ECE326

PROGRAMMING LANGUAGES

Lecture 18 : Concurrent Programming

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Concurrent Programming

- Multiple tasks execute simultaneously
- Thread
  - Independent sequence of execution
    - Has its own stack, but shares the heap with other threads
- Parallel computing
  - Threads executing at same physical time instant
    - Only possible if each thread runs on its own processor
- Concurrency
  - Threads may *interleave* on the same processor

Purpose

- Speed up program
  - Usually with more people, a job can get done faster
- Criteria for speed up
  - Threads can work relatively independently
    - Seldom need to wait for other threads
      - E.g. to access shared data
      - E.g. to wait for input produced by another thread
  - Threads are often waiting for IO (e.g. read from disk, network)
    - While one thread waits, other threads can still do work on processor
    - Only important if threads are sharing a processor

Closure

- Anonymous function
- Capture
  - Ability to use variables outside of closure
- Syntax
  - | *parameters...* | { *body* }

```
fn main() {
    let x = 5;
    let plus_x = |y| { x + y }; // x is captured by closure
    let z = plus_x(8);
    println!("x + y = {}", z);  // 13
}
```

Concurrent Programming

- Most programming languages provide *library support*
  - Creating and managing threads done through function calls
- Go has language support for creating threads

```
go f(x, y, z);  // starts a new thread (aka goroutine)
```

Concurrent Programming

- Most programming languages provide *library support*
  - Creating and managing threads done through function calls
  - E.g. Rust, C++, Python

```
use std::thread;
use std::time::Duration;

for i in 1..10 {
    thread::spawn(move || {
        println!("hi number {} from thread!", i);
        thread::sleep(Duration::from_millis(1));
    });
}
```

spawn can take a *closure* as argument

Ownership

- A thread can potentially live longer than its creator
  - By default, closures borrow outer variables
- Problem arises if closure references outer variable
  - Therefore, all outer variables must be “moved” into closure
    - If variable implements Copy trait, then it will be copied instead

```
fn main() {
	let v = vec![1, 2, 3];
	let handle = thread::spawn(move || {
		println!("Here's a vector: {:?}", v);
	});
	// you may no longer use ‘v’ here. main may exit first!
}
```

Basics

- A program always starts with one thread: **main**
- main creates new threads, and those can create more
- Creator *should* wait for the threads it created to end

```
fn main() {
    let handle = thread::spawn(|| {
        for i in 1..10 {
            println!("hi number {} from thread!", i);
            thread::sleep(Duration::from_millis(1));
        }
    });

    println!("hi from main!");
    handle.join().unwrap();  // wait for thread to finish
}
```

Does not need move if not capturing

Challenge

- Sharing data
  - Ownership
    - Threads need to jointly own an object
  - Updates to data can result in *race condition*
    - Caused by problematic interleaving of threads
    - Race condition can lead to unexpected and often incorrect results
      - Difficult to avoid because we cannot control order of thread execution
- Synchronization
  - Threads may need to communicate with each others
  - One thread may need to wait for another thread to advance

Reference Counting

- A commonly used technique to share an object
- Analogy
  - First person to walk into living room turns on TV
  - Subsequent people entering can sit down immediately
  - Last person to leave will turn off the TV
- Reference Counting
  - Creator of object sets reference count to 1
    - Others will increment count before use
  - Everyone decrements count after use
    - If count is 0, free the object

Smart Pointer

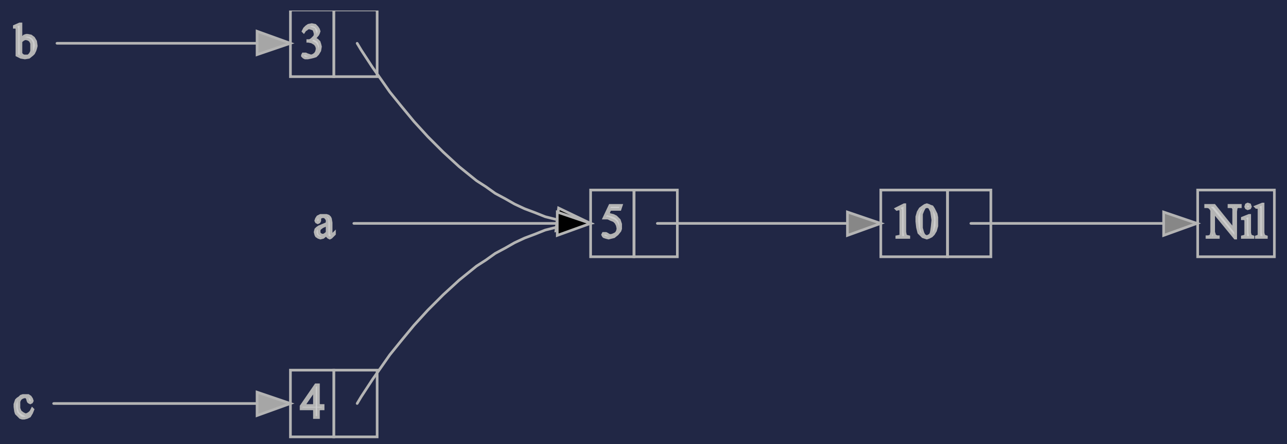
- A wrapper class over a pointer, and acts like a pointer
- C++ Example
  - unique_ptr
    - Automatically frees pointed-to object when it goes out of scope
- shared_ptr
  - A reference counting smart pointer
  - Allows multiple threads to share pointed-to object
  - Last reference holder will delete the object
    - May not be the original creator of the object

