Language-level Concurrency Support: Go

Chris Rossbach

Outline for Today

- Questions?
- Administrivia
    - Lab 3 looms large: Go go go!
- Agenda
    - Message Passing background
    - Concurrency in Go
    - Thoughts and guidance on Lab 3

- Acknowledgements: Rob Pike’s 2012 Go presentation is excellent, and I borrowed from it: https://talks.golang.org/2012/concurrency.slide

Faux Quiz questions

- How are promises and futures different or the same as goroutines
- What is the difference between a goroutine and a thread?
- What is the difference between a channel and a lock?
- How is a channel different from a concurrent FIFO?
- What is the CSP model?
- What are the tradeoffs between explicit vs implicit naming in message passing?
- What are the tradeoffs between blocking vs. non-blocking send/receive in a shared memory environment? In a distributed one?

Event-based Programming: Motivation

- Threads have a *lot* of down-sides:
  - Tuning parallelism for different environments
  - Load balancing/assignment brittle
  - Shared state requires locks →
    - Priority inversion
    - Deadlock
    - Incorrect synchronization
  - …

Remember this slide?

- Events: *restructure programming model to have no threads!*

~~Event-based Programming: Motivation~~

- Threads have a *lot* of down-sides:
  - Tuning parallelism for different environments
  - Load balancing/assignment brittle
  - Shared state requires locks →
    - Priority inversion
    - Deadlock
    - Incorrect synchronization
  - …

Remember this slide?

- Events: *restructure programming model to have no threads!*

Message Passing: Motivation

Message Passing: Motivation

- Threads have a *lot* of down-sides:
  - Tuning parallelism for different environments
  - Load balancing/assignment brittle
  - Shared state requires locks →
    - Priority inversion
    - Deadlock
    - Incorrect synchronization
  - …

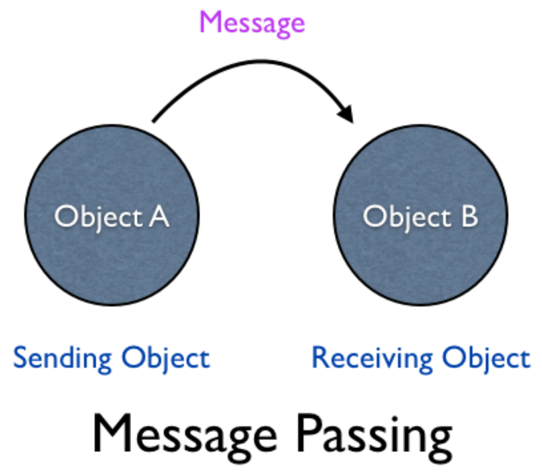
Message Passing: Motivation

- Threads have a *lot* of down-sides:
  - Tuning parallelism for different environments
  - Load balancing/assignment brittle
  - Shared state requires locks →
    - Priority inversion
    - Deadlock
    - Incorrect synchronization
  - …

Message Passing: Motivation

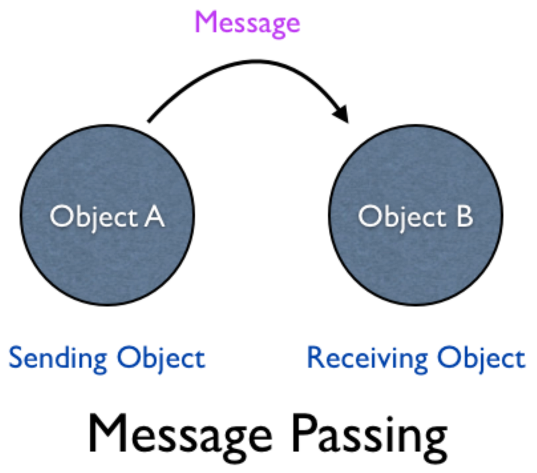
- Threads have a *lot* of down-sides:
  - Tuning parallelism for different environments
  - Load balancing/assignment brittle
  - Shared state requires locks →
    - Priority inversion
    - Deadlock
    - Incorrect synchronization
  - …
- Message passing:
  - *Threads aren't the problem, shared memory is*
  - *restructure programming model to avoid communication through shared memory (and therefore locks)*

Message Passing



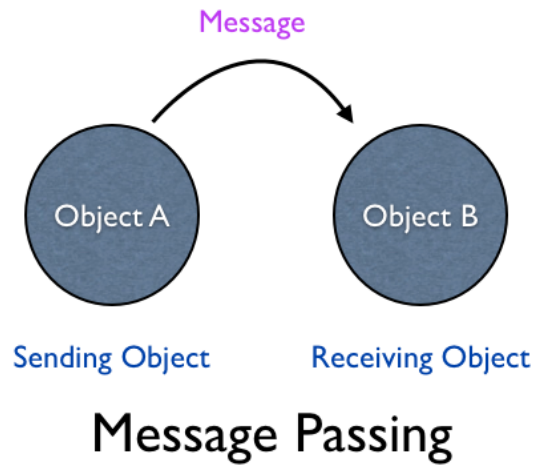
Message Passing

- Threads/Processes send/receive messages



Message Passing

- Threads/Processes send/receive messages
- Three design dimensions
  - Naming/Addressing: *how do processes refer to each other?*
  - Synchronization: *how to wait for messages (block/poll/notify)?*
  - Buffering/Capacity: *can messages wait in some intermediate structure?*



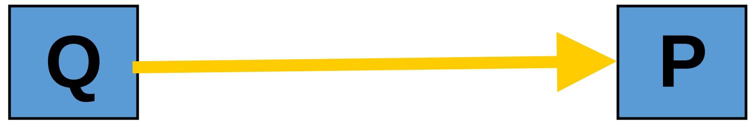
Naming: Explicit vs Implicit

Also: Direct vs Indirect

Naming: Explicit vs Implicit

Also: Direct vs Indirect

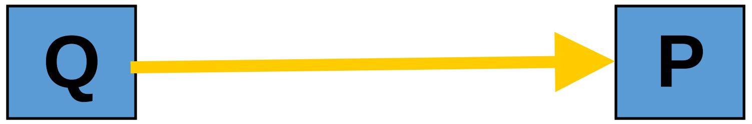
- Explicit Naming
  - Each process must explicitly name the other party
  - Primitives:
    - send(receiver, message)
    - receive(sender, message)

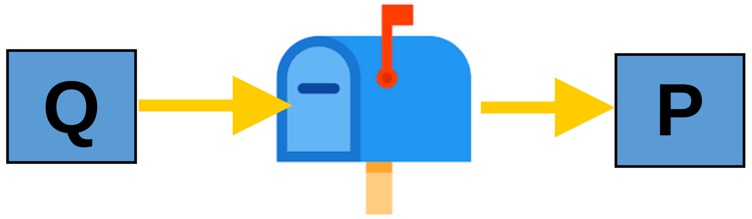


Naming: Explicit vs Implicit

Also: Direct vs Indirect

- Explicit Naming
  - Each process must explicitly name the other party
  - Primitives:
    - send(receiver, message)
    - receive(sender, message)
- Implicit Naming
  - Messages sent/received to/from mailboxes
  - Mailboxes may be named/shared
  - Primitives:
    - send(mailbox, message)
    - receive(mailbox, message)





Synchronization

Synchronization

- Synchronous vs. Asynchronous
    - Blocking send: sender blocks until received
    - Nonblocking send: send resumes before message received
    - Blocking receive: receiver blocks until message available
    - Non-blocking receive: receiver gets a message or null

Synchronization

- Synchronous vs. Asynchronous
  - Blocking send: sender blocks until received
  - Nonblocking send: send resumes before message received
  - Blocking receive: receiver blocks until message available
  - Non-blocking receive: receiver gets a message or null

Blocking:
+ simple
+ avoids wasteful spinning
- Inflexible
- Can hide concurrency

Non-blocking:
+ maximal flexibility
- error handling/detection tricky
- interleaving useful work non-trivial

Synchronization

- Synchronous vs. Asynchronous
  - Blocking send: sender blocks until received
  - Nonblocking send: send resumes before message received
  - Blocking receive: receiver blocks until message available
  - Non-blocking receive: receiver gets a message or null
- If ***both send and receive block***
  - “Rendezvouz”
  - Operation acts as an ordering primitive
  - Sender knows receiver succeded
  - Receiver knows sender succeeded
  - Particularly appealing in distributed environment

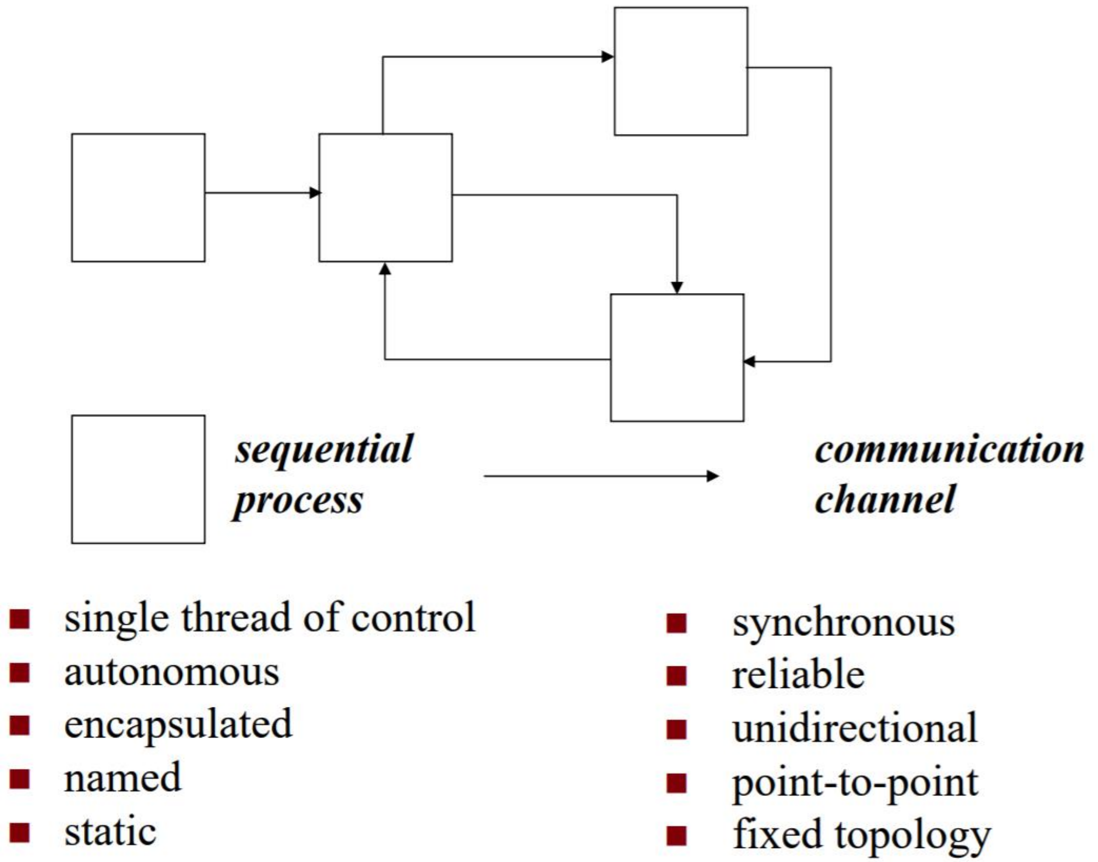
Blocking:
+ simple
+ avoids wasteful spinning
- Inflexible
- Can hide concurrency

Non-blocking:
+ maximal flexibility
- error handling/detection tricky
- interleaving useful work non-trivial

Communicating Sequential Processes
Hoare 1978

CSP: language for multi-processor machines

- Non-buffered **message passing**
  - No shared memory
  - **Send/recv are blocking**
- **Explicit naming** of src/dest processes
  - Also called direct naming
  - Receiver **specifies source** process
  - Alternatives: *indirect*
    - Port, mailbox, queue, socket
- **Guarded** commands to let processes wait



- single thread of control
- autonomous
- encapsulated
- named
- static

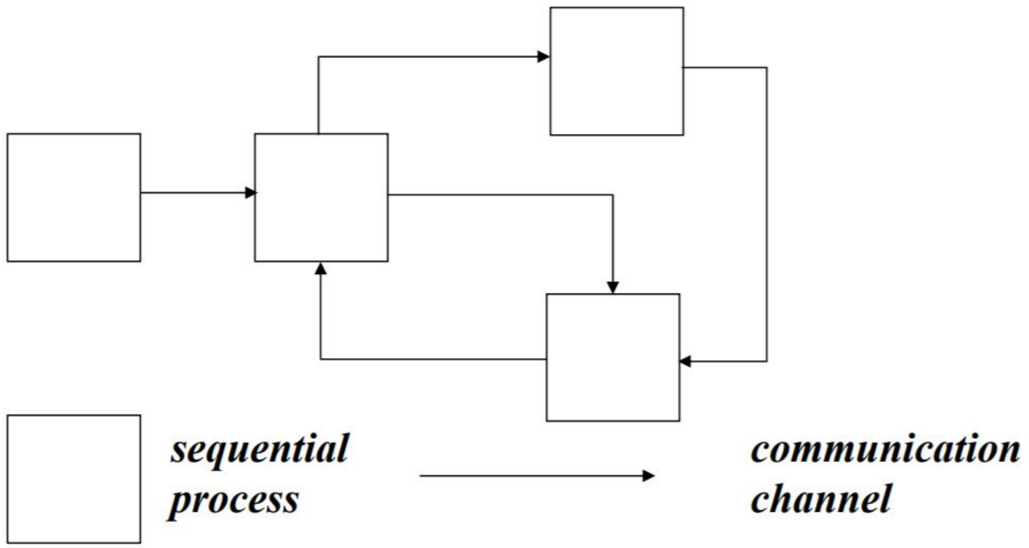
- synchronous
- reliable
- unidirectional
- point-to-point
- fixed topology

Communicating Sequential Processes

Hoare 1978

CSP: language for multi-processor machines

- Non-buffered **message passing**
    - No shared memory
    - **Send/recv are blocking**
- **Explicit naming** of src/dest processes
    - Also called direct naming
    - Receiver **specifies source** process
    - Alternatives: *indirect*
        - Port, mailbox, queue, socket
- **Guarded** commands to let processes wait



- single thread of control
- autonomous
- encapsulated
- named
- static

- synchronous
- reliable
- unidirectional
- point-to-point
- fixed topology

← Transputer!

