Lecture 17: Synchronization
(Producer-Consumer, Condition Variables, Semaphores, Dining Philosophers)

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Revisiting Spinlocks

Spinlocks

- A spinlock is a simple lock where a thread constantly checks for lock availability.
- Imagine a single key to a critical section. The first thread to acquire the key can enter.
- Hardware instructions ensure atomic key exchange.

Two locking methods: one works, one fails

```
// 0 means unlocked, 1 means locked
int lock = 0;

void acquire_lock(int *lock) {
   while (*lock != 0) { }
   *lock = 1;
}

void release_lock(int *lock) {
   *lock = 0;
}

void *foo(void *arg) {
   acquire_lock(&lock);
   // Critical section: Do work here ...
   release_lock(&lock);
   return NULL;
}
```

```
// 0 means unlocked, 1 means locked
int lock = 0;

int xchg(int *addr, int newval) {
   int result;
   asm volatile (
      "lock xchg %0, %1"
      : "+m" (*addr), "=a" (result)
      : "1" (newval)
      : "cc"
   );
   return result;
}

void acquire_lock(int *lock) {
   while (xchg(lock, 1)) { }

   }

void release_lock(int *lock) {
   xchg(lock, 0);
   }

void *foo(void *arg) {
   acquire_lock(&lock);
   // Critical section: Do work here ...
   release_lock(&lock);
   return NULL;
}
```

Understanding Spinlocks Thoroughly

- `lock == 0`: free, no owner, try to acquire
- `lock == 1`: busy, owned by another thread, keep spinning

```
void acquire_lock(int *lock) {
   while (*lock != 0) {}
   *lock = 1;
}
```

```
void acquire_lock(int *lock) {
   while (xchg(lock, 1)) {}

   }
```

The single atomic instruction (xchg) ensures no race condition.

Rules for Acquiring a Lock: Take first, then verify

- **Do not wait.** Do not precheck whether the lock is free. Compete for the lock.
- **Just do it.** Perform the atomic acquire first, then check the result.

Take first, verify after?

Analogy: one bottle of water in the desert

Many people are thirsty in a desert. There is one bottle in a cabinet. If you stop to check whether the bottle is there, you are late. Like a spinlock, you reach for it first, then verify whether you got it. If not, try again.

This philosophy does not always work in real life. Sometimes we must verify early. If we do not, we will end up busy-waiting like a spinlock.

So what should we be?

Be Water

Recap: Spinlocks

Spinlocks

- A spinlock is a simple lock where a thread constantly checks for lock availability.
- Imagine a single key to a critical section. The first thread to acquire the key can enter.
- Hardware instructions ensure atomic key exchange.

Performance Issue

- Spinlocks can cause inefficiency, especially if many threads compete for the same lock, leading to frequent context switches (Grab first, verify later).
- If a thread holding the lock is swapped out, all other threads continue busy-waiting, wasting CPU resources, because the CPU still considers them active (either in the Running or Ready to Run state).

Recap: Mutexes and Futexes

Mutexes

- The lock is managed by the OS kernel.
- When a thread attempts to acquire a mutex that is already locked, the OS puts the thread to sleep (blocked state) instead of busy-waiting.
- The kernel wakes up the thread when the lock becomes available, preventing it from wasting CPU time while waiting for the lock.

Futexes

- A futex is a combination of spinlocks and mutexes.
- It starts with spinning and escalates to a kernel-based mutex when needed.
- This hybrid approach improves performance by reducing both busy-waiting in user space and context switches to the kernel.

Example: Mutex with 3 Threads (Sleep and Wake-up)

1. **Thread X** acquires the lock first and enters the critical section.
2. **Thread Y** and **Thread Z** attempt to acquire the lock but go into a sleep (blocked state) since the lock is already held by **X**.
3. Once **X** finishes and releases the lock, the OS wakes up **Y**, typically following a first-come, first-served policy (FIFO) or priority-based scheduling.
4. After Thread **Y** completes its critical section and releases the lock, the OS wakes up **Z**, which then acquires the lock.

- The waking mechanism is managed by the OS, which monitors the release of the lock and uses it as the signal to wake the next waiting thread.

