - embarrassingly parallel computaton
    - e.g., estimating π
2. Multithreaded correctness
    - e.g., `Counter` example
    - mutual exclusion (continued next week)

Today:

- Single-threaded performance!
    - locality of reference
    - `LocalAdder.java`

`LocalAdder` Class

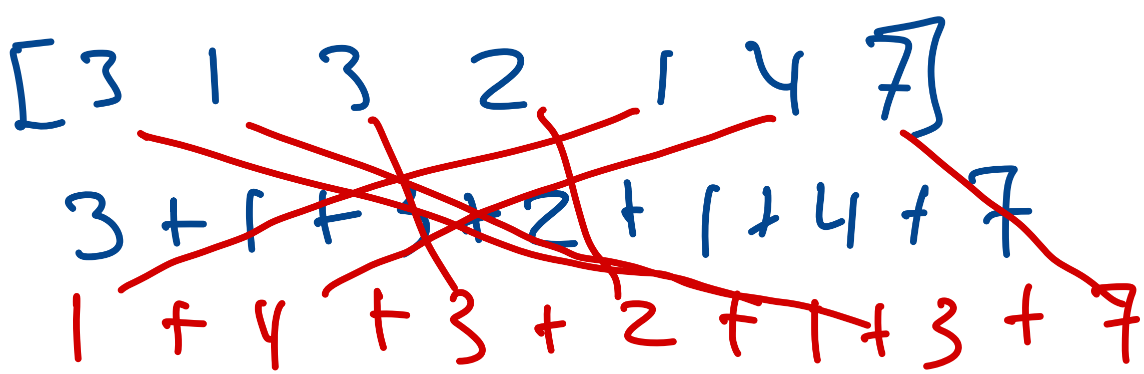
Task. Create an array of random (`float`) values and compute their sum.

`LocalAdder` Class

Task. Create an array of random (`float`) values and compute their sum.

Two Solutions.

1. Sum elements in sequential (linear) order
   - `linearIndex = [0, 1,...,size-1]`
2. Sum element in random order
   - `randomIndex` stores shuffled indices



Two Implementations

Linear Sum:

```
float total = 0;
for (int i = 0; i < size; ++i) {
    int idx = linearIndex[i];
    total += values[idx];
}
return total;
```

[0, 1, 2, ..., size-1]

scramble

Random Sum:

```
float total = 0;
for (int i = 0; i < size; ++i) {
    int idx = randomIndex[i];
    total += values[idx];
}
return total;
```

Tester

`AdderTester`:

- computes linear sum
- computes random sum
- compares running times

Parameters:

- `STEP` the step size been array tests
- `START` starting size value
- `MAX` maximum size value

Activity

Run `AdderTester` for a wide range of sizes:

START & STEP

- 1,000 – 10,000 ← MAX
- 10,000 – 100,000
- 100,000 – 1,000,000
- 1,0000,000 – 10,000,000
- 10,000,000 – 100,000,000

Questions.

1. How do running times compare between linear/random access for smaller arrays? What about larger arrays?
2. How does running time scale with linear/random access?
3. Did you expect to see the trend you see?

How do running times compare?

linear access vs random access?

Small: random better?

linear faster than random
for arrays

100M → 4.7 x

7.

