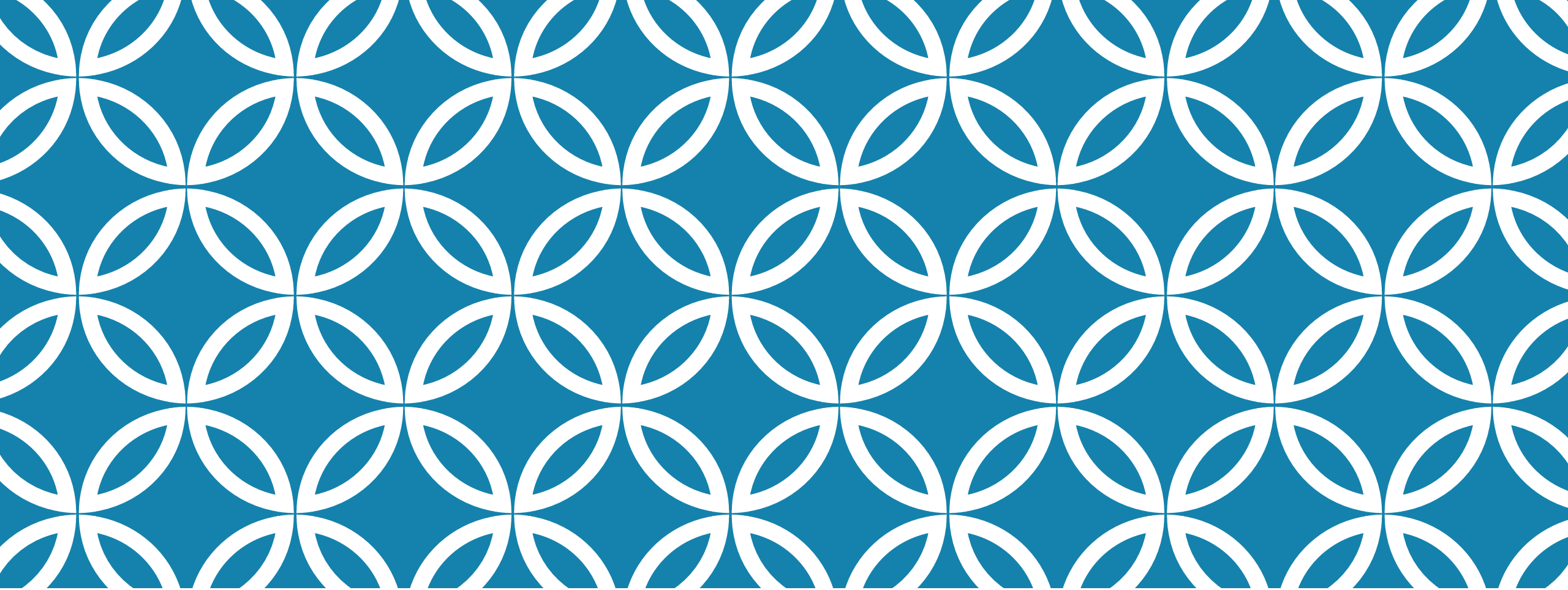


WELCOME TO CS4414 SYSTEMS PROGRAMMING

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.

