Scientific and Technical Computing

Hardware and Code Optimization

Lars Koesterke
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Discussion

What are the **primary components** of a computer?

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Can you already detect some limitations?

Discussion

What are the **primary components** of a computer?

- CPU
- Memory
- (Storage)
- (Motherboard, lots of wires)
- (Keyboard, screen)

Can you already detect some limitations?

- Number of pins connecting CPU and Memory to motherboard

Scope of this class

What **sciences and technologies** are

involved in designing and building a

CPU/Memory/Computer?

Scope of this class

What sciences and technologies are involved in designing and and building a CPU?

- Electrical engineering, physics, chemistry, math … (all the things you study)
- Cutting edge research
- A lot of institutional knowledge by people in companies and research institutions
  - Not everything is an exact science; many tricks are applied (a bit like cooking)
  - Design decisions are made on incomplete facts (humans weigh the pros and cons)
- Certainly many computers equipped with previous generations of CPUs

This is **not** what we will talk about in this section of the class segment
(Hardware and Code Optimization)

Scope of this class

What are we going to <u>explore</u> in the next 4 weeks?

High level overview of the architecture

- High level of abstraction
- (Very) simplified implementation details
- Features that allow for a very high peak performance

<u>How to write code that exploits the hardware features?</u>

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Scope of this class

Matching software to hardware: Why?

Much higher performance

- Orders of magnitude!

There is, of course, the idea to match the hardware to the software/purpose

This is done in other areas
In HPC the idea is not feasible (with one notable exception)

Conceptual understanding of hardware features guides software design

Assumption: You are in this class (and other TACC classes) to learn how to

- learn about high-performance computing (HPC)
- use a supercomputer (or any computer!) in an **efficient** and **effective** way
- write **fast** code
  - This class: exploiting parallelism of the hardware
  - Note: some/many bad code design decision cannot be reversed later
- write **parallel** code with OpenMP and MPI (PCSE in the spring semester)

Getting some scientific calculations done
Better than the competition

Terminology

Today's supercomputers are clusters

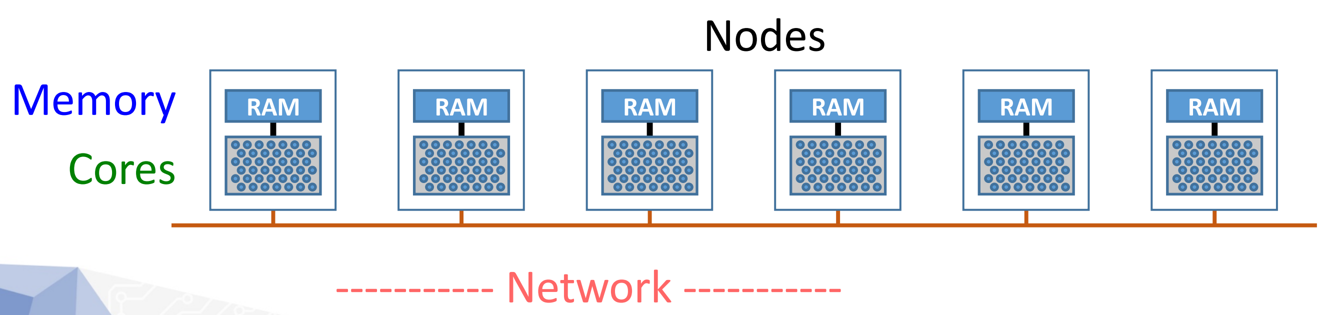
Components of a cluster

- Nodes
  - CPUs and memory
- Network
- (File system)

In this class we strongly focus on a single-node!

A cluster is build of individual computers which are called nodes

The nodes are connected through an interconnect



Discussion

What is a clock tick?

What is a clock cycle?

Discussion

What is a clock tick?

What is a clock cycle?

What does this mean?

Clock frequency = 2.2 GHz

Discussion

Some answers from the web

What is a clock tick?

What is a clock cycle?

Computers use an internal clock to synchronize all of their calculations. The clock ensures that the various circuits inside a computer work together at the same time.

