CS111, Lecture 12
Multithreading Introduction

Optional reading:

Operating Systems: Principles and Practice (2^{nd} Edition): Chapter 4 and Chapter 5 up through Section 5.1

😷 masks required

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

CS111 Topic 3: Multithreading

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

Why is answering this question important?

- Helps us understand how a single process can do multiple things at the same time, a technique used in various software (today)
- Provides insight into *race conditions*, unpredictable orderings that can cause undesirable behavior, and how to fix them (next few lectures)
- Allows us to see how the OS schedules and switches between tasks (after midterm)

assign4: implement several multithreaded programs while eliminating race conditions

CS111 Topic 3: Multithreading, Part 1

Multithreading Introduction	→	Race conditions and locks	→	Locks and Condition Variables	→	Multithreading Patterns
This Lecture		**Next Lecture**		**Lecture 14**		**Lecture 15**

assign4: implement several multithreaded programs while eliminating race conditions!

Learning Goals

- Learn about how threads allow for concurrency within a single process
- Understand the differences between threads and processes
- Discover some of the pitfalls of threads sharing the same virtual address space

Plan For Today

- Introducing multithreading
- **Example:** greeting friends
- Race conditions
- Threads share memory
- **Example:** selling tickets

```
cp -r /afs/ir/class/cs111/lecture-code/lect12 .
```

Plan For Today

- **Introducing multithreading**
- **Example:** greeting friends
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```

From Processes to Threads

Multiprocessing has allowed us to spawn other processes to do tasks or run programs

- Powerful; can execute/wait on other programs, secure (separate memory space), communicate with pipes and signals
- But limited; interprocess communication is cumbersome, hard to share data/coordinate
- Is there another way we can have concurrency beyond multiprocessing that handles these tradeoffs differently?

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
- Multithreading is common to parallelize tasks, especially on multiple cores
- In C++: spawn a thread using **thread()** and the **thread** variable type and specify what function you want the thread to execute (optionally passing parameters!)
- Each thread operates within the same process, so they *share a virtual address space* (!) (globals, heap, pass by reference, etc.)
- The processes's stack segment is divided into a "ministack" for each thread.
- In the OS, threads are actually the unit of concurrency, not processes (more on this later)
- Many similarities between threads and processes, but some key differences

Threads vs. Processes

Processes:

- isolate virtual address spaces (good: security and stability, bad: harder to share info)
- can run external programs easily (fork-exec) (good)
- harder to coordinate multiple tasks within the same program (bad)

Threads:

- share virtual address space (bad: security and stability, good: easier to share info)
- can't run external programs easily (bad)
- easier to coordinate multiple tasks within the same program (good)

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 upon execution
- **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();
}
```

Plan For Today

- Introducing multithreading
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```
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```

Our First Threads Program

```
static void greeting(size_t i) {
    cout << "Hello, world! I am thread " << i << endl;
}

...
```

friends.cc

Our First Threads Program

```
static const size_t kNumFriends = 6;

int main(int argc, char *argv[]) {
    cout << "Let's hear from " << kNumFriends << " threads." << endl;

    thread friends[kNumFriends];
    for (size_t i = 0; i < kNumFriends; i++) {
        friends[i] = thread(greeting, i);
    }

    // Wait for threads
    for (size_t i = 0; i < kNumFriends; i++) {
        friends[i].join();
    }

    cout << "Everyone's said hello!" << endl;
    return 0;
}
```

C++ Thread

We can make an array of threads as follows:

```
// declare array of empty thread handles
thread friends[5];

// Spawn threads
for (size_t i = 0; i < 5; i++) {
    friends[i] = thread(myFunc, arg1, arg2);
}
```

We can also initialize an array of threads as follows (note the loop by reference):

```
thread friends[5];
for (thread& currFriend : friends) {
    currFriend = thread(myFunc, arg1, arg2);
}
```

Plan For Today

- Introducing multithreading
- **Example:** greeting friends
- **Race conditions**
- Threads share memory
- **Example:** selling tickets

```
cp -r /afs/ir/class/cs111/lecture-code/lect12 .
```

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.
- A *thread-safe* function is one that will always execute correctly, even when called concurrently from multiple threads.
- **printf** is thread-safe, but **operator<<** is *not*. This means 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;
```

