Programming Parallel Computers

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Part 2A:
Multicore parallelism · OpenMP

Three forms of parallelism

- **Multicore parallelism:**
  - CPU has got ***multiple streams of instructions*** to process (“threads”)
  - each core can do useful work
- **Instruction-level parallelism:**
  - each CPU core ***processes its instruction stream as fast as possible***
  - all arithmetic units can do useful work in every clock cycle
- **Vector operations:**
  - each instruction ***does multiple similar operations in parallel***
  - all “lanes” of arithmetic units do useful work

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Week 1

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Today

- **Instruction-level parallelism:**
  - each CPU core ***processes its instruction stream as fast as possible***
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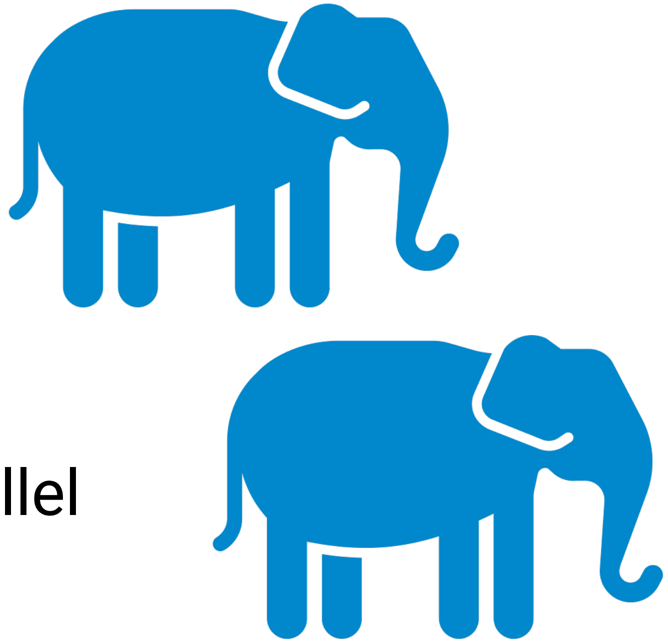
- **Vector operations:**
  - each instruction ***does multiple similar operations in parallel***
  - all “lanes” of arithmetic units do useful work

Today

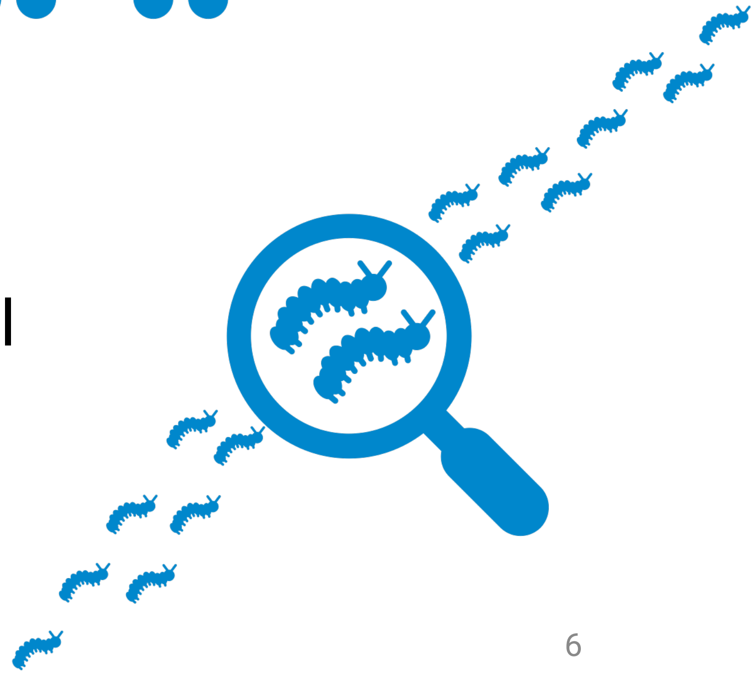
How to achieve it?