An important problem in the CSP model:

An important problem in the CSP model:

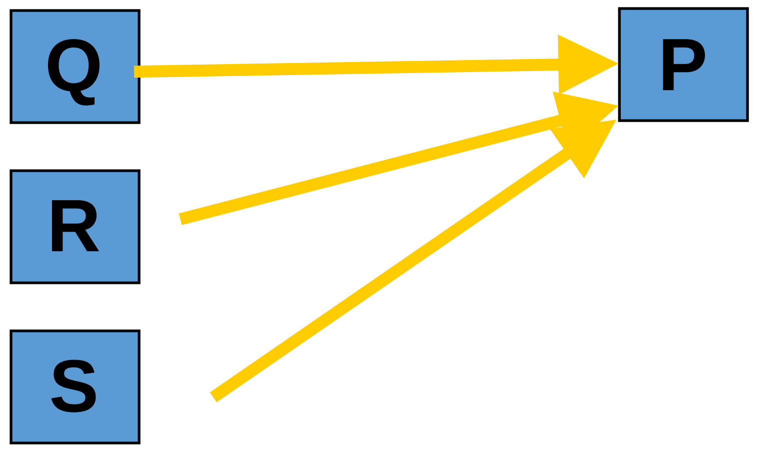
- Processes need to receive messages from different senders

An important problem in the CSP model:

- Processes need to receive messages from different senders
- Only primitive: blocking receive(<name>, message)

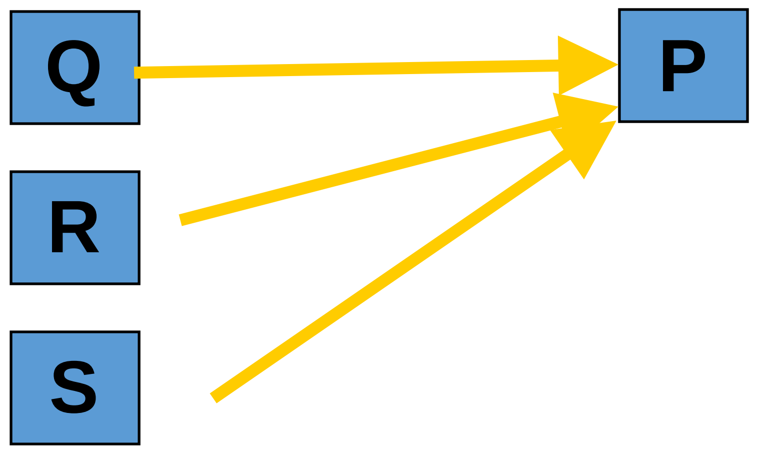
An important problem in the CSP model:

- Processes need to receive messages from different senders
- Only primitive: blocking receive(<name>, message)



An important problem in the CSP model:

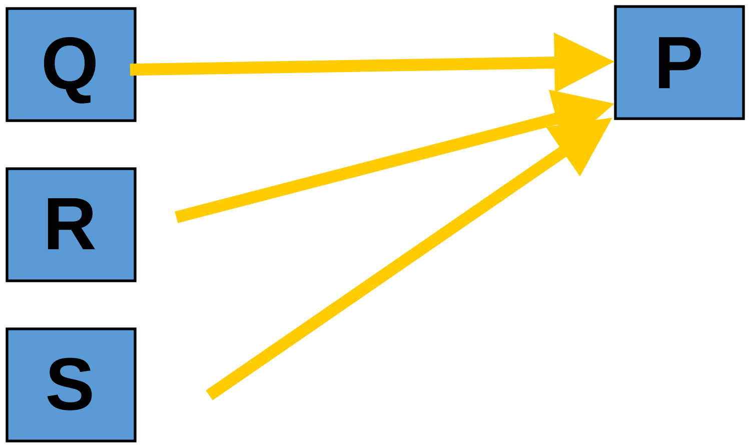
- Processes need to receive messages from different senders
- Only primitive: blocking receive(<name>, message)



```
recv_multi(Q) {
  receive(Q, message)
  receive(R, message)
  receive(S, message)
}
```

An important problem in the CSP model:

- Processes need to receive messages from different senders
- Only primitive: blocking receive(<name>, message)

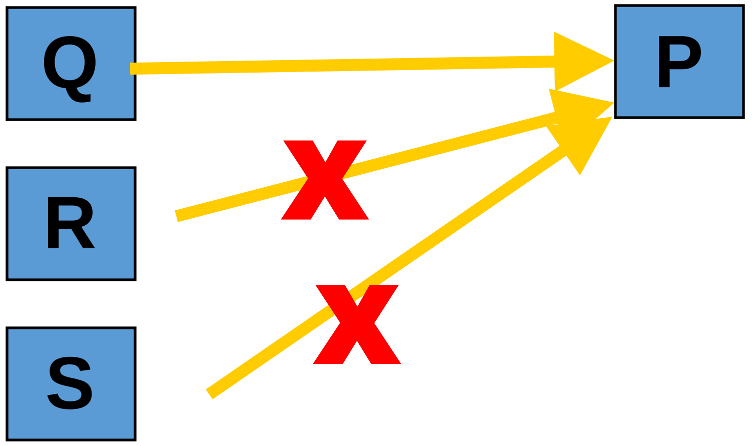


```
recv_multi(Q) {
  receive(Q, message)
  receive(R, message)
  receive(S, message)
}
```

Is there a problem with this?

An important problem in the CSP model:

- Processes need to receive messages from different senders
- Only primitive: blocking receive(<name>, message)



```
recv_multi(Q) {
  receive(Q, message)
  receive(R, message)
  receive(S, message)
}
```

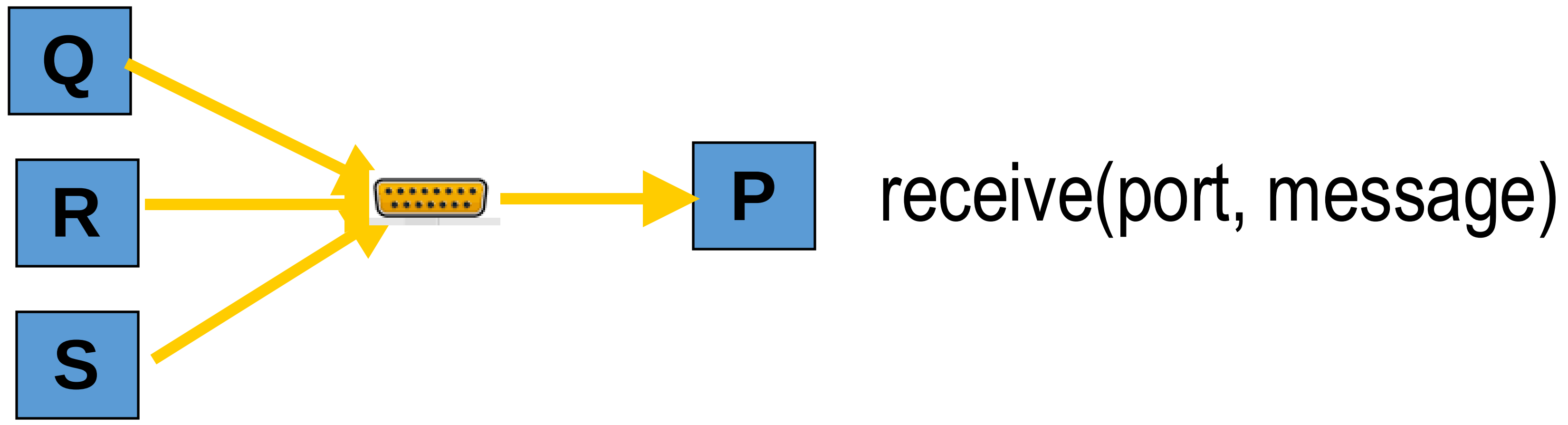
Is there a problem with this?

Blocking with Indirect Naming

- Processes need to receive messages from different senders
- ***blocking receive*** with ***indirect naming***
  - Process waits on port, gets first message first message arriving at that port

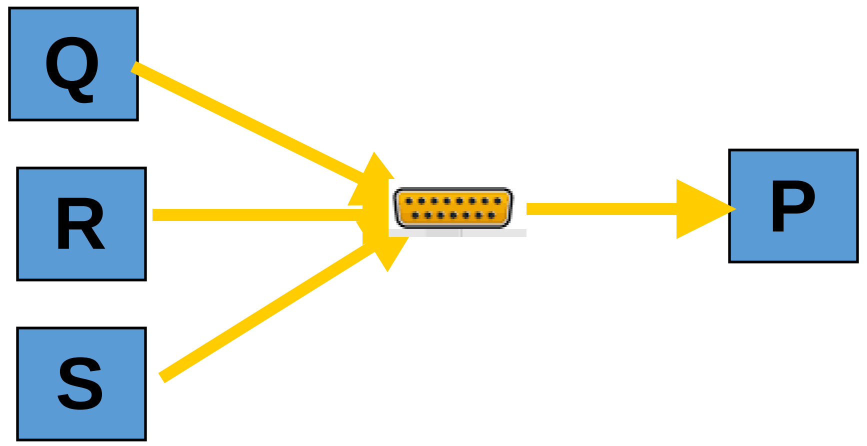
Blocking with Indirect Naming

- Processes need to receive messages from different senders
- ***blocking receive*** with ***indirect naming***
  - Process waits on port, gets first message first message arriving at that port



Blocking with Indirect Naming

- Processes need to receive messages from different senders
- ***blocking receive*** with ***indirect naming***
  - Process waits on port, gets first message first message arriving at that port



receive(port, message)

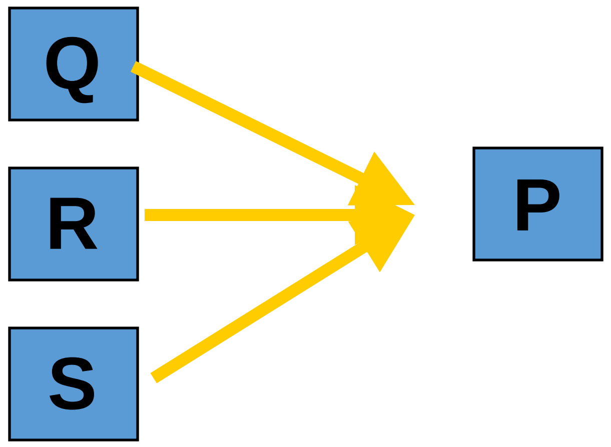
OK to block (good)
Requires indirection (less good)

Non-blocking with Direct Naming

- Processes need to receive messages from different senders
- ***Non-blocking receive*** with ***direct naming***
  - Requires receiver to poll senders

