COS 316 Precept: Concurrency

Today's Plan

- Background on concurrency
- Key Golang mechanisms for developing concurrent programs (used in assignment 5)

Background: Overview of Concurrency

<u>Sequential programs:</u>

- Single thread of control
- Subprograms / tasks - don't overlap in time - executed one after another

<u>Concurrent programs</u>

- Multiple threads of control
- Subprograms / tasks - may (conceptually) overlap in time - (appear to be) executed at the same time

- Computer with a single processor can have multiple processes at once
- OS schedules different processes - giving illusion that multiple processes are running simultaneously
- Note - parallel architectures can have N processes running simultaneously on N processors

- Let's give an overview of concurrency in the systems context
- We can start off by talking about a normal, sequential program
- For these, there is a single thread of execution
- The CPU processes these programs one at a time and there is no concurrency
- For concurrent programs, things are different
- There are multiple threads of control

Background: Operating System (Review)

- Allows many processes to execute concurrently
- Ensures each process' physical address space does not overlap
- Ensures all processes get fair share of processor time and resources
- Processes can run concurrently and (context) switch
- User's perspective: appears that processes run in parallel although they don't

- Operating systems are responsible for scheduling processes and isolating them from each other

Background: Context Switch

- Control flow changes from one process to another
  - E.g., switching from processA to processB
- Overhead:
  - Before each switch OS has to save the state (context) of currently running process and restore it when next time its execution gets resumed

Background: Threads vs Processes

- Processes
  - Process context switching time is long
    (change of *virtual* address space & other resources)
- Threads
  - thread is a “lightweight” process
  - thread shares some of the context with other threads in a process, e.g.
    - Virtual memory
    - File descriptors
- Private context for each thread:
  - Stack
  - Data registers
  - Code (PC)
- Switching between threads is faster because there is less context
  – less data that has to be read/written from/to memory

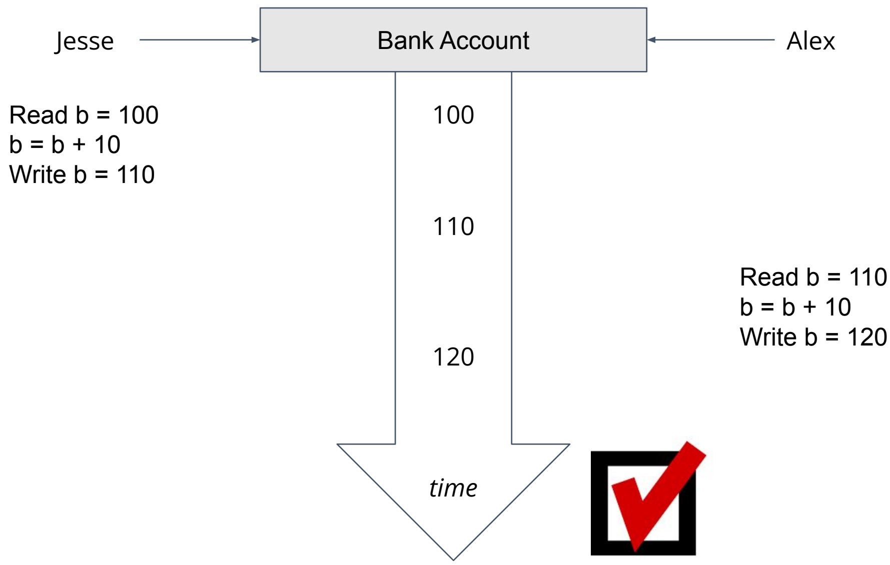
Background: Why Concurrency?