- **Multicore parallelism:**
  - we must create ***multiple threads*** — e.g. with OpenMP
- **Instruction-level parallelism:**
  - we must have ***independent operations*** in the instruction stream
  - CPU parallelizes them automatically whenever possible
- **Vector operations:**
  - we must use ***vector instructions*** — e.g. with vector types in GCC

Different scales



- **Multicore parallelism:**
  - very ***coarse-grained***
  - executing e.g. entire subroutines in parallel
  - amount of work per independent unit:
    e.g. 1 million multiplications
- **Instruction-level parallelism:**
  - very ***fine-grained***
  - executing machine language instructions in parallel
  - amount of work per independent unit:
    e.g. 1 multiplication



Multicore & multithreading

- **Assuming:**
  - we have a computer with a ***4-core*** CPU
  - we have a program that creates ***4 threads***
  - no other program is active at the same time
- **Then:**
  - the ***operating system*** will do the right thing
  - each CPU core will run one thread
  - resources fully utilized
    - at least until some of the threads finish their work…

Multicore & multithreading

- **More threads than cores?**
  - core 1 runs thread 1 for a short while
  - operating system makes a ***context switch***
  - core 1 runs thread 2 for a short while …
- **Fewer threads than cores?**
  - some cores are simply ***idle***
  - there is no way to use 4 cores if you run 1 program with 1 thread

Multicore & multithreading

- How to split long-running computation among multiple threads?
- **Hard way:** use low-level primitives and do everything manually
  - pthreads
  - `std::thread` …
- **Easy way:** use high-level parallelization tools that do almost everything for you
  - ***OpenMP***
  - Intel TBB …

Using OpenMP

OpenMP parallel for loop

```
for (int i = 0; i < 10; ++i) {
    c(i);
}
```

thread 0: c(0) c(1) c(2) c(3) c(4) c(5) c(6) c(7) c(8) c(9)

OpenMP parallel for loop

```
#pragma omp parallel for
for (int i = 0; i < 10; ++i) {
    c(i);
}
```

thread 0: c(0) c(1) c(2)

thread 1: c(3) c(4) c(5)

thread 2: c(6) c(7)

thread 3: c(8) c(9)

OpenMP parallel for loop

```
#pragma omp parallel for
for (int i = 0; i < 10; ++i) {
    c(i);
}
```

thread 0: c(0) c(1) c(2)

thread 1: c(3) c(4) c(5)

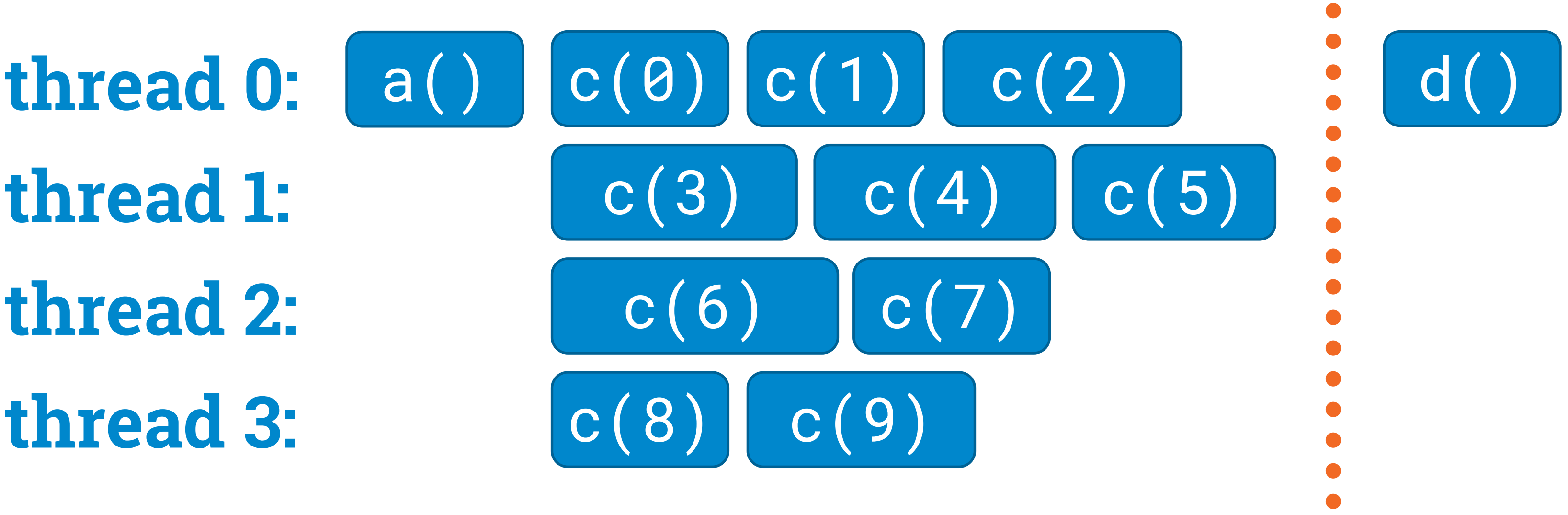
thread 2: c(6) c(7)

