THREADS!

We’ve heard about them but haven’t worked with them. … well, that’s about to change!

This topic starts a whole new unit — our “systems programming tour of Linux and C++” is finished.
Today starts a whole unit entirely focused on concurrency inside a C++ program and how to safely manage it.
REMINDER: WHAT IS A THREAD?

But we can also write a single program that, at runtime, uses parallelism internally, via what we call a *thread*.

Use of threads requires a deep understanding of performance consequences, overheads, and how to program correctly with concurrency.

Many programs would slow down or crash if you just threw threads in.
THREADS COME IN SEVERAL COLORS

**Heavyweight** threads are ones running on different CPUs

- They could be sharing one address space...
- ... or could be *distinct processes*, each with a distinct address space.

**Lightweight** threads are ones that share some single CPU. A scheduler context-switches between them periodically.
Linux itself is a multithreaded program. Each system call runs on a distinct thread, and the Linux scheduler and file system have additional threads of their own.

Linux evolved over decades to take full advantage of this power. It wasn’t obvious or easy!
Recall our word count from Lectures 1-3. It had:

- One “main” thread to process the arguments, then launch threads
- One thread just to open files
- N threads to count words, in parallel, on distinct subsets of the files and implement parallel count-tree merge

Main thread resumed control at the end, sorted output, printed it.
HEAVYWEIGHT OR LIGHTWEIGHT?

They all share one address space

But WordCount was coded to work correctly in either case:

- Linux decides how many cores to allow WordCount to use
- Then the thread scheduler (a part of std::thread) decides which WordCount threads get to run on their own CPU.
Any process can “clone itself” by calling \( \text{pid} = \text{fork()} \).  

The parent process will receive the pid of its new child.

The child process is identical to the parent (even shares the same open files, like stdin, stdout, stderr), but gets pid 0. Typically, the child immediately “sets up” a runtime environment for itself.
WHY “FORK”

Because of poetry!

Recall that in Linux, every process has a parent process, and /etc/init (runs at boot time) is the parent of everything.

The inventors of Unix (first version of Linux) visualized this a bit like that famous road in the woods…

“Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood…”

-- Robert Frost
THE TERM “FORK” HAS LINGERED

If someone says “fork off a thread” or “fork off a process” it refers to creating a new concurrent task.

Later, we might wait for that thread or thread to finish. This is called a join (like when a stream joins a river)
WITH THREADS, YOU CAN “FOLLOW BOTH PATHS” IN THE WOODS...

In computing, some ideas (like recursion) are really earth-shaking

Concurrency is one of them! In some ways very hard to do properly, because of mistakes that can easily arise, and hidden costs that can destroy the speedup benefits.

But in other ways, concurrency is revolutionary because we use the hardware so efficiently.
FORK FOLLOWED BY EXEC

In Linux we normally call exec after calling fork.

Fork creates the process and leaves the parent process an opportunity to “set up” the runtime environment of the child.

Then exec launches some other program, but it runs in the same process “context” that the forked child set up.
JOIN IS IMPORTANT, TOO!

If the main thread exits while child threads are still running, this kills the child threads in a chaotic way.

They might not get a chance to clean up and release external resources they were using, like special graphics hardware. They could also throw exceptions, causing your program to “crash” after the main thread was done!
HOW APPLICATIONS CREATE THREADS

Very easy to create: in effect, instead of calling a method, we “fork it off” in a thread of its own, and the call occurs there.

Like this:

```cpp
auto fileopener = std::thread(fopener, nfiles, (char**)file_names);
std::thread my_threads[MAXTHREADS];
for(int n = 0; n < nthreads; n++)
{
    my_threads[n] = std::thread(wcounter, n);
}
for(int n = 0; n < nthreads; n++)
{
    my_threads[n].join();
}
fileopener.join();
```
FEATURES OF THREADS