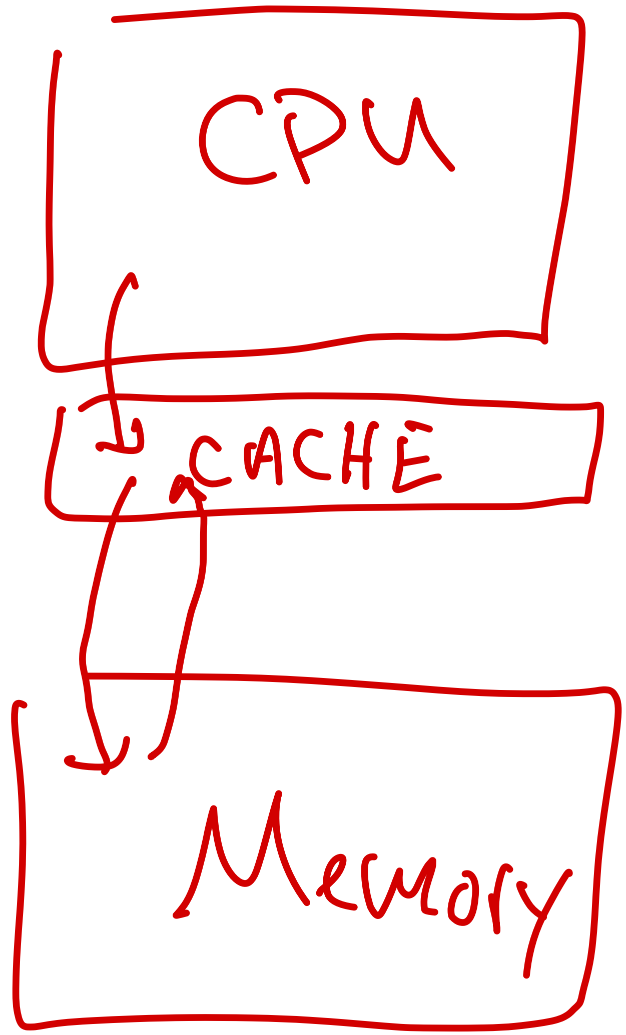
Can you explain the trend?

- Cache ?

Memory accesses are not all equal

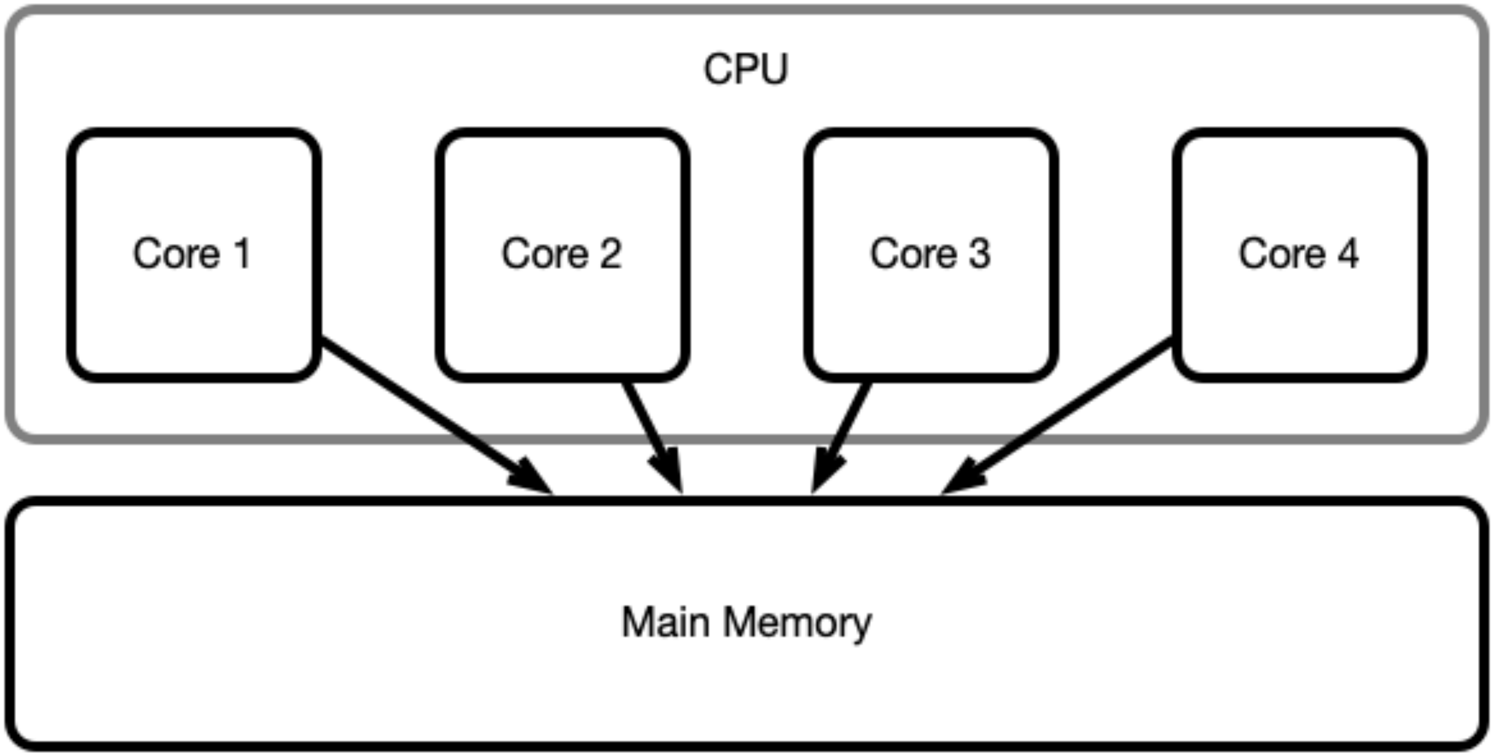
"Spatial locality"