thread 3: c(8) c(9)

Threads might do different amounts of work

```
a();
#pragma omp parallel for
for (int i = 0; i < 10; ++i) {
    c(i);
}
d();
```

Start & end coordinated



d knows that c(0), c(1), ..., c(9) have already finished their work

Loop scheduling

Example:
4 threads
40 iterations

```
#pragma omp parallel for
```

- **thread 0:** iterations 0, 1, ..., 9
- **thread 1:** iterations 10, 11, ..., 19

```
#pragma omp parallel for schedule(static,1)
```

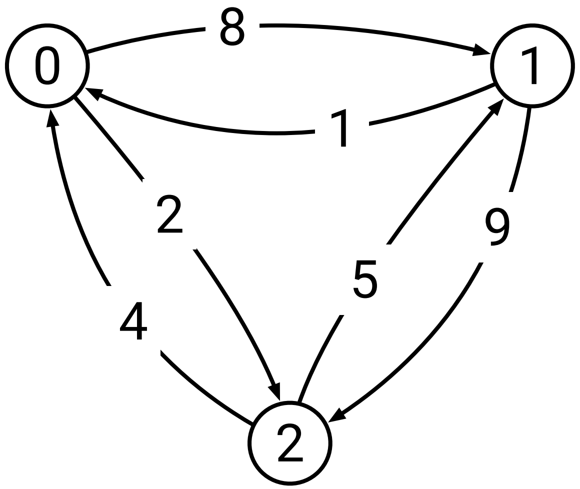
- **thread 0:** iterations 0, 4, 8, ..., 36
- **thread 1:** iterations 1, 5, 9, ..., 37

```
#pragma omp parallel for schedule(dynamic,1)
```

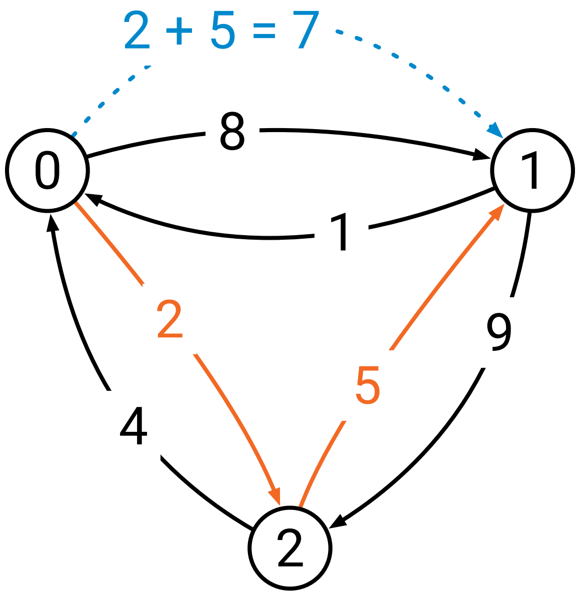
- iterations 0, 1, 2, ..., 39 are waiting in a queue
- whenever a thread is available, process the next iteration