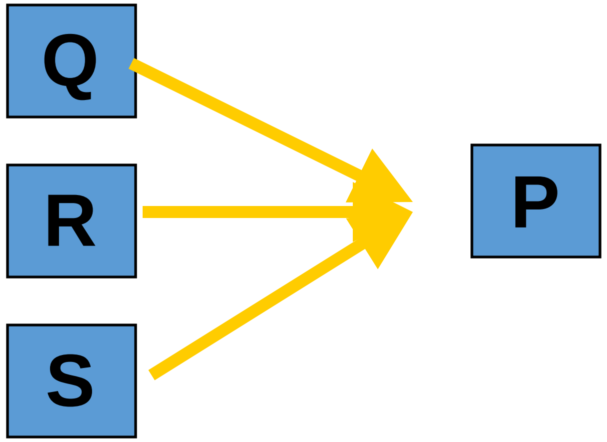
Non-blocking with Direct Naming

- Processes need to receive messages from different senders
- ***Non-blocking receive*** with ***direct naming***
    - Requires receiver to poll senders



Non-blocking with Direct Naming

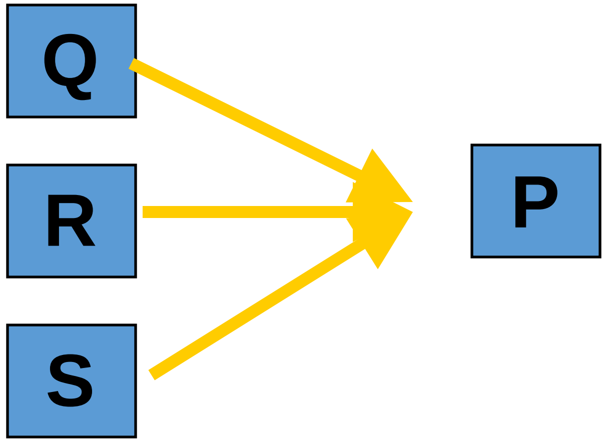
- Processes need to receive messages from different senders
- ***Non-blocking receive*** with ***direct naming***
  - Requires receiver to poll senders



```
while(…) {
  try_receive(Q, message)
  try_receive(R, message)
  try_receive(S, message)
}
```

Non-blocking with Direct Naming

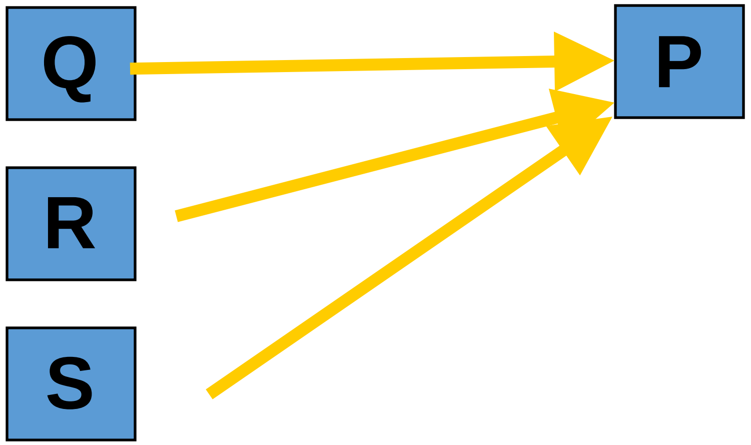
- Processes need to receive messages from different senders
- ***Non-blocking receive*** with ***direct naming***
  - Requires receiver to poll senders



```
while(…) {
  try_receive(Q, message)
  try_receive(R, message)
  try_receive(S, message)
}
```

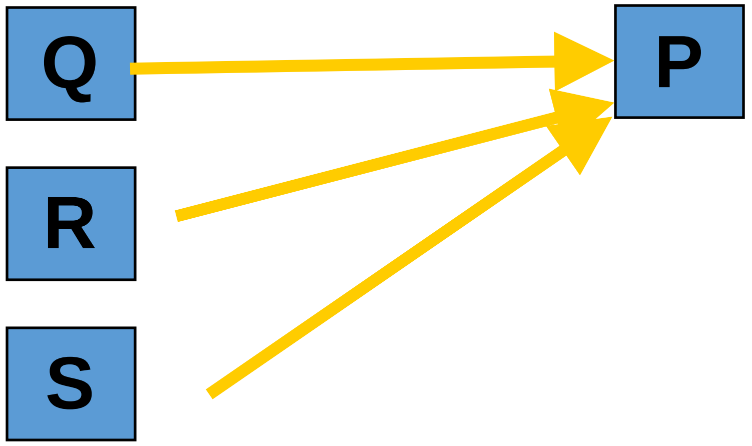
Polling (bad)
No indirection (good)

Blocking and Direct Naming



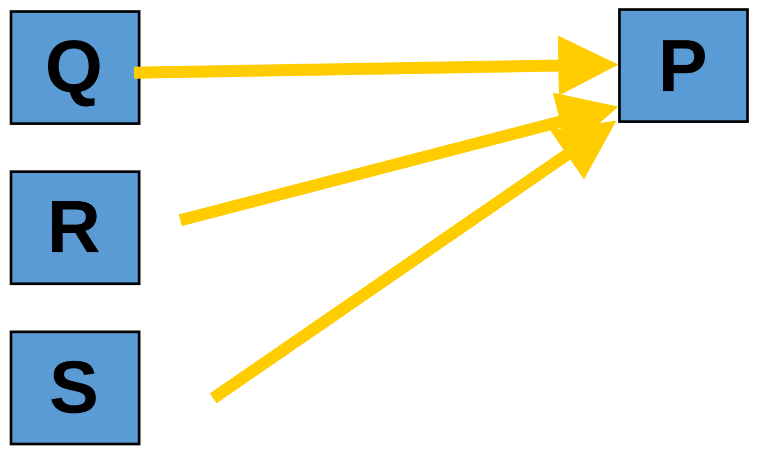
Blocking and Direct Naming

- How to achieve ***it?***



Blocking and Direct Naming

- How to achieve ***it?***
- ***CSP provides abstractions/primitives for it***



Alternative / Guarded Commands

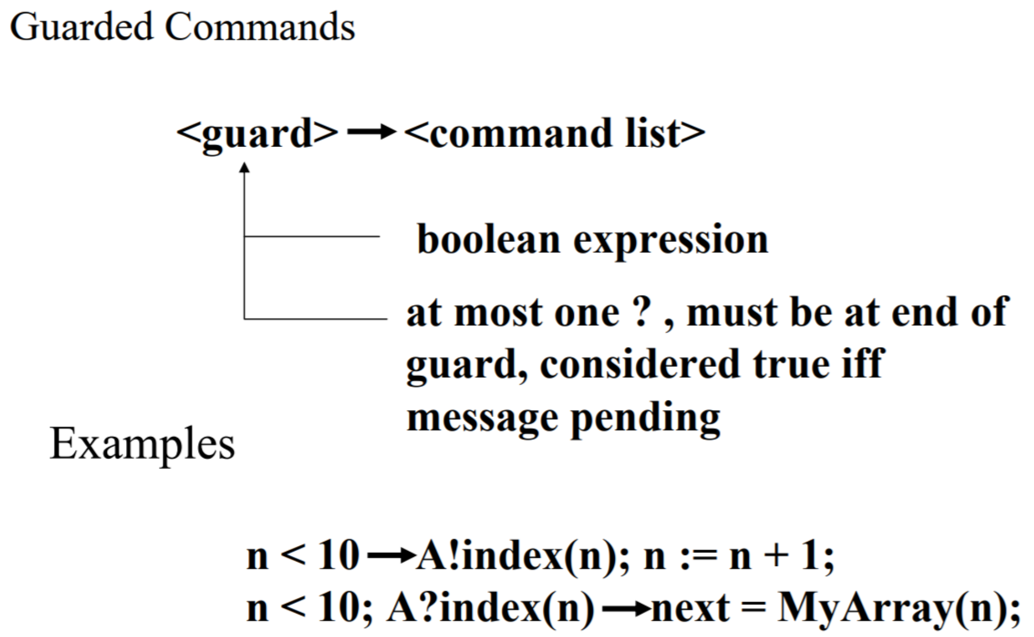
Guarded command is ***delayed*** until either

- ***guard succeeds*** → cmd executes *or*
- ***guard fails*** →command aborts

Alternative command:

- list of one or more guarded commands
- separated by ”||”
- surrounded by square brackets

[x ≥ y -> max:= x || y ≥ x -> max:= y]


Guarded Commands

<guard> → <command list>

boolean expression

at most one ? , must be at end of guard, considered true iff message pending

Examples

```
n < 10 → A!index(n); n := n + 1;
n < 10; A?index(n) → next = MyArray(n);
```

Alternative / Guarded Commands

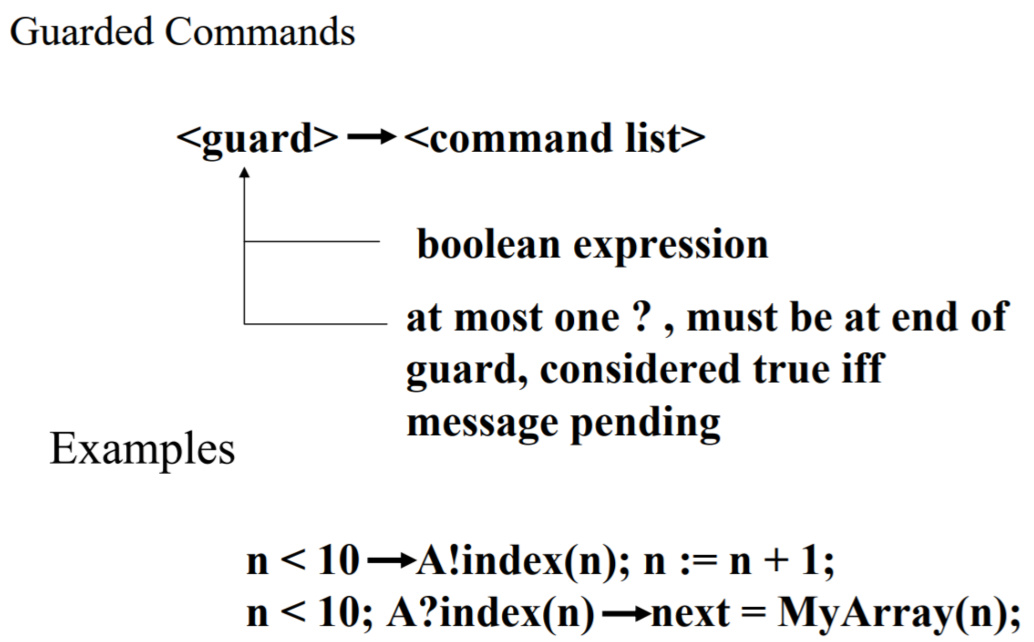
Guarded command is ***delayed*** until either

- ***guard succeeds*** → cmd executes *or*
- ***guard fails*** →command aborts

Alternative command:

- list of one or more guarded commands
- separated by ”||”
- surrounded by square brackets

[x ≥ y -> max:= x || y ≥ x -> max:= y]



Guarded Commands

<guard> ⟶ <command list>

boolean expression

at most one ? , must be at end of guard, considered true iff message pending

Examples

n < 10 ⟶A!index(n); n := n + 1;
n < 10; A?index(n) ⟶next = MyArray(n);

- Enable *choice* preserving concurrency
- *Hugely influential*
- goroutines, channels, select, defer:
  - ***Trying to achieve the same thing***

Go Concurrency

- CSP: the root of many languages
  - Occam, Erlang, Newsqueak, Concurrent ML, Alef, Limbo
- Go is a Newsqueak-Alef-Limbo derivative
  - Distinguished by ***first class channel support***
  - Program: ***goroutines*** communicating through ***channels***
  - Guarded and alternative-like constructs in ***select*** and ***defer***

A boring function

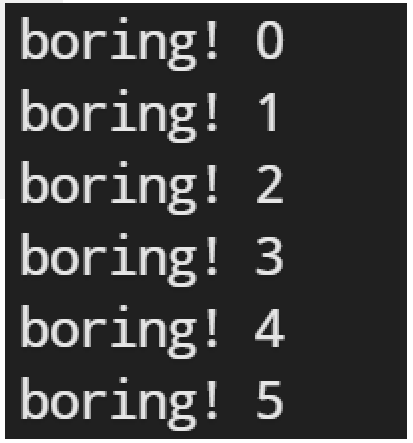
```
func boring(msg string) {
    for i := 0; ; i++ {
        fmt.Println(msg, i)
        time.Sleep(time.Duration(rand.Intn(1e3)) * time.Millisecond)
    }
}
```

```
func main() {
    boring("boring!")
}
```

A boring function

```
func boring(msg string) {
    for i := 0; ; i++ {
        fmt.Println(msg, i)
        time.Sleep(time.Duration(rand.Intn(1e3)) * time.Millisecond)
    }
}
```