"Paging"



Architecture, Less Oversimplified

Idealized Picture

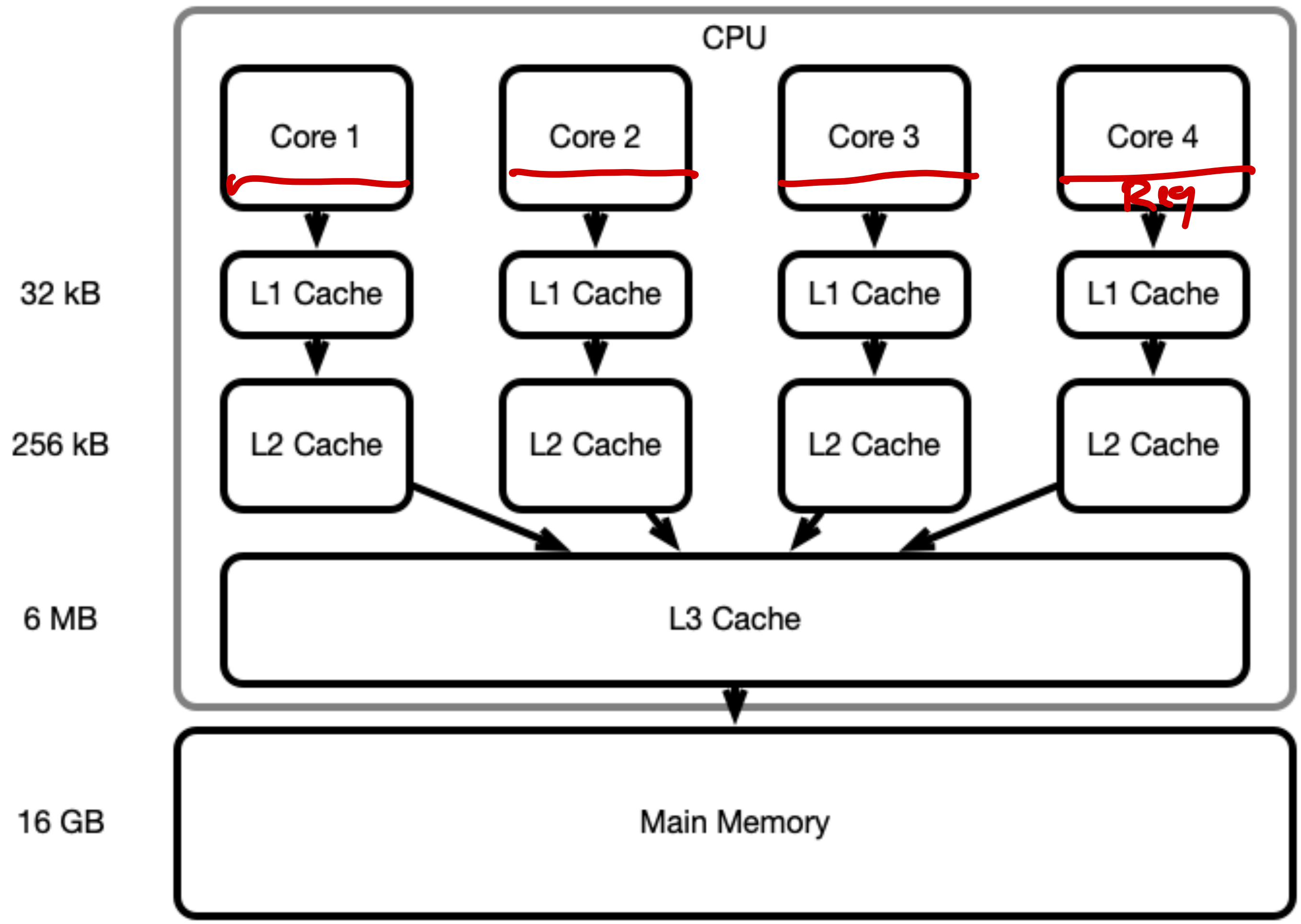


Unfortunately

Computer architechture is not so simple!

- Accessing main memory (RAM) directly is costly
  - ~100 CPU cycles to read/write a value!
- Use hierarchy of smaller, faster memory locations:
  - **caching**
  - different *levels* of cache: L1, L2, L3
  - cache memory integrated into CPU $\implies$ faster access

