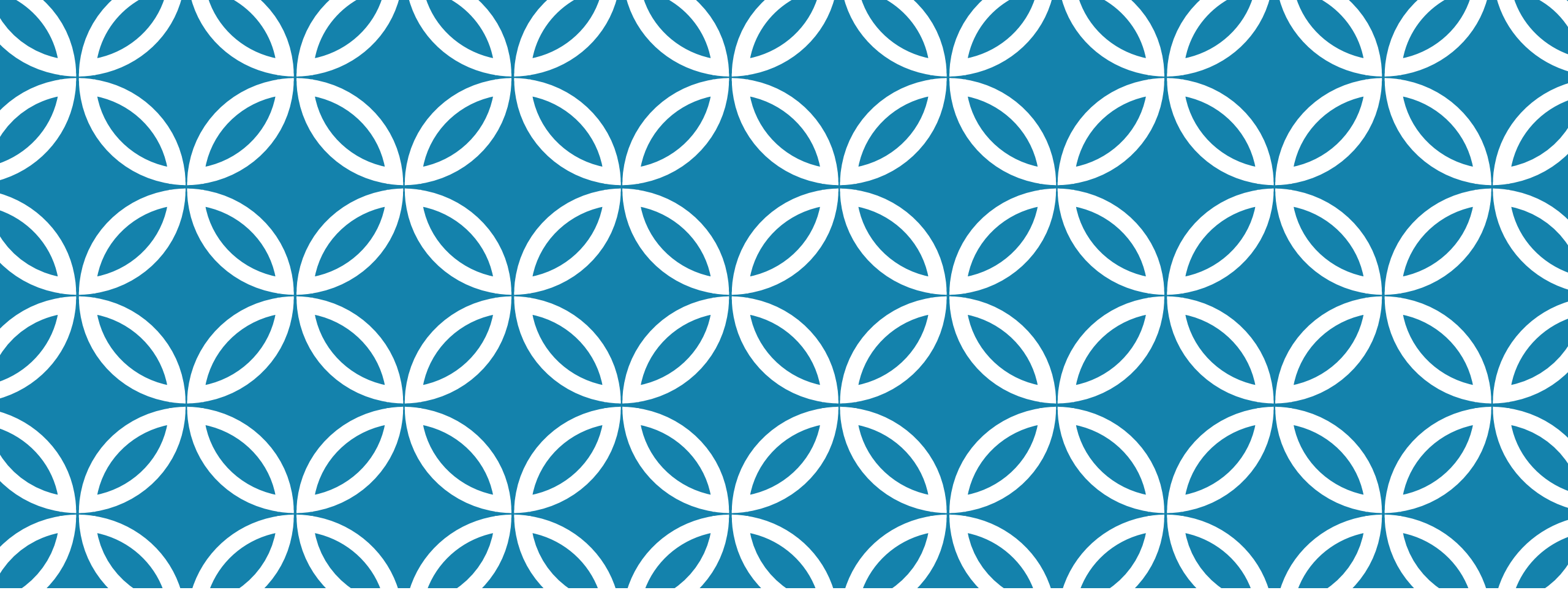


SYNCHRONIZATION PRIMITIVES

Professor Ken Birman

CS4414 Lecture 14

IDEA MAP FOR MULTIPLE LECTURES!

Reminder: Thread Concept

Lightweight vs. Heavyweight

Thread "context" and scheduling

C++ mutex objects. Atomic data types.

Race Conditions, Deadlocks, Livelocks

Today: Focus on the danger of sharing without synchronization and the hardware primitives we use to solve this.

… WITH CONCURRENT THREADS, SOME SHARING IS USUALLY NECESSARY

Suppose that threads A and B are sharing an integer **counter**. What could go wrong?

We saw this example briefly in an early lecture. A and B both simultaneously try to increment counter. But increment occurs in steps: load the counter, add one, save it back.

… they conflict, and we "lose" one of the counting events.

