CS111, Lecture 13
Race Conditions and Locks

Optional reading:

Operating Systems: Principles and Practice (2nd Edition): Sections 5.2-5.4 and Section 6.5

CS111 Topic 3: Multithreading, Part 1

Topic 3: **Multithreading** - How can we have concurrency within a single process? How does the operating system support this?

Multithreading Introduction	→	Race conditions and locks	→	Condition Variables	→	The Monitor Pattern	→	Trust and Race Conditions
Lecture 12		**This Lecture**		**Lecture 14**		**Lecture 15**		**Lecture 16**

assign4: implement several multithreaded programs while eliminating race conditions!

Learning Goals

- Understand how to identify critical sections and fix race conditions/deadlock
- Learn how locks can help us limit access to shared resources

Plan For Today

- **Recap:** Threads
- Mutexes
- Deadlock
- Dining Philosophers

```
cp -r /afs/ir/class/cs111/lecture-code/lect13 .
```

Plan For Today

- **Recap: Threads**
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```

From Processes to Threads

We can have concurrency *within a single process* using **threads:** independent execution sequences within a single process.

- Threads let us run multiple functions in our program concurrently (e.g. parallelize computation)
- Each thread operates within the same process, so they *share a virtual address space* (!) (globals, heap, pass by reference, etc.)

C++ Thread

A thread object can be spawned to run the specified function with the given arguments.

```
thread myThread(myFunc, arg1, arg2, ...);
```

- **myFunc:** the function the thread should execute asynchronously
- **args:** a list of arguments (any length, or none) to pass to the function
- **myFunc**’s function's return value is ignored (use pass by reference instead)
- Once initialized with this constructor, the thread may execute at any time!

C++ Thread

To wait on a thread to finish, use the **.join()** method:

```
thread myThread(myFunc, arg1, arg2);
...
// Wait for thread to finish (blocks)
myThread.join();
```

For multiple threads, we must wait on a specific thread one at a time:

```
thread friends[5];
...
for (int i = 0; i < 5; i++) {
      friends[i].join();
}
```

Race Conditions

- Like with processes, threads can execute in unpredictable orderings.
- A **race condition** is an unpredictable ordering of events where some orderings may cause undesired behavior.
- An example where race conditions can occur is with **operator<<**. e.g. **cout** statements could get interleaved!
- To avoid this, use **oslock** and **osunlock** (custom CS111 functions - **#include "ostreamlock.h"**) around streams. They ensure at most one thread has permission to write into a stream at any one time.

```
cout << oslock << "Hello, world!" << endl << osunlock;
```

Race Condition: Overselling Tickets

Simulation: let each thread help sell the 250 tickets until none are left.

There is a *race condition* here! Threads could interrupt each other in between checking for remaining tickets and selling them.

```
static void sellTickets(size_t id, size_t& remainingTickets) {
    while (remainingTickets > 0) {
        sleep_for(500); // simulate "selling a ticket"
        remainingTickets--;
        ...
    }
    ...
}
```

- If thread A sees tickets remaining and commits to selling a ticket, another thread B could come in and sell that same ticket before thread A does.
- This can happen because this portion of code isn't *atomic*.

Race Condition: Overselling Tickets

If thread A sees tickets remaining and commits to selling a ticket, another thread B could come in and sell that same ticket before thread A does.

```
static void sellTickets(size_t id, size_t& remainingTickets) {
    while (remainingTickets > 0) {
        sleep_for(500); // simulate "selling a ticket"
        remainingTickets--;
        ...
    }
    ...
}
```

- **Atomic** means it happens in its entirety without interruption. Cannot be observed in the middle.
- We want a thread to do the entire check-and-sell operation **uninterrupted** by other threads executing this region.

Critical Section

A **critical section** is a section of code that should be executed by only one thread at a time.

```
static void sellTickets(size_t id, size_t& remainingTickets) {
    while (remainingTickets > 0) {
        sleep_for(500); // simulate "selling a ticket"
        remainingTickets--;
        cout << oslock << "Thread #" << id << " sold a ticket ("
             << remainingTickets << " remain)." << endl << osunlock;
    }
    cout << oslock << "Thread #" << id
    << " sees no remaining tickets to sell and exits." << endl << osunlock;
}
```

What should we make a critical section? **Key:** keep them as small as possible to protect performance.