Sample application: cheapest 2-hop path

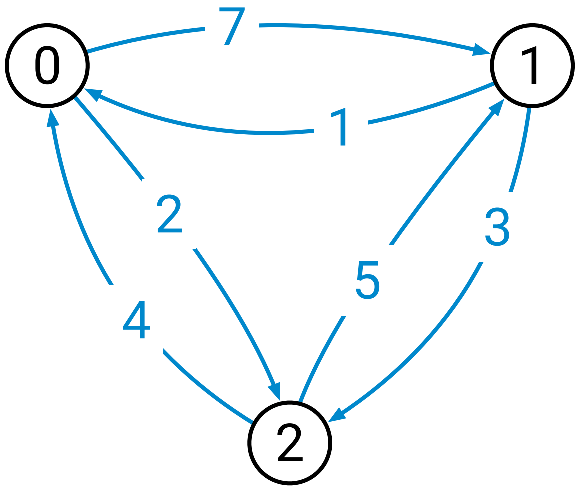
d (input):




```
d[] = { 0, 8, 2,
        1, 0, 9,
        4, 5, 0 }
```



r (output):




```
r[] = { 0, 7, 2,
        1, 0, 3,
        4, 5, 0 }
```

```
for (int i = 0; i < n; ++i) {
    for (int j = 0; j < n; ++j) {
        float v = infinity;
        for (int k = 0; k < n; ++k) {
            float x = d[n*i + k];
            float y = d[n*k + j];
            float z = x + y;
            v = min(v, z);
        }
        r[n*i + j] = v;
    }
}
```

Each iteration is independent of each other, could be done in parallel

```
#pragma omp parallel for
for (int i = 0; i < n; ++i) {
    for (int j = 0; j < n; ++j) {
        float v = infinity;
        for (int k = 0; k < n; ++k) {
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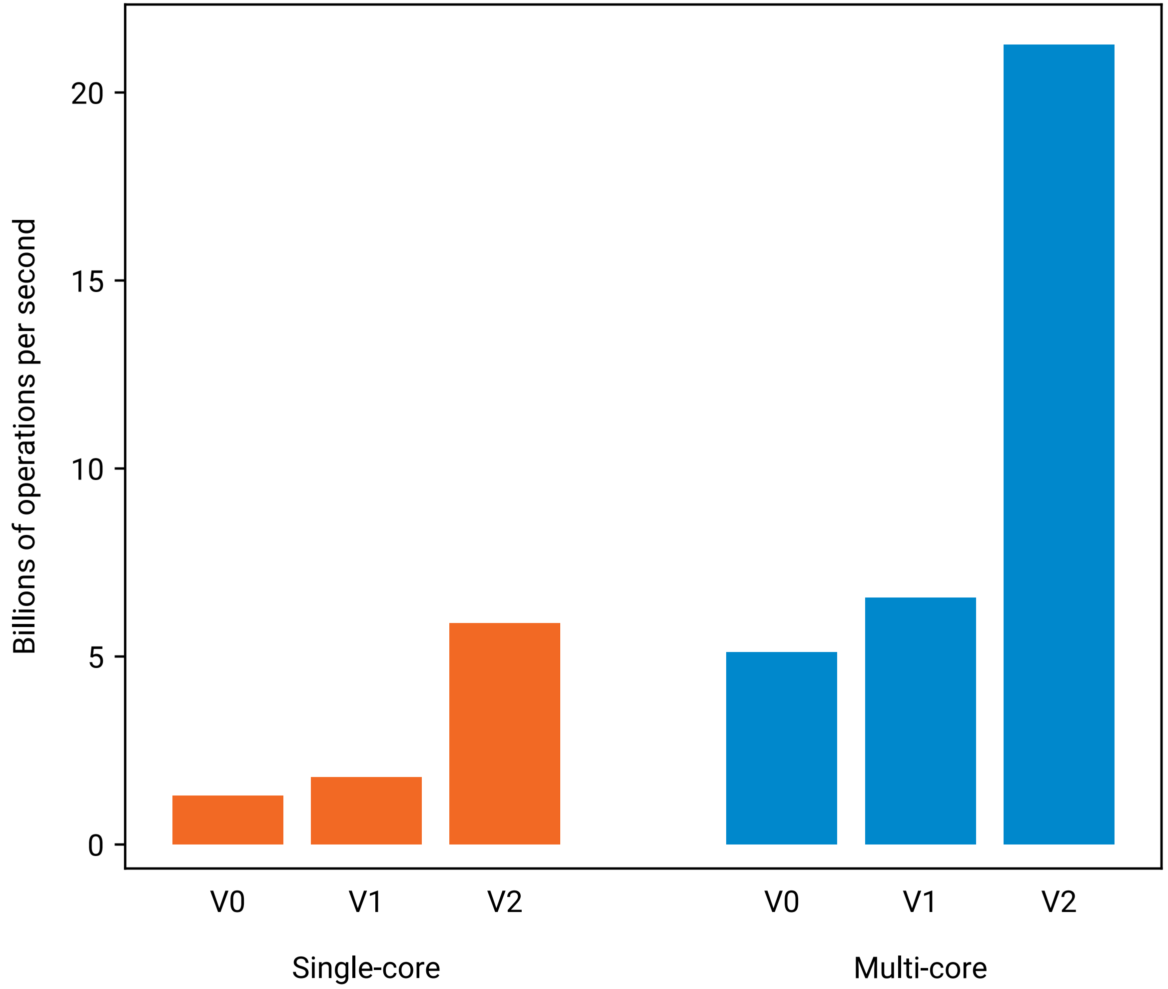
            float y = d[n*k + j];
            float z = x + y;
            v = min(v, z);
        }
        r[n*i + j] = v;
    }
}
```