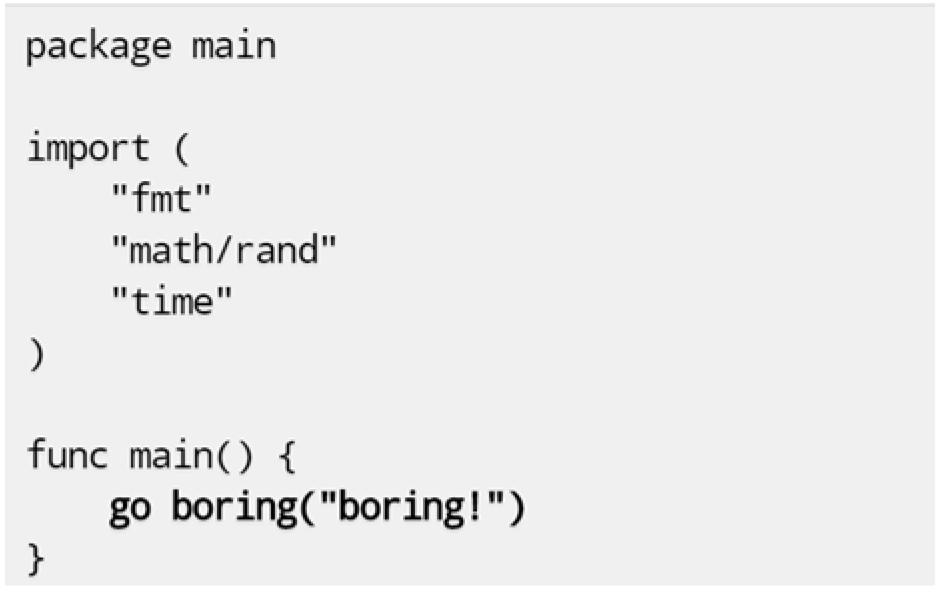
```
func main() {
    boring("boring!")
}
```



```
boring! 0
boring! 1
boring! 2
boring! 3
boring! 4
boring! 5
```

Ignoring a boring function

- Go statement runs the function
- Doesn’t make the caller wait
- Launches a goroutine
- Analagous to & on shell command



```
package main

import (
	"fmt"
	"math/rand"
	"time"
)

func main() {
	go boring("boring!")
}
```

Ignoring a boring function

- Go statement runs the function
- Doesn’t make the caller wait
- Launches a goroutine
- Analagous to & on shell command

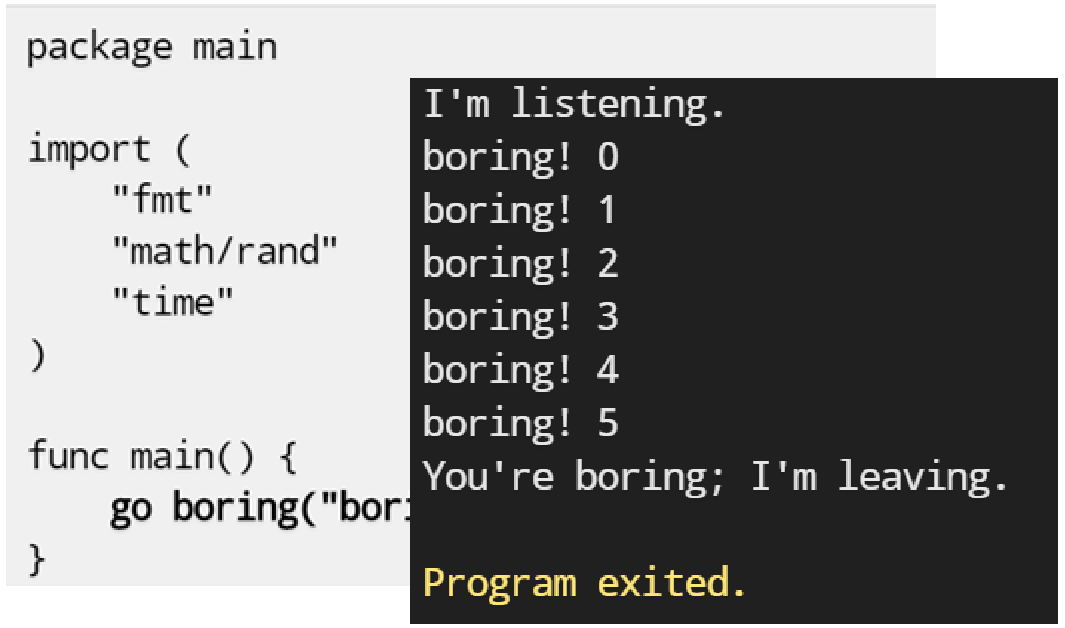
```
package main

import (
    "fmt"
    "math/rand"
    "time"
)

func main() {
    go boring("boring!")
}
```

- Keep main() around a while
- See goroutine actually running

```
func main() {
    go boring("boring!")
    fmt.Println("I'm listening.")
    time.Sleep(2 * time.Second)
    fmt.Println("You're boring; I'm leaving.")
}
```

Ignoring a boring function

- Go statement runs the function
- Doesn’t make the caller wait
- Launches a goroutine
- Analagous to & on shell command



```
package main

import (
    "fmt"
    "math/rand"
    "time"
)

func main() {
    go boring("bor
}
```

```
I'm listening.
boring! 0
boring! 1
boring! 2
boring! 3
boring! 4
boring! 5
You're boring; I'm leaving.

Program exited.
```

- Keep main() around a while
- See goroutine actually running

```
func main() {
    go boring("boring!")
    fmt.Println("I'm listening.")
    time.Sleep(2 * time.Second)
    fmt.Println("You're boring; I'm leaving.")
}
```

Goroutines

Goroutines

- Independently executing function launched by go statement

Goroutines

- Independently executing function launched by go statement
- Has own call stack

Goroutines

- Independently executing function launched by go statement
- Has own call stack
- Cheap: Ok to have 1000s…100,000s of them

Goroutines

- Independently executing function launched by go statement
- Has own call stack
- Cheap: Ok to have 1000s…100,000s of them
- Not a thread
    - One thread may have **1000s** of go routines!

Goroutines

- Independently executing function launched by go statement
- Has own call stack
- Cheap: Ok to have 1000s…100,000s of them
- Not a thread
  - One thread may have **1000s** of go routines!
- Multiplexed onto threads as needed to ensure forward progress
  - Deadlock detection built in

Channels

- Connect goroutines allowing them to communicate

```
// Declaring and initializing.
var c chan int
c = make(chan int)
// or
c := make(chan int)
```

```
// Sending on a channel.
c <- 1
```

```
// Receiving from a channel.
// The "arrow" indicates the direction of data flow.
value = <-c
```

Channels

- Connect goroutines allowing them to communicate

Channels

- Connect goroutines allowing them to communicate

```
func main() {
    c := make(chan string)
    go boring("boring!", c)
    for i := 0; i < 5; i++ {
        fmt.Printf("You say: %q\n", <-c) // Receive expression is just a value.
    }
    fmt.Println("You're boring; I'm leaving.")
}
```

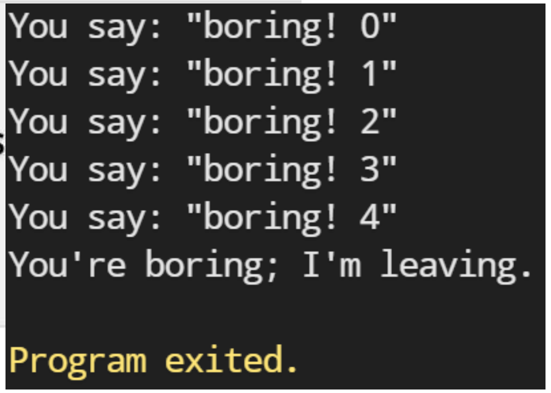
```
func boring(msg string, c chan string) {
    for i := 0; ; i++ {
        c <- fmt.Sprintf("%s %d", msg, i) // Expression to be sent can be any suitable value.
        time.Sleep(time.Duration(rand.Intn(1e3)) * time.Millisecond)
    }
}
```

Channels

- Connect goroutines allowing them to communicate

```
func main() {
    c := make(chan string)
    go boring("boring!", c)
    for i := 0; i < 5; i++ {
        fmt.Printf("You say: %q\n", <-c) // Receive expression is just a value.
    }
    fmt.Println("You're boring; I'm leaving.")
}
```

```
func boring(msg string, c chan string) {
    for i := 0; ; i++ {
        c <- fmt.Sprintf("%s %d", msg, i) // Expression to be sent can be any s
        time.Sleep(time.Duration(rand.Intn(1e3)) * time.Millisecond)
    }
}
```



```
You say: "boring! 0"
You say: "boring! 1"
You say: "boring! 2"
You say: "boring! 3"
You say: "boring! 4"
You're boring; I'm leaving.

Program exited.
```

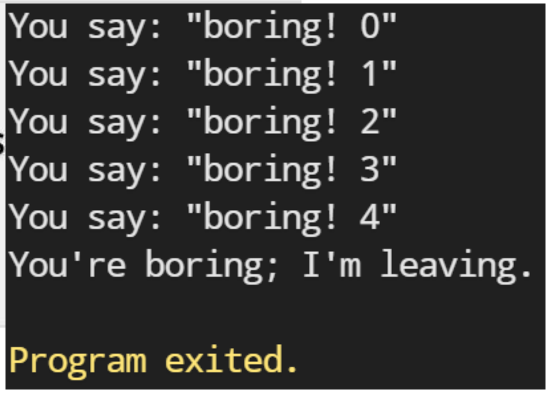
Channels

- Connect goroutines allowing th

- When main executes <-c, it blocks
- When boring executes c <- value it blocks
- Channels communicate *and* ***synchronize***

```
func main() {
    c := make(chan string)
    go boring("boring!", c)
    for i := 0; i < 5; i++ {
        fmt.Printf("You say: %q\n", <-c) // Receive expression is just a value.
    }
    fmt.Println("You're boring; I'm leaving.")
}
```

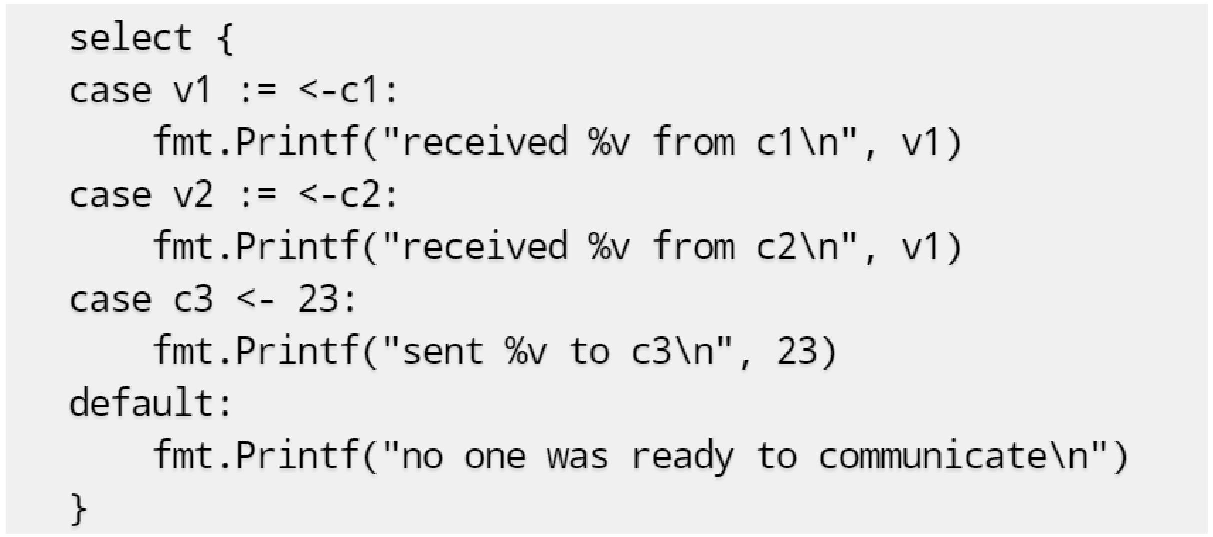
```
func boring(msg string, c chan string) {
    for i := 0; ; i++ {
        c <- fmt.Sprintf("%s %d", msg, i) // Expression to be sent can be any s
        time.Sleep(time.Duration(rand.Intn(1e3)) * time.Millisecond)
    }
}
```



```
You say: "boring! 0"
You say: "boring! 1"
You say: "boring! 2"
You say: "boring! 3"
You say: "boring! 4"
You're boring; I'm leaving.

Program exited.
```