A More Accurate Picture

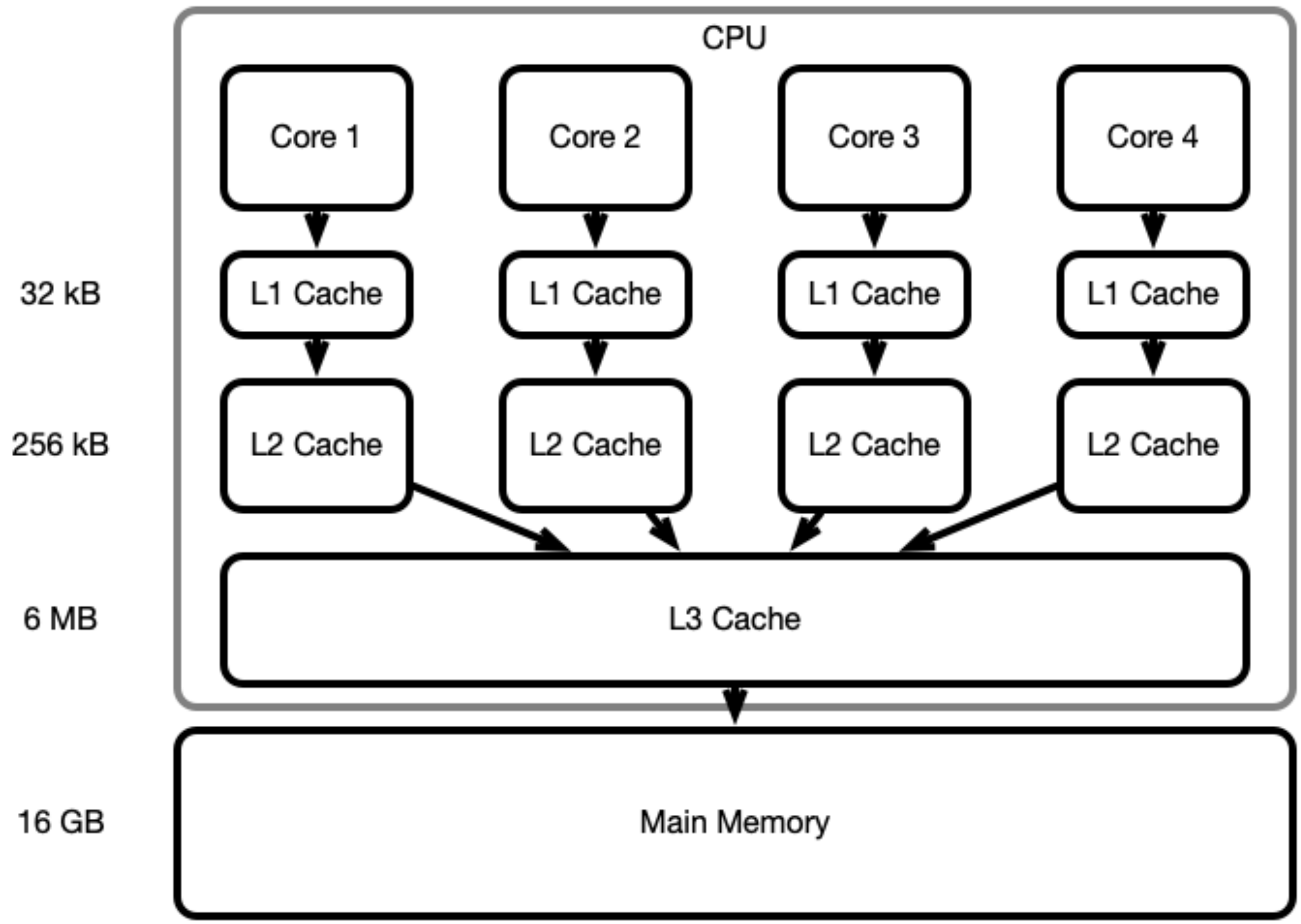