The Essence of Collaborative Relationships

- Collaborative relationships are a combination of Competition Relationships and Dependency Relationships

Competition Relationships

- Involves access and modification of shared resources within threads
- When threads are independent
  - The main concern is to avoid Competition Relationships
  - Use synchronization mechanisms like Spinlocks and Mutex Locks
  - Ensure only one thread accesses the shared resource at a time
  - Avoid data inconsistency and race conditions
- Focus on safe access within threads

Dependency Relationships

- Involves execution order and causal relationships between threads
- When one thread must complete before another can execute
  - Use mechanisms like Condition Variables and Semaphores
  - Control the execution order of threads
  - Satisfy logical dependency requirements
- Focus on correct coordination between threads

Real-World Application

Core Question

- How do you coordinate multiple threads to handle tasks efficiently in real-world systems?

Example: E-commerce Platform Order Processing System

- **Order Validation:** Check product inventory, user balance, and coupon validity.
- **Payment Processing:** Deduct from user accounts or process third-party payments.
- **Inventory Update:** Deduct product stock to prevent overselling.
- **Logistics Arrangement:** Generate shipping orders and arrange delivery.
- **Notify Users:** Send confirmation emails or SMS to users.

Real-World Application (Cont.)

Challenges and Solutions

- **Managing Shared Resources (Competition)**:
  - Multiple threads updating inventory or user balances may cause race conditions.
  - **Solution:** Use Mutex locks to ensure only one thread modifies shared resources at a time.
  - Also, use transactions to roll back in case of failures, ensuring data consistency.
- **Managing Dependencies Between Threads (Dependency)**:
  - Notification threads must wait until order processing is complete.
  - **Solution:** Use condition variables or semaphores to signal thread progress and control execution order.
  - Task queues can be used to arrange execution based on dependencies.

Outline: How to Coordinate Threads

- Modeling Synchronization
- Producer-Consumer Problem
- Condition Variables
- Semaphores
- Dining Philosophers Problem

Synchronization Model

Synchronization

Definition: Two or more time-varying quantities maintain a defined relationship over time.

- iPhone/iCloud sync (phone vs. computer vs. cloud)
- Gearbox synchronizer (aligns fast and slow gear wheels)
- Synchronous motor (rotor speed equals magnetic field speed)
- Synchronous circuit (all flip-flops trigger on a clock edge at the same time)

Asynchronous = not synchronized

- Many of the above have asynchronous versions (asynchronous motors, circuits, threads)

Synchronization in Concurrent Programs

It is hard to keep concurrent programs “exactly consistent.”

Thread synchronization: at some point in time, all threads reach a mutually known state.

Think of threads as ourselves:

- Partner: “I’ll head out after I wash my hair / finish this game.”
- Labmate: “We’ll eat after I fix this bug.”
- Advisor: “We’ll discuss this after I return from the trip.”

Modeling Synchronization Problems

Producer-Consumer Problem

- A fundamental synchronization problem that allows you to solve 99.9% of real-world concurrency issues.

Dining Philosophers Problem

- Another classic problem that demonstrates how multiple entities share limited resources (like CPUs).

Key Tools

Condition Variables

- A flexible synchronization primitive that allows threads to wait until a specific condition is met.

Semaphores

- A more rigid mechanism used to control access to shared resources by multiple threads.

Producer-Consumer Problem

Producer-Consumer Problem

Producer ”O” and Consumer ”X”

Producer:

- Produces an item (”O”)
- Waits if storage is full
- Must be synchronized with the consumer

Consumer:

- Consumes an item (”X”)
- Waits if no item is available
- Synchronization ensures no consumption before production

- We need to ensure that the symbols (”O” and ”X”) are printed in a valid sequence:
- Example:
  - $n = 3$, OOOXXOXXOOO (valid)
  - $n = 3$, OOOOXXXX, OOXXX (invalid)

Why Producer-Consumer is Widely Representative

- Involves two types of threads: Producers (generate data) and Consumers (process data)
- Producers don't overflow the buffer and consumers don't try to consume data that's not yet available.

Challenges:

- Synchronization and mutual exclusion
- Managing dependencies and inter-thread communication

Initial Attempt

- Ensure the condition is met using mutex locks.
  - Have A Try: producer_consumer.c
- Stress Testing
  - Have A Try: producer_consumer.c
  - Command: `./producer_consumer 2 | python3 pc_checker.py 2`
- **Bad News:**
  - After running the program for several hours, it actually failed!
  - The issue is difficult to reproduce and to fix.
  - Concurrent programming is highly challenging.
- **Good News:**
  - The problem occurred while it was in your hands.
  - Avoid taking shortcuts and always stick to the most reliable methods.