Our First Threads Program

```
static void greeting(size_t i) {
    cout << oslock << "Hello, world! I am thread " << i << endl <<
osunlock;
}

...
```

friends.cc

Plan For Today

- Introducing multithreading
- **Example:** greeting friends
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```
cp -r /afs/ir/class/cs111/lecture-code/lect12 .
```

Threads Share Memory

Unlike parent/child processes, threads execute in the same virtual address space

- This means we can e.g. pass parameters by reference and have all threads access/modify them!
- To pass by reference with **thread()**, we must use the special **ref()** function around any reference parameters:

```
static void greeting(size_t& i) {
    ...
}

for (size_t i = 0; i < kNumFriends; i++) {
    friends[i] = thread(greeting, ref(i));
}
```

friends.cc

Threads Share Memory

- Here, all threads are referencing the same copy of **i**, which is updated in the **for** loop. It could be that by the time the threads access it, it's already been incremented all the way to 6!
- While in this example we can just pass by copy, we must keep an eye out for the consequences of shared memory.

Plan For Today

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```

Parallelizing Tasks

Threads allow a process to parallelize a program across multiple cores.

- Consider a scenario where we want to sell 250 tickets and have 10 cores
- **Simulation**: let each thread help sell tickets until none are left

Parallelizing Tasks

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

```
const size_t kNumTicketAgents = 10;
int main(int argc, const char *argv[]) {
    thread ticketAgents[kNumTicketAgents];
    size_t remainingTickets = 250;

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

    for (size_t i = 0; i < kNumTicketAgents; i++) {
        ticketAgents[i].join();
    }
    cout << "Ticket selling done!" << endl;
    return 0;
}
```

Demo: `confused-ticket-agents.cc`

Overselling Tickets

```
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 might have caused us to oversell tickets?

Respond with your thoughts on PollEv:
pollev.com/cs111 or text CS111 to 22333 once to join.

What might have caused us to oversell tickets?

Race Condition: Overselling Tickets

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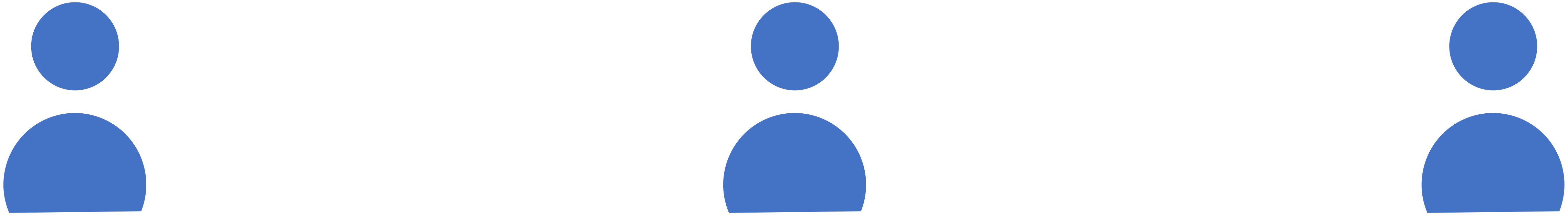
             << remainingTickets << " remain)." << endl << osunlock;
    }
    cout << oslock << "Thread #" << id
    << " sees no remaining tickets to sell and exits." << endl << osunlock;
}
```

remainingTickets = 1



Thread #1 Thread #2 Thread #3

Race Condition: Overselling Tickets

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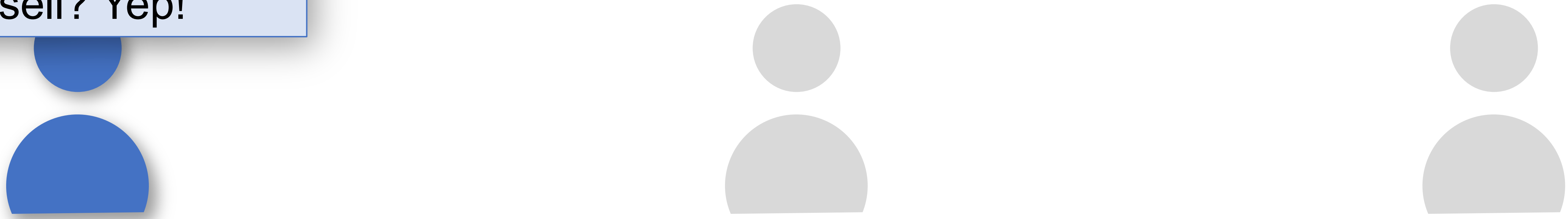
}
```

remainingTickets = 1

Are there tickets to sell? Yep!