How Memory is Accessed

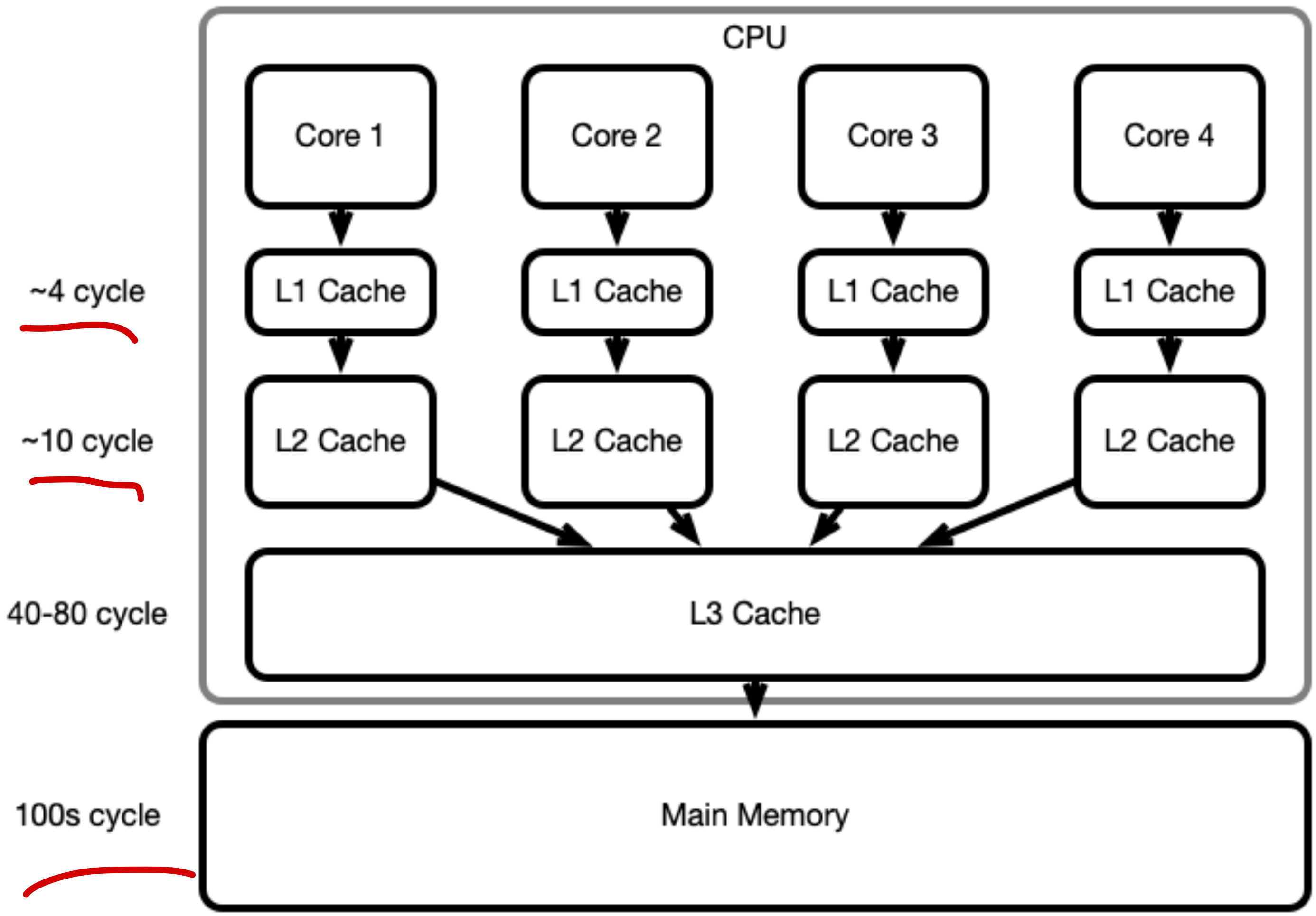
When reading or writing:

- Look for symbol (variable) successively deeper memory locations
  - L1, L2, L3, main memory
- Fetch symbol/value into L1 cache and do manipulations here
- When a cache becomes full, push its contents to a deeper level
- Periodically push changes down the heirarchy

Memory Access Illustrated



Why Is Caching Done? Efficiency!



Why Caching Is Efficient

Heuristic:

- Most programs read/write to a relatively small number of memory locations often
- These values remain in low levels of the hierarchy
- Most commonly performed operation are performed efficiently

Why Caching is Problematic

Cache (in)consistency

- L1, L2 cache *for each* core
- Multiple cores modify same variable concurrently
- Only version stored in local cache modified quickly
- Same variable has multiple values simultaneously!

Takes time to propogate changes to values

- Shared changes only occur periodically!

What Your Computer (Probably) Does

`arr` a large array

On read/write `arr[i]`, search for `arr[i]` successively in

- L1 cache
- L2 cache
- L3 cache
- main memory

Copy `arr[i]` **and surrounding values** to L1 cache

- usually `arr[i-a],...,arr[i+a]` ends up in L1

This process is called **paging**

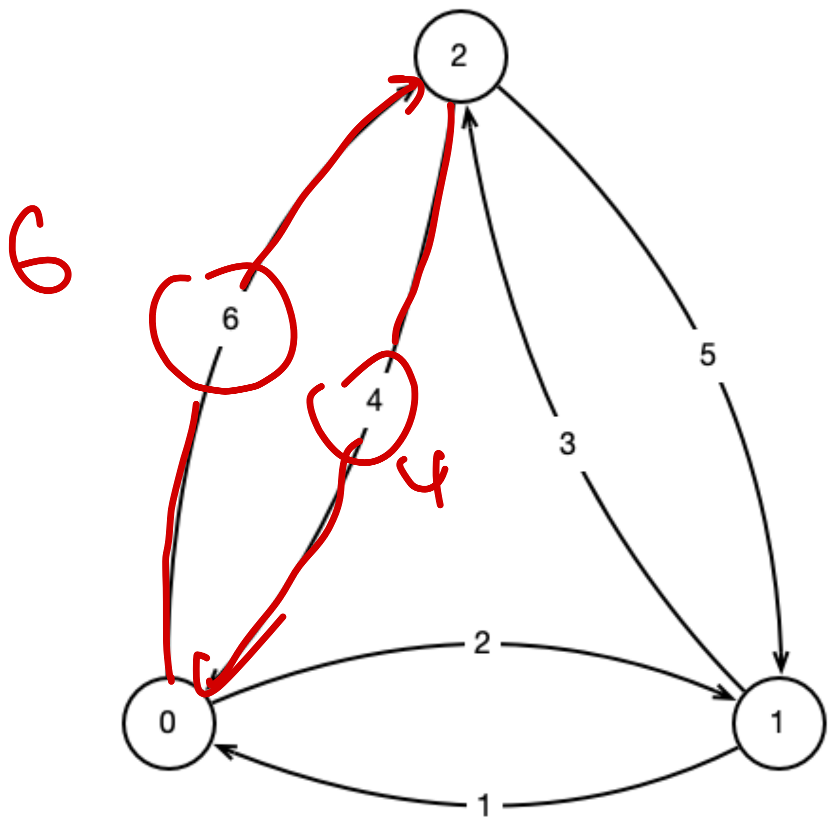
Performance Tuning

Be aware of your program's **memory access pattern**

- reading values sequentially can be 10s of times faster than reading randomly or jumping around