**That's all!
It works!**

It works!

Multithreading with OpenMP helped by a ***factor of 3.6***

Overall 16 times faster than our starting point



Careful with OpenMP!

```
#pragma omp parallel for
for (int i = 0; i < n; ++i) {
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            float y = d[n*k + j];
            float z = x + y;
            v = min(v, z);
        }
        r[n*i + j] = v;
    }
}
```

Private variables (one for each thread)

```
#pragma omp parallel for
for (int i = 0; i < n; ++i) {
    for (int j = 0; j < n; ++j) {
        float v = infinity;
        for (int k = 0; k < n; ++k) {
            float x = d[n*i + k];
            float y = d[n*k + j];
            float z = x + y;
            v = min(v, z);
        }
        r[n*i + j] = v;
    }
}
```

Shared read-only variables

```
#pragma omp parallel for
for (int i = 0; i < n; ++i) {
    for (int j = 0; j < n; ++j) {
        float v = infinity;
        for (int k = 0; k < n; ++k) {
            float x = d[n*i + k];
            float y = d[n*k + j];
            float z = x + y;
            v = min(v, z);
        }
        r[n*i + j] = v;
    }
}
```

Shared read-only variables

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#pragma omp parallel for
for (int i = 0; i < n; ++i) {
    for (int j = 0; j < n; ++j) {
        float v = infinity;
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            float x = d[n*i + k];
            float y = d[n*k + j];
            float z = x + y;
            v = min(v, z);
        }
        r[n*i + j] = v;
    }
}
```

e.g. n = 10:

- i = 0: r[0] ... r[9]
- i = 1: r[10] ... r[19]
- i = 2: r[20] ... r[29]

. . .

- i = 9: r[90] ... r[99]

Each thread writes different elements, no thread reads them

Rules

- Private data:
  - **OK:** everything
- Shared data:
  - **OK:** multiple threads read, nobody writes
  - **OK:** only one thread touches it
  - ***bad:*** one thread reads, another writes
  - ***bad:*** multiple threads write

} "Data race"

Cannot parallelize

```
for (int i = 0; i < 10; ++i) {
    x[i + 1] = f(x[i]);
}
```

Cannot parallelize

```
for (int i = 0; i < 10; ++i) {
    y[0] = f(x[i]);
}
```

OK

```
#pragma omp parallel for
for (int i = 0; i < 10; ++i) {
    y[i] = f(x[i]);
}
```