Think of an assembly line

- Smallest unit of time to ‘do’ something
- One or multiple instructions are executed
- An instruction may take several cycles

Same as a cycle, the smallest unit of time recognized by a device. For personal computers, clock ticks generally refer to the main system clock, which runs at 66 MHz. This means that there are 66 million clock ticks (or cycles) per second. Since modern CPUs run much faster (up to 3 GHz), the CPU can execute several instructions in a single clock tick.

Examples of instructions are

- Multiply two numbers
- Load data into a register

"The processor clock coordinates all CPU and memory operations by periodically generating a time reference signal called a *clock cycle or tick*. Clock frequency is specified in gigahertz (GHz), which specifies billions of ticks per second. Clock speed determines how fast instructions execute. Some instructions require one tick, others multiple ticks, and some processors execute multiple instructions during one tick."

‘Instruction’ can mean many things. Let’s leave it a bit vague for now

Intermission

Let's talk about how to proceed

I'd like to organize this class having this in mind:

- What and how to learn?
- What will be on the slides?
- How to participate?
- Give me feedback!
- How participation will affect your grade?
- Teamwork
- Let me know (at a later point) what you are interested in

Experiment: Prepare something at home

Your tasks

- Look up what the 'Horner scheme' is
  - Wikipedia entry (English Wikipedia site) is very good
  - To be specific, Horner's notation: $((((z+\ldots)\times z+\ldots)\times z \ldots$
- Describe the 'Horner notation'
  - Three to four sentences
  - General context (Note: you don't have to explain what a polynomial is)
  - What is the 'trick'?
  - Why would you use it when writing code?
- 'Present' in class next week
  - Nothing dramatic, I'll explain
  - Write the 3 sentences down, if that helps you

Let's make our computer do something

$$a = b + c$$

Let's make our computer do something

$$a = b + c$$

What needs to happen so that the CPU can calculate?

Where is the data coming from?

Where is the data going?

What part of the hardware performs the operation?

Let’s make our computer do something

$$a = b + c$$

What needs to happen so that the CPU can calculate?

Where is the data coming from?	Memory
Where is the data going?	Memory
What part performs the operation?	Floating Point Unit (FPU) in the CPU (Central Processing Unit)

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Let's make our computer do something

$$a = b + c$$

What needs to happen so that the CPU can calculate?

How long does it take?

Where is the data coming from?	Memory
Where is the data going?	Memory
What part performs the operation?	FPU in the CPU

Let's make our computer do something

$$a = b + c$$

What needs to happen so that the CPU can calculate?		How long does it take?
Where is the data coming from?	Memory	A very long time
Where is the data going?	Memory	A very long time
What part performs the operation?	FPU in the CPU	A very short time

Let's make our computer do something

$$a = b + c$$

What needs to happen so that the CPU can calculate?		How long does it take?
Where is the data coming from?	Memory	300 cycles
Where is the data going?	Memory	300 cycles
What part performs the operation?	FPU in the CPU	3 cycles

What a bummer! Actual work takes 0.5% of the total time
We may have built the 'most ineffective computer' ever!

Does this help us?

$$a(i) = b(i) + c(i)$$

Does this help us?

$$a(i) = b(i) + c(i)$$

Hint: where would you likely find such a statement?

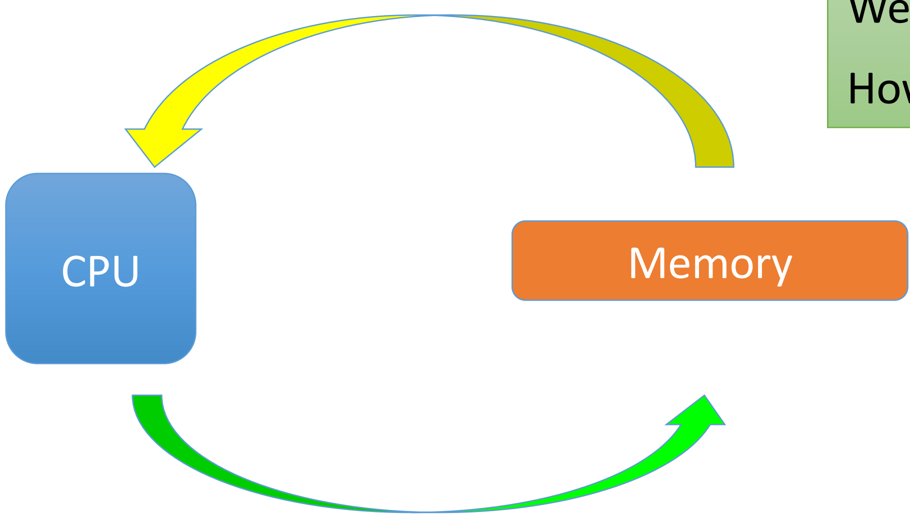
Does this help us?