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

https://venturebeat.com July 15, 2020

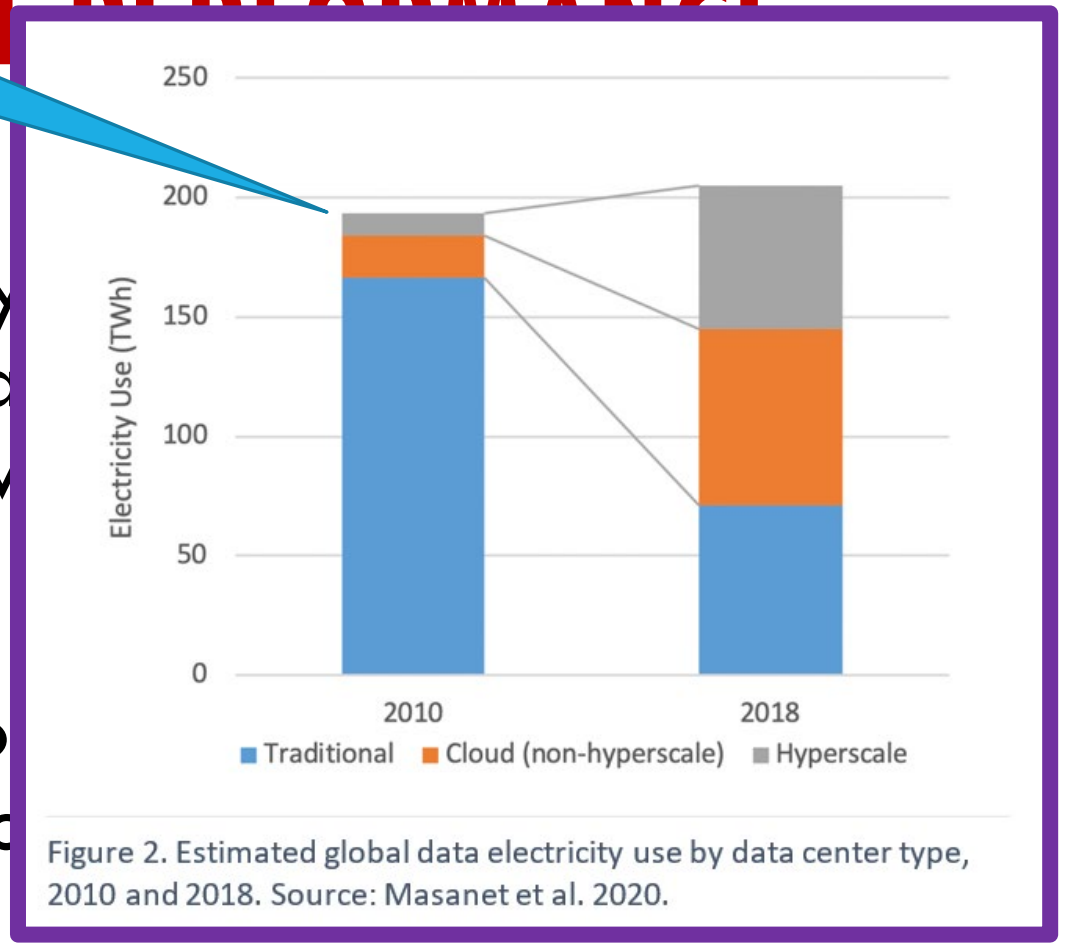
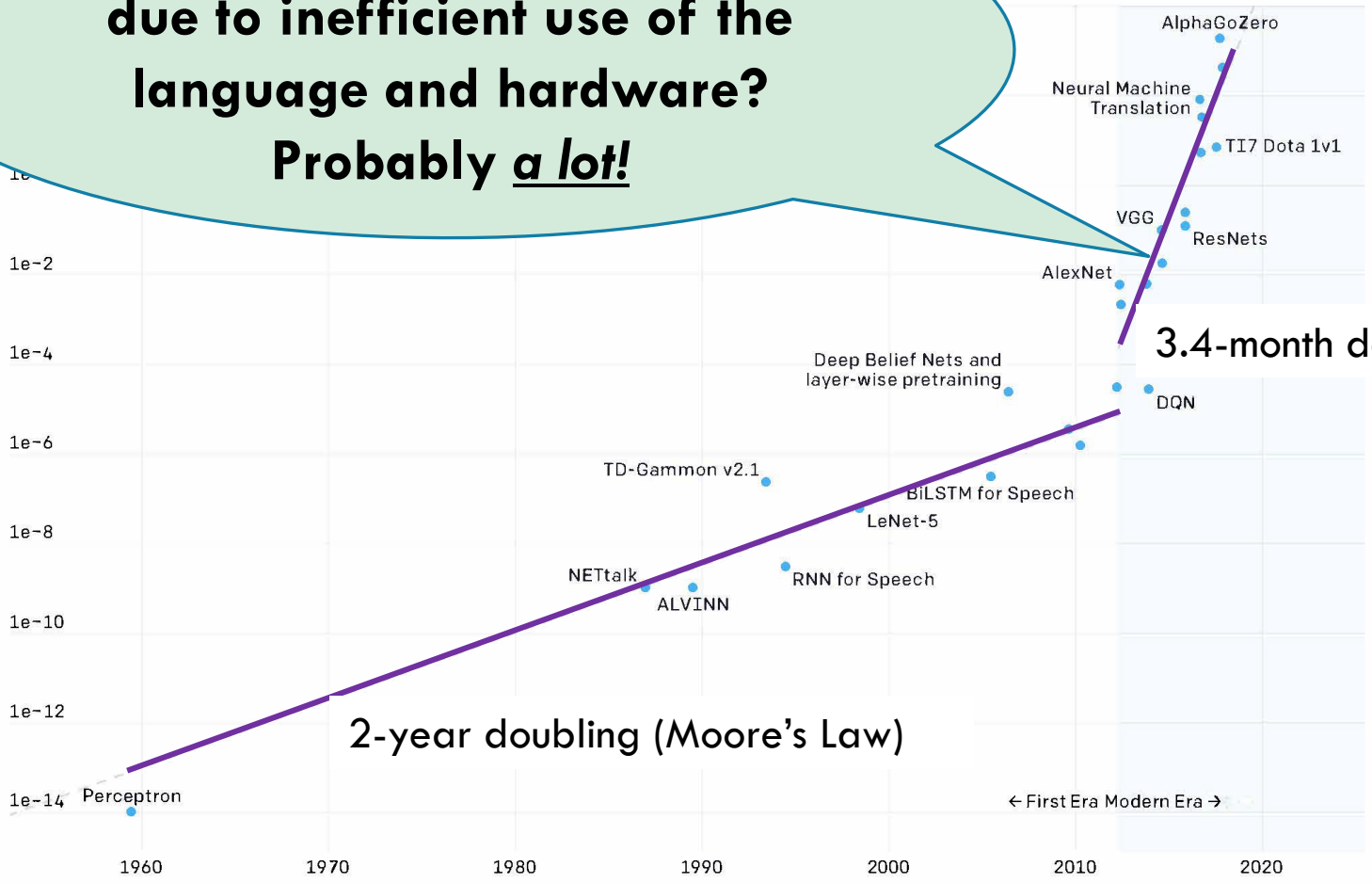


Figure 2. Estimated global data electricity use by data center type, 2010 and 2018. Source: Masanet et al. 2020.

https://energyinnovation.org/2020/03/20/how-much-energy-do-data-centers-really-use/