THREADS A AND B SHARE A COUNTER

Thread A:

counter++;

```
movq    counter,%rax
addq    $1,%rax
movq    %rax,counter
```

Thread B:

counter++;

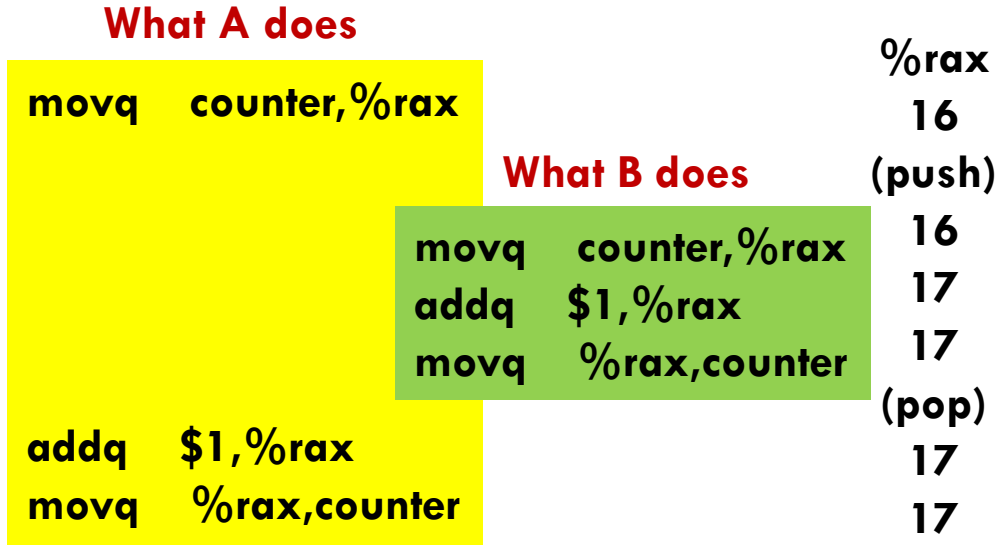
```
movq    counter,%rax
addq    $1,%rax
movq    %rax,counter
```

Either context switching or NUMA concurrency could cause these instruction sequences to interleave!

EXAMPLE: COUNTER IS INITIALLY 16, AND BOTH A AND B TRY TO INCREMENT IT.

The problem is that A and B have their own private copies of the counter in %rax

With pthreads, each has a private set of registers: a private %rax



With lightweight threads, context switching saved A's copy while B ran, but then reloaded A's context, which included %rax

THIS INTERLEAVING CAUSES A BUG!

If we increment 16 twice, the answer should be 18.

If the answer is shown as 17, all sorts of problems can result.