Lab 02: Computing Shortucts

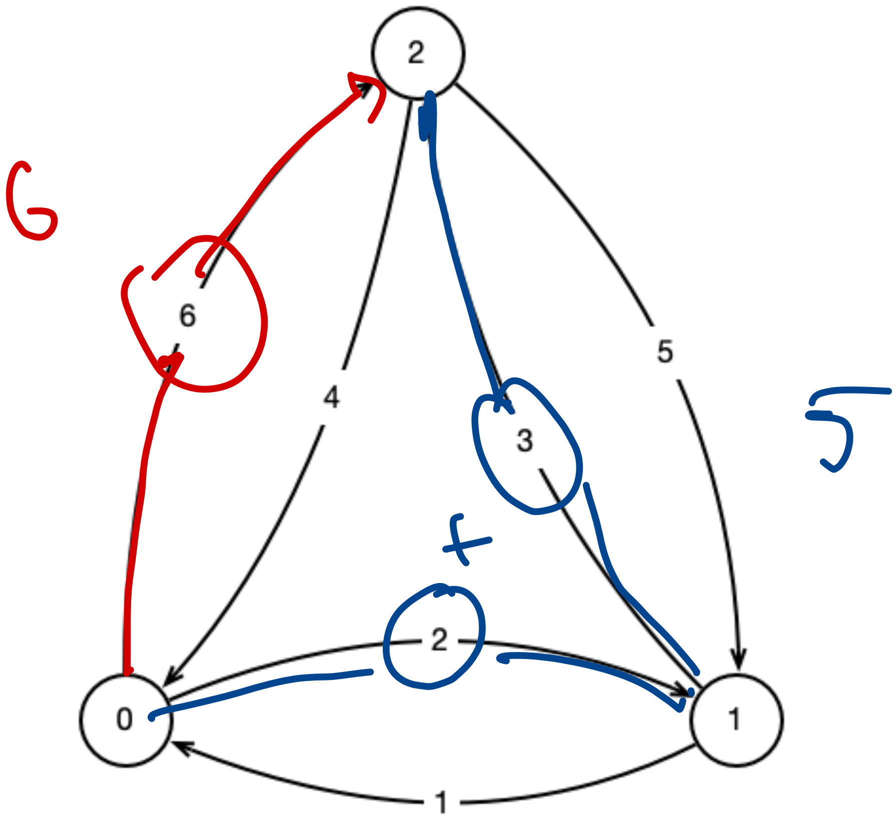
A Network



Network

- **nodes** and **edges** between nodes
  - nodes labeled $0, 1, \ldots, n-1$
  - *directed* edges (i, j) from i to j for each $i \neq j$
- edges (i, j) have associated **weight**, $w(i, j) \geq 0$
  - weight indicates *cost* or *distance* to move from i to j

Shortcuts



Blue Path = shortcut

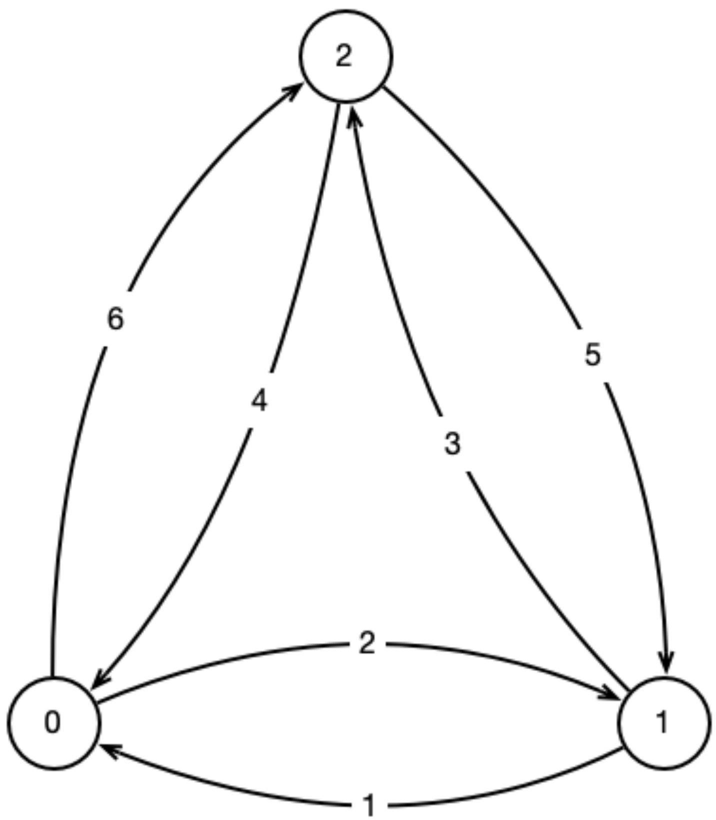
What is cheapest path from 0 to 2?