COMPUTE TIME TO TRAIN ML MODELS

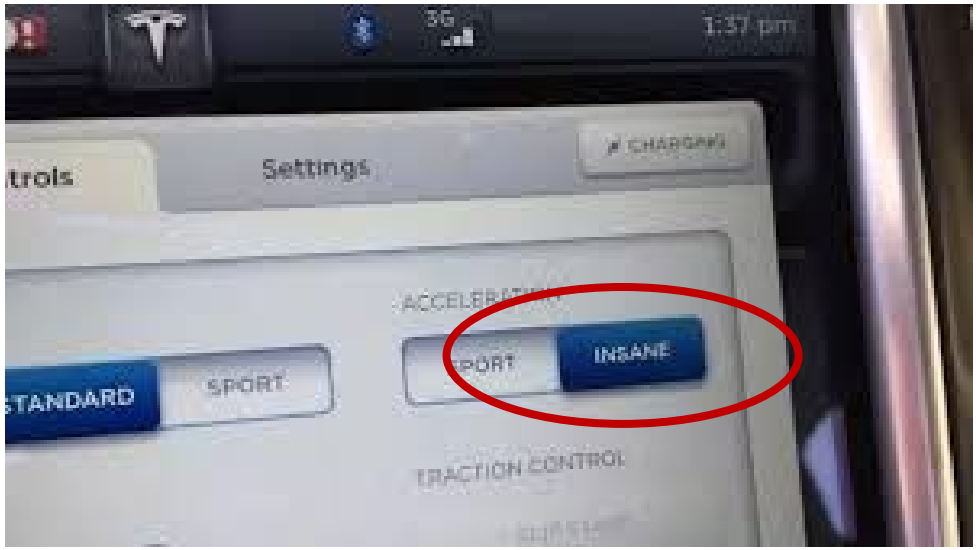
How much of this is really due to inefficient use of the language and hardware? Probably *a lot!*



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)

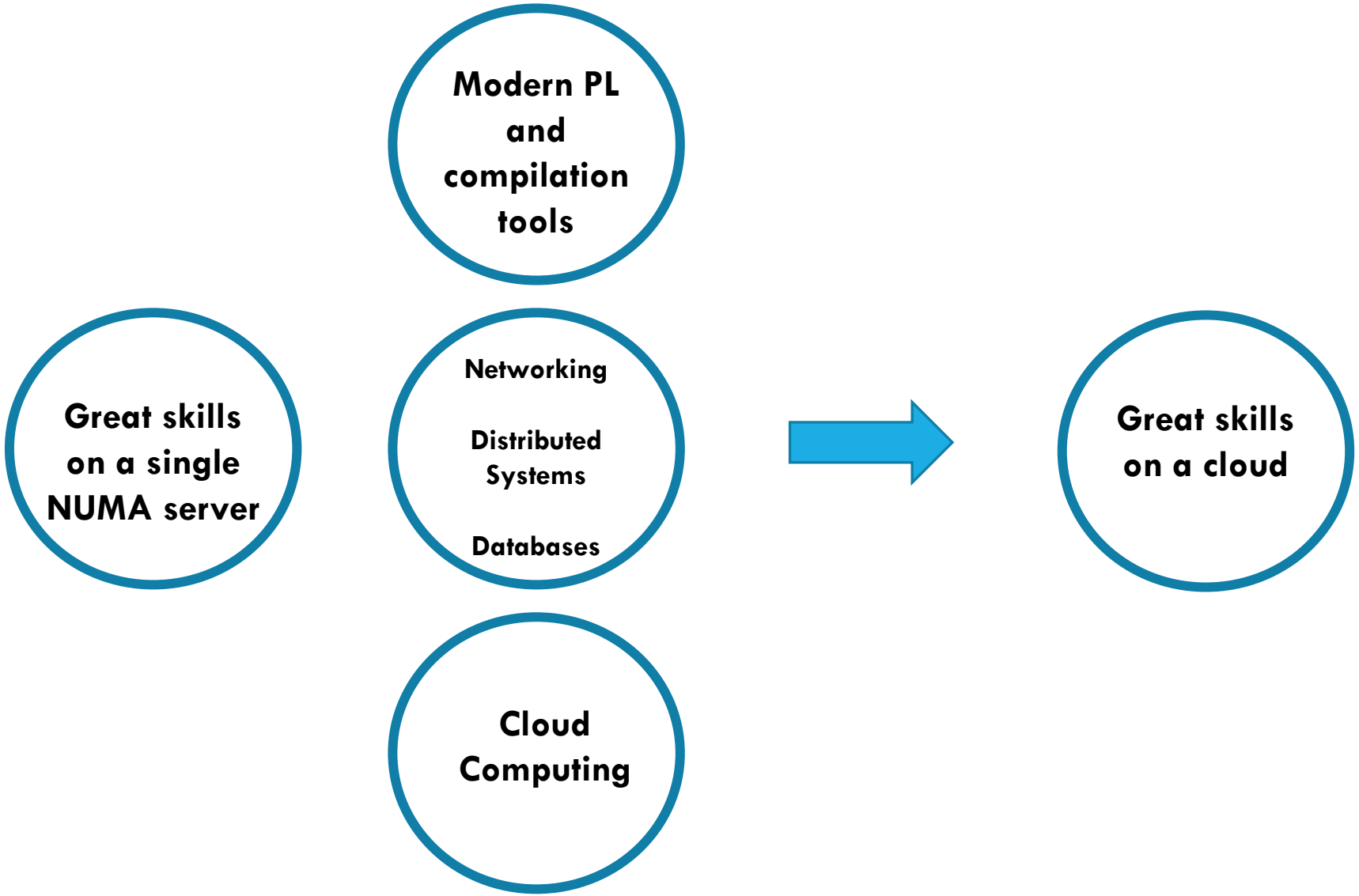
SMART USE OF THE "PLATFORM" IS HOW!

