WELCOME TO CS4414 SYSTEMS PROGRAMMING

Professor Ken Birman

Lecture 1

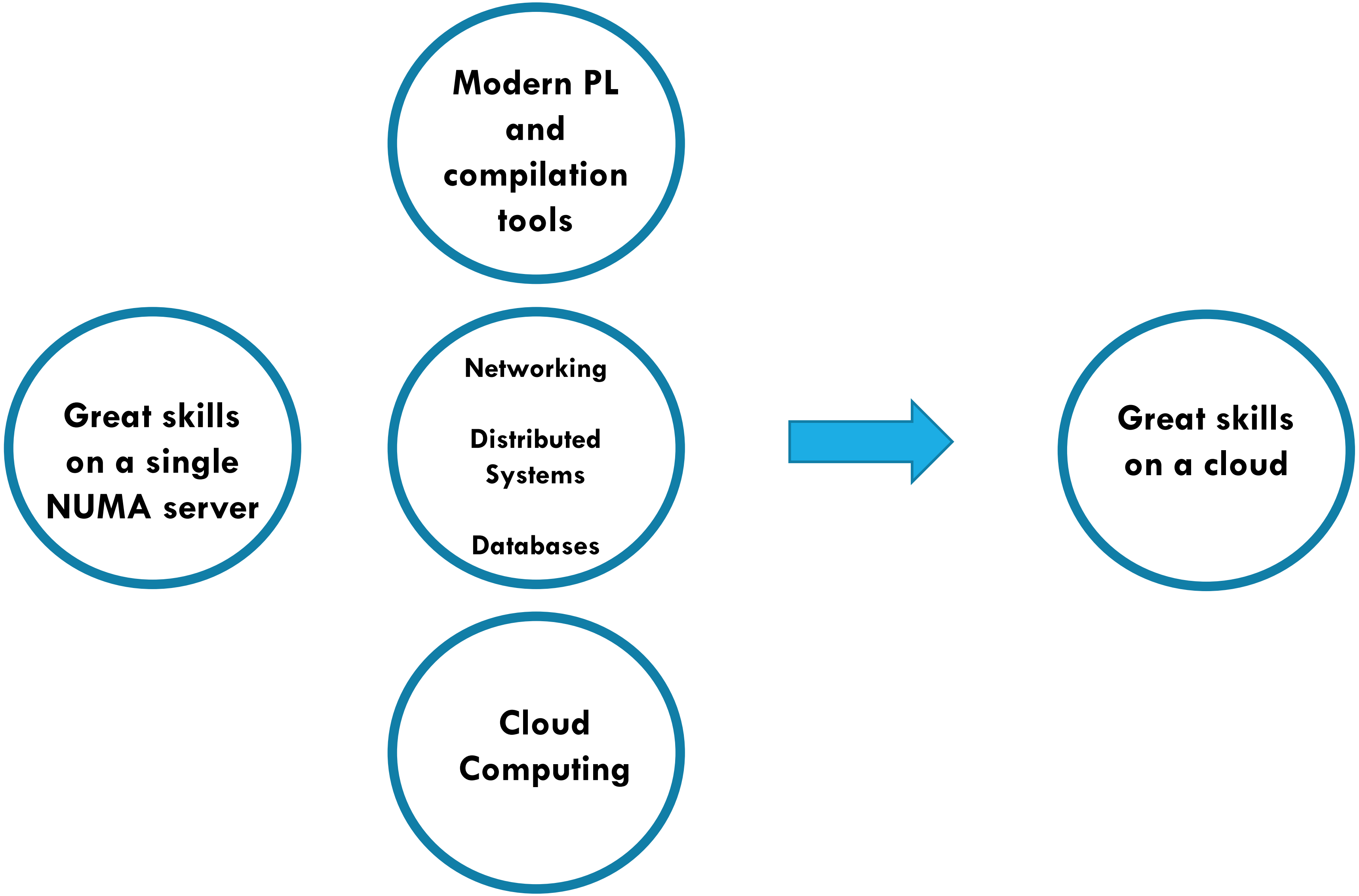
THE MODERN COMPUTING WORLD IS COMPLEX!

“Cloud” computing systems at an insane scale, truly huge

So many moving parts…

New concept: SYSML. This relates to the idea that we are creating systems to assist machine learning.