Worse, the schedule is unpredictable. This kind of bug could come and go…

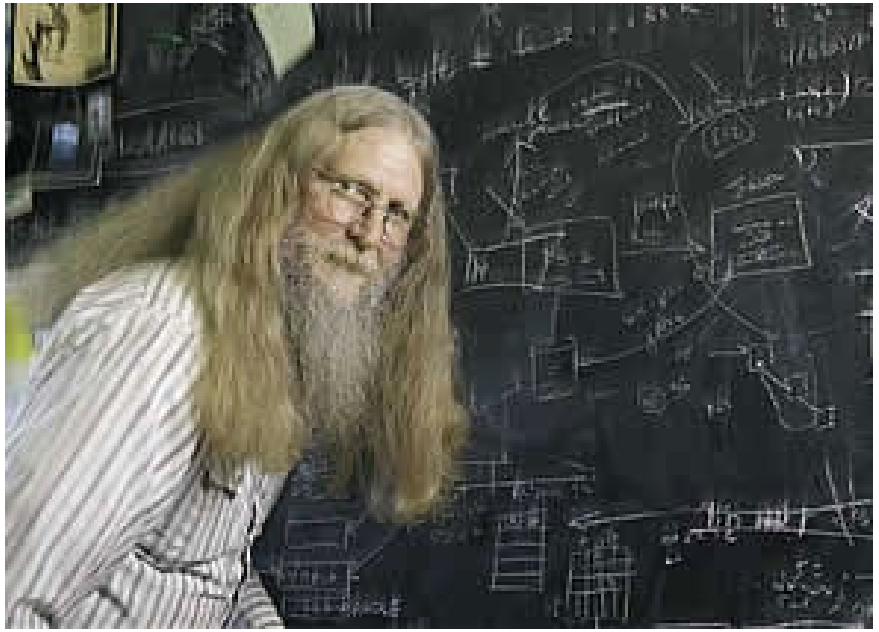
STL REQUIREMENT

Suppose you are using the C++ std library (the STL):

- Every library method can simultaneously be called by multiple read-only threads. If only readers are active, no locks are needed.
- Every library method can be called by a single writer. No locking is needed in this case either (this assumes no readers are active).

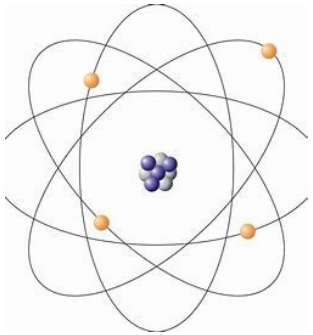
… However, you must protect against having multiple writers or a mix of readers and writers that concurrently access the library.

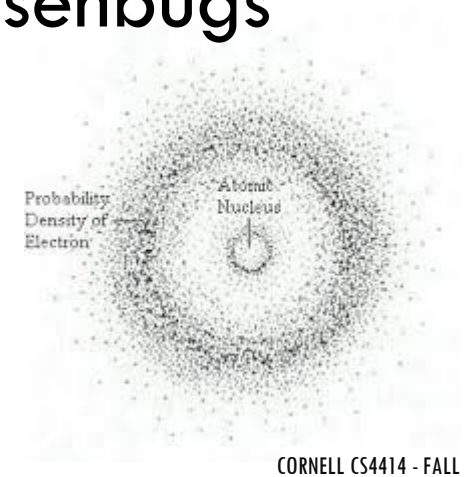
BRUCE LINDSAY



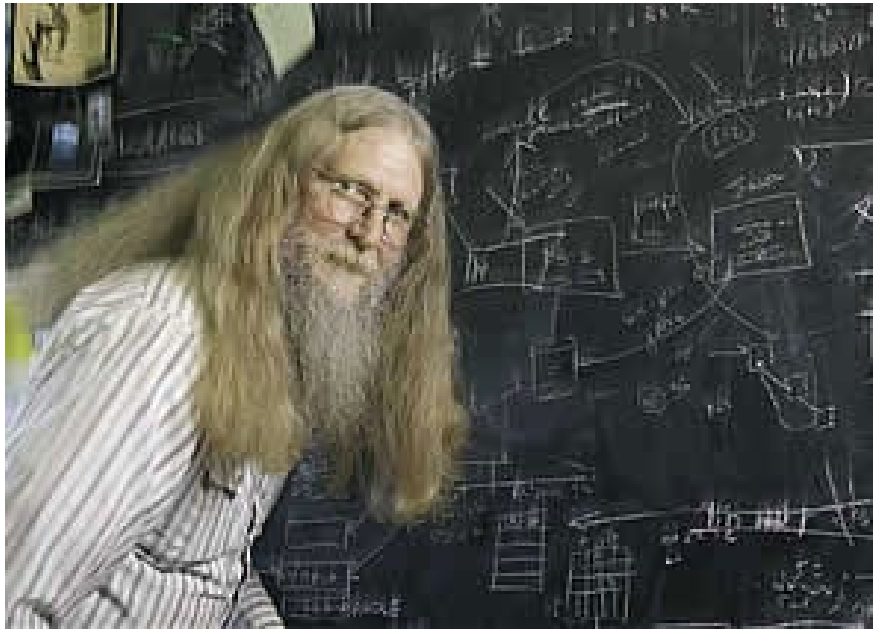
A famous database researcher

Bruce coined the terms “Bohrbugs” and “Heisenbugs”





BRUCE LINDSAY



In a concurrent system, we have two kinds of bugs to worry about

A Bohrbug is a well-defined, reproducible thing. We test and test, find it, and crush it.