Select: Handling Multiple Channels

- All channels are evaluated
- Select blocks until one communication can proceed
  - Cf. Linux select system call, Windows WaitForMultipleObjectsEx
  - Cf. Alternatives and guards in CPS
- If multiple can proceed select chooses randomly
- Default clause executes immediately if no ready channel



```
select {
case v1 := <-c1:
    fmt.Printf("received %v from c1\n", v1)
case v2 := <-c2:
    fmt.Printf("received %v from c2\n", v1)
case c3 <- 23:
    fmt.Printf("sent %v to c3\n", 23)
default:
    fmt.Printf("no one was ready to communicate\n")
}
```

Select: Handling Multiple Channels

- All channels are evaluated
- Select blocks until one communication can proceed
    - Cf. Linux select system call, Windows WaitForMultipleObjectsEx
    - Cf. Alternatives and guards in CPS
- If multiple can proceed select chooses randomly
- Default clause executes immediately if no ready channel

```
select {
case v1 := <-c1:
    fmt.Printf("received %v from c1\n", v1)
case v2 := <-c2:
    fmt.Printf("received %v from c2\n", v1)
case c3 <- 23:
    fmt.Printf("sent %v to c3\n", 23)
default:
    fmt.Printf("no one was ready to communicate\n")
}
```

```
select {
case v1 := <-c1:
    fmt.Printf(…)
case v2 := <-c2:
    fmt.Printf(…)
}
```

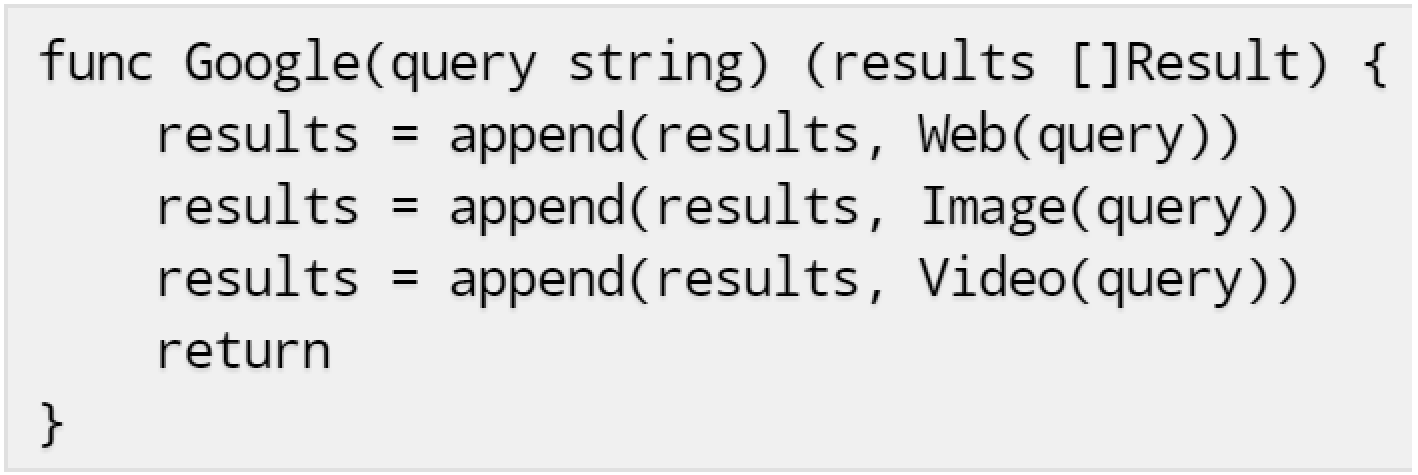
Without default clause becomes rendezvous!

Google Search

- Workload:
- Accept query
- Return page of results (with ugh, ads)
- Get search results by sending query to
  - Web Search
  - Image Search
  - YouTube
  - Maps
  - News, etc
- How to implement this?

Search 1.0

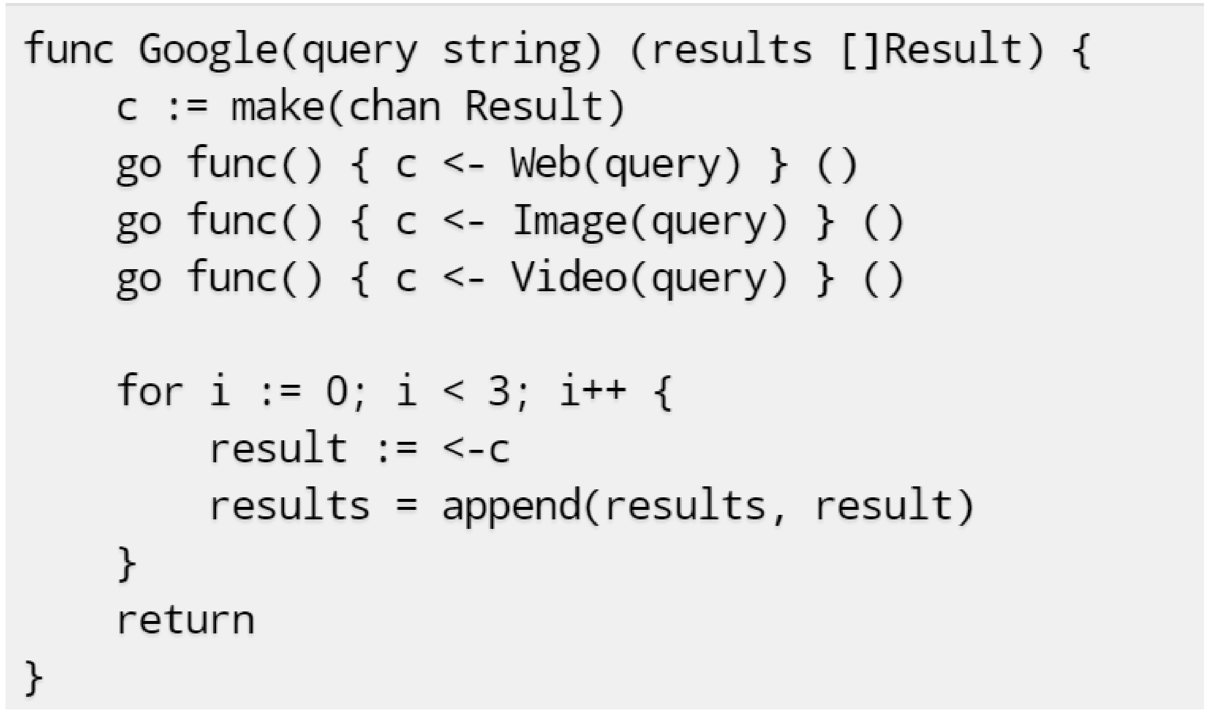
- Google function takes query and returns a slice of results (strings)
- Invokes Web, Image, Video search serially



```go
func Google(query string) (results []Result) {
    results = append(results, Web(query))
    results = append(results, Image(query))
    results = append(results, Video(query))
    return
}
```

Search 2.0

- Run Web, Image, Video searches concurrently, wait for results
- No locks, conditions, callbacks



```go
func Google(query string) (results []Result) {
    c := make(chan Result)
    go func() { c <- Web(query) } ()
    go func() { c <- Image(query) } ()
    go func() { c <- Video(query) } ()

    for i := 0; i < 3; i++ {
        result := <-c
        results = append(results, result)
    }
    return
}
```

Search 2.1

- Don’t wait for slow servers: No locks, conditions, callbacks!

```
c := make(chan Result)
go func() { c <- Web(query) } ()
go func() { c <- Image(query) } ()
go func() { c <- Video(query) } ()

timeout := time.After(80 * time.Millisecond)
for i := 0; i < 3; i++ {
    select {
    case result := <-c:
        results = append(results, result)
    case <-timeout:
        fmt.Println("timed out")
        return
    }
}
return
```

Search 3.0

- Reduce tail latency with replication. No locks, conditions, callbacks!

```go
c := make(chan Result)
go func() { c <- First(query, Web1, Web2) } ()
go func() { c <- First(query, Image1, Image2) } ()
go func() { c <- First(query, Video1, Video2) } ()
timeout := time.After(80 * time.Millisecond)
for i := 0; i < 3; i++ {
    select {
    case result := <-c:
        results = append(results, result)
    case <-timeout:
        fmt.Println("timed out")
        return
    }
}
return
```

```go
func First(query string, replicas ...Search) Result {
    c := make(chan Result)
    searchReplica := func(i int) { c <- replicas[i](query) }
    for i := range replicas {
        go searchReplica(i)
    }
    return <-c
}
```

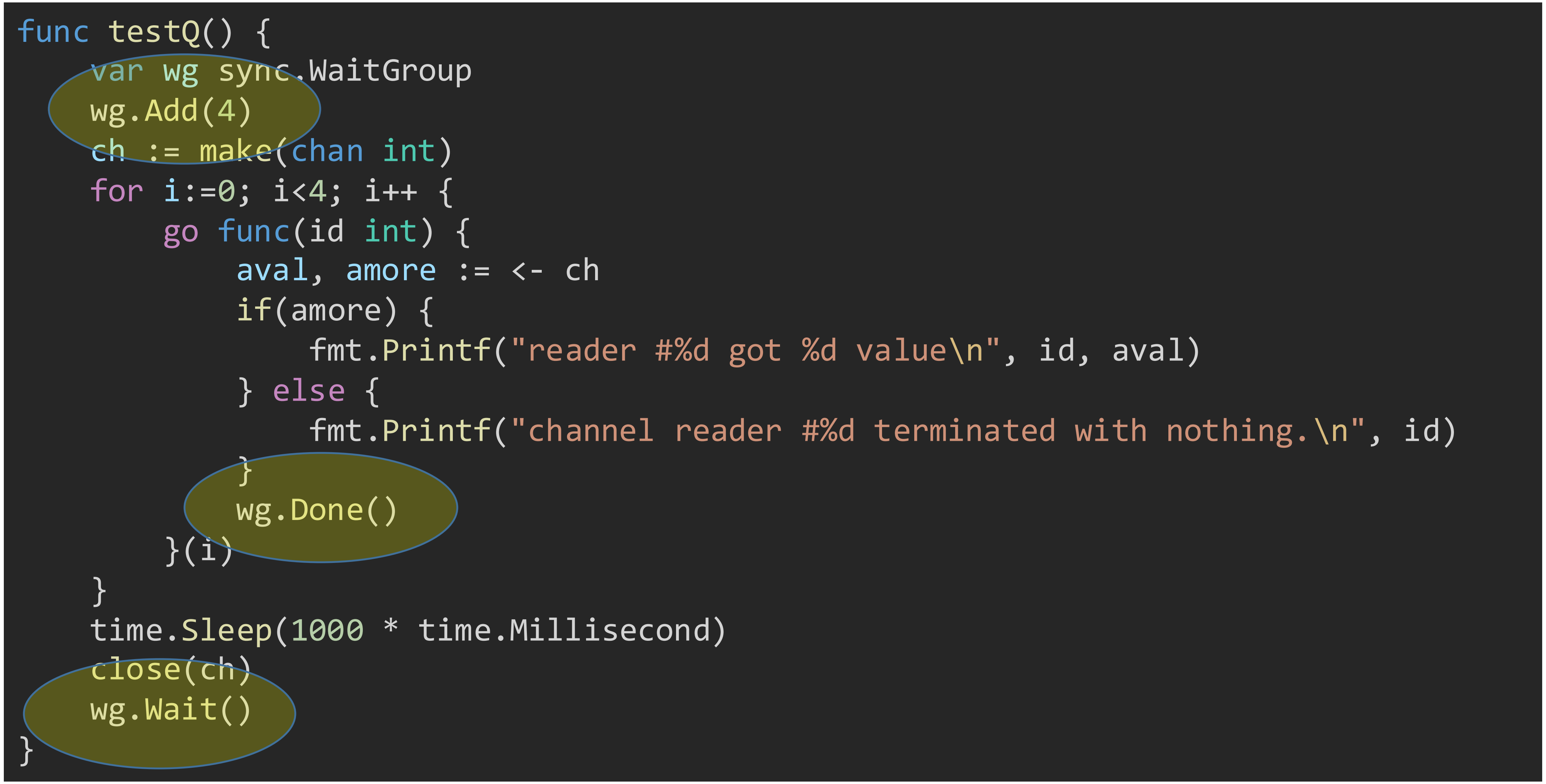
Other tools in Go

- Goroutines and channels are the main primitives
- Sometimes you just need a reference counter or lock
    - “sync” and “sync/atomic” packages
    - Mutex, condition, atomic operations
- Sometimes you need to wait for a go routine to finish
    - Didn’t happen in any of the examples in the slides
    - WaitGroups are key