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

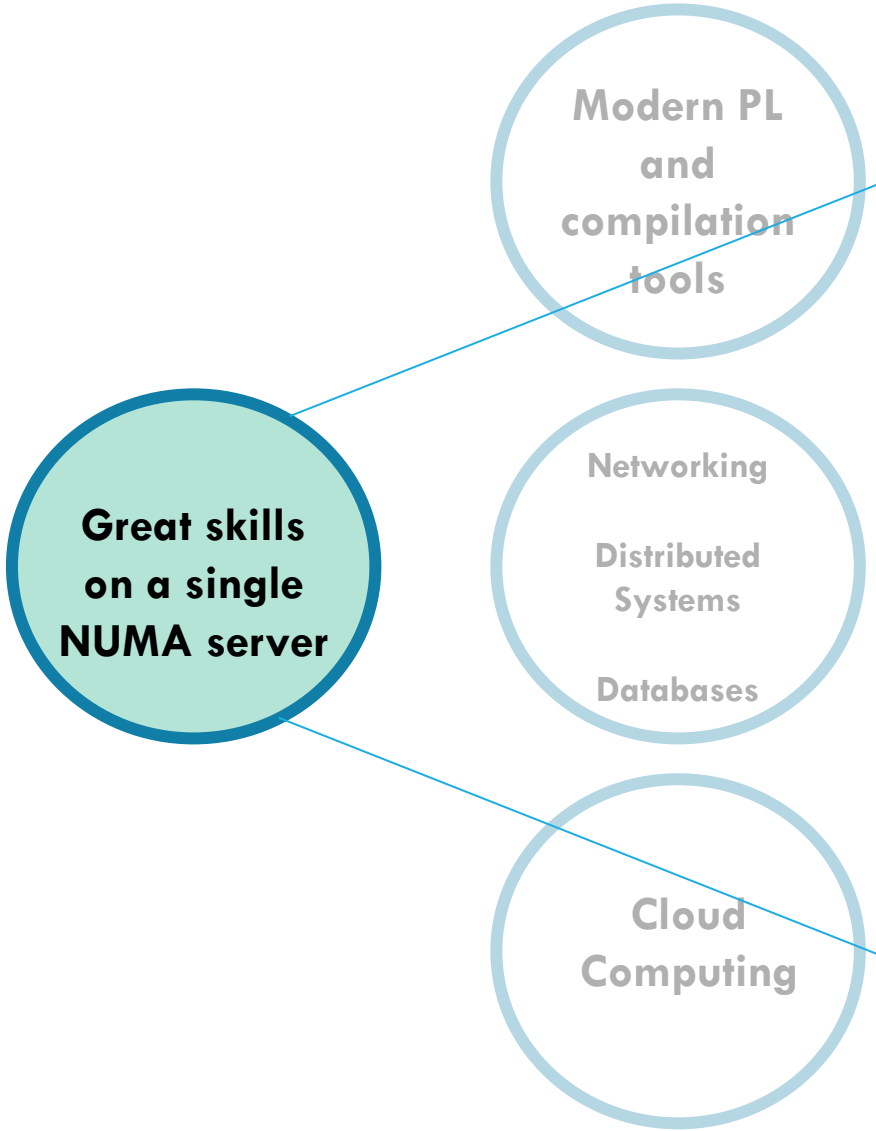
We will use C++ 20 as our programming language. You can go with C++ 23 if you prefer, and we will switch to it in 2025.

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

HOW WE THINK OF THIS IN CS AT CORNELL



HOW WE THINK OF THIS IN CS AT CORNELL



- 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

We

For te
dat

In t pay
for what you use. So performance = $$$.

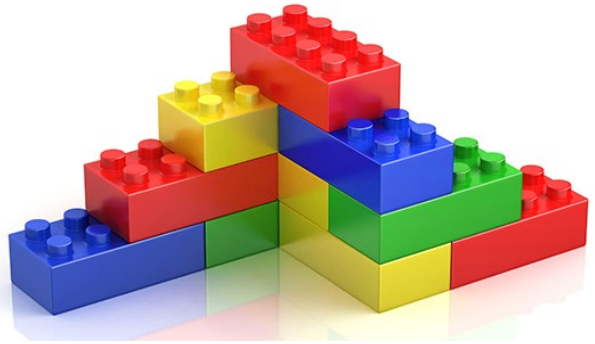
Which *performs* better?

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

… why?

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

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 infers types, which makes coding easier. Then it 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

PARALLELISM

… in fact, it is very hard to exploit parallelism in a single Python program.

This is because the Python model is "single threaded". Even so, PyTorch is highly parallel, because it leverages GPUs.

Java does allow parallelism, via "parallel threads"

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

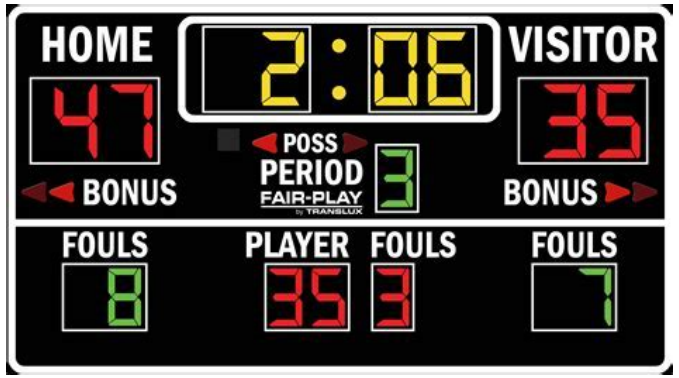
THE PARTICIPANTS

Ken, back when he was kind of new to C++

Sagar, our head PhD TA in the early days, who was a hard-code C++ coder, spent two summers as a Microsoft employee.

Lucy, undergraduate coding superstar

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!