Critical Section

A **critical section** is a section of code that should be executed by only one thread at a time.

```
static void sellTickets(size_t id, size_t& remainingTickets) {
    while (true) {
        if (remainingTickets == 0) break;
        size_t myTicket = remainingTickets;
        remainingTickets--;
        sleep_for(500); // simulate "selling a ticket"
        cout << oslock << "Thread #" << id << " sold a ticket ("
             << myTicket - 1 << " remain)." << endl << osunlock;
    }
    cout << oslock << "Thread #" << id
    << " sees no remaining tickets to sell and exits." << endl << osunlock;
}
```

Critical Section

A **critical section** is a section of code that should be executed by only one thread at a time.

```
static void sellTickets(size_t id, size_t& remainingTickets) {
    while (true) {
        🚦🚦🚦  // only 1 thread can proceed at a time
        if (remainingTickets == 0) break;
        size_t myTicket = remainingTickets;
        remainingTickets--;
        // once thread passes here, another can go
        sleep_for(500); // simulate "selling a ticket"
        cout << oslock << "Thread #" << id << " sold a ticket ("
             << myTicket - 1 << " remain)." << endl << osunlock;
    }
    cout << oslock << "Thread #" << id
    << " sees no remaining tickets to sell and exits." << endl << osunlock;
}
```

Plan For Today

- **Recap:** Threads
- **Mutexes**
- Deadlock
- Dining Philosophers

```
cp -r /afs/ir/class/cs111/lecture-code/lect13 .
```

Mutexes

A **mutex** (”mutual exclusion”) is a type of variable meant to be shared across threads, and which can be “owned” by only 1 thread at a time.

If you have a mutex **myMutex**, call **lock** on it to take ownership of it (behaves as an atomic operation):

```
myMutex.lock();
```

Call **unlock** on it when you are the owner and want to give up ownership of it (behaves as an atomic operation):

```
myMutex.unlock();
```

Critically: lock() will *block* if a thread calls **lock** and another thread currently owns that mutex. **lock()** unblocks once the lock is available again.

(A mutex is initially unlocked when created)

Mutexes

```
int main(int argc, const char *argv[]) {
    thread ticketAgents[kNumTicketAgents];
    size_t remainingTickets = 250;
    mutex counterLock;

    for (size_t i = 0; i < kNumTicketAgents; i++) {
        ticketAgents[i] = thread(sellTickets, i, ref(remainingTickets), 
ref(counterLock));
    }
    ...
}
```

Mutexes

Lock the mutex at the start of the critical section to limit only 1 thread at a time to execute the critical section.

```
static void sellTickets(size_t id, size_t& remainingTickets, mutex&
counterLock) {
    while (true) {
        counterLock.lock();  // only 1 thread can proceed at a time
        if (remainingTickets == 0) break;
        size_t myTicket = remainingTickets;
        remainingTickets--;
        // once thread passes here, another can go
        sleep_for(500); // simulate "selling a ticket"
        cout << oslock << "Thread #" << id << " sold a ticket ("
             << myTicket - 1 << " remain)." << endl << osunlock;
    }
    ...
```

Mutexes

<u>When a thread calls lock():</u>

- If the lock is unlocked: the thread now owns the lock and continues execution
- If the lock is locked: the thread blocks and waits until the lock is unlocked
- If multiple threads are waiting for a lock: they all wait until it's unlocked, one receives lock (not necessarily one waiting longest)

```
static void sellTickets(size_t id, size_t& remainingTickets, mutex&
counterLock) {
    while (true) {
        counterLock.lock();  // only 1 thread can proceed at a time
        if (remainingTickets == 0) break;
        size_t myTicket = remainingTickets;
        remainingTickets--;
        // once thread passes here, another can go
        sleep_for(500); // simulate "selling a ticket"
        cout << oslock << "Thread #" << id << " sold a ticket ("
             << myTicket - 1 << " remain)." << endl << osunlock;
    }
    ...
```

Mutexes

Unlock the mutex at the end of the critical section.

Calling **unlock** lets another waiting thread (if any) take ownership of the lock.

(“Bridge” that only 1 thread can cross at a time)

```
static void sellTickets(size_t id, size_t& remainingTickets, mutex&
counterLock) {
    while (true) {
        counterLock.lock();  // only 1 thread can proceed at a time
        if (remainingTickets == 0) break;
        size_t myTicket = remainingTickets;
        remainingTickets--;
        counterLock.unlock(); // once thread passes here, another can go
        sleep_for(500); // simulate "selling a ticket"
        cout << oslock << "Thread #" << id << " sold a ticket ("
             << myTicket - 1 << " remain)." << endl << osunlock;
    }
    ...
```

Mutexes

Unlock the mutex at the end of the critical section.