HOW WE THINK OF THIS IN CS AT CORNELL



Modern PL and compilation tools

Great skills on a single NUMA server

Networking

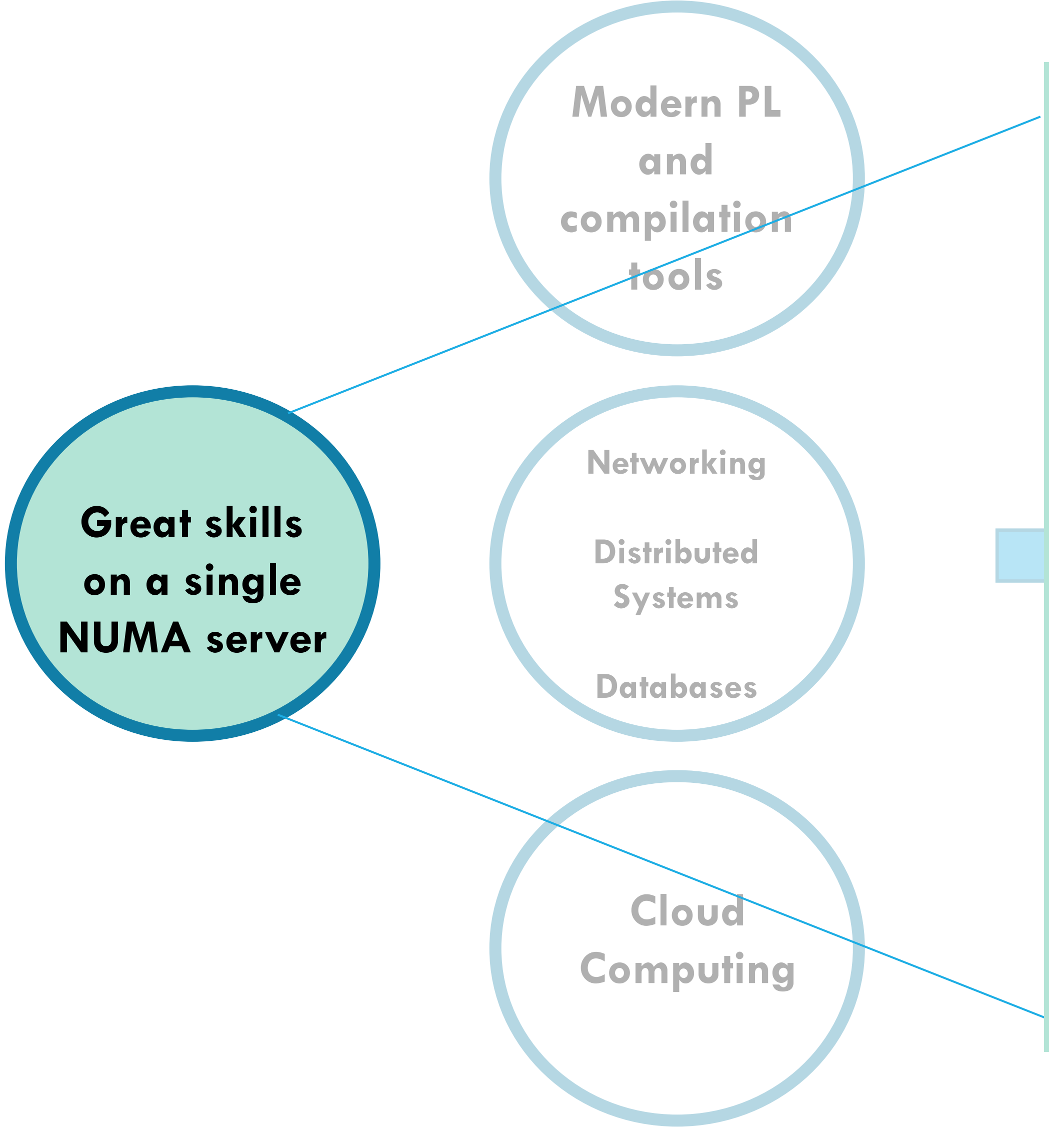
Distributed Systems

Databases

Great skills on a cloud

Cloud Computing

HOW WE THINK OF THIS IN CS AT CORNELL


Modern PL and compilation tools
Great skills on a single NUMA server
Networking
Distributed Systems
Databases
Cloud Computing

- Writing code that can perform extremely well and keep the CPU busy in a productive way
- Learning to leverage concurrency in a correct, secure, effective way
- Understanding ways of "taking control" over the hardware and the OS so they will be ideally effective

AGENDA FOR THIS FIRST LECTURE?

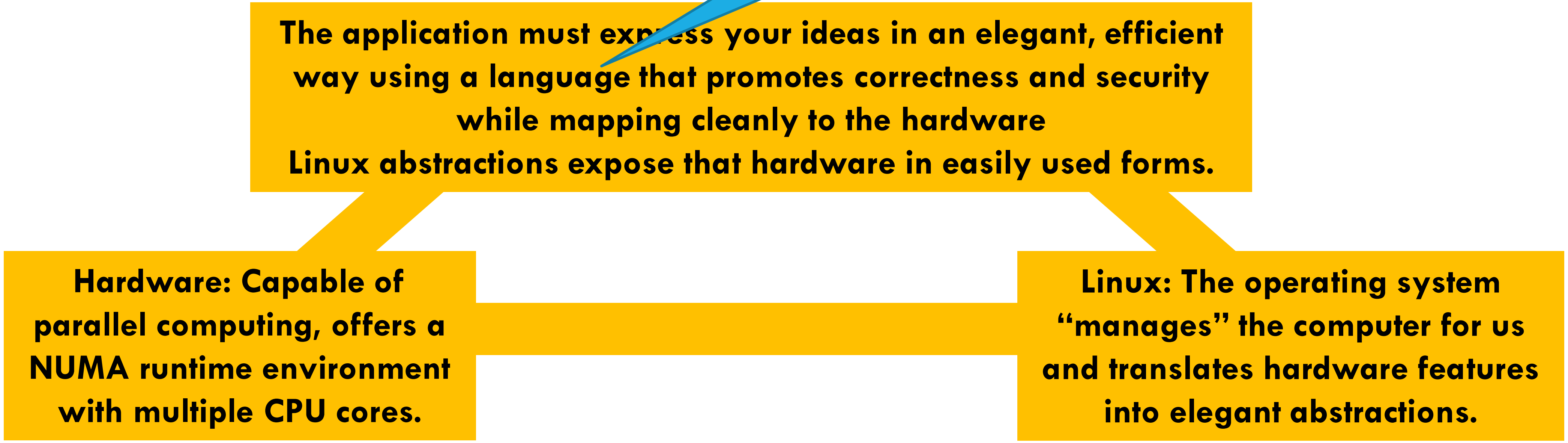
A glimpse of this entire complicated, huge, crazy puzzle!

What does it even mean to "be in control" of the computer and the OS and the disk?

Why start with C++ and Linux?

“IDEA MAP” FOR THE WH

We favor C++ 20 here. It isn’t the only option (Rust is cool, for example), but we’ll use C++ 20 because industry seems to like it. C++ 20 is very stable, but C++ 23 will eventually replace it



The application must express your ideas in an elegant, efficient way using a language that promotes correctness and security while mapping cleanly to the hardware
Linux abstractions expose that hardware in easily used forms.

Hardware: Capable of parallel computing, offers a NUMA runtime environment with multiple CPU cores.

Linux: The operating system “manages” the computer for us and translates hardware features into elegant abstractions.

WHEN YOU WRITE A PROGRAM, DOES IT MATTER HOW IT GETS EXECUTED?

Most people are familiar with Java and Python

Java has lots of data types (and lots of fancy syntax!), generics, other elaborate language features and compiles to a mix of machine code and programming language runtime logic.

Python is easier: No need to fuss with data types, easy to create arrays and transform all the objects with just one step.

WHEN YOU WRITE A PROGRAM, DOES IT MATTER HOW IT GETS EXECUTED?

Which is better?

1) Java
2) Python

… why?

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Python is easier: No need to fuss with data types, easy to create arrays and transform all the objects with just one step.