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Race Condition: Overselling Tickets

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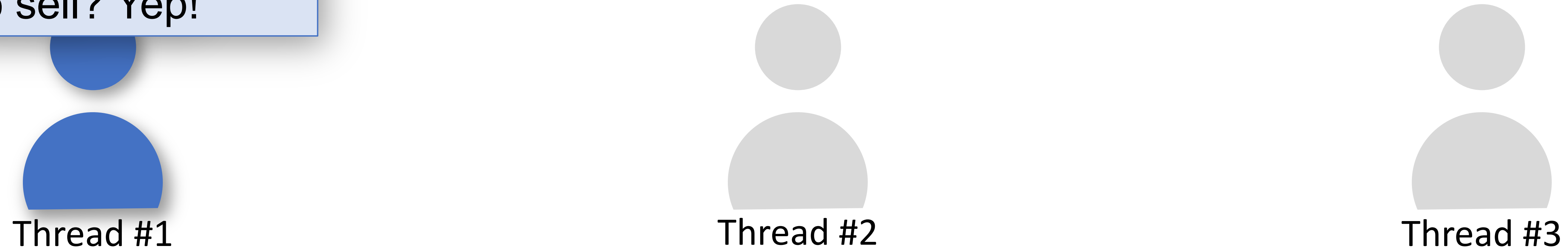

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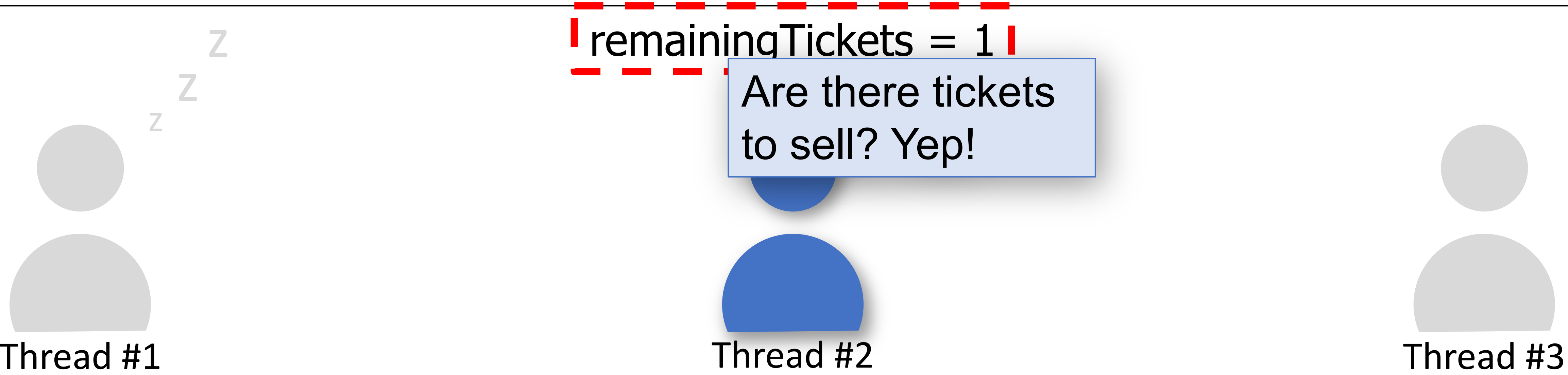