$$a(i) = b(i) + c(i)$$

```
loop with index i
  a(i) = b(i) + c(i)
end loop
```

Data

a(i) = b(i) + c(i)



We have a lot of data to process

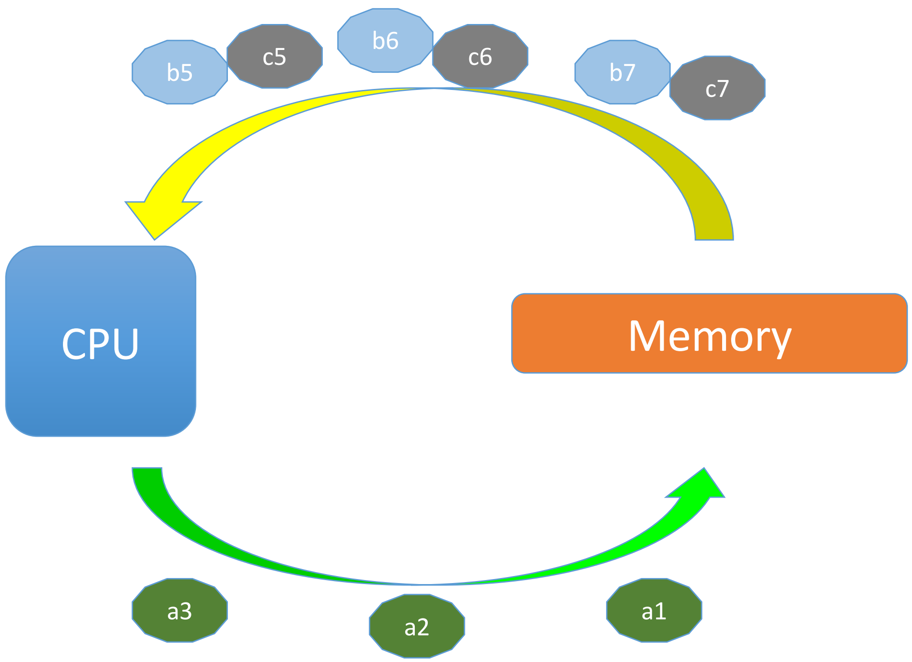
How can that help to **'getting more done'**?

'getting more done'

We are mostly interested in floating point operations (flops) that move the calculation closer to the solution

Data Streams

a(i) = b(i) + c(i)



<u>Some data is 'en route'</u>

b and c: from memory to CPU

a: from CPU to memory

<u>Some data is being processed</u>

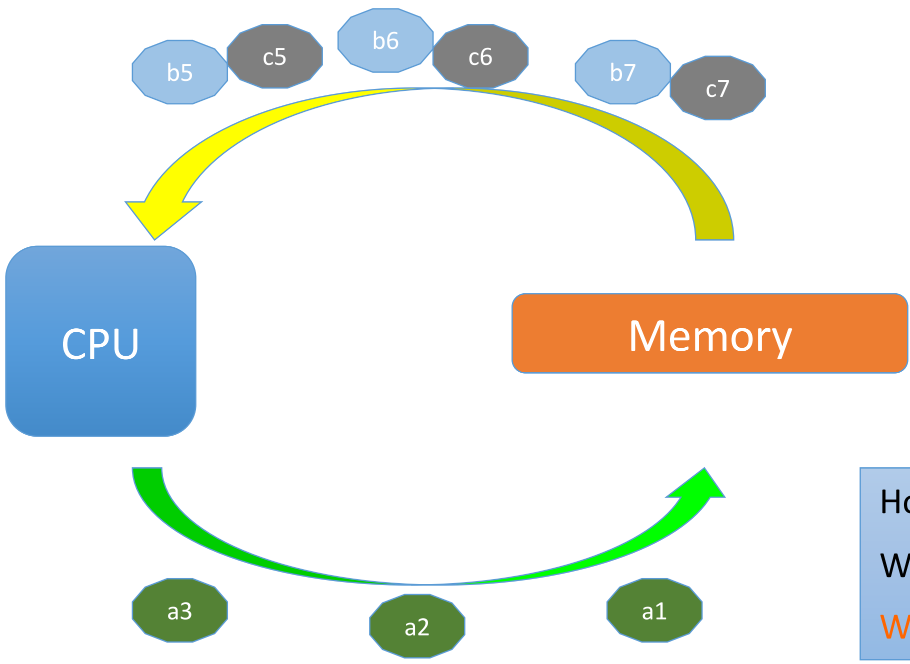
a(i) = b(i) + c(i)