CONSIDERATIONS PEOPLE OFTEN CITE

Expressivity and Efficiency: Can I code my solution elegantly and easily? Will my solution perform well?

Correctness: If I end up with buggy code, I'll waste time (and my boss won't be happy). A language should facilitate correctness.

Productivity: A language is just a tool. The easier it is to do the job (which is to solve some concrete problem), the better!

A SUBTLE CONSIDERATION: MODULARITY AND COMPOSITIONALITY

Don’t fix things that already work. Ideally, we want the system to provide lots of pre-packaged solutions for common tasks.

As a systems person, I’m very focused on this idea of pre-packaged modular solutions.

Modern machine learning forces us to think in these terms!

MICROSOFT FARMBEATS EXAMPLE

How many programs are in use here?

… hundreds!
A modern computing applications is a *software ecosystem*

… THIS IS THE COMPLICATION

As we deal with larger and larger scale, the “modules” won’t be simple things like a library that deals with managing a sorted list

We may need to “compose” entire programs or even systems, which will need to share files or perhaps “objects”.

… the programming language is just a part of this ecology

DRILL-DOWN CONSIDERATIONS

We want our solutions to perform well and “scale well”.

For many tasks this involves working on the “cloud” (big remote data centers, like AWS or Microsoft Azure or Google).

In the cloud you rent the machines you need, as needed, but pay for what you use. So performance ≅ $$$.

DRILL-DOWN CONSIDERATIONS

Which *performs* better?

1) Java
2) Python
3) … something else?

… why?

We

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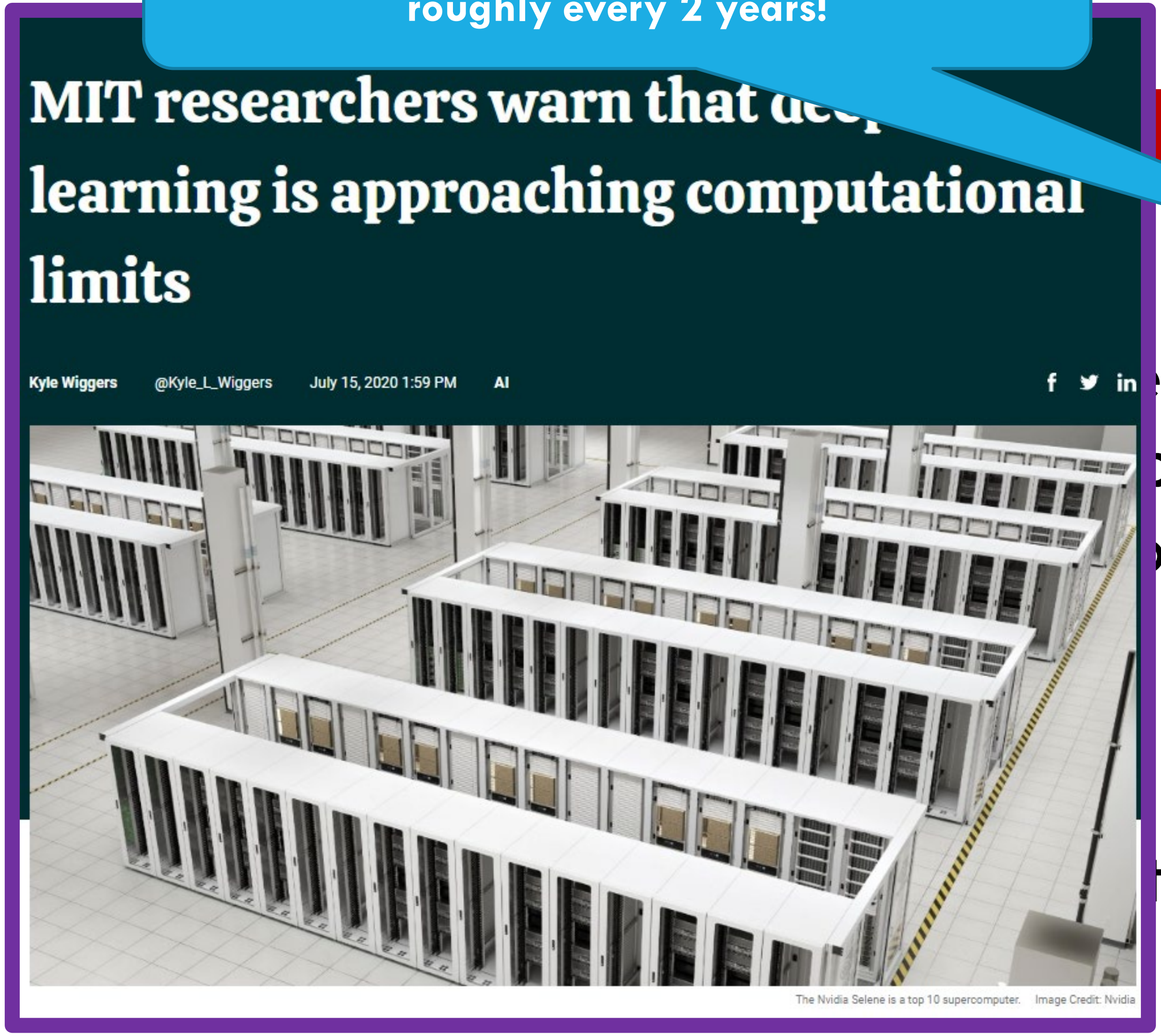
for what you use. So performance = $$$.

REASONS WE CARE ABOUT PERFORMANCE

Modern forms of computing are very power-hungry! And this is causing growing impact on the global “electricity footprint” associated with popular ways of solving problems.

Future of civilization might depend on whether your code can minimize the amount of electricity it consumes!

Roughly 1% of global electric use, doubling roughly every 2 years!