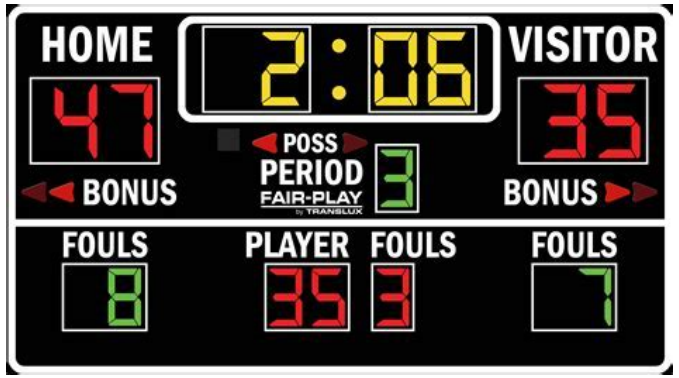
#3 Lucy's Java version (no threads)

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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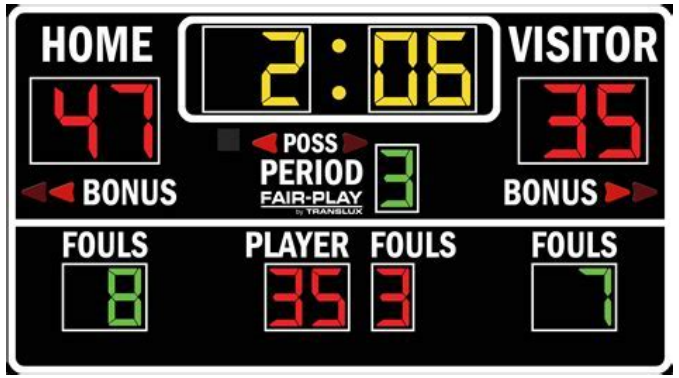
THE SCO

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



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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!

QUICK DIVE INTO WORD COUNT IN C++

We'll learn all of this over a few weeks

But today, we already might have a glimpse.

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;
}
```

MY CODE VERSUS SAGAR'S

My code understood that in files, data is just a long "vector" of characters – bytes – with some '\n' characters (end of line).

My word-count kept the data in that form and only created std::string objects at the last moment, to increment the count:

"wptr" is a pointer directly to the bytes in the input buffer

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

Used in the hacking competition for lecture 1. All source code is on our web site!

A CHUNK OF LINUX SOURCE CODE

Notice: this has text (words) but also lots of other stuff, like spaces and tabs, special chars like (){};/_&* etc.

End of line is a special ascii char, '\n' (code == 0x12).

```
#ifdef CONFIG_DMA_PERNUMA_CMA
void __init dma_pernuma_cma_reserve(void)
{
        int nid;

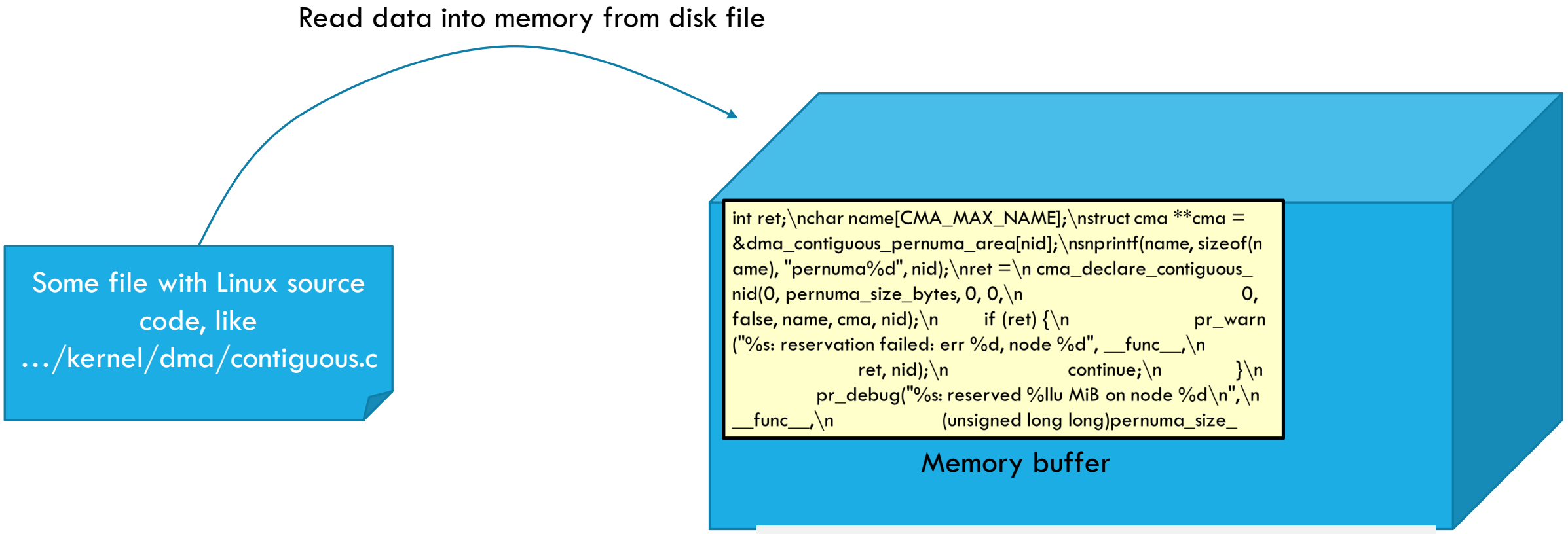
        if (!pernuma_size_bytes)
                return;

        for_each_online_node(nid) {
                int ret;
                char name[CMA_MAX_NAME];
                struct cma **cma = &dma_contiguous_pernuma_area[nid];

                snprintf(name, sizeof(name), "pernuma%d", nid);
                ret = cma_declare_contiguous_nid(0, pernuma_size_bytes, 0, 0,
                                                 0, false, name, cma, nid);
                if (ret) {
                        pr_warn("%s: reservation failed: err %d, node %d", __func__,
                                ret, nid);
                        continue;
                }