Rc<T>

- Allows sharing data in single-threaded setting

```rust
enum List { Cons(i32, Rc<List>), Nil, }
use List::{Cons, Nil};
use std::rc::Rc;

fn main() {
        let a = Rc::new(Cons(5, Rc::new(Cons(10, Rc::new(Nil)))));
        let b = Cons(3, Rc::clone(&a));
        let c = Cons(4, Rc::clone(&a));
}
```



Each time Rc::clone is called, reference count of a increases by 1.

Lost Update

- One potential problem caused by race condition
  - Assume both threads are running on same processor

```
Thread 1                                  Thread 2
get(x)
5            thread switch
                                          get(x)
                                          5
             thread switch                x = x + 1
                                          (x is now 6)
x = x + 1
(x is still 6)
```

- Solution: atomic instructions

Arc<T>

- Allows sharing data across different threads
  - A in Arc stands for *atomic*
- Atomic instruction
  - A single, uninterruptible instruction on processor
  - Can complete without interference from other threads
  - Generally not used because it is more expensive (time-wise)
  - E.g. fetch-and-add

```
function FetchAndAdd(address location, int inc) {
      int value := *location
      *location := value + inc
      return value
}
```

Arc<T>

- Arc<T> uses atomic instructions to update counter
  - Unlike regular Rc<T>, which is not *thread safe*
- Thread safety
  - Function using shared data behaves correctly during simultaneous execution by multiple threads
    - E.g. freedom from race condition

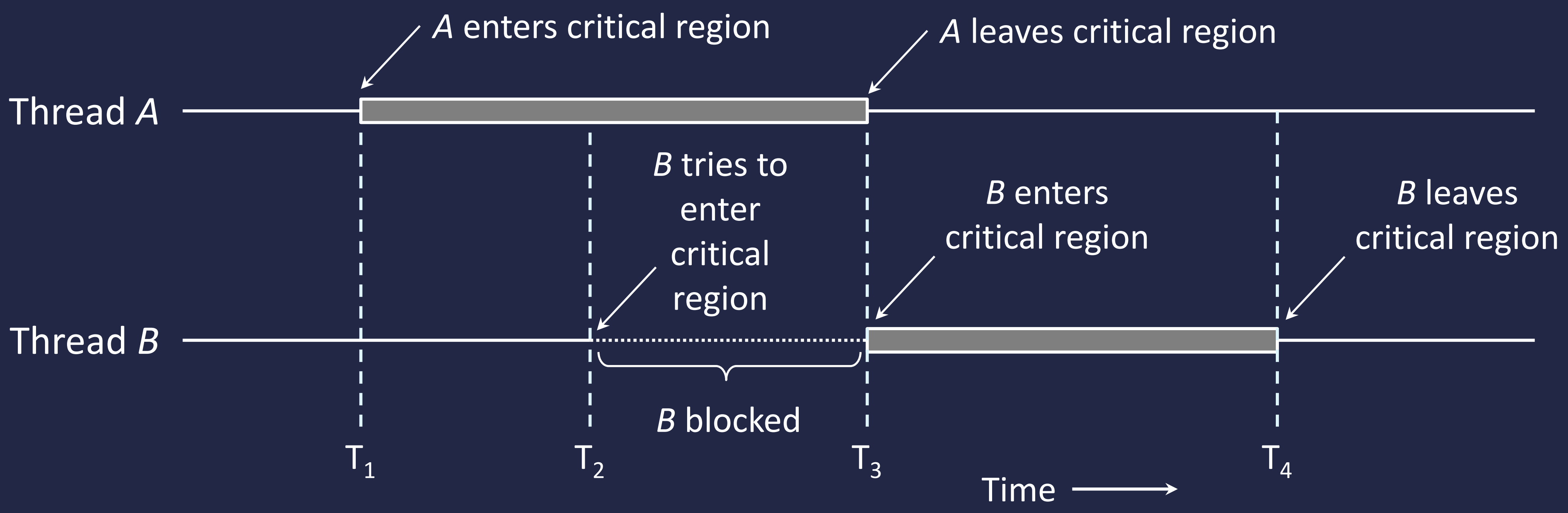
```
use std::sync::Arc;
let foo = Arc::new(vec![1.0, 2.0, 3.0]);
// The two syntaxes below are equivalent.
let a = foo.clone();
let b = Arc::clone(&foo);
// a, b, and foo all point to the same shared memory location
```