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}
for(int n = 0; n < nthreads; n++)
{
    my_threads[n].join();
}
fileopener.join();
```

In fast-wc, wcounter was a method that takes an integer id as its single argument.

Join pauses to wait for the designated thread to finish.
**FIRST CHALLENGE?**

We will have two things (or many) running in one address space.

How will each thread know what to do? For example, “wcounter” needs to know its thread number (for tree-merge)

One option is for a main thread to simply tell them. `std::thread` will pass any extra arguments to the function you provide (much like `printf`, this is done with variadic template logic)
OTHER OPTIONS FOR SENDING DATA TO A THREAD YOU CREATE?

As we will see later in this lecture, and the next ones, we could also have some form of “queue of work to be done”

Then threads can remove jobs from the work queue.

For example, wcounter (in fast-wc) had a queue of files to be scanned. Each thread looped, scanning the next file. The file opener thread filled this queue, then (after all files) signaled “done”.
THE THREAD-CREATION OPERATION CAN TAKE ARGUMENTS

A thread calls a method that returns void, but can have arguments.

In this example, “fopener” is being passed a list of files to open:

```cpp
auto fileopener = std::thread(fopener, nfiles, (char**)file_names);
```
A PUZZLE TO THINK ABOUT

Which value of “n” will wcounter see? What if someone is updating nfiles: will fopener see the original value from when std::thread was called, or an updated version?

Important to make a decision: by-value arguments are “copied” when std::thread is invoked. By-reference arguments are just alias names for the value (like “n”). This can lead to bugs!
SLIGHT DIGRESSION: LAMBDAS

To understand the most widely popular notation C++ uses for launching and coordinating threads we need to pause and discuss lambdas

Then we can resurface and talk more about threads
A thread can run a method with no name. This is popular in C++

A lambda is just a method that doesn’t have a given name.

In effect, a lambda is an expression that can be used as a method:

```cpp
auto fileopener = std::thread([&nfiles, file_names](){ code for file opener });
```
A lambda is just a method that doesn’t have a given name.

In effect, an expression that can be used as a method:

```cpp
auto fileopener = std::thread([nfiles, file_names](){
  code for file opener
});
```

(): this lambda has no arguments.

Arguments (if any) are supplied at the time the lambda is invoked.
A lambda is just a method that doesn’t have a given name.

In effect, an expression that can be used as a method:

```cpp
auto fileopener = std::thread([nfiles, file_names](){ code for file opener });
```

Lambda syntax: `[ stuff ] ( args ) { code }`

Arguments (if any) are supplied at the time the lambda is invoked.
CONCEPT OF CAPTURE

Capture: a clean way to access variables in the caller’s scope:

```cpp
auto fileopener = std::thread([&nfiles, file_names](){ code for file opener });
```

[nfiles, file_names]... variables “captured” from the caller’s runtime context
PASSING A FUNCTION OR A VOID METHOD TO SOMETHING THAT CALLS IT

void CallSomething( (int)(std::string) f, std::string str)
{
    cout << "I called f, and it returned " << f(str) << endl;
}

λ's
PASSING A FUNCTION OR A VOID METHOD TO SOMETHING THAT CALLS IT

```cpp
void CallSomething( (int)(std::string) f, std::string str)
{
    cout << "I called f, and it returned " << f(str) << endl;
}

int func(std::string s)
{
    cout << "This is f, and my argument was " << s << endl;
    return s.size();
}
```
**PASSING A FUNCTION OR A VOID METHOD TO SOMETHING THAT CALLS IT**

```cpp
void CallSomething( (int)(std::string) f, std::string str)
{
    cout << "I called f, and it returned " << f(str) << endl;
}

int func(std::string s)
{
    cout << "This is f, and my argument was " << s << endl;
    return s.size();
}

// Example call
CallSomething(func, "Hello");
```

λ’s
PASSING A FUNCTION OR A VOID METHOD TO SOMETHING THAT CALLS IT

void CallSomething((int)(std::string) f, std::string str)
{
    cout << "I called f, and it returned " << f(str) << endl;
}

int func(std::string s)
{
    cout << "This is f, and my argument was " << s << endl;
    return s.size();
}

CallSomething(func, "Hello");

This is a notation for the type corresponding to a function that takes a string argument and returns an int.

λ's
PASSING A FUNCTION OR A VOID METHOD TO SOMETHING THAT CALLS IT

```cpp
void CallSomething((int)(std::string) f, std::string str)
{
    cout << "I called f, and it returned " << f(str) << endl;
}
int func(std::string s)
{
    cout << "This is f, and my argument was " << s << endl;
    return s.length();
}
```

Identical logic, but now “func” is passed as a lambda