                pr_debug("%s: reserved %llu MiB on node %d\n", __func__,
                        (unsigned long long)pernuma_size_bytes / SZ_1M, nid);
        }
}
#endif
```

VISUALIZATION OF MY WORD COUNT RUNNING



WHAT DO WE MEAN BY "READ DATA INTO MEMORY?"

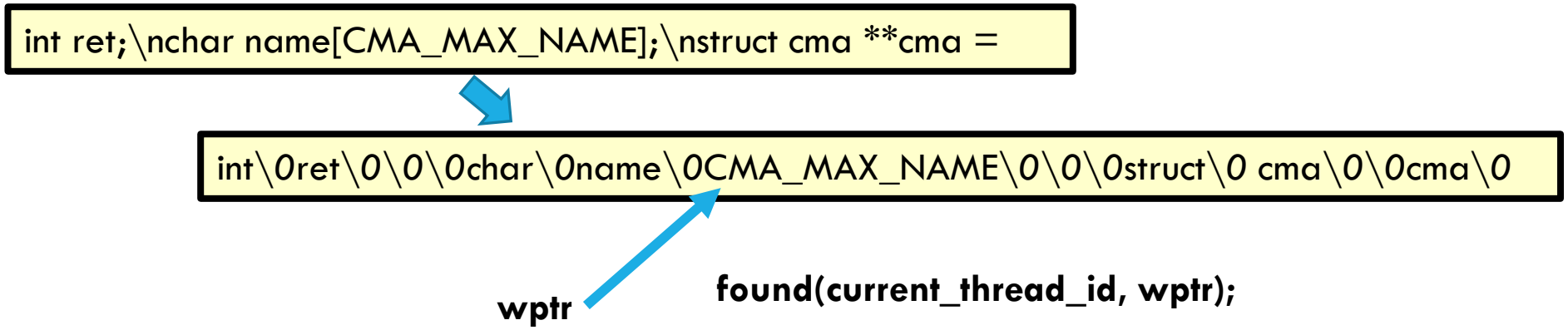
In my program, some space gets allocated – set aside – in the address space as a place for file data to be held.

The program opened a source file and told Linux to copy 4096 bytes (one block) into that buffer area.

The text that you saw in that screenshot was stored there as a series of ascii bytes, a code that uses values 0..128

HOW MY CODE ACTUALLY WORKED

Change all “white space” to \0 (byte containing 0). Now each word is a null-terminated char* vector (a “c-string”)



Converted from a c-string to std::string in **found**:

```
sub_count[tn][std::string(word)]++;
```

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

WHAT MADE SAGAR'S VERSION SLOWER?

If you look at his code, you'll find that it converts the whole file into std::string objects, line by line

Then it splits lines into substrings using a "splitter" method. Each chunk will be a std::string. But many won't be "words"

If the substring matching the rule for a word, Sagar's code uses a map like Ken's code and increments the count.

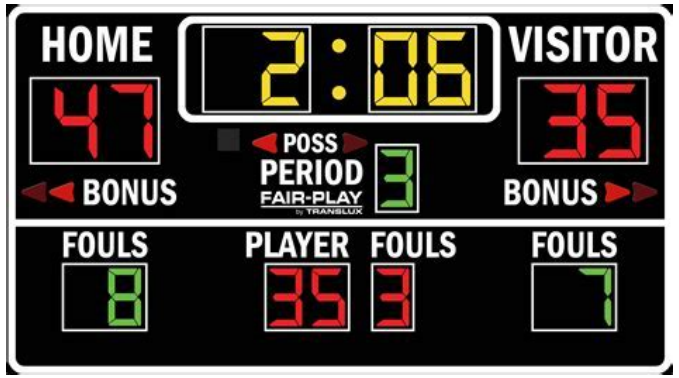
WHAT MADE SAGAR'S CODE SLOWER?

This means Sagar was creating perhaps 5-10x more std::string objects. At scale, with 50,000 files and millions of lines to scan, he does a lot of object creation, splitting and deletion, copying, garbage collection. Ken's code "skipped" 95% of that work!

… So Ken's code was way faster!
Yet Sagar's was closer to being pure C++. Ken's mixed C++ with C