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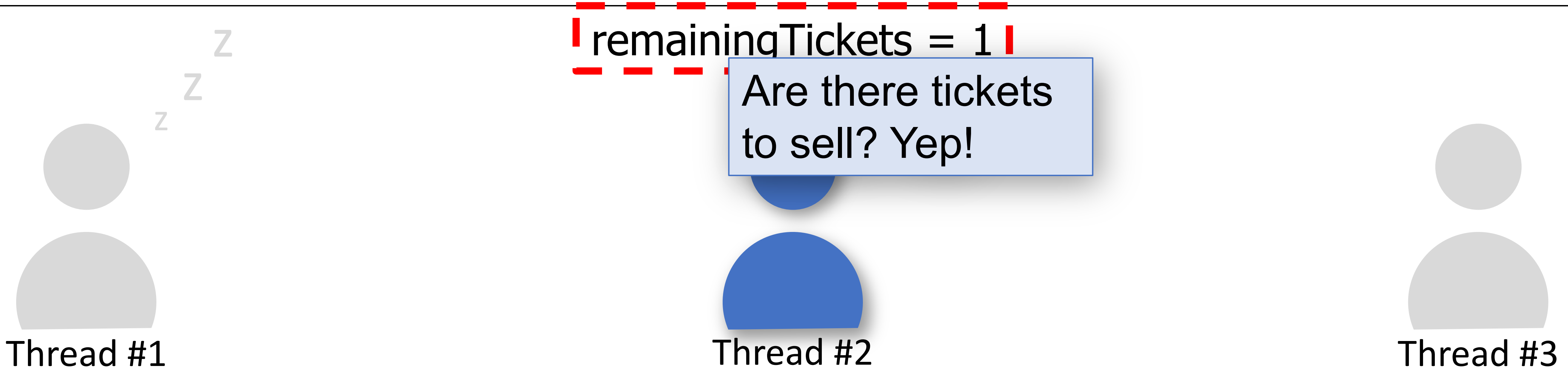

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             << remainingTickets << " remain)." << endl << osunlock;
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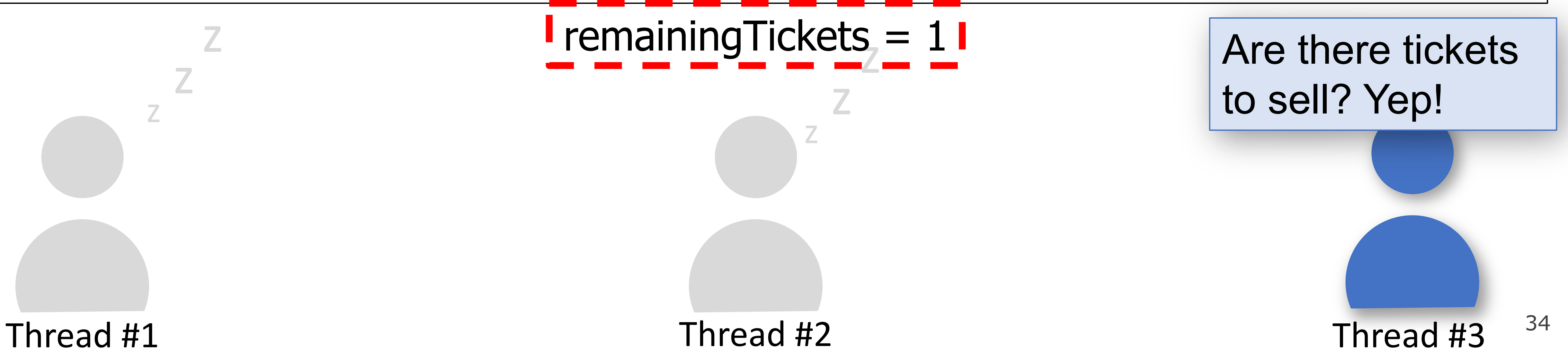