- Performance gain
  - Google search queries
- Application throughput
  - Throughput = amount of work that a computer can do in a given time period
  - When one task is waiting (blocking) for I/O another task can continue its execution
- Model real-world structures
  - Multiple sensors
  - Multiple events
  - Multiple activities

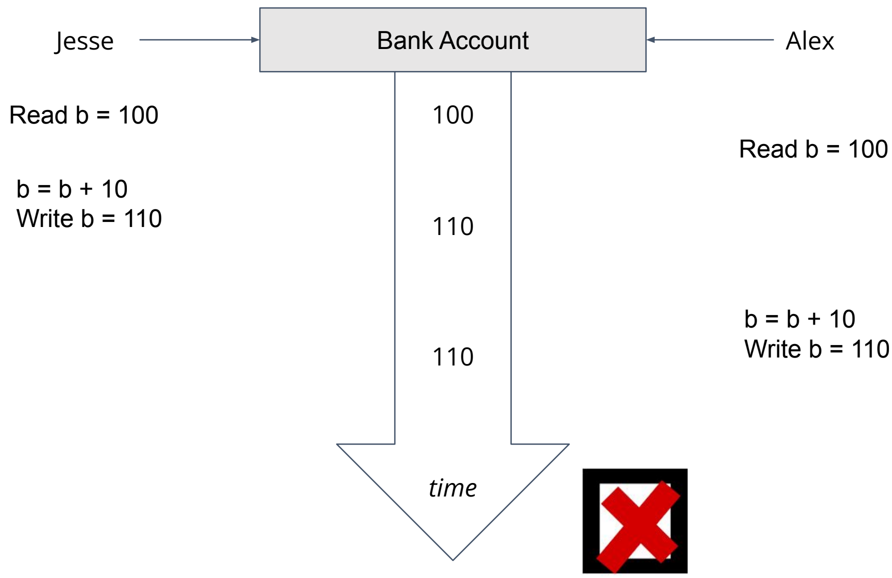
Tradeoffs - Concurrent Programming

- Complex
- Error-prone
- Hard to debug

Example


Jesse
Bank Account
Alex
Read b = 100
b = b + 10
Write b = 110
100
110
Read b = 110
b = b + 10
Write b = 120
120
time

Example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Read b = 100
100
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110
b = b + 10
Write b = 110
110
time

Go and Concurrency

- Goroutines
- The sync package - https://golang.org/pkg/sync
  - sync.Mutex
  - sync.Cond

Goroutines

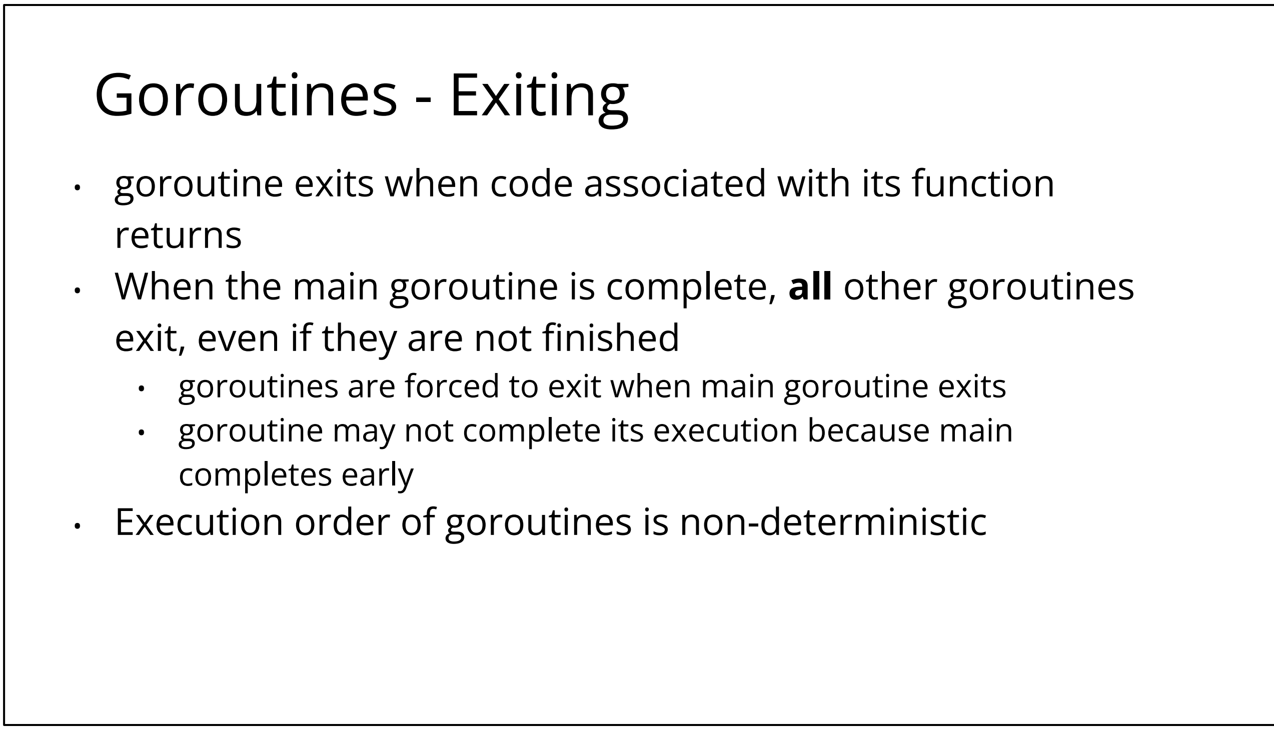
- A lightweight thread managed by the Go runtime
- Many goroutines execute within a single OS thread
  - One goroutine is created automatically to execute the main()
  - Other goroutines are created using the **go** keyword
  - Order of execution depends on the Go scheduler
    - Go takes a process with main thread and schedules / switches goroutines within that thread