Condition Variables: A Universal Synchronization Method

The Essence of Synchronization

- The essence of synchronization is ensuring that multiple threads or processes reach a **known state** at the same time, so that they can proceed in coordination.

Example:

- Imagine two people (threads) trying to meet for dinner (a task).
- One is playing a game (task A), and the other is fixing a bug (task B).
- They can't start dinner (synchronized task) until both have finished their tasks (**known state**).
- Even if one person finishes earlier, they must wait for the other.

Core Concept

- The core of synchronization is waiting for all necessary conditions to be met before proceeding together.

In-Class Quiz

Synchronization Example

- From the very beginning when you started working with threads, you were already using synchronization.
- Can you find which part is synchronization?

```
pthread_t t1, t2;

pthread_create(&t1, NULL, foo, NULL);
pthread_create(&t2, NULL, foo, NULL);

pthread_join(t1, NULL);
pthread_join(t2, NULL);
```

Synchronization Example (Cont.)

- From the very beginning when you started working with threads, you were already using synchronization.
- Can you find which part is synchronization?
  - `pthread_join` ensures that the main thread waits for the other threads to finish before continuing.
  - This is a form of synchronization because it guarantees that all threads reach a known state (completion) before the program proceeds.

```
pthread_t t1, t2;

pthread_create(&t1, NULL, foo, NULL);
pthread_create(&t2, NULL, foo, NULL);

pthread_join(t1, NULL);
pthread_join(t2, NULL);
```

Problems with Initial Attempt

```
void *Tproduce(void *arg) {
  while (1) {
retry:
    pthread_mutex_lock(&lk);
    if (count == n) {
      pthread_mutex_unlock(&
    lk);
      goto retry;
    }
    count++;
    printf("O");
    pthread_mutex_unlock(&lk
    );
  }
  return NULL;
}
```

```
void *Tconsume(void *arg) {
  while (1) {
retry:
    pthread_mutex_lock(&lk);
    if (count == 0) {
      pthread_mutex_unlock(&
    lk);
      goto retry;
    }
    count--;
    printf("X");
    pthread_mutex_unlock(&lk
    );
  }
  return NULL;
}
```

Problems with Initial Attempt (Cont.)

- **Busy Waiting:** Both producer and consumer continuously retry when the buffer is full or empty. This leads to a waste of CPU resources.
- **Resource Contention:** Multiple threads constantly lock and unlock the same mutex without meaningful progress when conditions are not met, causing unnecessary contention.
- **High CPU Utilization:** The goto retry causes the threads to remain in a tight loop, consuming CPU cycles even when they should be waiting.

Why Avoid Busy Waiting?

"Haste makes waste."

Constant spinning and busy waiting lead to errors. Slowing down with condition variables reduces mistakes.

- Have A Try: condition_varaibles.c

Tip 1: pthread_cond_wait

```
void *Tproduce(void *arg) {
  while (1) {
    pthread_mutex_lock(&lk);
    while (count == n) {
      pthread_cond_wait(&
    not_full, &lk);
    }
    count++;
    printf("O");
    pthread_cond_signal(&
    not_empty);
    pthread_mutex_unlock(&lk
    );
  }
  return NULL;
}
```

```
void *Tconsume(void *arg) {
  while (1) {
    pthread_mutex_lock(&lk);
    while (count == 0) {
      pthread_cond_wait(&
    not_empty, &lk);
    }
    count--;
    printf("X");
    pthread_cond_signal(&
    not_full);
    pthread_mutex_unlock(&lk
    );
  }
  return NULL;
}
```

Tip 1: pthread_cond_wait (Cont')

```
void *Tproduce(void *arg) {
  while (1) {
    pthread_mutex_lock(&lk);
    while (count == n) {
      pthread_cond_wait(&
    not_full, &lk);
    }
    ...
}
```

```
void *Tconsume(void *arg) {
  while (1) {
    pthread_mutex_lock(&lk);
    while (count == 0) {
      pthread_cond_wait(&
    not_empty, &lk);
    }
    ...
}
```

- `pthread_cond_wait`: A thread goes to sleep and releases the mutex while waiting for a condition (e.g., buffer not empty/full).
- `pthread_cond_wait` must be used with a mutex.
  - The thread must first acquire the mutex lock before calling `pthread_cond_wait`.
    - `pthread_cond_wait` only handles waiting for a condition to be met, it does not handle acquiring the lock.