WaitGroups

```go
func testQ() {
    var wg sync.WaitGroup
    wg.Add(4)
    ch := make(chan int)
    for i:=0; i<4; i++ {
        go func(id int) {
            aval, amore := <- ch
            if(amore) {
                fmt.Printf("reader #%d got %d value\n", id, aval)
            } else {
                fmt.Printf("channel reader #%d terminated with nothing.\n", id)
            }
            wg.Done()
        }(i)
    }
    time.Sleep(1000 * time.Millisecond)
    close(ch)
    wg.Wait()
}
```

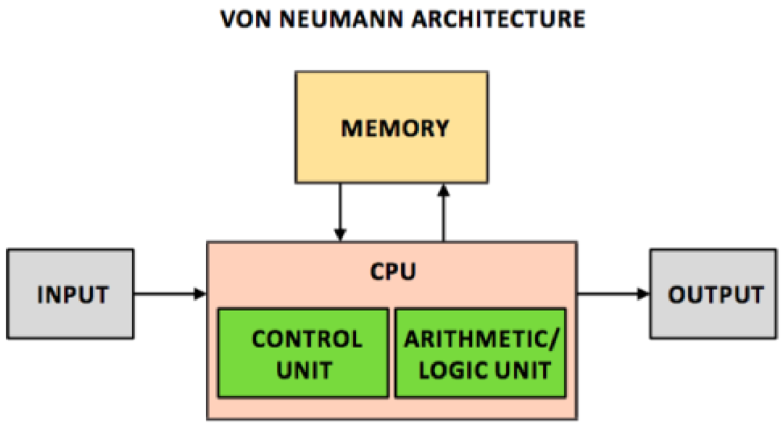
WaitGroups



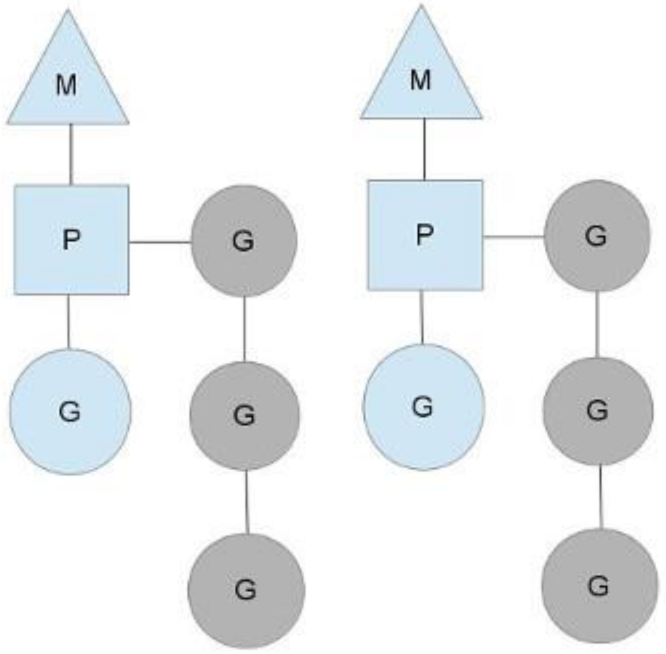
```go
func testQ() {
    var wg sync.WaitGroup
    wg.Add(4)
    ch := make(chan int)
    for i:=0; i<4; i++ {
        go func(id int) {
            aval, amore := <- ch
            if(amore) {
                fmt.Printf("reader #%d got %d value\n", id, aval)
            } else {
                fmt.Printf("channel reader #%d terminated with nothing.\n", id)
            }
            wg.Done()
        }(i)
    }
    time.Sleep(1000 * time.Millisecond)
    close(ch)
    wg.Wait()
}
```

Go: magic or threadpools and concurrent Qs?

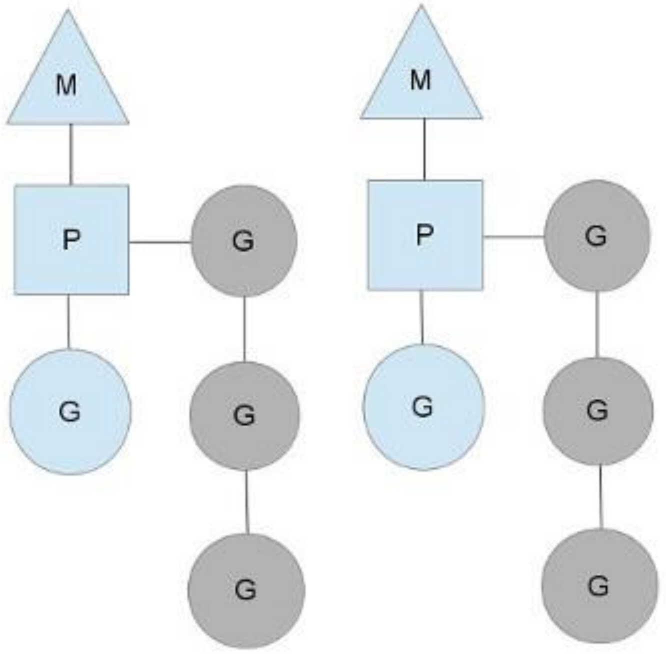
- We've seen several abstractions for
  - Control flow/exection
  - Communication
- Lots of discussion of pros and cons
- Ultimately still CPUs + instructions
- Go: just sweeping issues under the language interface?
  - Why is it OK to have 100,000s of goroutines?
  - Why isn't composition an issue?



Go implementation details

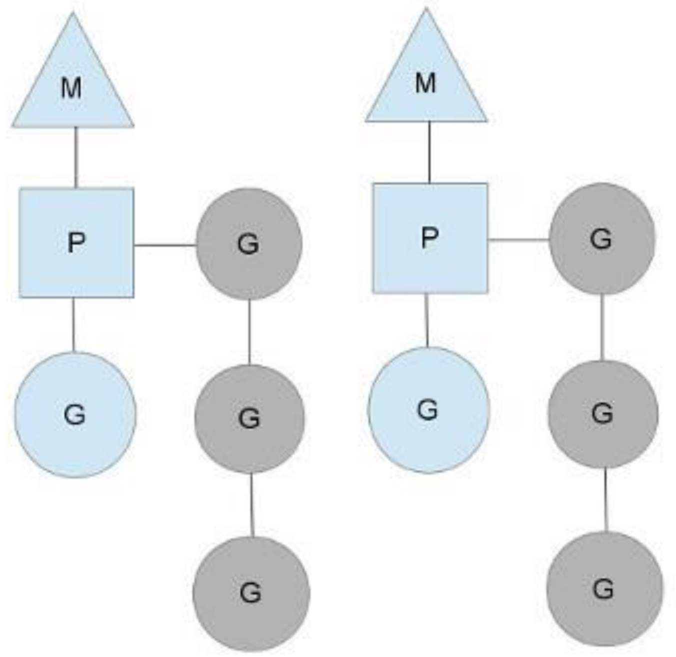


Go implementation details



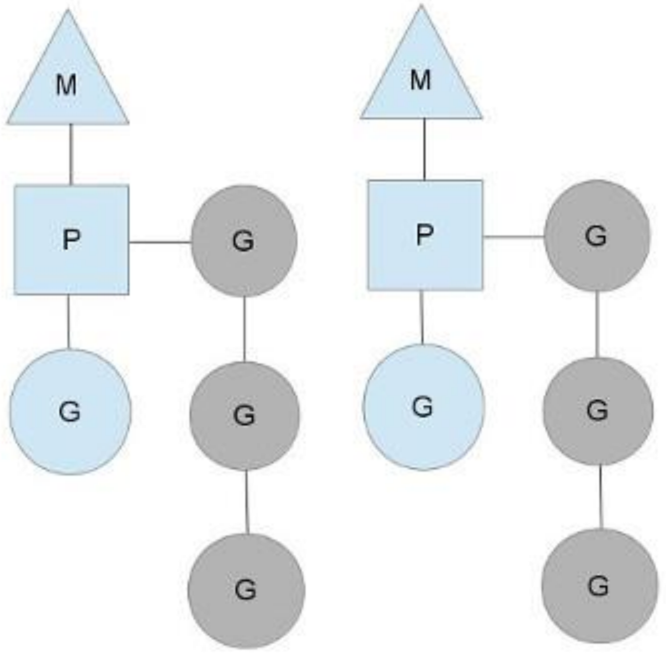
- M = “machine” → OS thread

Go implementation details



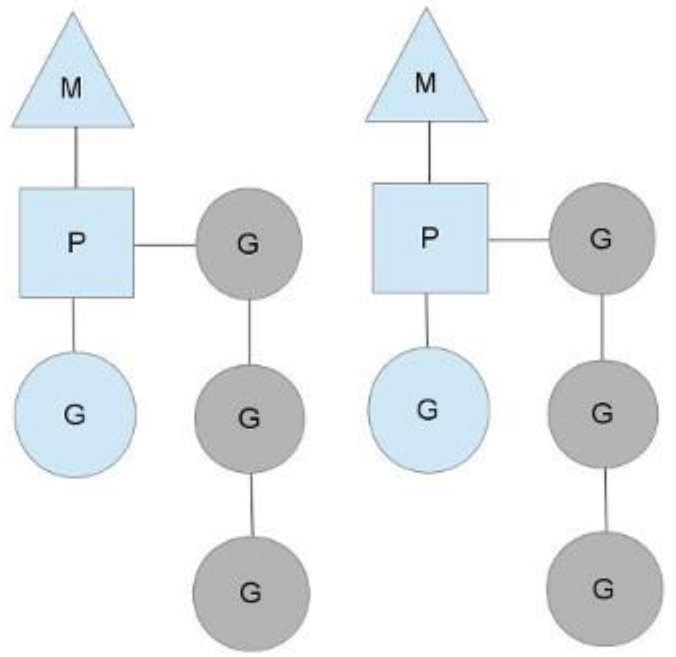
- M = “machine” → OS thread
- P = (processing) context

Go implementation details



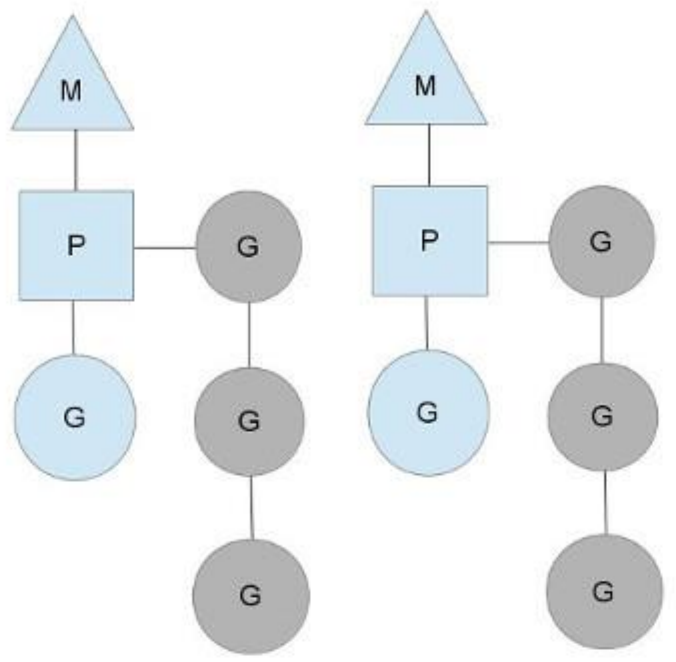
- M = “machine” → OS thread
- P = (processing) context
- G = goroutines

Go implementation details



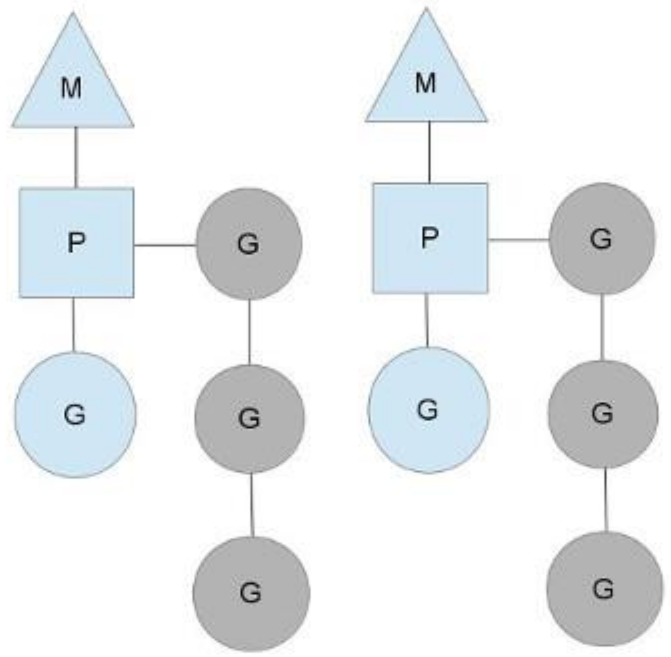
- M = “machine” → OS thread
- P = (processing) context
- G = goroutines
- Each ‘M’ has a queue of goroutines