MIT researchers warn that deep learning is approaching computational limits

Kyle Wiggers @Kyle_L_Wiggers July 15, 2020 1:59 PM AI

The Nvidia Selene is a top 10 supercomputer. Image Credit: Nvidia

https://venturebeat.com July 15, 2020

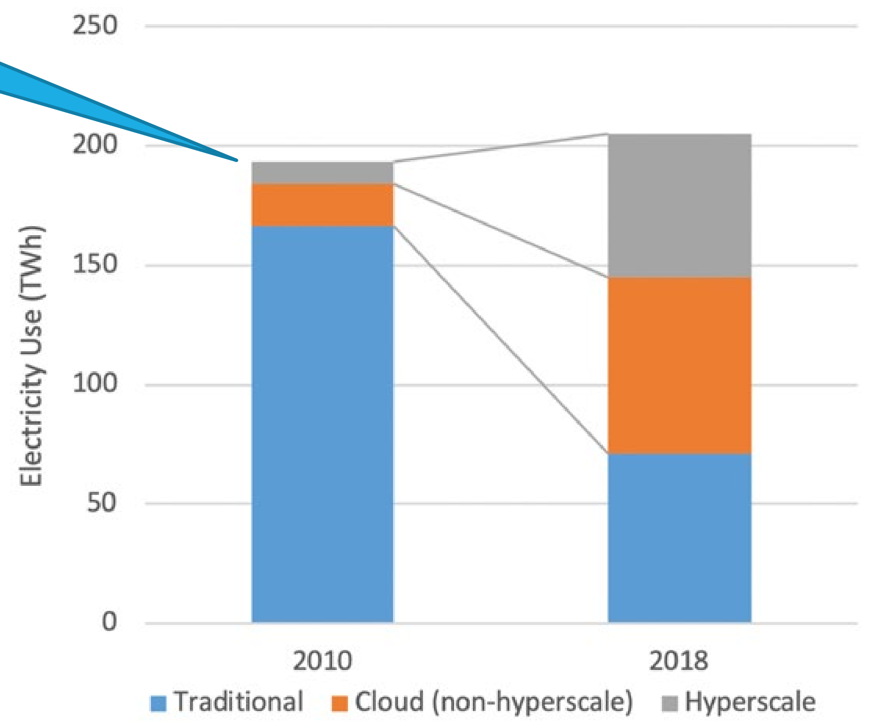
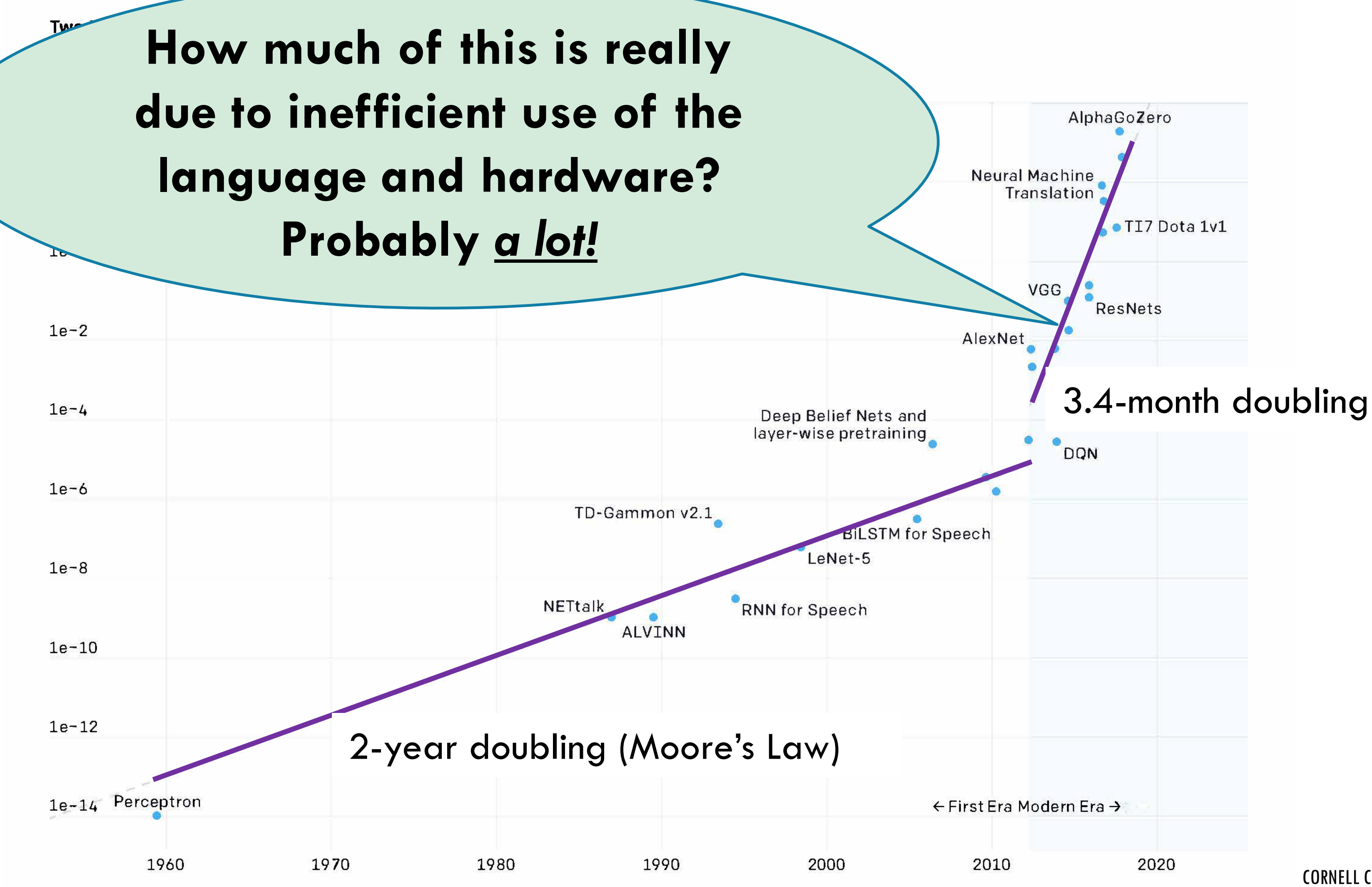


Figure 2. Estimated global data electricity use by data center type, 2010 and 2018. Source: Masanet et al. 2020.

https://energyinnovation.org/2020/03/17/how-much-energy-do-data-centers-really-use/

COMPUTE TIME TO TRAIN ML MODELS



How much of this is really due to inefficient use of the language and hardware? Probably ***a lot!***