Concurrency can cause Heisenbugs… they are very hard to reproduce. People often misunderstand them, and just make things worse and worse by patching their code without fixing the root cause!

THIS LEADS TO THE CONCEPT OF A CRITICAL SECTION

A critical section is a block of code that accesses variables that are read **and updated.** You must have two or more threads, at least one of them doing an update (writing to a variable).

The block where A and B access the counter is a critical section. In this example, both update the counter.

Reading constants or other forms of unchanging data is not an issue. And you can safely have many simultaneous *readers*.

WE TO ENSURE THAT A AND B CAN'T BOTH BE IN THE CRITICAL SECTION AT THE SAME TIME!

Basically, when A wants to increment counter, it goes into the critical section… and locks the door.

Then it can change the counter safely.

If B wants to access counter, it has to wait until A unlocks the door.

C++ ALLOWS US TO DO THIS.

```
std::mutex mtx;


void safe_inc(int& counter)
{
        std::scoped_lock  lock(mtx);
        counter++;
}
```

C++ ALLOWS US TO DO THIS.

```
std::mutex mtx;


void safe_inc(int& counter)
{
        std::scoped_lock  lock(mtx);
        counter++;                    // A critical section!
}
```

C++ ALLOWS US TO DO THIS.

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std::mutex mtx;

void safe_inc(int& counter)
{
        std::scoped_lock lock(mtx);
        counter++;                    // A critical section!
}
```

This is a C++ type!

C++ ALLOWS US TO DO THIS.

```
std::mutex mtx;


void safe_inc(int& counter)
{
        std::scoped_lock lock(mtx);
        counter++;                    // A critical section!
}
```

This is a variable name!

C++ ALLOWS US TO DO THIS.

```
std::mutex mtx;


void safe_inc(int& counter)
{
        std::scoped_lock  lock(mtx);
        counter++;                    // A critical section!
}
```

The mutex is passed to the scoped_lock constructor

RULE: SCOPED_LOCK

```
std::scoped_lock  lock(mtx);
```

Your thread might pause when this line is reached.

Question: How long can the variable “lock” be accessed?

Answer: Until it goes out of scope when the thread exits the block in which it was declared.

RULE: SCOPED_LOCK

```
std::scoped_lock  lock(mtx);
```

Your thread might pause when this line is reached.

Suppose counter is accessed in two places?

… use std::scoped_lock something(mtx) in both, *with the same mutex*. ***"The mutex, not the variable name, determines which threads will be blocked".***

RULE: SCOPED_LOCK