Tip 2: pthread_cond_signal (Cont')

```
void *Tproduce(void *arg) {
    ...
    pthread_cond_signal(&
   not_empty);
    ...
}
```

```
void *Tconsume(void *arg) {
    ...
    pthread_cond_signal(&
   not_full);
    ...
}
```

- `pthread_cond_signal`: Wake up one waiting thread when the condition is met (e.g., an item is produced or consumed).
  - Which thread is woken up?
    - If multiple threads are waiting, the OS decides which thread to wake up based on a scheduling policy, usually first-come, first-served (FIFO) or priority-based.

Tip 3: You can also use pthread_cond_broadcast

```
void *Tproduce(void *arg) {
    ...
    pthread_cond_broadcast(&
    not_empty);
    ...
}
```

```
void *Tconsume(void *arg) {
    ...
    pthread_cond_broadcast(&
    not_full);
    ...
}
```

- `pthread_cond_broadcast`: Wake up all waiting threads when the condition is met.
    - When to use `pthread_cond_broadcast`?
        - Use `pthread_cond_broadcast` when a global state changes that affects all threads.

The Most Important Tip: Two Condition Variables!

```
pthread_cond_t not_full = PTHREAD_COND_INITIALIZER;
pthread_cond_t not_empty = PTHREAD_COND_INITIALIZER;
```

- Avoid waking the same type of thread:
  - Producers should not wake other producers, and consumers should not wake other consumers.
  - Producer thread:
    - Waits on `not_full` when the buffer is full.
    - Signals `not_empty` after producing an item, allowing consumers to wake up and consume.
  - Consumer thread:
    - Waits on `not_empty` when the buffer is empty.
    - Signals `not_full` after consuming an item, allowing producers to wake up and produce.

Deadlock with Single Condition Variable Example

```
pthread_cond_t buffer_change = PTHREAD_COND_INITIALIZER;
```

- Scenario:
  - Buffer size (n = 1) Have A Try: condition_variable_deadlock.c
  - 2 producer threads (P1, P2) and 2 consumer threads (C1, C2)
  - The buffer is empty and C1 and C2 are sleeping
  - P2 is also sleeping due to the buffer being full previously.
- Process:
  - P1 produces an item, filling the buffer (count = 1), then signals 'buffer_change' (P1 is ready to run and not sleeping)
  - The signal wakes up P2
  - P2 is woken up, but finds the buffer is full, so P2 goes back to sleep without sending any signal
  - P1 is scheduled by the OS, but P1 also finds the buffer is full and goes to sleep without sending any signal
  - The OS may now try to schedule C1 or C2, but they are still sleeping, waiting for the signal that hasn't been sent
- Result:
  - All threads are now in a sleeping state, resulting in deadlock

Cause of Single Condition Variable Deadlock

- All threads rely on a signal to wake up, rather than automatically waking when the condition becomes true.
- A single condition variable may wake up the same type of thread repeatedly.
- No further signals can be sent, leading to deadlock.

- Role of the Operating System:
  - Manages thread scheduling and CPU time allocation
  - Does not manage thread synchronization or signal passing
  - Cannot wake threads
- Thread Communication:
  - Synchronization happens through condition variables (signals) and mutexes
  - Signals must be explicitly sent and received between threads
  - Proper signal passing is critical for correct thread coordination

Why Two Condition Variables Prevent Deadlock

- A producer's ‘not_empty‘ signal only wakes consumers.
- A consumer's ‘not_full‘ signal only wakes producers.