Make sure to trace each thread's possible paths of execution to ensure they **always** give back shared resources like locks.

```
static void sellTickets(size_t id, size_t& remainingTickets, mutex&
counterLock) {
    while (true) {
        counterLock.lock();  // only 1 thread can proceed at a time
        if (remainingTickets == 0) {
            counterLock.unlock(); // once thread passes, another can go
            break;
        }
        size_t myTicket = remainingTickets;
        remainingTickets--;
        counterLock.unlock(); // once thread passes here, another can go
        sleep_for(500); // simulate "selling a ticket"
        ...
```

Ticket Agents

```
static void sellTickets(size_t id, size_t& remainingTickets, mutex&
counterLock) {
    while (true) {
        counterLock.lock();  // only 1 thread can proceed at a time
        if (remainingTickets == 0) break;   // omitted unlock here
        size_t myTicket = remainingTickets;
        remainingTickets--;
        counterLock.unlock(); // once thread passes here, another can go
        sleep_for(500); // simulate "selling a ticket"
        cout << oslock << "Thread #" << id << " sold a ticket ("
             << myTicket - 1 << " remain)." << endl << osunlock;
    }
    ...
```

What would happen if we forgot to unlock before exiting the loop?

Respond on PollEv:
pollev.com/cs111

What would happen if we forgot to unlock before exiting the loop?

Nobody has responded yet.

Hang tight! Responses are coming in.

Demo: `stalled-ticket-agents.cc`

Mutex Uses

Other times you need a mutex:

- When there are multiple threads **writing** to a variable
- When there is a thread **writing** and one or more threads **reading**

Note: data structures in particular are not always thread-safe – generally not safe to assume they are unless explicitly stated.

Why do you not need a mutex when there are no writers (only readers)?

Multiple Mutexes

It's possible to have more than one mutex per program – e.g. to limit access to separate and unrelated critical sections.

```
void func1(int& counter1,
                mutex& counter1Lock) {
    counter1Lock.lock();
    counter1++;
    counter1Lock.unlock();
}
```

```
void func2(int& counter2,
                mutex& counter2Lock) {
    counter2Lock.lock();
    counter2--;
    counter2Lock.unlock();
}
```

```
int main() {
    int counter1 = 0;
    int counter2 = 0;
    mutex counter1Lock;
    mutex counter2Lock;
    thread t1(func1, ref(counter1), ref(counter1Lock));
    thread t2(func2, ref(counter2), ref(counter2Lock));
    ... // make more threads that also call these functions
```

Multiple Mutexes

It's possible to have more than one mutex per program – e.g. to limit access to separate and unrelated critical sections.

```
void func1(int& counter1,
                mutex& counter1Lock) {
    counter1Lock.lock();
    counter1++;
    counter1Lock.unlock();
}
```

```
void func2(int& counter2,
                mutex& counter2Lock) {
    counter2Lock.lock();
    counter2--;
    counter2Lock.unlock();
}
```

```
int main() {
    int counter1 = 0;
    int counter2 = 0;
    mutex counter1Lock;
    mutex counter2Lock;
    thread t1(thread1, 
    thread t2(thread2, 
    ... // make more threads that also call these functions
```

Ok for a thread to modify counter1 and another thread to modify counter2 concurrently, but not ok for two threads to both modify counter1, or both modify counter2.

Multiple Mutexes

It's possible to have more than one mutex per program – e.g. to limit access to separate and unrelated critical sections.

```
void func1(int& counter1,
                mutex& counter1Lock) {
    counter1Lock.lock();
    counter1++;
    counter1Lock.unlock();
}
```

```
void func2(int& counter2,
                mutex& counter2Lock) {
    counter2Lock.lock();
    counter2--;
    counter2Lock.unlock();
}
```

```
int main() {
    int counter1 = 0;
    int counter2 = 0;
    mutex counter1Lock;
    mutex counter2Lock;
    thread t1(thread1, re
    thread t2(thread2, ref(counter2), ref(counter2Lock));
    ... // make more threads that also call these functions
```

Rule of thumb: we usually create a mutex for each single variable or critical section that we must limit thread access to.

Mutexes Summary

A **mutex** (”mutual exclusion”) is a type of variable meant to be shared across threads, and which can be owned by only 1 thread at a time.