```
std::scoped_lock  lock(mtx);
```

When a thread "acquires" a lock on a mutex, it has sole control!

You have "locked the door". Until the current code block exits, you hold the lock and no other thread can acquire it!

Upon exiting the block, the lock is released (this works even if you exit in a strange way, like throwing an exception)

PEOPLE USED TO THINK LOCKS WERE THE SOLUTION TO ALL OUR CHALLENGES!

They would just put a std::scoped_lock whenever accessing a critical section.

They would be very careful to use the same mutex whenever they were trying to protect the same resource.

It felt like magic! At least, it did for a little while…

BUT THE QUESTION IS NOT SO SIMPLE!

Locking is costly. We wouldn't want to use it when not needed.

And C++ actually offers *many* tools, which map to some very sophisticated hardware options.

Let's learn about those first.

ISSUES TO CONSIDER

Data structures: The thing we are accessing might not be just a single counter.

Threads could share a std::list or a std::map or some other structure with pointers in it. These complex objects may have a complex representation with several associated fields.

Moreover, with the alias features in C++, two variables can have different names, but refer to the same memory location.

HARDWARE ATOMICS

Hardware designers realized that programmers would need help, so the hardware itself offers some guarantees.

First, memory accesses are *cache line atomic*.

What does this mean?

CACHE LINE: A TERM WE HAVE SEEN BEFORE!

All of NUMA memory, including the L2 and L3 caches, are organized in blocks of (usually 64) bytes.

Such a block is called a cache line for historical reasons. Basically, the "line" is the width of a memory bus in the hardware.

CPUs load and store data in such a way that any object that fits in one cache line will be *sequentially consistent*.

SEQUENTIAL CONSISTENCY

Imagine a stream of reads and writes by different CPUs

Any given cache line sees a *sequence* of reads and writes. A read is guaranteed to see the value determined by the prior writes.

For example, a CPU never sees data "halfway" through being written, if the object lives entirely in one cache line.

SEQUENTIAL CONSISTENCY IS ALREADY ENOUGH TO BUILD LOCKS!

This was a famous puzzle in the early days of computing.

There were many proposed algorithms… and some were incorrect!

Eventually, two examples emerged, with nice correctness proofs

DEKKER'S ALGORITHM FOR TWO PROCESSES

P0 and P1 can enter freely, but if both try at the same time, the "turn" variable allows first one to get in, then the other.

```
variables
    wants_to_enter : array of 2 booleans
    turn : integer

wants_to_enter[0] ← false
wants_to_enter[1] ← false
turn ← 0   // or 1
```

```
p0:
   wants_to_enter[0] ← true
   while wants_to_enter[1] {
      if turn ≠ 0 {
         wants_to_enter[0] ← false
         while turn ≠ 0 {
           // busy wait
         }
         wants_to_enter[0] ← true
      }
   }

   // critical section
   ...
   turn ← 1
   wants_to_enter[0] ← false
   // remainder section
```

```
p1:
   wants_to_enter[1] ← true
   while wants_to_enter[0] {
      if turn ≠ 1 {
         wants_to_enter[1] ← false
         while turn ≠ 1 {
           // busy wait
         }
         wants_to_enter[1] ← true
      }
   }

   // critical section
   ...
   turn ← 0
   wants_to_enter[1] ← false
   // remainder section
```

Note: You are not responsible for Dekker's algorithm, we show it just for completeness.

DECKER'S ALGORITHM WAS…

Fairly complicated, and not small (wouldn't fit on one slide in a font any normal person could read)

Elegant, but not trivial to reason about.

In CS4410 we develop proofs that algorithms like this are correct, and those proofs are not simple!

Note: You are not responsible for Dekker's algorithm, we show it just for completeness.

LESLIE LAMPORT

Lamport extended Decker's for many threads.

He uses a visual story to explain his algorithm: a Bakery with a ticket dispenser

Note: You are not responsible for the Bakery algorithm, we show it just for completeness.

LAMPORT'S BAKERY ALGORITHM FOR N THREADS

If no other thread is entering, any thread can enter

If two or more try at the same time, the ticket number is used.

Tie? The thread with the smaller id goes first