- Compare

- Sequential Program
- https://play.golang.org/p/PLeCGtRp2QB

- Concurrent program
- https://play.golang.org/p/sDitCEr_3vX

- Go employs what we call green threads and they call goroutines, which means that instead of using the operating system's threading infrastructure, it uses its own form of threads
- Go has its own scheduler for deciding which goroutine should be running at any given moment
- Separate go routines are created and executed using the go keyword



- Goroutines have a separate thread of control from the main thread
- They terminate whenever their code is done being run
- However, even if they haven't finished running, the termination of the main thread causes all goroutines to terminate
- In addition, their execution order is non-deterministic.
- This means that there there's no way to predict when a goroutine will finish relative to the main goroutine or any other goroutine

A simple example to show non-determinism

- https://play.golang.org/p/sDitCEr_3vX
- Switch the order of the calls from

```
go say("world")         say("hello")
say("hello")            go say("world")
```

  - What happens?
  - How to fix?

We can use Go’s synchronization tools which we will talk about in the next few slides to address this non-determinism.
Out-of-scope solution with WaitGroup: https://go.dev/play/p/bPVORhgVDWY

Synchronization

- Synchronization is when multiple threads agree on a timing of an event
- Global *events* whose execution is viewed by all threads, simultaneously
- One goroutine does not know the timing of other goroutines
- Synchronization can introduce some global events that every thread sees at the same time

Synchronization and Go

- `type Cond`
  - `Func (*Cond) Signal()`
  - `func (*Cond) Broadcast()`
  - `func (*Cond) Wait()`

- `type Mutex`
  - `func (m *Mutex) Lock()`
  - `func (m *Mutex) Unlock()`

- Channels
  - See COS 418

Mutex (Mutual Exclusion)

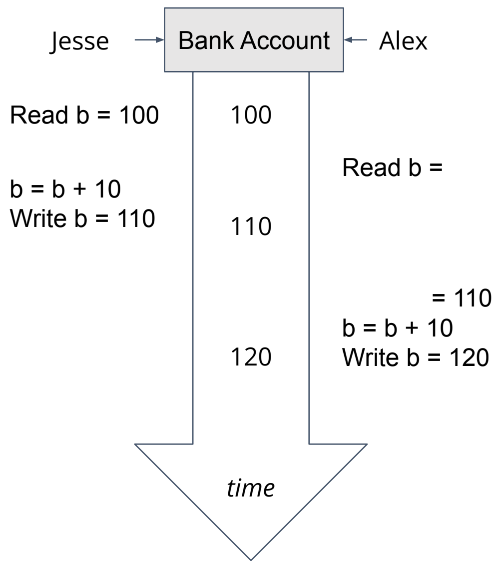
- Sharing variables between goroutines (concurrently) can cause problems
- Two goroutines writing to the same shared variable can interfere with each other
- Function/goroutine is said to be concurrency-safe if can be executed concurrently with other goroutines without interfering improperly with them
  - e.g., it will not alter variables in other goroutines in some unexpected/unintended/unsafe way