```
int ret;\nchar name[CMA_MAX_NAME];\nstruct cma **cma =
&dma_contiguous_pernuma_area[nid];\nsnprintf(name, sizeof(n
ame), "pernuma%d", nid);\nret =\n cma_declare_contiguous_
nid(0, pernuma_size_bytes, 0, 0,\n                    0,
false, name, cma, nid);\n        if (ret) {\n                pr_warn
("%s: reservation failed: err %d, node %d", __func__,\n
                ret, nid);\n                continue;\n        }\n
        pr_debug("%s: reserved %llu MiB on node %d\n",\n
__func__,\n                (unsigned long long)pernuma_size_
```

THE SCOREBOARD



Total compute "load" was actually a lot lower for Ken's C++ program. Hence… less energy consumed

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CENTRAL MESSAGE HERE?

Understanding how the machine is representing your data can really matter if you want that last factor of 2x (or sometimes even 10x or 100x). Even C++ itself might miss that opportunity

So we need to learn about how NUMA computers represent data, and how our C++ code compiles to instructions that execute to perform the tasks we are coding!

HOW CAN WE "ANTICIPATE" THE COSTS OF TOO MANY USES OF STD::STRING?

We know that a file is basically a long vector of bytes.

A text file holds ascii chars with '\n' for newline. A c-string is a region holding chars, ending with '\0'. Ken worked from this.

In contrast, a std::string is an object. At a minimum it has a string length and its own copy of the c-string holding the string data. It must be constructed and freed. *That has to be costly.*

HOW COSTLY?

It wasn't a huge effect

Yet because Sagar created a std::string for every "non-word" operator, plus braces, etc, he created a LOT of unneeded strings

And this added up to a surprising overhead!

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.

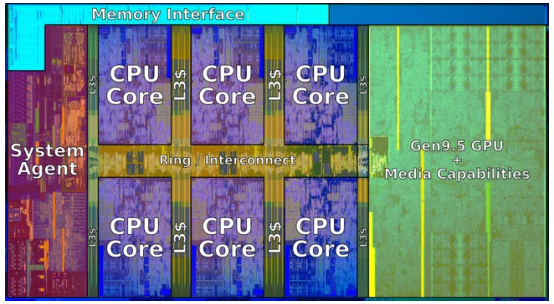
DIDN'T I PROMISE "THOUSANDS X" HOW DID THAT DROP TO 30X?

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.

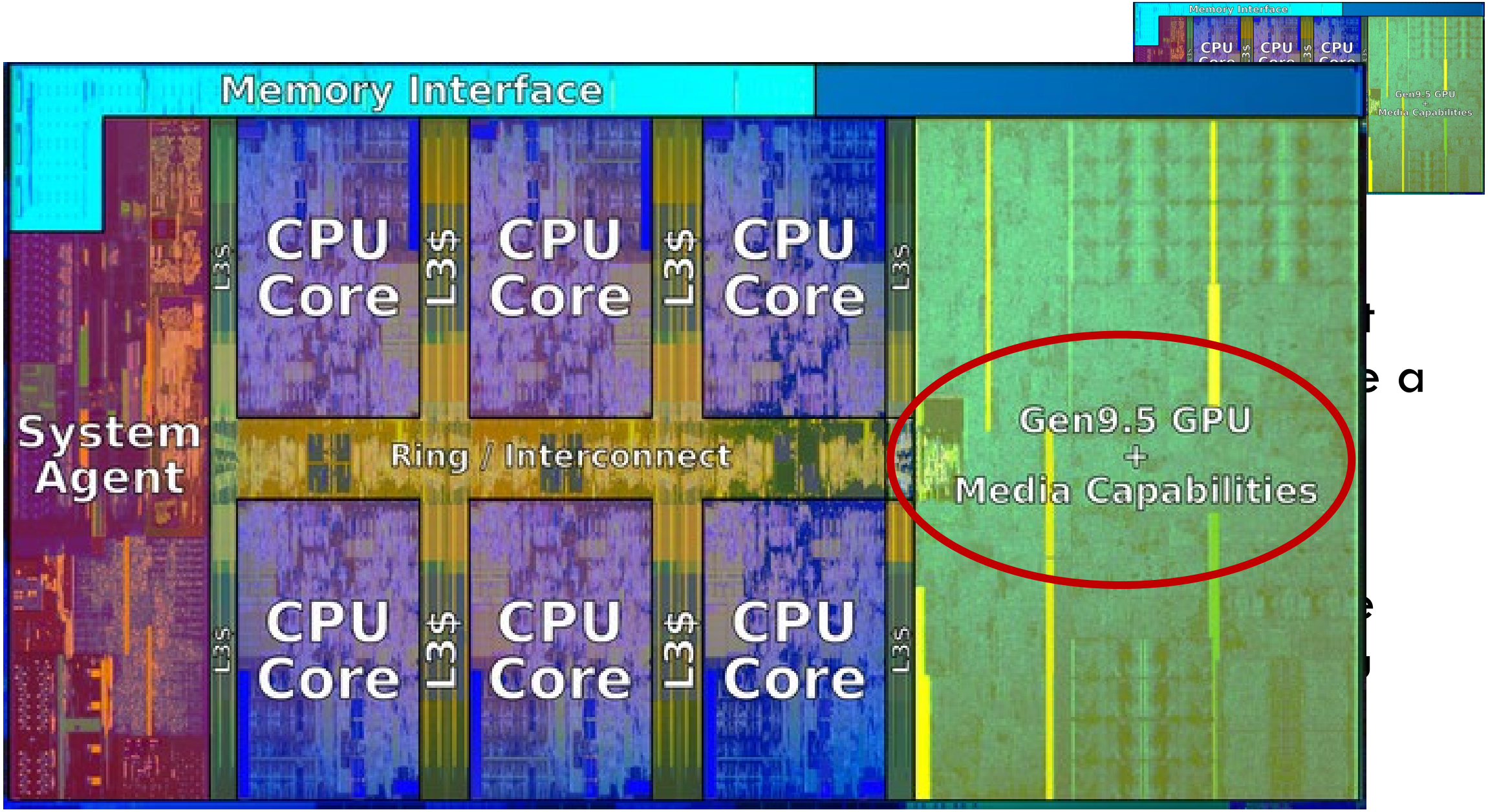
PARALLELISM IN YOUR COMPUTER



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

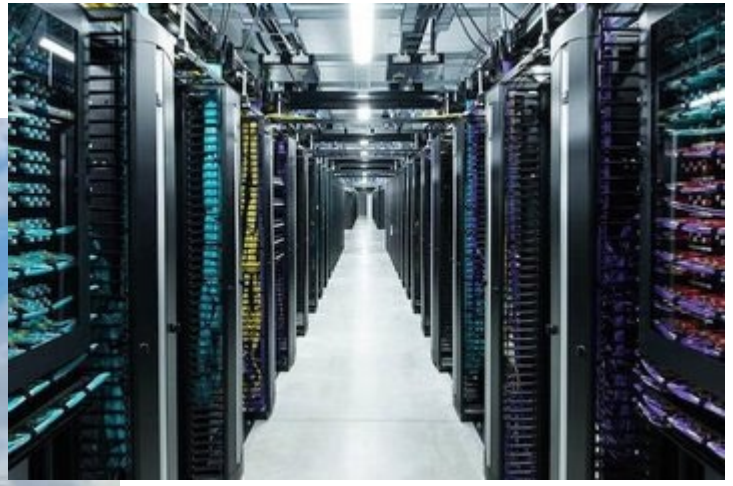
TOPIC FROM BEYOND CS4414: CLOUD COMPUTING TAKES THIS FURTHER

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



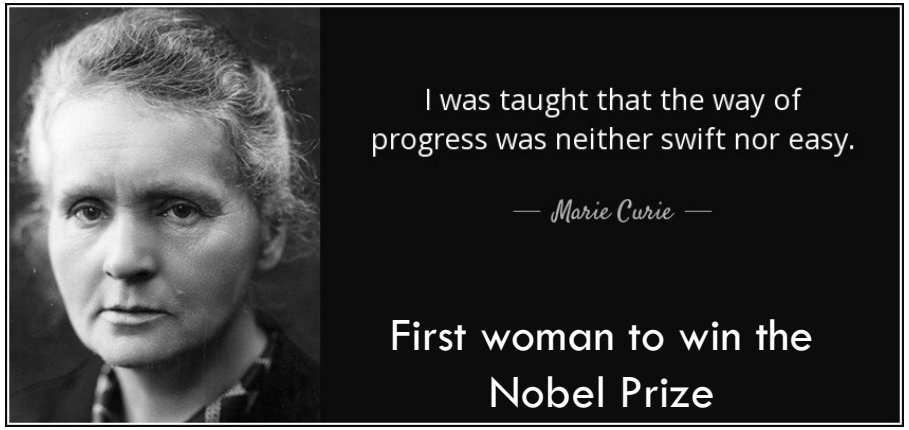
ISSUES INTRODUCED BY LARGE SCALE

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…



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

ROLL YOUR OWN? OR LEARN SOME WEIRD LIBRARY INTERFACE?

Once Sagar saw my version, he sped up his version, using more std::xxx methods – he basically ended up with something more standard.

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!

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   |  1202461
```