Go implementation details



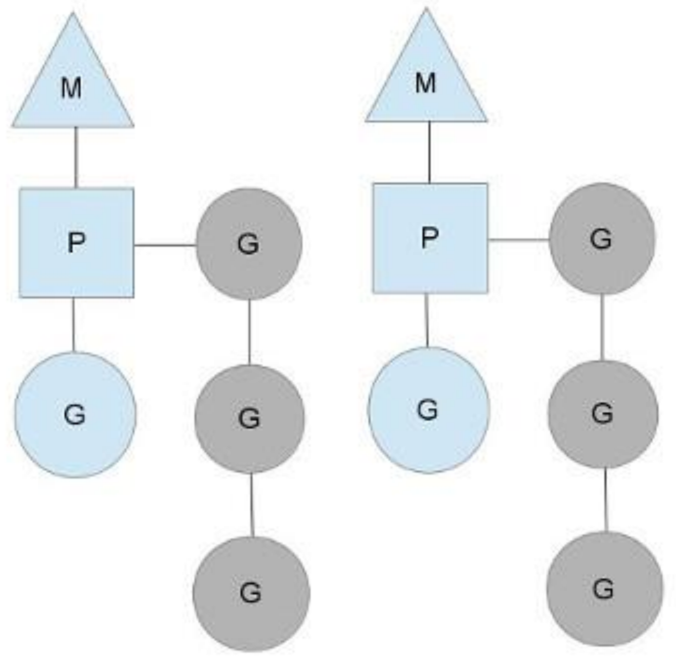
- M = “machine” → OS thread
- P = (processing) context
- G = goroutines
- Each ‘M’ has a queue of goroutines
- Goroutine scheduling is cooperative

Go implementation details



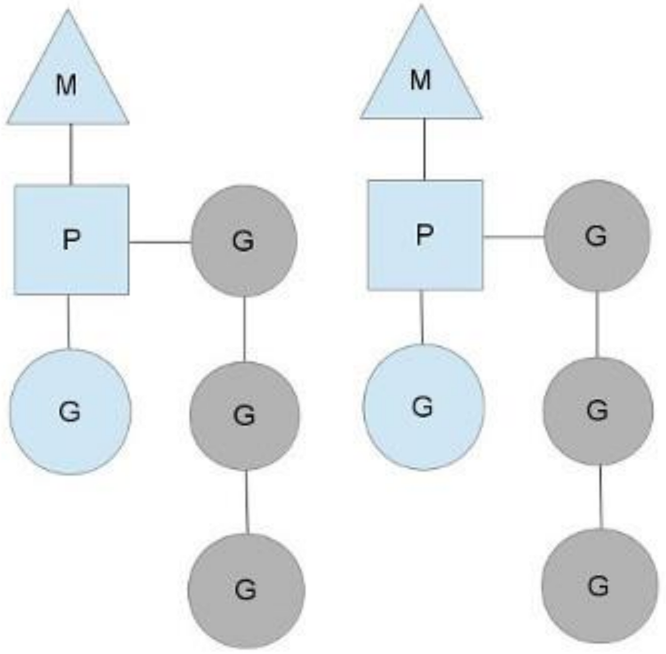
- M = “machine” → OS thread
- P = (processing) context
- G = goroutines
- Each ‘M’ has a queue of goroutines
- ~~Goroutine scheduling is cooperative~~
- Go routine scheduling was cooperative
  - Switch out on complete or block
  - Very light weight (fibers!)
  - Scheduler does work-stealing

Go implementation details

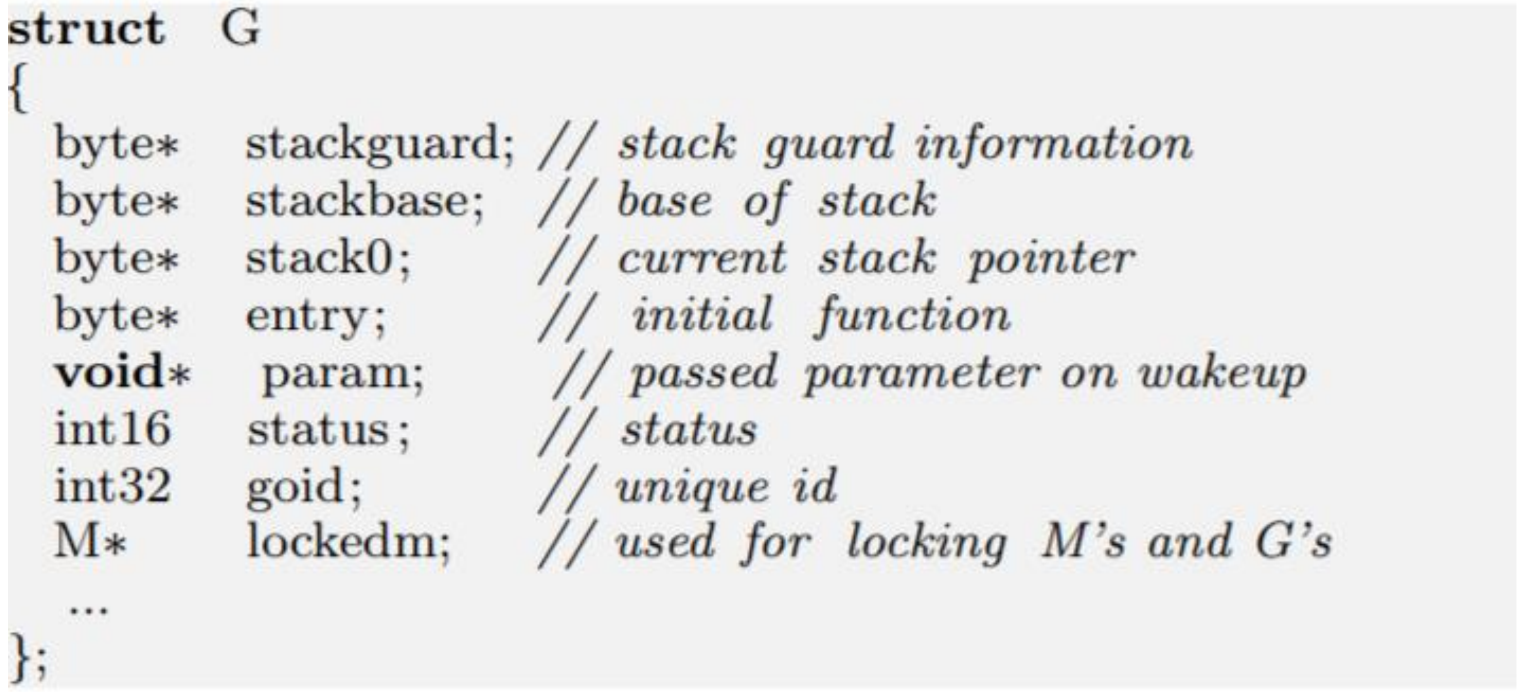


- M = “machine” → OS thread
- P = (processing) context
- G = goroutines
- Each ‘M’ has a queue of goroutines
- Goroutine scheduling was cooperative
  - Switch out on complete or block
  - Very light weight (fibers!)
  - Scheduler does work-stealing

Go implementation details

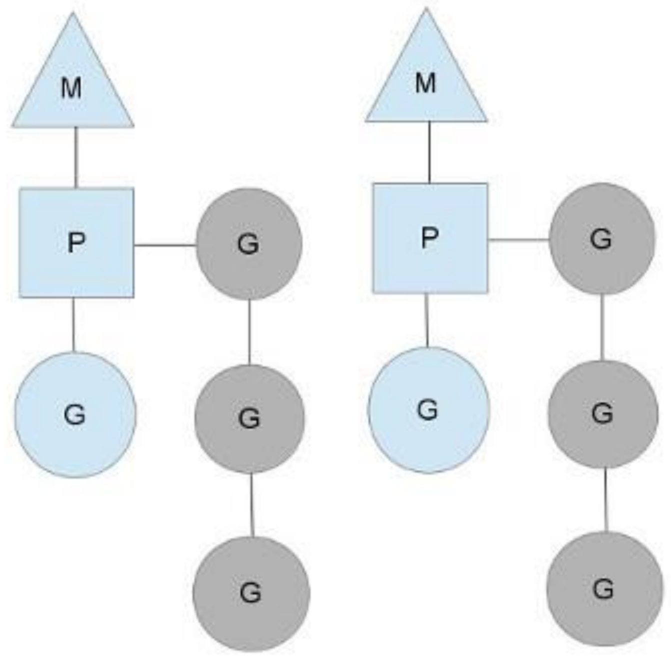


- M = “machine” → OS thread
- P = (processing) context
- G = goroutines
- Each ‘M’ has a queue of goroutines



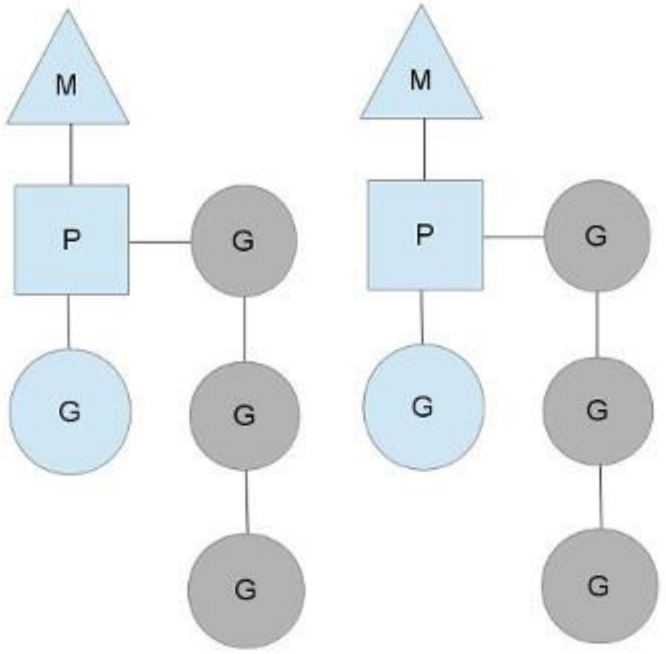
```
struct  G
{
  byte*    stackguard; // stack guard information
  byte*    stackbase;  // base of stack
  byte*    stack0;     // current stack pointer
  byte*    entry;      //  initial function
  void*     param;      // passed parameter on wakeup
  int16    status;     // status
  int32    goid;       // unique id
  M*       lockedm;    // used for locking M's and G's
   ...
};
```

Go implementation details

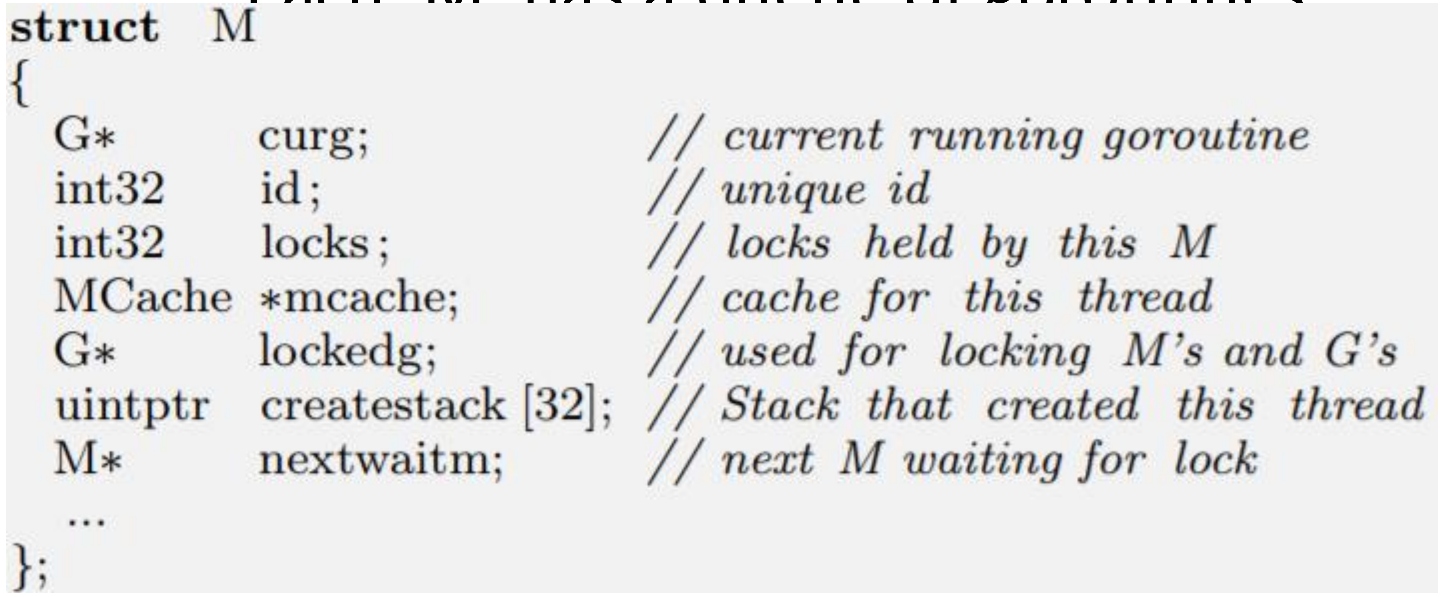


- M = “machine” → OS thread
- P = (processing) context
- G = goroutines
- Each ‘M’ has a queue of goroutines
- Goroutine scheduling was cooperative
  - Switch out on complete or block
  - Very light weight (fibers!)
  - Scheduler does work-stealing