Sync.Mutex

- A mutex ensures *mutual exclusion*
- Uses a binary semaphore
  - If flag is up → shared variable is in use by somebody
- Only one goroutine can write into variable at a time
- Once goroutine is done with using shared variable it has to put the flag down
  - if flag is down → shared variable is available
- If another goroutine see that flag is down it knows it can use the shared variable but first it has to put the flag up

A semaphore ~= a signal

Back to our example




```
func Deposit(amount) {

    lock balanceLock
    read balance
    balance = balance + amount
    write balance
    unlock balanceLock

}
```

CRITICAL SECTION

Sync.Mutex

- **`Lock()`**
  - Puts the flag up (if none of other goroutines has already put the flag up)
  - If second goroutine also calls **`Lock()`** it will be blocked, it has to wait until first goroutine releases the lock
  - Note - any number of goroutines (not just two) competing to **`Lock()`**
- **`Unlock()`**
  - Puts the flag down
  - When **`Unlock()`** is called, a blocked **`Lock()`** can proceed
- In general: put **`Lock()`** at the beginning of the critical section and call **`Unlock()`** at the end of it; ensures that only one goroutine will be in critical section region

- Create a Mutex

```
var mut sync.Mutex
```

- To lock a critical section

```
mut.Lock()
```

- To unlock a critical section

```
mut.Unlock()
```

Mutex Exercise

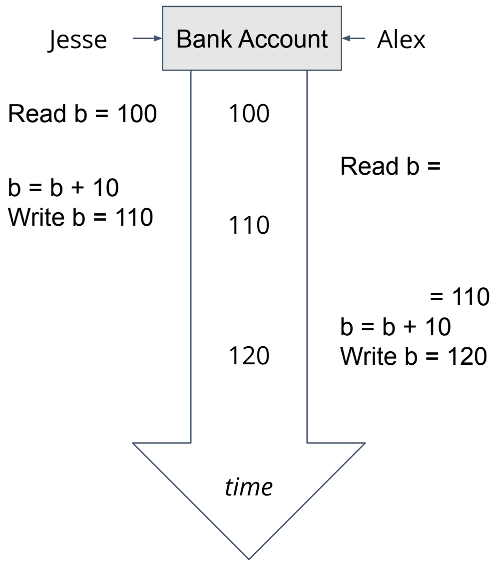
Consider:

```
var i int = 0
var wg sync.WaitGroup
func inc() {
   i = i + 1
   wg.Done()
}
func main() {
   wg.Add(2)
   go inc()
   go inc()
   wg.Wait()
   fmt.Println(i)
}
```

- Run the program
  https://play.golang.org/p/hNevYkKDp30
- Is it concurrency-safe?
- Use `Lock()` and `Unlock()` to make these programs concurrency-safe

Solution: https://go.dev/play/p/HnJIXA67slb

Mutex Exercise - Bank Account



- Make this code concurrency-safe

https://go.dev/play/p/VboCb85otn0

Solution: https://go.dev/play/p/Q12qkDAajCK

Interesting Example

Consider:

```
var mu sync.Mutex
func funcA() {
    mu.Lock()
    funcB()
    mu.Unlock()
}
func funcB() {
    mu.Lock()
    fmt.Println("Hello, World")
    mu.Unlock()
}
func main() {
    funcA()
}
```

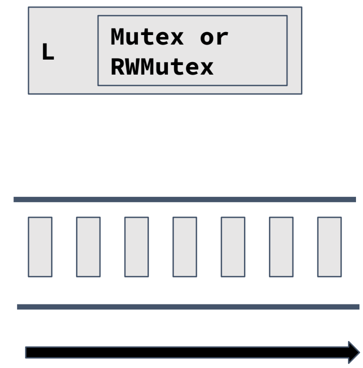
- Run the program
  https://play.golang.org/p/c2Qgo-W_4mP

- What happens?