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!

REMAINDER OF WORD COUNT IN C++

I didn't show you:

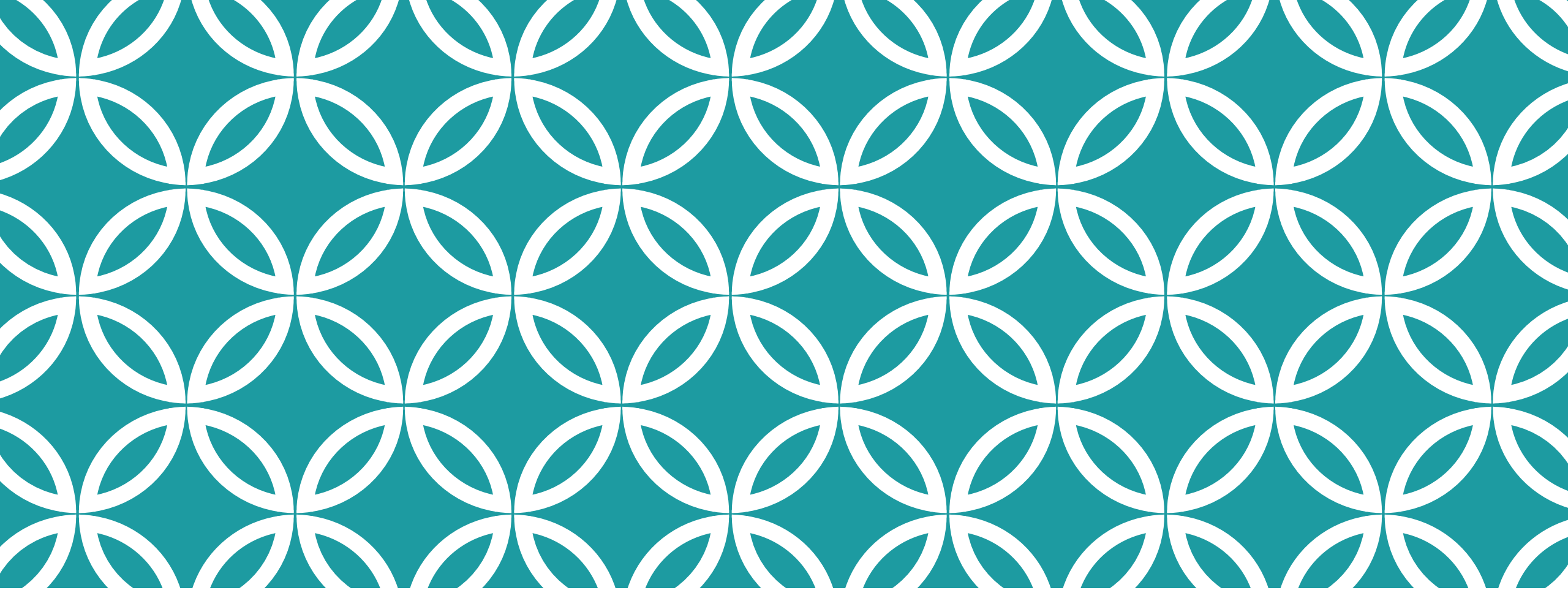
- The standard includes required to import the std:: libraries
- The main program that calls the "getWordCount" method
- A bunch of little helper methods I wrote.

CONFUSED? NO WORRIES…

New ideas are always confusing, especially if seen rapidly.

We will revisit all of these concepts much more carefully soon

Today was a big-picture perspective, and we don't expect you to be able to do the same kind of thing… yet



PRACTICAL CONSIDERATIONS

Organizational stuff

RECITATIONS MATTER!

In CS4414, we use the recitations to teach you C++ and Linux. We require them and we test on the material they cover.

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. And even a person who knows C++ can learn new things from Alicia, Jonathan and Pengyue.

SETUP

We will have everyone using the same version of GCC and the same version of Linux (Ubuntu)

This makes autograding possible, and also makes TA advising easier.

YOU CAN LEARN IN GROUPS… BUT MUST WORK 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 your individual work.*

ChatGPT and similar bots are not particularly good at C++ so you can use them safely, without it being cheating.

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 lectures. If people stop attending we might give a snap quiz from time to time. Videos from prior years are for catching up, not 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. Taking the final can never raise a grade from A to A+.

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