- lets us enforce this pattern of only 1 thread having access to something.
- Also known as a *lock* (there are other types of locks as well)
- A way to add a *constraint* to your program: “only one thread may access or execute this at a time”.
- You make a mutex for each distinct thing you need to limit access to.

Plan For Today

- **Recap:** threads and overselling tickets
- Mutexes
- **Deadlock**
- Dining Philosophers

```
cp -r /afs/ir/class/cs111/lecture-code/lect13 .
```

Deadlock

Deadlock occurs when multiple threads are all blocked, waiting on a resource owned by one of the other threads. None can make progress! Example:

Thread A	Thread B
`mutex1.lock();`	`mutex2.lock();`
`mutex2.lock();`	`mutex1.lock();`
`...`	`...`

E.g. if thread A executes 1 line, then thread B executes 1 line, deadlock!

One prevention technique - prevent circularities: all threads request resources in the same order (e.g., always lock mutex1 before mutex2.)

Another – limit number of threads competing for a shared resource

Plan For Today

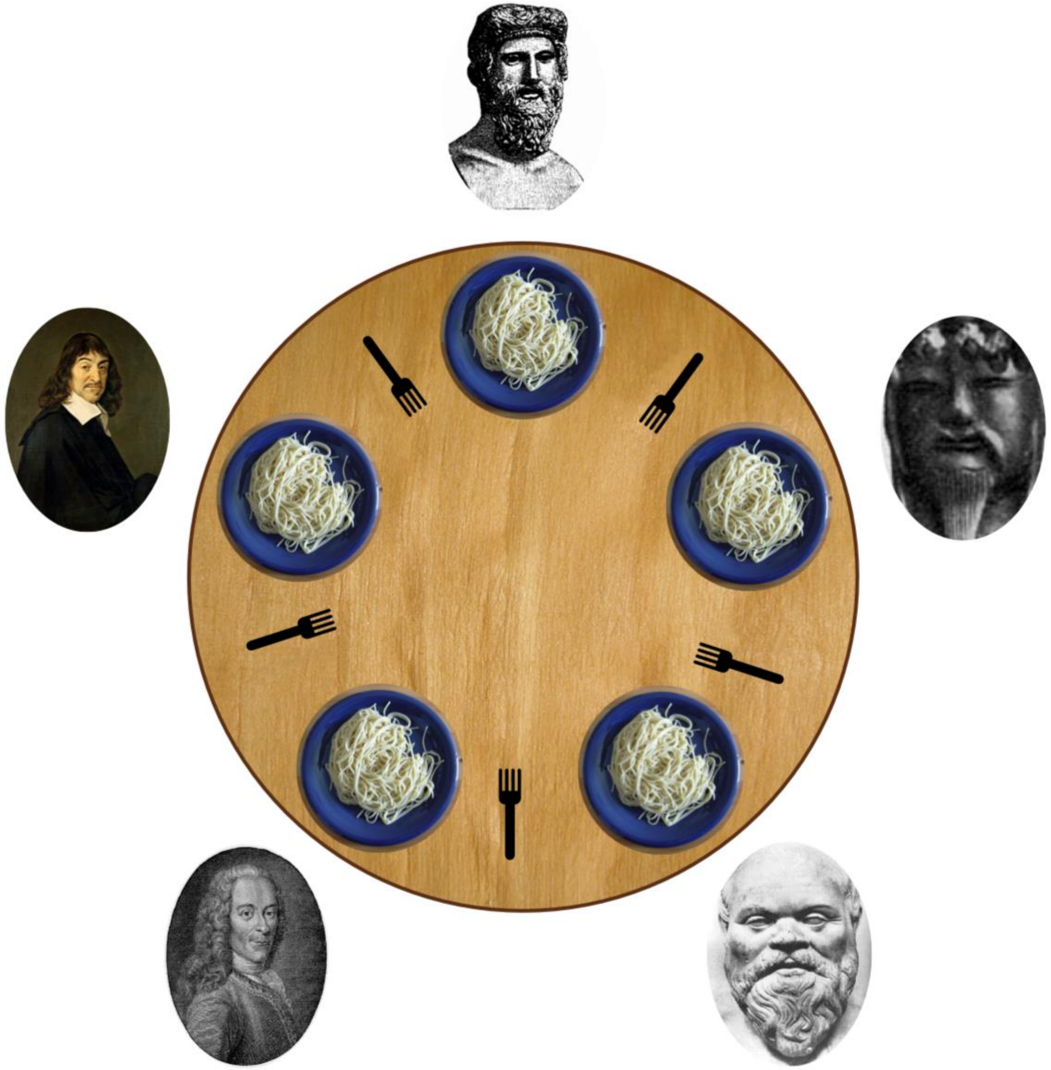
- **Recap:** threads and overselling tickets
- Critical Sections
- Mutexes
- Deadlock
- **Dining Philosophers**

```
cp -r /afs/ir/class/cs111/lecture-code/lect13 .
```