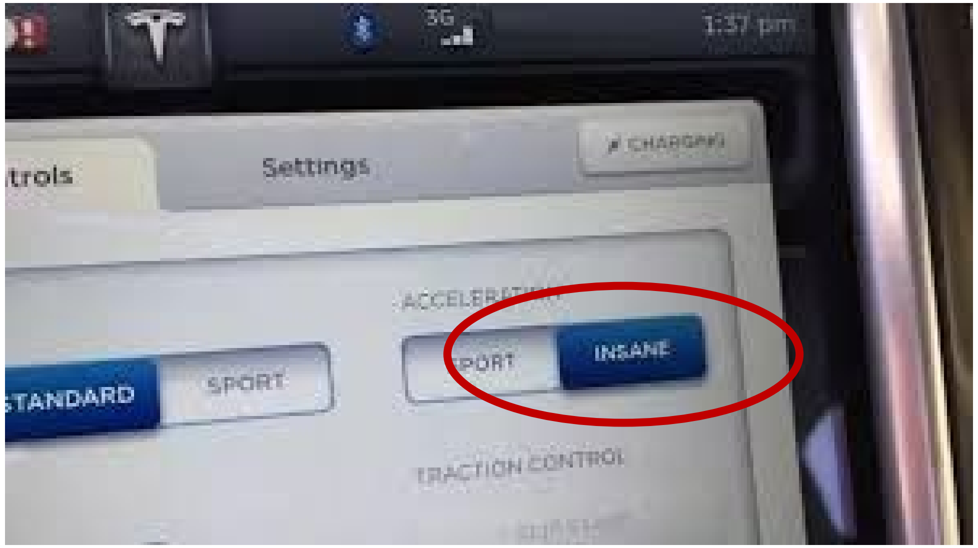
3.4-month doubling

2-year doubling (Moore's Law)

SOME CARS HAVE INSANE SPEED BUTTONS…

Guess what? So do computers!

In CS4414 we'll push the button.



(in ways that are correct, secure, natural, elegant)

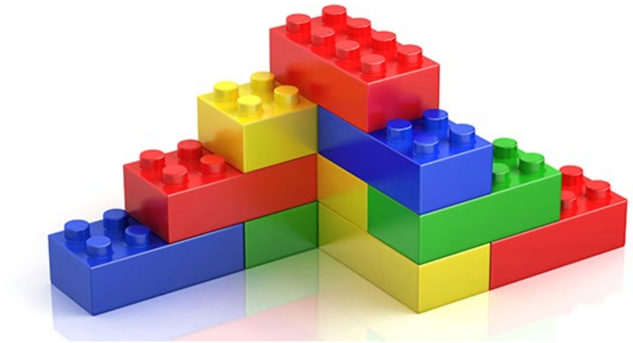
SMART USE OF THE “PLATFORM” IS HOW!

In CS4414 we will be learning about the Linux operating system. Linux is universal these days.

We will use C++ 20 as our programming language.

And we’ll learn to write code in smart ways that use the hardware and software “ideally” to get the best possible speed.

WHY LINUX? DOES THE O/S EVEN MATTER?



When building "interesting" applications we often put a few building blocks together, Lego style.

Linux is full of small, easily used building blocks for common tasks, and has easy ways to connect things to make a bigger application from little pieces.

Productivity rises because you often don't need to build new code– you can just use these existing standard programs in flexible ways.

LINUX AND THE HARDWARE: TWO SIDES OF THE SYSTEM ARCHITECTURE

Machine Hardware
Operating System
Application

We will be learning about the modern computer hardware, not so much from an internals perspective, but as users.

Linux lets you design applications that correspond closely to the hardware. But then we need a programming language that lets us talk directly to the operating system and the hardware.

WHY ARE PYTHON AND JAVA EXPENSIVE?

Python: Interpreted

Compiles to a high-level representation that enables an "interpretive" execution model.

In fact, Python is like a "general machine" controlled by your code: Python itself runs on the hardware. Then your code runs on Python!

Gradual typing: Python is very laissez-faire and can't optimize for specific data types.

Java: Runtime overheads

Compiles (twice: to byte code, then via JIT) but rarely exploits full power of hardware. Limited optimizations, parallelism

Dynamic types and polymorphism are costly.

Everything is an object, causing huge need for copying and garbage collection.

It feels as if your programs run inside layers and layers of "black boxes"

HOW DOES C++ AVOID THESE PITFALLS?

C++ objects are a compile-time feature. At runtime, all the type-related work is finished: no runtime dynamics.

The compiler "inline expands" and optimizes heavily. You help it.

Computers execute billions of instructions per second, yet we can write code that will minimize the instructions and shape the choices.

Parallelism is easy, and the compiler automatically leverages modern hardware features to ensure that you will have highly efficient code.

LET'S DRILL DOWN ON SPEED

For some situations, C++ can be *thousands of times faster* than Python or Java, on a single machine!

- Typically, these are cases where the application has a lot of *parallelism* that the program needs to exploit.
- For example, identifying animals in a photo entails a lot of steps that involve pixel-by-pixel analysis of the image
- But in fact, we can get substantial speedups just scanning large numbers of big files… hence our word-count demo

LET’S DRILL DOWN ON SPEED

We said that Python is slowest, Java is pretty good, but C++ can beat both. C++ knocks the socks off Java for parallel tasks.

What would be a good way to “see that in action”?

A small example: “word count” in Python, Java and C++

WORD COUNT TASK

Basically, we take our input files and “parse” them into words. All three languages have prebuilt library methods for this. Discard non-words (things like punctuation marks).

Keep a sorted list of words. As we see a word, we look it up and increment a count for that word (adding it if needed).

At the end, print out a nicely formatted table of the words/counts in descending order by count, alphabetic order for ties

THE SCOREBOARD

#1-A: Ken's C++ Faster, but more complex…

```
real    4.645s
user   14.779s
sys     1.983s
```

#1-B (Sagar's code, shorter & better use of C++…)

```
real    8.200s
user   49.295s
sys     2.145s
```

#2 Lucy's Python version

```
real    1m30.857s
user   1m30.276s
sys     0.572s
```

This was only 19 lines of code!