Arc<T>

- Limitations
  - Arc<T> makes sharing objects thread safe
  - However, it does *not* make using the objects thread safe
    - E.g. methods of the object may be thread unsafe
  - Object within Arc<T> is *immutable*
- Need
  - A construct that allows shared mutable object
  - A construct that makes using objects thread safe

Mutual Exclusion

- Ensures only one thread can access shared data at once
- Critical region
  - Time that a thread uses to update shared data



Mutex<T>

- Provides mutual exclusion
- When mutex is locked, no other threads can use object
  - Locking mutex creates a MutexGuard

```rust
use std::sync::Mutex;

fn main() {
      let m = Mutex::new(5);
      {     // num is a MutexGuard around the data
            let mut num = m.lock().unwrap();
            *num = 6;
      }     // num goes out of scope and unlocks m

      println!("m = {:?}", m);
}
```

Mutex<T>

- Caveat
  - Mutex is not sharable (ownership rule)
- Must be combined with Arc<T>
- Provides *interior mutability*
  - The mutex is immutable, but the data it contains is mutable

```
let counter = Arc::new(Mutex::new(0));
for _ in 0..10 {
        let counter = Arc::clone(&counter);
        let handle = thread::spawn(move || {
                let mut num = counter.lock().unwrap();
                *num += 1;
        });
}
```

synchronized

- Language support in Java for mutual exclusion

```
class ThreadedSend extends Thread {
      private String msg;
      Sender sender;      // shared among different threads

      ThreadedSend(String m, Sender obj) {
            msg = m; sender = obj;
      }

      public void run() {
            // Only one thread can send message at a time.
            synchronized(sender) {
                  // synchronizing the send object
                  sender.send(msg);
            }
      }
}
```

synchronized

- Alternatively, can make an entire method critical region

```
class Sender {
    // Same effect as previous slide, only one thread can send
    public synchronized void send(String msg) {
        System.out.println("Sending\t" + msg );
        try {
            Thread.sleep(1000);
        }
        catch (Exception e) {
            System.out.println("Thread interrupted.");
        }
        System.out.println("\n" + msg + "Sent");
    }
}
```

Polling

- Also known as busy looping
  - Continuously lock shared data to check on condition in a loop
  - OK on multiple processors if wait time is short
  - On uniprocessor, reduces performance of entire system
- Example: bounded buffer problem

```
mutex l; char buf[n]; // circular buffer

void send(char msg) {
      lock(l);
      /* buffer is full, keep checking if space becomes available */
      while ((in-out+n)%n == n - 1) { unlock(l); lock(l); }
      buf[in] = msg;
      in = (in + 1) % n;
      unlock(l);
}
```

Message Passing

- Threads communicate by sending message with data
- Allows threads to *synchronize*
  - i.e. thread waits for condition to satisfy before continuing
- Thread sleeps while waiting for message
  - Sleeping thread will not be scheduled to run by OS
- Another thread can wake it up by sending a message
  - Once woken up, thread can check the message

channel<T>

- Creates a sender and a receiver end, thread safe
- Must send/receive same data type

```
use std::thread;
use std::sync::mpsc;

fn main() {
      let (tx, rx) = mpsc::channel();
      thread::spawn(move || {
            let val = String::from("hi");
            tx.send(val).unwrap();   // val moves into send()
      });
      let received = rx.recv().unwrap();
      println!("Got: {}", received);
}
```

mpsc::channel

- Multiple producers, single consumer
- iteration on rx finishes when channel is closed
  - i.e. when all senders close their end

```
let (tx, rx) = mpsc::channel();
for i in 1..10 {
        let tx = mpsc::Sender::clone(&tx);
        thread::spawn(move || {
                tx.send(String::from("hello")).unwrap();
        });
}
for received in rx {
        println!("Got: {}", received);
}
```

Can clone tx to allow for multiple producers. rx cannot be cloned!