```cpp
CallSomething([ ](std::string s){ cout << ... << endl; return s.size(); }, "Hello")
```

λ’s
The lambda can obtain a reference to any valuable in the caller’s scope [\&x] or can capture the value [x]. Value means “make a copy for this lambda call”

You can also mix the two, by adding “=“, like this: [\&x, =y]

Once a lambda captures a scope variable by reference, we say that it has an “alias” to that variable.
WHY DOES C++ THREAD CREATE HAVE BOTH CAPTURE AND ALSO THREAD ARGUMENTS?

It may feel as if the variables in the [...] part are no different from the parameters in the (...) part.

The difference is that when launching a thread, the caller supplies the arguments. Each could have a different argument.

Capture is useful because a lambda is actually an “expression” — you can define a lambda in one place but use it elsewhere. In the code that calls the lambda, those captured variables might not be in scope.
... BACK ON TOPIC

Now we know lambda syntax and can return to talking about threads

You’ll see more examples using lambda in these slides but also in future lectures.
... AND NOW OUR THREADS CAN RUN!

Once we have created our threads, each will have:

- Its own stack, on which local variables will be allocated
- Its own “PC” register, and other registers
- Its own independent execution.
- Access to objects that might also be accessed by other threads!

This last case can cause issues, as we will see in future lectures. The big risk is that one thread could modify something while another is looking, causing one or both to crash. But we can use locking for thread-safety.
Which core will a thread run on?

In fact, unless you specify that you want to use more than one core, Linux will run all the threads on the same core!

So if we do nothing and create 20 threads, the one CPU core must context switch between those 20 threads. (Linux does this automatically).
We say that a thread is “lightweight” if it doesn’t have a core dedicated to it. A “heavyweight” thread has its own core.

With lightweight threads we can have many per core.
HOW IT WORKS

Internal to Linux is a clock, and this clock is configured by the kernel to interrupt at various rates.

When your lightweight thread is running, the threads library asks Linux to send a signal after, say, 25ms.

The clock interrupts the kernel, and Linux signals std::thread
AT THIS POINT THE SIGNAL HANDLER IS RUNNING IN STD::THREAD

Recall that running a signal handler is like doing a method call, except that the kernel “caused” the method to run.

So at this moment, registers and the PC of the current thread have been pushed to the stack!

We call this stack and saved register state a “context”.
Multiple threads can be associated with a process

- Each thread has its own logical control flow
- Each thread shares the same code, data, and kernel context
- Each thread has its own stack for local variables
  - but not protected from other threads
- Each thread has its own thread id (TID)

Thread 1 context:
- Data registers
- Condition codes
- SP\(_1\)
- PC\(_1\)

Thread 2 context:
- Data registers
- Condition codes
- SP\(_2\)
- PC\(_2\)

Shared code and data:
- Shared libraries
- Run-time heap
- Read/write data
- Read-only code/data

Kernel context:
- VM structures
- Descriptor table
- Brk pointer
THREAD STACKS

Although the main thread has a stack that can grow without limit, this is *not* the situation for spawned child threads.

They have limited stack sizes (default: 2MB, but you can specify a larger size)

Overflow will cause the entire process to crash.
STACK ALLOCATION: SAFE, BUT BE CAUTIOUS

2MB is a large amount of space and won’t easily be used up. C++ gives a stack overflow exception if you manage to do so.

But we can’t put really big objects on the stack, or do really deep recursion with even medium-sized objects on the stack.
CONTEXT SWITCHING

The std::thread scheduler looks at the list of currently active threads to see if any are runnable.

This means: ready to execute, but currently paused.

In some order, it picks one of the runnable threads, and “context switches” to it, meaning that in that other thread, we return from the signal that was used to pause it!
POLICIES FOR SCHEDULING THREADS

We call this context switching step a “scheduling” event.

Modern schedulers treat threads differently based on how they are behaving.

A thread that crunches without pausing for long periods will be scheduled for long “quanta” (means “chunks of time”).
A thread that frequently pauses (like to wait for I/O) will be scheduled more urgently, but with a very small quanta.

The idea is that we want snappy responses to the console, or to other I/O events. In contrast, we shouldn’t incur too much overhead for the data-crunching threads, so we let them run for a longer period.