- At least one thread type can always proceed and change the buffer state
- Eliminates the possibility of all threads waiting at the same time

More Robust Design

- Use two condition variables: `not_empty` for consumers, `not_full` for producers.
- Always wait with `while` to recheck the predicate under the mutex.
- Use `signal` to wake the right side only. Use `broadcast` only when you are unsure.
- Add `assert` in development to catch logic bugs early.

```
void *Tproduce(void *arg) {
    ...
    while (count == n) {
      pthread_cond_wait(&
    not_full, &lk);
    }
    assert(count < n);
    ...
    pthread_cond_broadcast(&
    not_empty);
    ...
}
```

```
void *Tconsume(void *arg) {
    ...
    while (count == 0) {
      pthread_cond_wait(&
    not_empty, &lk);
    }
    assert(count > 0);
    ...
    pthread_cond_broadcast(&
    not_full);
    ...
}
```

A Quirky Interview Question

- There are three threads that print “<”, “>”, and “_”.
- Synchronize them so the output is always sequences of <><_ and ><>_

Using condition variables, answer three questions:

- What is the condition to print “<”?
- What is the condition to print “>”?
- What is the condition to print “_”?

Have A Try: fish.c

Semaphores

Limitations of Condition Variables

- Imagine a buffer with 5 slots, initially empty / full.
- If 5 producer / consumer threads want to produce / consume ’O’, a condition variable only allows one thread to produce / consume at a time.
- But what if we want multiple threads to produce / consume ’O’ concurrently?

Semaphores

- **Semaphore** is a synchronization mechanism used to control access to shared resources in concurrent systems.
- It acts as an integer counter that tracks the availability of a limited number of resources.
- It can allow multiple threads to enter the critical section simultaneously.
    - However, you must ensure that there are no race conditions when multiple threads are in the critical section. If there are no such issues, semaphores can be used effectively.

Semaphore Operations

- Semaphores were first introduced by **Edsger W. Dijkstra** in the 1960s.
- Semaphores operate similarly to **condition variables**, allowing threads to wait and be signaled based on certain conditions.

Semaphores have two primary operations:

- **P operation** (from Dutch *proberen*, meaning ”to try”):
  - Decreases the semaphore’s value by 1.
  - If the value becomes negative, the thread performing the P operation is blocked until the semaphore’s value becomes positive.
- **V operation** (from Dutch *verhogen*, meaning ”to increment”):
  - Increases the semaphore’s value by 1.
  - If there are any blocked threads, the V operation wakes up one of them.

Code Comparison

```
// Condition Variables
void *Tproduce(void *arg) {
  while (1) {
    pthread_mutex_lock(&lk);
    while (count == n) { pthread_cond_wait(&not_full, &lk);}
    count++;
    printf("O");
    pthread_cond_signal(&not_empty);
    pthread_mutex_unlock(&lk);
  }
  return NULL;
}
void *Tconsume(void *arg) {
  while (1) {
    pthread_mutex_lock(&lk);
    while (count == 0) { pthread_cond_wait(&not_empty, &lk);}
    count--;
    printf("X");
    pthread_cond_signal(&not_full);
    pthread_mutex_unlock(&lk);
  }
  return NULL;
```

Code Comparison (Cont.)

```
// Semaphores
void *Tproduce(void *arg) {
  while (1) {
    P(&empty_sem);
    pthread_mutex_lock(&mutex);
    printf("O");
    pthread_mutex_unlock(&mutex);
    V(&full_sem);
  return NULL;
}

void *Tconsume(void *arg) {
  while (1) {
    P(&full_sem);
    pthread_mutex_lock(&mutex);
    printf("X");
    pthread_mutex_unlock(&mutex);
    V(&empty_sem);
  }
  return NULL;
}
```

Semaphores vs Condition Variables: Key Differences

- **Resource Management:**
  - Semaphores have a built-in counter to manage resource availability.
  - Condition variables do not track resource availability. The programmer must manage resource state manually.
- **Wait/Wake Mechanism:**
  - Semaphores use the **P (wait)** and **V (signal)** operations to automatically handle the blocking and unblocking of threads.
  - Condition variables use **pthread_cond_wait()** to put a thread to sleep and **pthread_cond_signal()** or **pthread_cond_broadcast()** to wake up waiting threads.
- **Mutex Usage:**
  - Semaphores can be used with or without a mutex, allowing multiple threads to access the critical section simultaneously based on the semaphore's value.
  - Condition variables must be used with a mutex, typically allowing only one thread in the critical section at a time, even if multiple threads are woken up.