Monitor

- Allows for both mutual exclusion and synchronization
- Allows for multiple producers and multiple consumers
- Mutual exclusion
  - Provided by a mutex object
- Synchronization
  - Provided by one or more *condition variables*
    - Allows arbitrary condition for synchronization
  - Thread *wait* on a condition variable to be *signalled*
    - Thread sleeps while waiting

Condition Variable

- Allows thread to relinquish lock and go to sleep
- Automatically re-acquires lock prior to wake up

Condvar

- wait(&self, val: MutexGuard)
  - Thread waits until condvar is notified
  - Re-acquire lock on val before waking up
- notify_one(&self)
  - Wakes up exactly one thread waiting on the condvar
  - Equivalent to signal() in other literature
- notify_all(&self)
  - Wakes up all threads waiting on the condvar
  - Equivalent to broadcast() in other literature

Condition Variable

```
use std::sync::{Arc, Mutex, Condvar};
let pair = Arc::new((Mutex::new(false), Condvar::new()));
let pair2 = pair.clone();

thread::spawn(move|| {
      let (lock, cvar) = &*pair2;
      let mut started = lock.lock().unwrap();
      *started = true;
      cvar.notify_one(); // notify that the value has changed.
});

let (lock, cvar) = &*pair;
let mut started = lock.lock().unwrap();
while !*started
{     // wait for started to become true
      started = cvar.wait(started).unwrap();
}
```

Example

- Multiple producers, multiple consumers problem

```
const MAXLEN: usize = 8;
struct Bounded { buffer: [i32; MAXLEN], top: usize, bottom: usize, }
impl Bounded {
        fn push(& mut self, val: i32) {
                self.buffer[self.top] = val;
                self.top = (self.top + 1) % MAXLEN;
        }
        fn pop(& mut self) -> i32 {
                let val = self.buffer[self.bottom];
                self.bottom = (self.bottom + 1) % MAXLEN;
                val
        }
        fn is_empty(& self) -> bool { self.bottom == self.top }
        fn is_full(& self) -> bool {
                (self.bottom + 1) % MAXLEN == self.top
        }
}
```

Example

- Create a monitor around the bounded buffer

```
use std::sync::{Arc, Mutex, Condvar};
struct Monitor<T> {
        mutex: Mutex<T>,
        empty: Condvar,
        full: Condvar,
}
fn main() {
        let mut threads = vec![];
        let monitor = Arc::new(Monitor {
                mutex: Mutex::new(Bounded {
                        buffer: [0; MAXLEN], top: 0, bottom: 0
                }),
                empty: Condvar::new(),
                full: Condvar::new(),
        });
        …
```

Stores all the handles for each thread so we can call join() on them.

Example

- Producer threads

```
const NPRODUCER: i32 = 3;                    const NPRODUCT: i32 = 10;
for i in 1..=NPRODUCER {
    let monitor = monitor.clone();
    threads.push(thread::spawn(move || {
        for j in 0..NPRODUCT {
            let val = i * 10 + j;
            let Monitor {mutex, empty, full} = &*monitor;
            let mut circ = mutex.lock().unwrap();
            while circ.is_full() {
                circ = full.wait(circ).unwrap();
            }
            circ.push(val);
            empty.notify_all();
        }
    }));
}
```

Wait for the bounded buffer to have space.

Notify consumer that data is available

Example

- Consumer threads

```
for i in 1..=NCONSUMER {
    let monitor = monitor.clone();
    threads.push(thread::spawn(move || {
        let mut v = vec![];
        while v.len() < NCONSUMED {
            let Monitor {mutex, empty, full} = &*monitor;
            let mut circ = mutex.lock().unwrap();
            while circ.is_empty() {
                circ = empty.wait(circ).unwrap();
            }
            v.push(circ.pop());
            full.notify_all();
        }
        println!("thread {} consumed: {:?}", i, v);
    }));
}
```

Collect up to 15 pieces of data and exit.

Example

- Wait for all threads to finish before main exits

```
fn main() {
        let mut threads = vec![];
        /* creating producer and consumer threads */
        for child in threads {
            child.join().unwrap();
        }
}
```

- Output

thread 1 consumed: [10, 20, 11, 12, 21, 34, 13, 22, 14, 36, 15, 38, 23, 39, 16]
thread 2 consumed: [30, 31, 32, 33, 35, 37, 24, 17, 18, 25, 19, 26, 27, 28, 29]

Deadlock

- Circular waiting
- Each thread is holding a resource that the other needs to be able to continue (e.g., two pieces of shared data)
- Rust cannot prevent deadlocks
- Possible solutions
  - Lock ordering
    - Always acquire a set of locks in same order
  - Try lock
    - If one of the locks already taken, release all locks you own and restart