Deadlock Example: Dining Philosophers Simulation

- Five philosophers sit around a **circular table**, eating spaghetti
- There is **one fork** for each of them
- Each philosopher **thinks, then eats**, and repeats this **three times** for their three daily meals.
- **To eat**, a philosopher must grab the fork on their left *and* the fork on their right. Then they chow on spaghetti to nourish their big, philosophizing brain.
- When they're full, they put down the forks in the same order they picked them up and return to thinking for a while.
- **To think**, a philosopher keeps to themselves for some amount of time. Sometimes they think for a long time, and sometimes they barely think at all.

Dining Philosophers



https://commons.wikimedia.org/wiki/File:An_illustration_of_the_dining_philosophers_problem.png

Dining Philosophers

Goal: we must encode resource constraints into our program.

Example: for a given fork, how many philosophers can use it at a time? **One**.

How can we encode this into our program? Make a mutex for each fork.

Dining Philosophers

```
static void philosopher(size_t id, mutex& left, mutex&
right) { ... }

int main(int argc, const char *argv[]) {
    mutex forks[kNumForks];
    thread philosophers[kNumPhilosophers];
    for (size_t i = 0; i < kNumPhilosophers; i++) {
        philosophers[i] = thread(philosopher, i,
                    ref(forks[i]),
                    ref(forks[(i + 1) % kNumPhilosophers]));
    }
    for (thread& p: philosophers) p.join();
    return 0;
}
```

Dining Philosophers

A philosopher thinks and eats, and repeats this 3 times.

```
static void philosopher(size_t id, mutex& left, mutex&
right) {
    for (size_t i = 0; i < kNumMeals; i++) {
        think(id);
        eat(id, left, right);
    }
}
```

Dining Philosophers

think is modeled as sleeping the thread for some amount of time.

```
static void think(size_t id) {
    cout << oslock << id << " starts thinking."
         << endl << osunlock;
    sleep_for(getThinkTime());
    cout << oslock << id << " all done thinking. "
         << endl << osunlock;
}
```

Dining Philosophers

eat is modeled as grabbing the two forks, sleeping for some amount of time, and putting the forks down.

```
static void eat(size_t id, mutex& left, mutex& right) {
    left.lock();
    right.lock();
    cout << oslock << id << " starts eating om nom nom
nom." << endl << osu
    sleep_for(getEat
    cout << oslock <
         << osunlock
    left.unlock();
    right.unlock();
}
```

Spoiler: there is a race condition here that leads to **deadlock** – deadlock occurs when multiple threads are all blocked, waiting on a resource owned by one of the other blocked threads. When could this happen?

Food For Thought

What if: all philosophers grab their left fork and then go off the CPU?

- Deadlock! All philosophers will wait on their right fork, which will never become available
- **Testing our hypothesis**: insert a **sleep_for** call in between grabbing the two forks
- We should be able to insert a **sleep_for** call anywhere in a thread routine and have no concurrency issues. Let's try it!

dining-philosophers-with-deadlock.cc

Food For Thought

What if: all philosophers grab their left fork and then go off the CPU?

- Deadlock! All philosophers will wait on their right fork, which will never become available
- We (incorrectly) assumed that at least one philosopher is always able to pick up both of their forks.

dining-philosophers-with-deadlock.cc

Encoding Resource Constraints

Goal: we must encode resource constraints into our program.

Example: how many philosophers can *try* to eat at the same time? (Or alternatively, how many philosophers can *eat* at the same time?)

How can we encode this into our program?

More next time…

Recap

- **Recap:** Threads
- Critical Sections
- Mutexes
- Deadlock
- Dining Philosophers

Lecture 13 takeaway: A mutex ("lock") can help us limit critical sections to 1 thread at a time. A thread can lock a mutex to take ownership of it, and unlock it to give it back. Locking a locked mutex will block the thread until the mutex is available. We must watch out for race conditions!

Next time: condition variables

```
cp -r /afs/ir/class/cs111/lecture-code/lect13 .
```