#3 Lucy's Java version (no threads)

```
real    1m49.373s
user   3m16.950s
sys     8.742s
```

#4: Pure Linux (buggy sort order)

```
real    2m38.965s
user   2m43.999s
sys     27.084s
```

THE SCORE

C++ version was 34x faster than Linux, 20x faster than Java or Python

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real 1m49.373s

user 3m16.950s

sys 8.742s

#4: Pure Linux (buggy sort order)

real 2m38.965s

user 2m43.999s

sys 27.084s

THE SCO

Notice that the user time is 3x larger than the real time.
Puzzle: how can this be true?

#1-A: Ken's C++ Faster, but more complex…

```
      real    4.645s
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      sys     1.983s
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      sys     27.084s
```

HOW CAN A PROGRAM DO 14.7779s OF COMPUTING IN 4.645s?

A 3-horsepower system

Could this just be a measurement mistake in Linux?

… in fact, if a process is using more than one thread it can harness more than one CPU at the same time.

With 3 CPUs running continuously at full speed, it can do 3x more work than the elapsed wall-clock time!

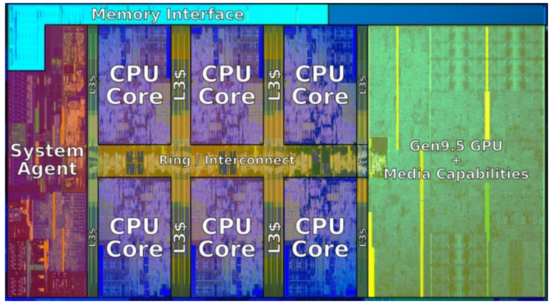
DIDN’T I PROMISE “THOUSANDS X” HOW DID THAT DROP TO 30X?

We counted words in text files: Limited parallelism.

The C++ program is able to process them in parallel side-by-side streams, which was how we got the speedup.

With image processing or machine learning (tensor arithmetic), the value of parallel processing is dramatically larger.

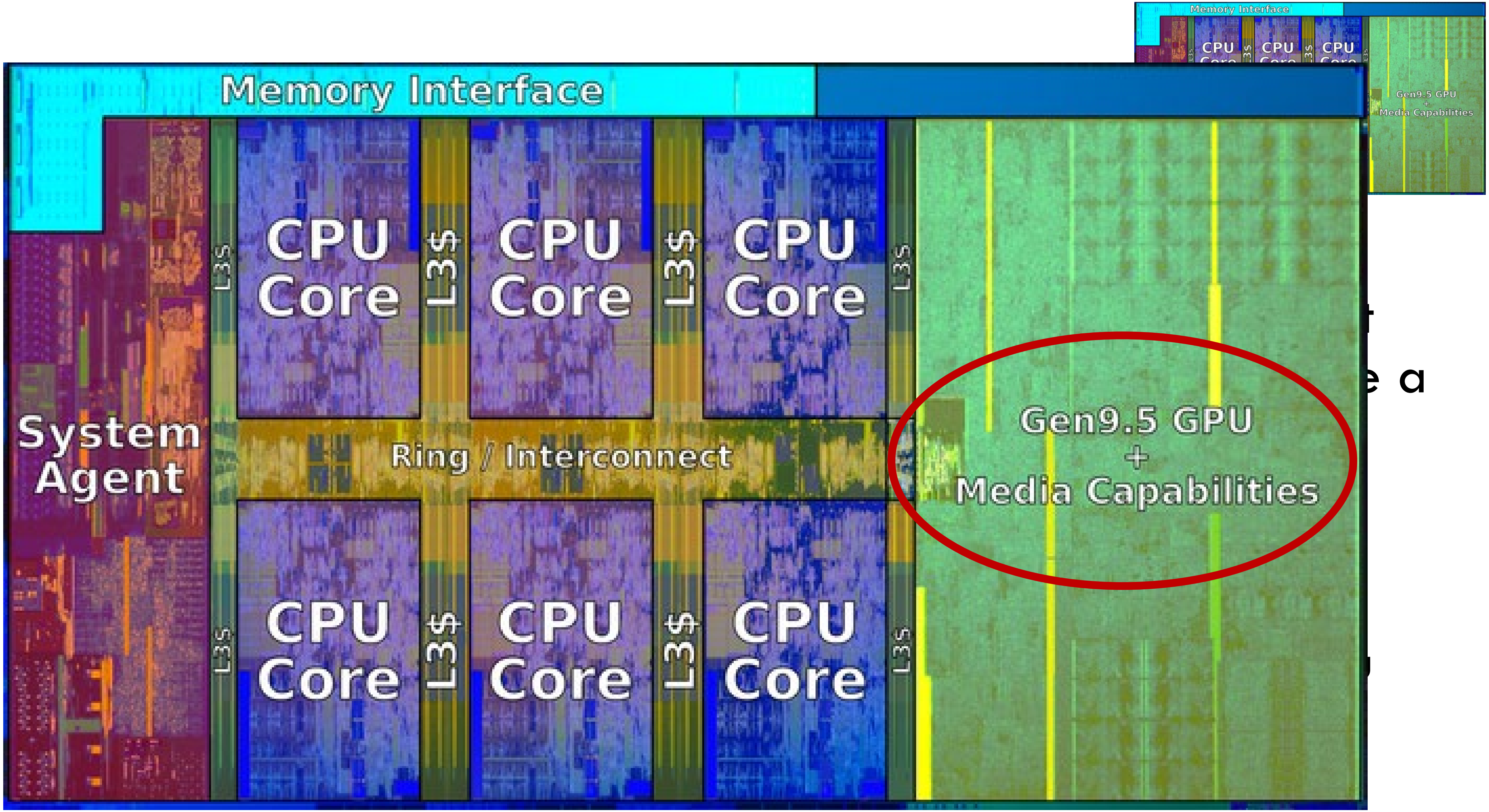
PARALLELISM IN YOUR COMPUTER



6-core Intel chip with GPU

A modern computer has multiple smaller computers (cores) that all run on the same computer memory (RAM). It may also have a special form of "accelerator" called a GPU.

To leverage this power, the computer offers special hardware instructions. The compiler can use those for big speedups. You can also use "threads": a method of having more than one computational activity running within a single program.