How much data has to be 'en route'?

What is the main factor?

Data Streams

a(i) = b(i) + c(i)



<u>Some data is 'en route'</u>
b and c: from memory to CPU
a: from CPU to memory

<u>Some data is being processed</u>
a(i) = b(i) + c(i)

How much data has to be 'en route'?

What is the main factor?

What if I had drawn CPU and Memory further apart?

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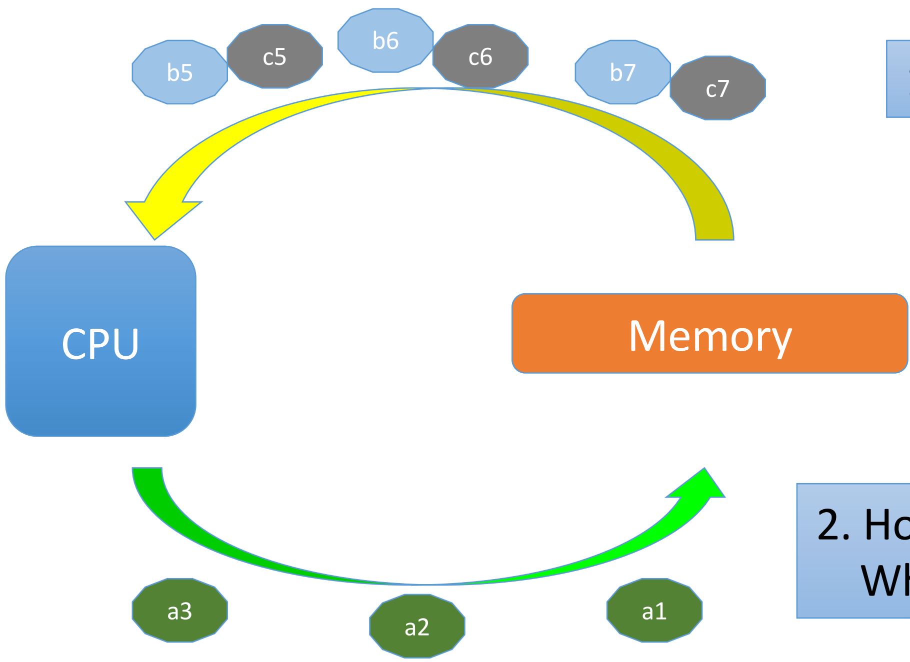
Data Streams

a(i) = b(i) + c(i)



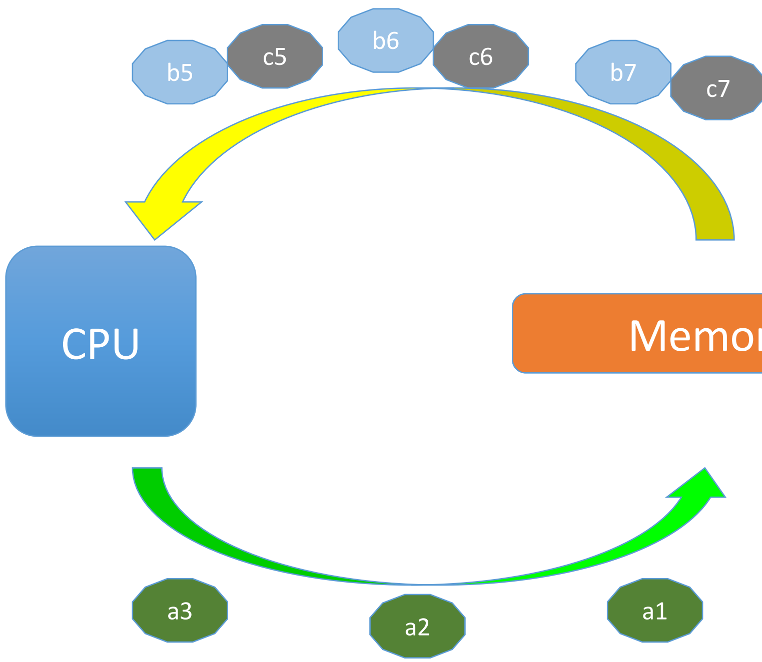
1. How much data has to be ‘en route’?