A Problem

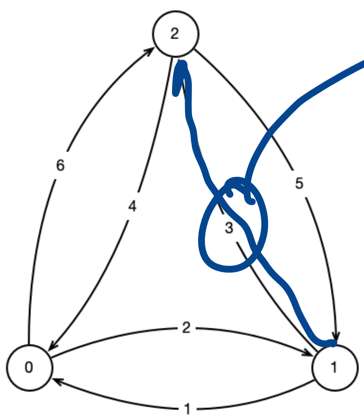
Given a network as above, for all $i \neq j$, find cheapest path of length (at most) 2 from i to j

- weight of a *path* is sum of weight of edges
- convention: $w(i, i) = 0$
- a *shortcut* from i to j is a path $i \to k \to j$ where $w(i, k) + w(k, j) < w(i, j)$

Shortcut Distances



Representing Input



3

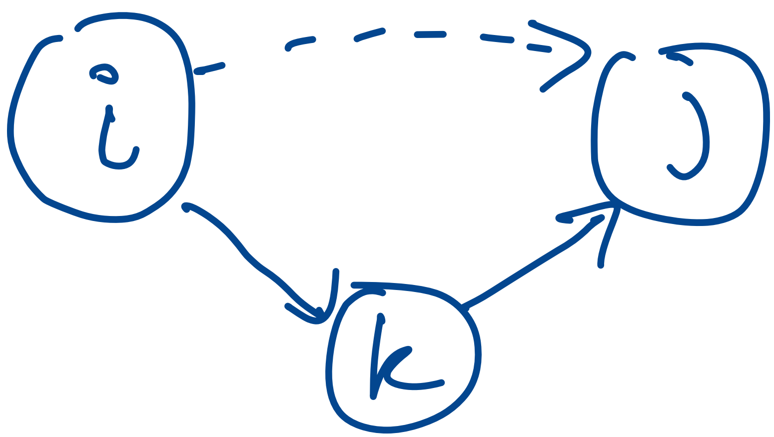
rows = starting nodes
columns = ending nodes

-

$$D = \begin{pmatrix} 0 & 2 & 6 \\ 1 & 0 & 3 \\ 4 & 5 & 0 \end{pmatrix}$$

Computing Output

- $D = (d_{ij})$
- Output $R = (r_{ij})$
  - r_{ij} = shortcut distance from i to j
  - computed by $r_{ij} = \min_k d_{ik} + d_{kj}$



Example

-

$$D = \begin{pmatrix} 0 & 2 & 6 \\ 1 & 0 & 3 \\ 4 & 5 & 0 \end{pmatrix}$$

-

In Code

- Create a `SquareMatrix` object
- `SquareMatrix` stores a 2d array of `float`s called `matrix`
  - `matrix[i][j]` stores $w(i,j)$

Your Assignment

Write a program that computes shortcut matrix as quickly as possible!

- You'll be given
  - `getShortcutMatrixBaseline()`
- Your assignment is to optimize the code to write
  - `getShortcutMatrixOptimized ()`

Assignment Challenges

1. Optimize memory access pattern for operations
    - make access pattern linear, when possible
2. Apply multithreading to get further speedup
    - partition the problem into smaller parts

Payoff: optimized program will be 10s of times faster on your computer, 100s of times faster on HPC cluster!