Memory Interface
System Agent
CPU Core
CPU Core
CPU Core
CPU Core
CPU Core
CPU Core
L3$
L3$
L3$
L3$
L3$
L3$
L3$
L3$
Ring / Interconnect
Gen9.5 GPU + Media Capabilities

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TOPIC FROM BEYOND CS4414: CLOUD COMPUTING TAKES THIS FURTHER

For compute-intensive tasks, companies set up an account on a big commercial data center called a cloud. “Rent, don’t own”.

You can easily run a program on hundreds of thousands of computers, each instance processing different input files.

- So a single job might have millions of threads working in parallel, and each using parallel computing instructions!
- … the hard part is when they need to combine their results.

MODERN CLOUD COMPUTING DATA CENTER

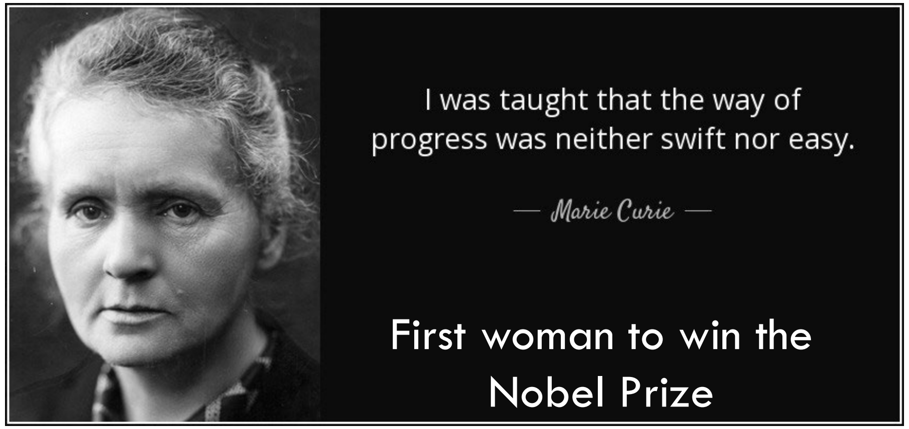
ISSUES INTRODUCED BY LARGE SCALE

Program design: When we use networking to let processes talk to one-another, they need ways to share data, cooperate, coordinate, recover from failures.

Algorithmic: Just like in a single machine, there are more efficient and less efficient data structures and "protocols"

Security: At scale it is common to run into new kinds of attacks, and we need different styles of defense. Sensitive data is an especially important concern (like private information).

AND YET…



I was taught that the way of progress was neither swift nor easy.

— Marie Curie —

First woman to win the Nobel Prize

Many jobs today involve larger scale computing platforms, even if you don’t work “for” a cloud company.

A factor of 10x can be dramatic if the code is used by Google to respond to a search or is part of the Facebook image feed.

C++ is the “way of progress” for demanding tasks.

LEARNING LINUX AND C++

You came into this class comfortable in an object oriented language, and learned data structures, so C++ should be easy to learn.

- The operators and syntax and features will remind you of Java
- There are *extra* operators, and those we will teach you, and things like dynamic memory management, but we won’t teach basics: those you need to learn in a hands-on way!
- Similarly, we will provide pointers to lists of Linux commands and bash syntax, but these are topics for experiential learning

EXAMPLE: HELLO WORLD IN C++

```
// My first C++ program

#include<iostream>

int main() {
   std::cout << "Hello World“ << std::endl;
   return 0;
}
```

First you’ll create a file, hello.cpp

Next, it must be compiled, for example:

```
g++ -std=c++20 hello.cpp –o hello
```

… and finally, launched:

```
./hello
Hello World
```

We will be doing these steps from within Visual Studio Code

This “IDE” includes support for editing, compiling, debugging and executing your programs.

EXAMPLE: WORD COUNT IN C++

This is the "core" of the counting logic:

```
using          WC = std::map<std::string, int>;
WC             sub_count[MAXTHREADS];

inline void found(int& tn, char*& word)
{
        sub_count[tn][std::string(word)]++;
}
```

EXAMPLE: WORD COUNT IN C++

… and here is the core of the sorting logic:

```
struct SortOrder: public std::binary_function<std::pair<int, std::string>, std::pair<int, std::string>, bool>
{
    bool operator()(const std::pair<int, std::string>& lhs, const std::pair<int, std::string>& rhs) const
    {
        return lhs.first > rhs.first || (lhs.first == rhs.first && lhs.second < rhs.second);
    }
};

using SO = std::map<std::pair<int, std::string>, int, SortOrder>;
SO sorted_totals;
for(auto wc: totals)
{
        std::pair<int,std::string> new_pair(wc.second, wc.first);
        sorted_totals[new_pair] = wc.second;
}
```

EXAMPLE: WORD COUNT IN C++

Same logic but expressed using the c++2a **decltype** feature

```
using SO = std::map<std::pair<int, std::string>, int,
                decltype([](const std::pair<int, std::string>& lhs, const std::pair<int, std::string>& rhs)
                               {return lhs.first > rhs.first | | (lhs.first == rhs.first && lhs.second < rhs.second); })>;

SO sorted_totals;

for(auto wc: totals)
{
       std::pair<int,std::string> new_pair(wc.second, wc.first);
       sorted_totals[new_pair] = wc.second;
}
```

SOME PEOPLE THINK C++ HAS SCARY SYNTAX!

But the course staff is used to C++ and we can help.

Once you really learn it, you'll start to find it much more natural.

The one big thing to know is that even a single misplaced character can trigger pages of compiler complaints, so you do need to understand exactly what you are "asking it to do!"

THE WAY OF PROGRESS BEING “NEITHER EASY NOR FAST” ASPECT?

C++ will eventually start to feel much easier, after a few weeks.

But you don’t *automatically* get high speed. That takes more work – rewarding work, because you can measure the improvements as you make them, but it does take effort!

The key is to be able match your coding goals to the hardware.

WHEN I FIRST CODED MY SOLUTION, MY PROGRAM WAS VERY SHORT, BUT RATHER SLOW.

I added parallel threads – which complicated the solution but helped a lot. Then because file opening was slow, I added a thread to “preopen” files before they were needed.

The C++ library for file opening and reading files was a bottleneck, so I switched to calling Linux file open and Linux file read, directly. This gave an additional speedup

FINAL VERSION

With threads, my code was “part way” to the goal.