Operation: 3 cycles
Data transfer: 300 cycles

2. How many results ‘a’ do we get per cycle? What is the speedup?

Data Streams

a(i) = b(i) + c(i)



1. How much data has to be 'en route'?

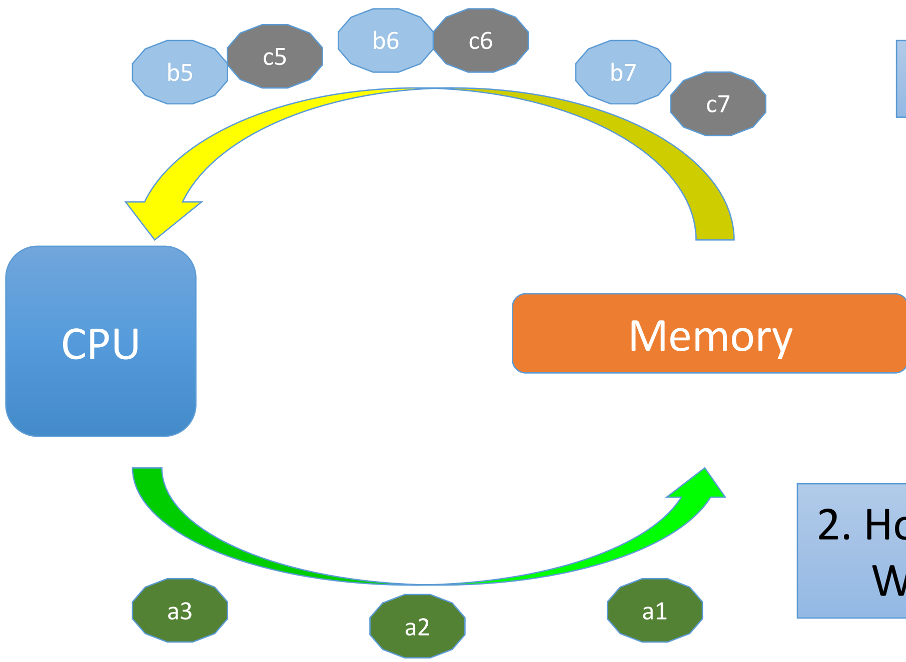
Operation: 3 cycles
Data transfer: 300 cycles

100 elements of a, b, and c

2. How many results (a) do we get per cycle? What is the speedup?

Data Streams

a(i) = b(i) + c(i)



1. How much data has to be 'en route'?

Operation:	3 cycles
Data transfer:	300 cycles
Ratio:	1/100

100 elements of a, b, and c

2. How many results (a) do we get per cycle?
What is the speedup?

1 result every 3 cycles
Speedup is 200×

Hooray!

We have just discovered one of the most important hardware features in a CPU: Data streams

- Data Streams
  - Long distance (in terms of cycles) between main memory and CPU
  - Short time to execute 'add' operation (few cycles)
  - Streaming data: Data 'en route' filling the pipeline between memory and CPU
- Questions for later
  - How do we or the CPU 'organize' the data stream?
  - How does this look in code?

There are 2 fundamental bottlenecks

1. The data supply to the CPU
2. The actual operations (flops)

There are 3 major technologies that are applied
(we can argue about the exact number)

1. Data streams
2. 'Improving CPU throughput'
3. 'Improving data movement'

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