Race Condition: Overselling Tickets

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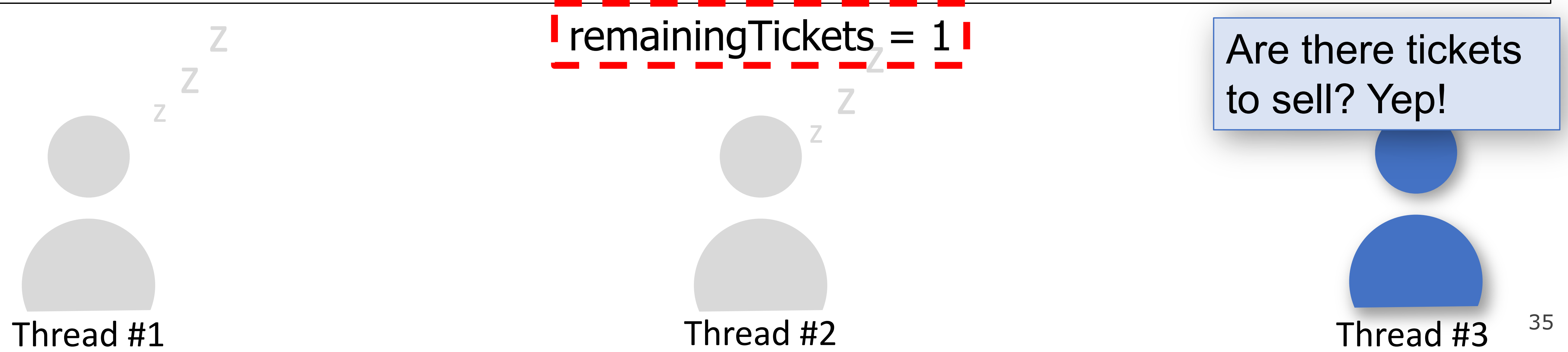

Race Condition: Overselling Tickets

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        remainingTickets--;
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             << remainingTickets << " remain)." << endl << osunlock;
    }
    cout << oslock << "Thread #" << id
    << " sees no remaining tickets to sell and exits." << endl << osunlock;
}
```

remainingTickets = 0

Let's sell a ticket!

Thread #1

Thread #2

Thread #3

Race Condition: Overselling Tickets

```
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;
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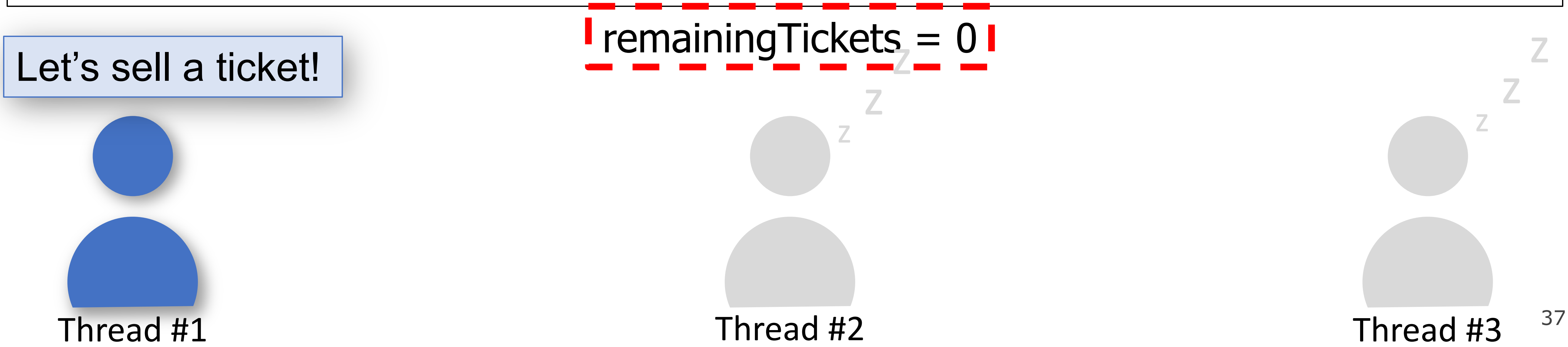
}
```



Race Condition: Overselling Tickets

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             << remainingTickets << " remain)." << endl << osunlock;
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    cout << oslock << "Thread #" << id
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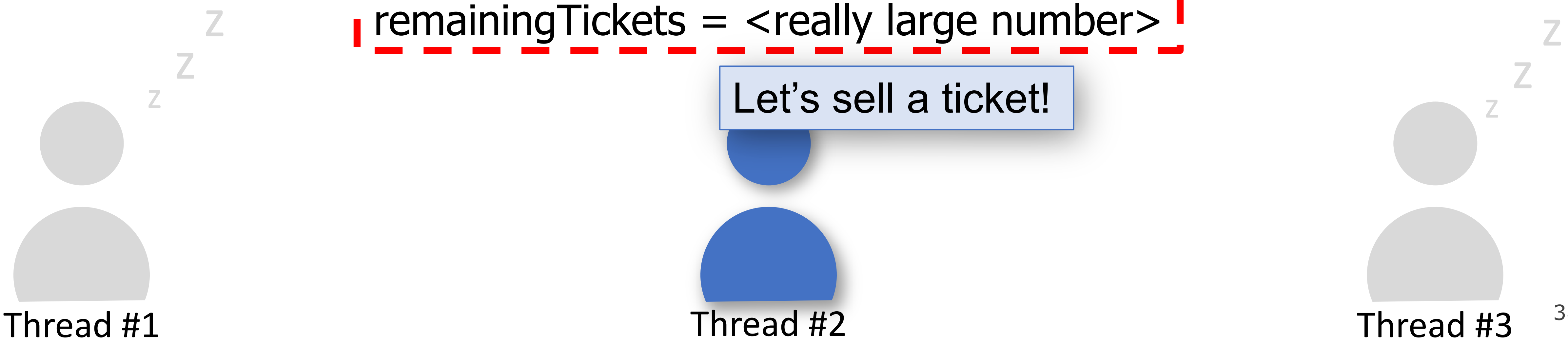
}
```