```
0   // declaration and initial values of global variables
1   Entering: array [1..NUM_THREADS] of bool = {false};
2   Number: array [1..NUM_THREADS] of integer = {0};
3
4   lock(integer i) {
5       Entering[i] = true;
6       Number[i] = 1 + max(Number[1], ..., Number[NUM_THREADS]);
7       Entering[i] = false;
8       for (integer j = 1; j <= NUM_THREADS; j++) {
9           // Wait until thread j receives its number:
10          while (Entering[j]) { /* nothing */ }
11          // Wait until all threads with smaller numbers or with the same
12          // number, but with higher priority, finish their work:
13          while ((Number[j] != 0) && ((Number[j], j) < (Number[i], i))) { /* nothing */ }
14      }
15  }
16
17  unlock(integer i) {
18      Number[i] = 0;
19  }
20
21  Thread(integer i) {
22      while (true) {
23          lock(i);
24          // The critical section goes here...
25          unlock(i);
26          // non-critical section...
27      }
28  }
```

Note: You are not responsible for the Bakery algorithm, we show it just for completeness.

LAMPORT'S CORRECTNESS GOALS

An algorithm is *safe* if "nothing bad can happen." For these mutual exclusion algorithms, safety means "at most one thread can be in a critical section at a time."

An algorithm is *live* if "something good eventually happens". So, eventually, some thread is able to enter the critical section.

An algorithm is *fair* if "every thread has equal probability of entry"

Note: You are not responsible for the Bakery algorithm, we show it just for completeness.

THE BAKERY ALGORITHM IS TOTALLY CORRECT

It can be proved safe, live and even fair.

For many years, this algorithm was actually used to implement locks, like the scoped_lock we saw on slide 11

These days, the C++ libraries for synchronization use **atomics**, and we use the library methods (as we will see in Lecture 15).

Note: You are not responsible for the Bakery algorithm, we show it just for completeness.

TERM: "ATOMICITY"

This means "all or nothing"

It refers to a complex operation that involves multiple steps, but in which no observer ever sees those steps in action.

We only see the system before or after the atomic action runs.

ATOMIC MEMORY OBJECTS

Modern hardware supports atomicity for memory operations.

If a variable is declared to be atomic, using the C++ atomics templates, then basic operations occur to completion in an indivisible manner, even with NUMA concurrency.

For example, we could just declare

```
std::atomic<int>  counter;          // Now ++ is thread-safe
```

SOME ISSUES WITH ATOMICS

Atomic variables are slow to access: we wouldn't want to use this annotation frequently!

Often, a critical section would guard multiple operations. With atomics, the *individual* operations are safe, but perhaps not the block of operations.

VOLATILE

Volatile tells the compiler that a non-atomic variable might be updated by multiple threads… the value could change at any time.

This prevents C++ from caching the variable in a register as part of an optimization.

Volatile is only needed if you do completely unprotected sharing. With C++ library synchronization, you never need this keyword.

WHEN WOULD YOU USE VOLATILE?

Suppose that thread A will do some task, then set a flag "A_Done" to true. Thread B will "busy wait":

```
while(A_Done == false) ;          // Wait until A is done
```

Here, we need to add **volatile** (or **atomic**) to the declaration of A_Done. Volatile is faster than atomic, which is faster than a lock.

HIGHER LEVEL SYNCHRONIZATION: BINARY AND COUNTING SEMAPHORES (~1970'S)

We'll discuss the counting form

- A form of object that holds a lock and a counter. The developer initializes the counter to some non-negative value.
- **Acquire** pauses until counter > 0, then decrements counter and returns
- **Release** increments semaphore (if a process is waiting, it wakes up).

C++ has semaphores. The pattern is easy to implement.

PROBLEMS WITH SEMAPHORES

It turned out that semaphores were a cause of many bugs. Consider this code that protects a critical section:

```
mySem.acquire();