This is a deadlock; we have func A holding the lock that func B is waiting for, but func A calls func B so A can't terminate before B, hence nothing terminates and both funcs wait endlessly

Condition Variables - `sync.Cond`

- [`sync.Cond`] type - provides an efficient way to send notifications among goroutines
- `sync.Cond` value holds a [`sync.Locker`] field with name `L` - field value is of type `*sync.Mutex` or `*sync.RWMutex`
  - E.g.:
    - `cond := sync.NewCond(&sync.Mutex{})`
    - `cond.L.Lock()`
    - `cond.L.UnLock()`
- `sync.Cond` value holds a FIFO queue of waiting goroutines
- commonly used to allow threads to wait on a *condition* to be true: consumers *wait* until a producer *signals* that something happened



Condition Variables - `L.Lock()`, `L.Unlock()`, `Wait()`, `Broadcast()`, `Signal()`

- `cond := sync.NewCond(&sync.Mutex{})`
- `cond.L.Lock()`
- `cond.Wait()`

- Call L.Lock() before Wait()
- Insert calling goroutine in queue and block (wait)
- Calls L.Unlock()

- `cond.Broadcast()`

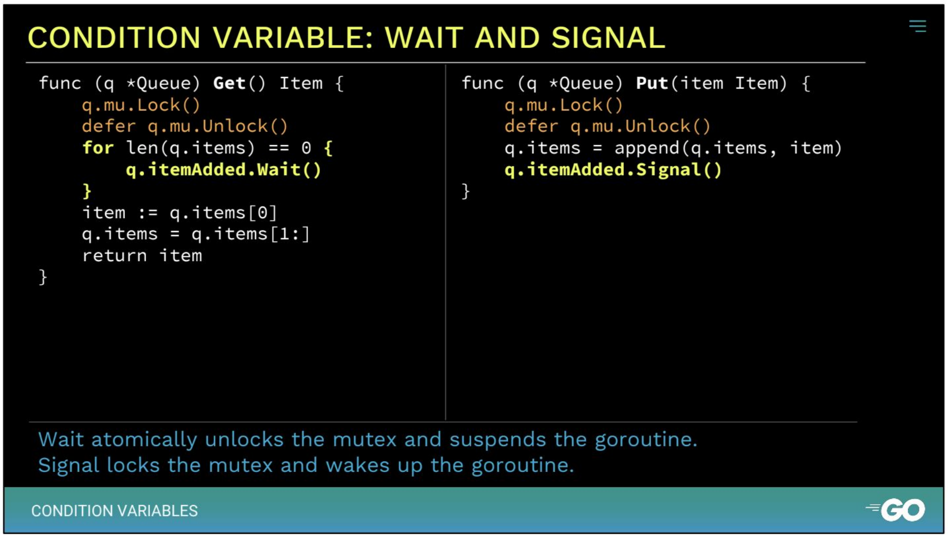
Unblock *all* the goroutines in (and remove them from) the waiting goroutine queue

- `cond.Signal()`

Unblock the head goroutine in (and remove them from) the waiting goroutine queue

- Blocked routines go back to running state
- Invokes cond.L.Lock() (in the resumed cond.Wait() call) to try to acquire and hold the lock cond.L again
- cond.Wait() call exits after the cond.L.Lock() call returns

A Basic Example:



- The two basic operations on condition variables are Wait, and Signal.
- Wait atomically unlocks the mutex and suspends the calling goroutine.
- Signal wakes up a waiting goroutine, which relocks the mutex before proceeding.
- In our queue, we can use Wait to block on the availability of enqueued items, and Signal to indicate when another item has been added.

Slide from here: https://drive.google.com/file/d/1nPdvhB0PutEJzdCq5ms6UI58dp50fcAN/view (also linked here on go's sync documentation https://pkg.go.dev/sync#Cond)

`sync.Cond` – Always Check the Condition!

- Why is this loop here?
- `cond.Wait()` does not guarantee the condition holds when it returns
- The condition could have been made false again while the goroutine was waiting to run
- Always check the condition, and keep waiting if it does not hold

```
checkCondition := func() bool {
    // Check the condition
}

for !checkCondition() {
    cond.Wait()
}
cond.L.Unlock()
```