Have A Try: semaphore.c

Semaphores without Mutex

```
void *Tproduce(void *arg) {
  while (1) {
    P(&empty_sem);
    printf("O");
    V(&full_sem);
  }
  return NULL;
}
```

```
void *Tconsume(void *arg) {
  while (1) {
    P(&full_sem);
    printf("X");
    V(&empty_sem);
  }
  return NULL;
}
```

Have A Try: semaphore_no_mutex.c

- Producers and consumers only do two things: `P/V` operations and `printf`.
- The code has no real shared buffer, read/write indices, or shared counters written by multiple threads, so there is no critical section to protect.

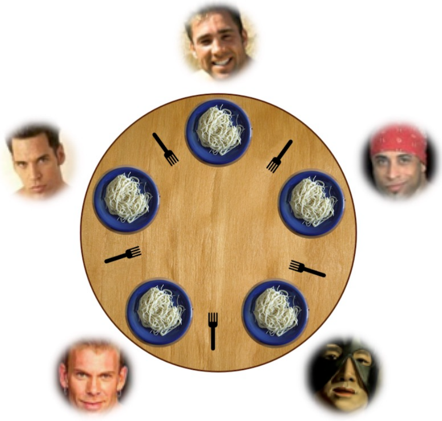
Considerations for Semaphore Usage

- If you plan to implement more complex buffer operations (e.g., actually storing data instead of just printing characters), you will need to use a mutex to avoid race conditions.
- While semaphores may seem convenient, they become less effective as more rules are added, making them harder to manage.
- It’s often better to use **condition variables** for complex synchronization needs.

Dining Philosophers Problem

Dining Philosophers Problem (E. W. Dijkstra, 1960)

- Philosophers (threads) alternate between thinking and eating.
- To eat, a philosopher must hold both the left and the right fork at the same time.
- If a fork is held by someone else, the philosopher must wait. How do we synchronize?
- How can we implement this using mutexes or semaphores?



A Failed Attempt

Have A Try: philosopher.c

```
void Tphilosopher(int id) {
    int lhs = (id + N - 1) % N;
    int rhs = id % N;
    while (1) {
        P(&avail[lhs]);
        printf("+ %d by T%d\n", lhs, id);
        P(&avail[rhs]);
        printf("+ %d by T%d\n", rhs, id);
        // Eat.
        // Philosophers are allowed to eat in parallel.
        printf("- %d by T%d\n", lhs, id);
        printf("- %d by T%d\n", rhs, id);
        V(&avail[lhs]);
        V(&avail[rhs]);
    }
}
```

When each philosopher grabs the left fork first, they all block waiting for the right fork, causing a deadlock.

A Working Pattern

If you want a working pattern, just use condition variables.

```
/* Try to take both forks */
pthread_mutex_lock(&mutex);

while (!(avail[lhs] && avail[rhs])) {
    pthread_cond_wait(&cv, &mutex);
}

avail[lhs] = avail[rhs] = false;    // reserve both

pthread_mutex_unlock(&mutex);

/* ... eat ... */

/* Release and notify */
pthread_mutex_lock(&mutex);
avail[lhs] = avail[rhs] = true;
pthread_cond_broadcast(&cv);        // wake all to recheck
pthread_mutex_unlock(&mutex);
```

No Semaphores: Let One Manager Handle the Forks

Leader / follower = producer / consumer

- A common pattern in distributed systems (e.g., HDFS): one coordinator grants access.
- Philosophers send requests; the waiter decides who may eat.

```
void Tphilosopher(int id) {
  send_request(id, EAT);
  P(allowed[id]); // The waiter hands the fork to the
    philosopher.
  philosopher_eat();
  send_request(id, DONE);
}

void Twaiter() {
  while (1) {
    (id, status) = receive_request();
    if (status == EAT) { ... }
    if (status == DONE) { ... }
  }
}
```

Forget the Fancy Synchronization Algorithms

You might worry that a single waiter (manager) is a performance bottleneck:

- A big table, everyone calling the waiter
- Premature optimization is the root of all evil (D. E. Knuth)

Start from the workload. Optimize only when needed.

- Eating time is usually much longer than the time to ask the waiter.
- If one manager cannot keep up, use more than one.
- Design the system so the coordinator does not become a bottleneck.
    - Millions of Tiny Databases (NSDI'20)

Takeaways

- Most of the synchronization problems you will face are just variations of the **Producer-Consumer problem**.
- Mastering **condition variables** is enough to handle most real-world scenarios.
- The rest is just icing on the cake.