do something;              // This is the critical section

mySem.release();
```

… unusual control flow could prevent the release(), such as a **return** or **continue** statement, or a **caught exception**.

PROBLEMS WITH SEMAPHORES

It is also tempting to use semaphores as a form of "go to"

Process A

runB.release();

Process B

runB.acquire();

This is kind of ugly and can easily cause confusion

BETTER HIGH-LEVEL SYNCHRONIZATION

The complexity of these mechanisms led people to realize that we need higher-level approaches to synchronization that are safe, live, fair and make it easy to create correct solutions.

Let's look at an example of a higher level construct: a bounded buffer

BOUNDED BUFFER (LIKE A LINUX PIPE!)

We have a set of threads.

Some produce objects (perhaps, cupcakes!)

Others consume objects (perhaps, children!)

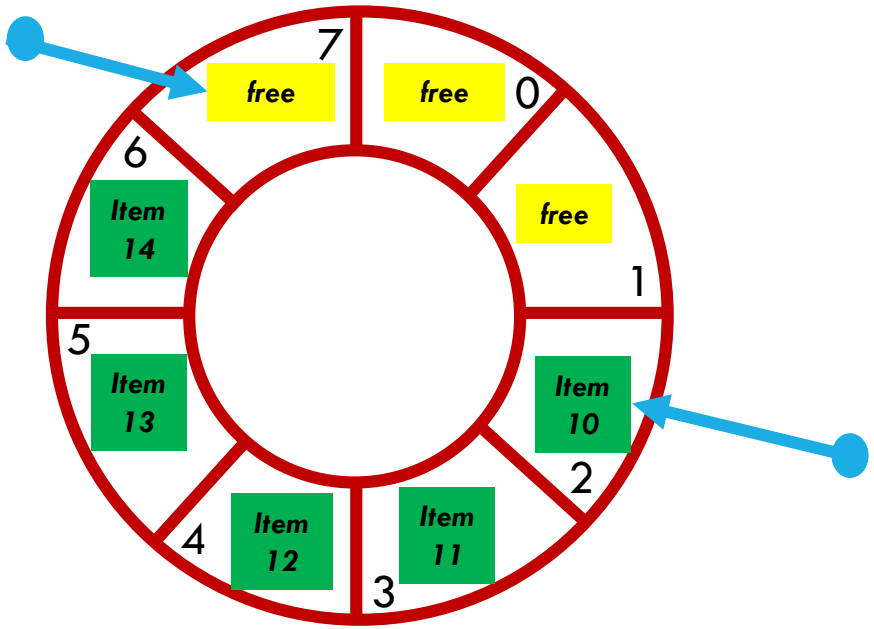
Goal is to synchronize the two groups.

A RING BUFFER

We take an array of some fixed size, LEN, and think of it as a ring. The k'th item is at location (k % LEN). Here, LEN = 8

Producers write to the next free entry

nfree =3
free_ptr = 15
15 % 8 = 7



Consumers read from the head of the full section

nfull =5
next_item = 10
10 % 8 = 2

A PRODUCER OR CONSUMER WAITS IF NEEDED

Producer:

```
void produce(Foo obj)
{
      if(nfull == LEN) wait;
      buffer[next_ptr++ % LEN] = obj;
      ++nfull;
      - - nempty;
}
```

Consumer:

```
Foo produce()
{
      if(nfull == 0) wait;
      ++nempty;
      - - nfull;
      return buffer[next_item++ % LEN];
}
```

As written, this code is unsafe… we can't fix it just by adding atomics or locks!

WE WILL SOLVE THIS PROBLEM IN LECTURE 15

Doing so yields a very useful primitive!

Putting a safe bounded buffer between a set of threads is a very effective synchronization pattern!

Example: In fast-wc we wanted to open files in one thread and scan them in other threads. A bounded buffer of file objects ready to be scanned was a perfect match to the need!

WHY ARE BOUNDED BUFFERS SO HELPFUL?

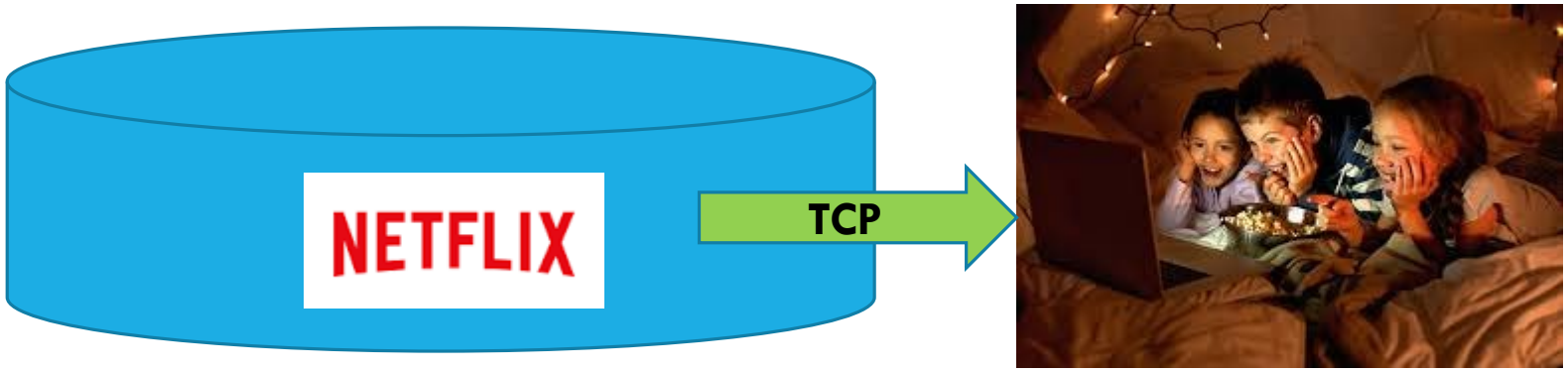
… in part, because they are safe with concurrency.

But they also are a way to absorb *transient rate mismatches.*

- A baker prepares batches of 24 cupcakes at a time.
- The school children buy them one by one.

If LEN ≥ 24, a bounded buffer of LEN cupcakes lets our baker make new batches *continuously*. The children can snack whenevermm they like.

TCP



The famous TCP networking protocol builds a bounded buffer that has two replicas separated by an Internet ink.

On one side, we have a server (perhaps, streaming a movie).

On the other, a consumer (perhaps, showing the movie)!

BUT ONE SIZE DOESN'T "FIT ALL CASES"

Only some use cases match this bounded buffer example (which, in any case, we still need to solve!)

Locks, similarly, are just a partial story.

So we need to learn to do synchronization in complex situations.

CRITICAL SECTIONS CAN BE SUBTLE!

By now we have seen several forms of aliasing in C++, where a variable in one scope can also be accessed in some other scope, perhaps under a different name.

In C++ it is common to overload operators like +, -, even [ ]. So almost any code could actually be calling methods in classes, or functions elsewhere in the program.

WE ALSO USE STD::XXX LIBRARIES

Without looking at the code in the library, the user won't know how it was implemented (and even if you look, an implementation can evolve!)

Some libraries are documented as thread safe (for example, the iostreams library that implements cout, cin).

But most C++ libraries do not do any locking.

YOUR JOB AS DEVELOPER

You must always have a visual image in your mind of the data objects your program is working with.

Among those, always ask yourself: could these objects or data structures be concurrently read and updated by multiple threads?

If so, you need to identify the "borders" around the code blocks that perform these accesses!

MANY CRITICAL SECTIONS… ONE OBJECT?

A single object or data structure will often be accessed in many places.

So this can mean that the single object "causes" you to identify multiple critical sections, namely multiple blocks of code where those access events occur.

Thread A and thread B could be accessing **counter** in very different parts of a multithreaded program. Yet these can still clash.

YOU ALSO SHOULD THINK ABOUT DEADLOCKS

We also need to worry about situations in which the locking we introduce *causes* bugs.

A process is *deadlocked* if there are any threads within it that will never make progress because they are stuck waiting for a lock.

A process is *livelocked* if two or more threads loop endlessly attempting to enter a critical section, but neither ever succeeds.

SUMMARY

Unprotected critical sections cause *serious* bugs!

Locks are an example of a way to protect a critical section, but the bounded buffer clearly needs "more"

What we really are looking for is a methodology for writing thread-safe code that uses C++ libraries safely.