remainingTickets = <really large number>



Race Condition: Overselling Tickets

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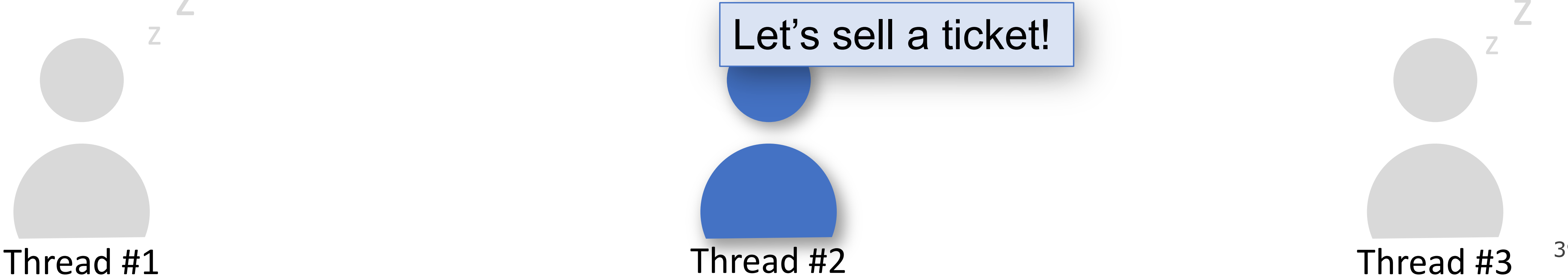
}
```

remainingTickets = <really large number>



Race Condition: Overselling Tickets

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        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;
}
```

remainingTickets = <really large number - 1>

Let's sell a ticket!

Thread #1

Thread #2

Thread #3

Race Condition: Overselling Tickets

```
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;
}
```

remainingTickets = <really large number - 1>

Race Condition: Overselling Tickets

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--;
        ...
    }
    ...
}
```

- Atomicity: externally, the code has either executed or not; external observers do not see any intermediate states mid-execution.
- We want a thread to do the entire check-and-sell operation **uninterrupted** by other threads.

Atomicity

- C++ statements aren't inherently atomic.
- Even single C++ statements like **remainingTickets--** take multiple operations and could be interrupted in the middle. (multiple assembly instructions to get value, decrement value, and save updated value).
- Even if we altered the code as below, it still wouldn't fix the problem:

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

It would be nice if we could allow only one thread at a time to execute a region of code.

Recap

- Introducing multithreading
- **Example:** greeting friends
- Race conditions
- Threads share memory
- **Example:** selling tickets

Lecture 12 takeaway: A process can have multiple threads executing tasks simultaneously. Threads share the same virtual address space, and race conditions can cause unintended problems!

Next time: introducing mutexes

```
cp -r /afs/ir/class/cs111/lecture-code/lect12 .
```