SCHEDULER CONCEPT: MULTILEVEL FEEDBACK QUEUE WITH ROUND ROBIN SCHEDULING

This is a clever idea for letting the behavior of the threads shape the choice of which scheduling quanta to use.

We start with the concept of a round-robin queue.

Our runnable threads are pushed to the end of the queue. The scheduler runs the thread at the front of the queue for a fixed quanta (or until the thread itself pauses to wait for something).
Each paused thread has an associated scheduler data structure plus a context. The one on the queue longest is at the front.”

Thread A:
Runnable
Has run for 81ms
Context = [....]

Thread C:
Runnable
Has run for 19ms
Context = [....]

Thread D:
Runnable
Has run for 28ms
Context = [....]

... Here, thread D will run next
MULTILEVEL FEEDBACK QUEUE: AN ARRAY OF QUEUES!

std::list<std::list<ThreadContext>>

Long-running threads larger scheduling δ

Thread X:
Runnable
Has run for 261ms
Context = [....]

Thread Y:
Runnable
Has run for 1819ms
Context = [....]

Thread D:
Runnable
Has run for 127ms
Context = [....]

Thread C:
Runnable
Has run for 19ms
Context = [....]

Short-running threads smaller scheduling δ

Thread X:
Runnable
Has run for 261ms
Context = [....]

Thread A:
Runnable
Has run for 81ms
Context = [....]
RULE FOR MOVING FROM QUEUE TO QUEUE

Track how long each thread has been running (without waiting)

If a thread has run long enough it moves to the next queue up.

If a thread pauses after a very short total time, it moves down.
We can have as many levels as we find helpful, but usually 2 or 3 suffice.

Now, the scheduler can rotate between queues. For total time $\Delta$ it runs jobs on the long-running jobs queue. Then it drops to the smaller-jobs queue and runs those.

The long-running jobs get a big per-job $\delta$. Shorter jobs get a smaller $\delta$. So, we run many short jobs compared to long-running jobs.
THAT WAS ALL WITH A SINGLE CORE!

Now we can introduce more than one core to the mix!

In Linux, this requires that you tell bash you wish to use multiple cores, with a command called taskset.

Each core has a number, and taskset takes a bit-array (in hex) indicating which cores this job will be using, e.g. taskset 0xFF.
ONE CORE PER THREAD: -PTHREAD, TASKSET

To activate multicore parallelism you must
1) Compile your program with the gcc flag –lpthread
2) Use “taskset mask” when launching your program:
   taskset 0xFF fast-wc -n7 -s
   ... this example says “run fast-wc on cores 0…7”, and also
   passes in two arguments, -n7, -s. Fast-wc will run with 7
   word-counter threads and one file opener, in “silent” mode.
HOW TASKSET WORKS

Taskset waits for “exclusive ownership” of the requested cores. Only one application can own a given core.

The pthread library is told which cores it owns.

Pthreads will scatter threads over the cores unless you specify a desired core when launching them (via std::thread).
DANGER! REMOTE MEMORY!

Recall from early lectures: on a NUMA machine, memory access speeds are very dependent on which core is accessing data in which memory.

NUMA looks like one big memory, but in fact is split into memory banks, and a core is only “close” to one of the memory units.
BUT GOOD NEWS: MALLOC KNOWS ABOUT THREADS

Malloc knows that...

- Objects can be shared without any form of segmentation faults
- But local memory accesses are much faster than remote, unless the remote object is pulled into the L2/L3 cache hierarchy.

Malloc automatically creates new objects in the memory pool closest to that thread’s core, if it has room to do so.
In Ken’s word counter, each wcouter thread had its own std::map tree, to hold the (word, counter) pairs.

Those trees were automatically close to the thread that created them, which made them fast to access.

Had wcouter used a single tree, shared by all, the program would have been significantly slower!
WE OFTEN MAKE SPARE COPIES TO SHARE AMONG THREADS!

With read-only objects, we often make a replica of the object for each thread to ensure that we will get the fastest possible access to it.

We do this by passing a reference to the “original” copy, and then having the thread make a copy as it starts up, or by passing the object by value as a captured object or argument.
THREADS: THE MAIN RISKS

Synchronization to prevent concurrent memory operations from interfering (if two or more threads access the same data)

Your code might not even speed up, unless you are smart about memory costs and synchronization costs.

Clean termination can be challenging.
SUMMARY

It is quite easy to create both lightweight and heavyweight threads.

One core can be shared by multiple lightweight threads.

We also learned new C++ features for writing this kind of code more concisely (lambda expressions).