Thinking about bottlenecks, I decided to add one more parallel computing idea (we’ll see it soon). Then I changed some of my very heavily-used methods to be “inlined”

This gave that 20x-30x compared to Python and Java.

ROLL YOUR OWN? OR LEARN SOME WEIRD LIBRARY INTERFACE?

In C++ we could certainly code everything from scratch.

But library solutions have the benefit of being standard, widely used, and heavily tested.

C++ libraries are also exceptionally performant, and for our course this is an important consideration!

REMAINDER OF WORD COUNT IN C++

I didn't show you:

- The standard includes required to import the std:: libraries
- The main program that calls the "getWordCount" method
- A bunch of little helper methods I wrote.

WHY WOULD PEOPLE CARE ABOUT WORD COUNTING IN A MODERN SYSTEM, LIKE FOR NLP?

Natural language programs are *based on word counts*, but :

- White space, punctuation, hyphenation is removed
- Conjunctions such as “a”, “and”, “or” are discarded
- Upper case is mapped to lower-case
- Stems are removed: “**fly**ing” might map to “fly”.

WHY DO NLP SYSTEMS CARE ABOUT STEMS?

When people do a web search such as “learn to fly small plane” or “birds that cannot fly” small style differences arise.

Stems have been shown to be much more stable and consistent

Web pages for flying schools would probably use “fly” very extensively. In contrast “that” and “to” are less relevant…

WHAT SHAPES THE PERFORMANCE OF "STEMMED, LOWER-CASE WORD COUNT"?

- Speed of reading the data, especially if the file is large. At Google, some AI systems that learn from web pages scan hundreds of billions of them.
- Splitting, stemming, mapping to lower case, discarding conjunctions
- If we use new variables to hold stemmed words, we'll need to "allocate" memory and initialize the object.
- We'll need to keep a sorted list of words, and look for each word as we discover it, and increase the associated counter.

GLIMPSE OF LINUX AND BASH

This bash command runs c++, telling it to optimize the code, warn in a “fussy” way.

```
% g++ -std=c++11  -O3 -Wall -Wpedantic -pthread  -o fast-wc fast-wc.cpp
```

This does a timed run of the program (fast-wc):

```
% time taskset 0xFF ./fast-wc -n4 -p
```

```
fast-wc with 4 cores, 50095 files, 16 blocks per read, parallel merge ON
                    define    |  2008083
                     struct   |  1694853
                          0   |  1268529
                         if   |  1172461
```

MORE FUN WITH BASH

In fact we can use bash to…

- Automatically open a file and have it look like “console input” in our C++ program.
- Put the program output into a file
- Run a program in the background
- Put the program output into a bash variable, and then pass that variable as a command-line argument to some other program
- … the list goes on for quite a while!

PRACTICAL CONSIDERATIONS

Organizational stuff

RECITATIONS MATTER!

In CS4414, we use the recitations to teach you C++ and Linux

We also are asking the ugrad TAs to organize a few longer "workshops" where they would problem solve while you watch (those will be on Zoom and recorded).

C++ is easy but it takes time and help to learn. And even a person who knows C++ can learn new things from Ricky and Alicia.

IS C++ HARD TO LEARN?

C++ is easy to learn at a basic level (in CS4414 we won't dive into the really fancy, obscure, C++ features).

C++ was designed to make the mapping to the hardware and to the machine instructions "evident". An interview with the inventor of C++.

Unlike that sense of black-boxes everywhere, with C++ you can know everything your code is doing, even to very low levels.

DEVELOPER TOOLS (IDE)

Ken and Alicia and Ricky do many things at the “command line” layer of Linux.   In fact you can build and compile C++ without any IDE, but the IDE makes it easier.

We teach Visual Studio Code but you can use other IDEs if you like

Linux comes in many flavors. We prefer Ubuntu, the bash shell, and the “cmake” application builder.

RESOURCES

The whole course closely tracks the main textbook by Bryant and O'Halloran at CMU.

- Main difference is that CMU CS213 views the class as an introduction to programming languages and compilers
- CS4414 has a systems-centric focus. But in fact the textbook includes this material, even if CMU's course brushes over it

To fill in gaps, we also recommend getting a C++ textbook and learning to access the online Linux materials

SETUP

Setting up Linux can be annoying… so we decided to do it!

You will

1. Install visual studio code on your laptop.
2. Tell it to “ssh” into a Cornell CS server (we have a bunch)
3. Once logged in, you can work through visual studio’s API or talk to bash on the remote machine through a console window

YOU CAN <u>LEARN</u> IN GROUPS… BUT MUST <u>WORK</u> ALONE

We encourage study groups. Learning as a group is great!

But… *every single thing you do on a graded homework must be done by you, and not with any help from friends or CourseHero or other cheats. Graded work must be <u>your</u> individual work.*

We have outstanding TAs (ugrad and PhD) to help if you get stuck, and you can also post questions on Ed Discussions (or answer them)

EXAMS (SOME), HOMEWORK

We use the exact same grading formula as CS4410: 50% exams, 50% homework. There will be two prelims but no final. Cornell exam schedules will show the exact dates, times and rooms.

You are required to attend every lecture. Cornell asked us not to create videos for offline viewing. We will anyhow, but those are people who are sick – not for skipping lecture

CURVE

We curve the course

Our feeling is that most students should easily be able to earn a grade in the range from B- to A+. But A+ is “special” and not strictly from a formula. The instructor decides how many to give

Grades below B- would only be used if a student really isn’t doing well, especially if that person is also skipping lectures.

ACADEMIC INTEGRITY

We use automated tools to look for suspicious code.

Ask us for help if you fall behind or have trouble with a homework. We'll help, and you'll do well in the course.

If you cheat in CS4414 you trade a B- or better for an F. You can't drop a class once this happens or expunge that F, it goes on your record, and you could be expelled from the CS program.

DOWNSTREAM COURSES

CS4414 is a great preparation for other courses!

In AI and ML courses, you'll need to write really high quality, fast code. The experience you gain here will pay off there.

CS4414 feeds naturally into systems courses like O/S, programming languages and compilers, security, networking, databases, embedded systems and IoT, cloud computing…