Go implementation details

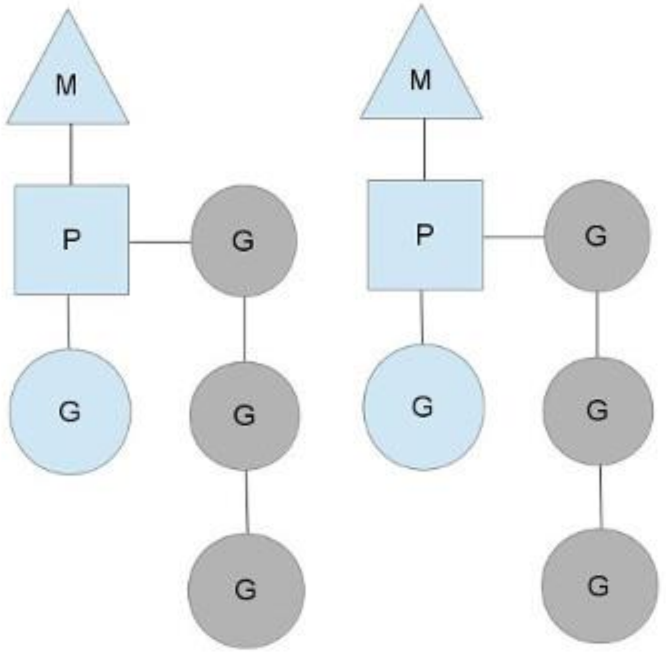


- M = “machine” → OS thread
- P = (processing) context
- G = goroutines
- Each ‘M’ has a queue of goroutines

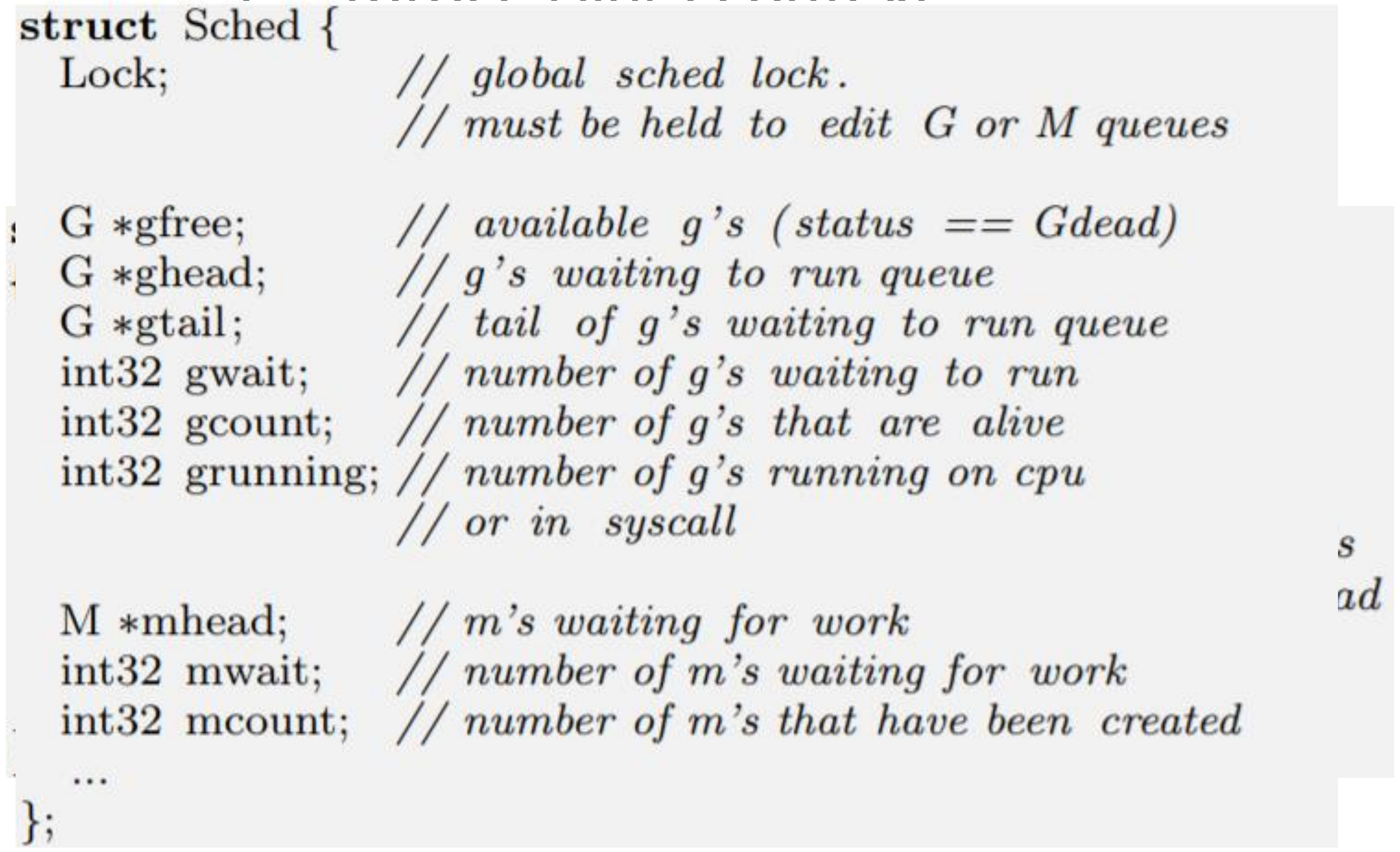


```
struct  M
{
  G*        curg;                // current running goroutine
  int32     id;                  // unique id
  int32     locks;               // locks held by this M
  MCache    *mcache;             // cache for this thread
  G*        lockedg;             // used for locking M's and G's
  uintptr   createstack [32];    // Stack that created this thread
  M*        nextwaitm;           // next M waiting for lock
   ...
};
```

Go implementation details

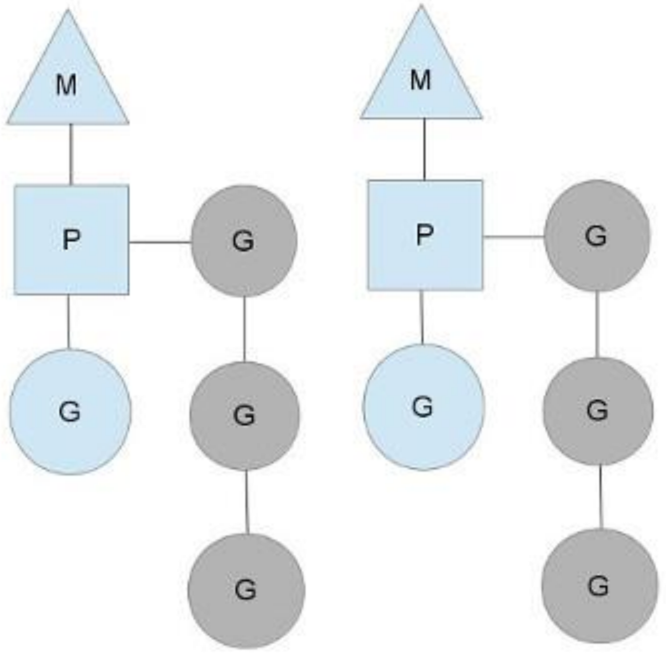


- M = “machine” → OS thread
- P = (processing) context

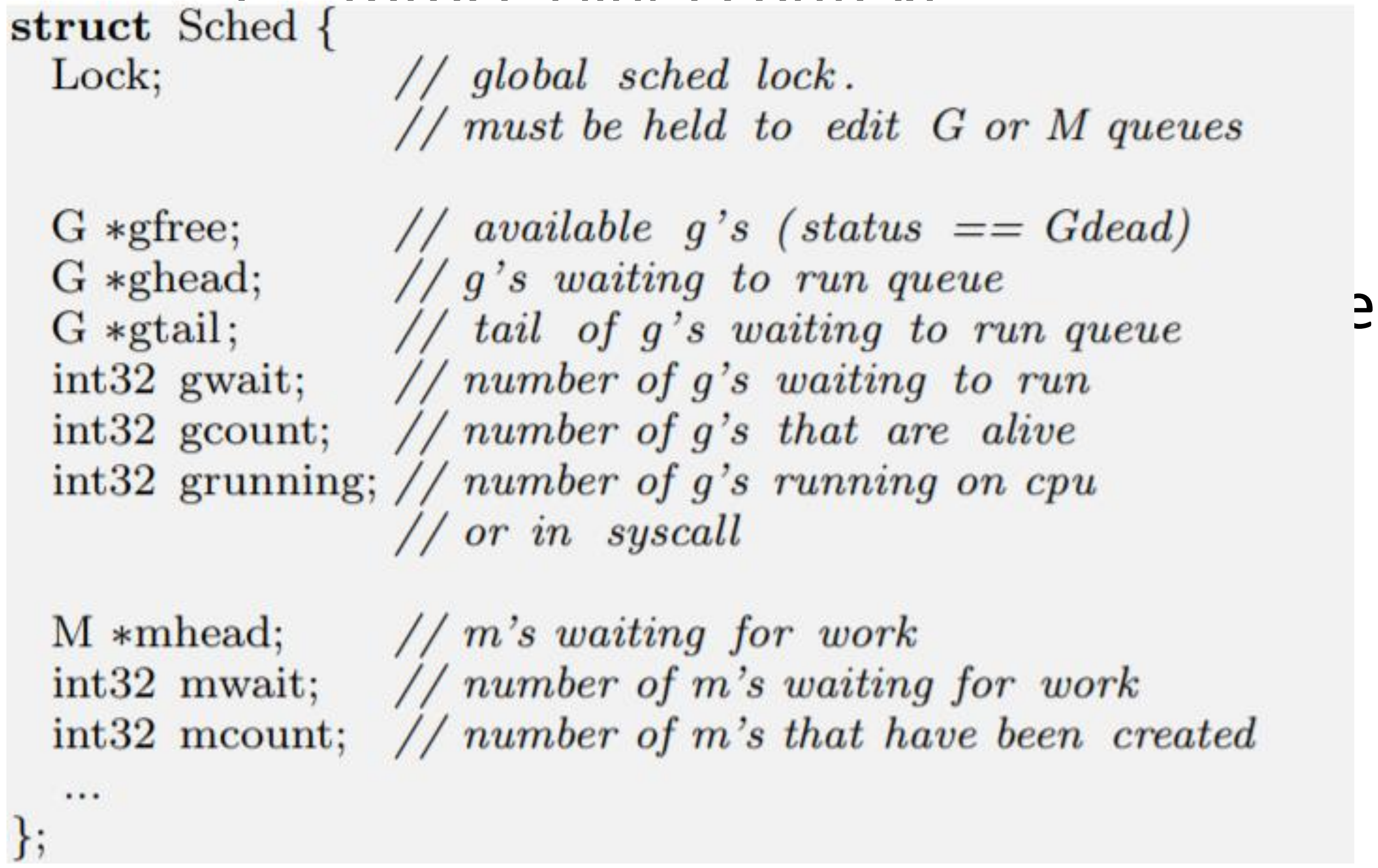


```
struct Sched {
  Lock;             // global sched lock.
                    // must be held to edit G or M queues

  G *gfree;         // available g's (status == Gdead)
  G *ghead;         // g's waiting to run queue
  G *gtail;         // tail of g's waiting to run queue
  int32 gwait;      // number of g's waiting to run
  int32 gcount;     // number of g's that are alive
  int32 grunning;   // number of g's running on cpu
                    // or in syscall

  M *mhead;         // m's waiting for work
  int32 mwait;      // number of m's waiting for work
  int32 mcount;     // number of m's that have been created
  ...
};
```

Go implementation details



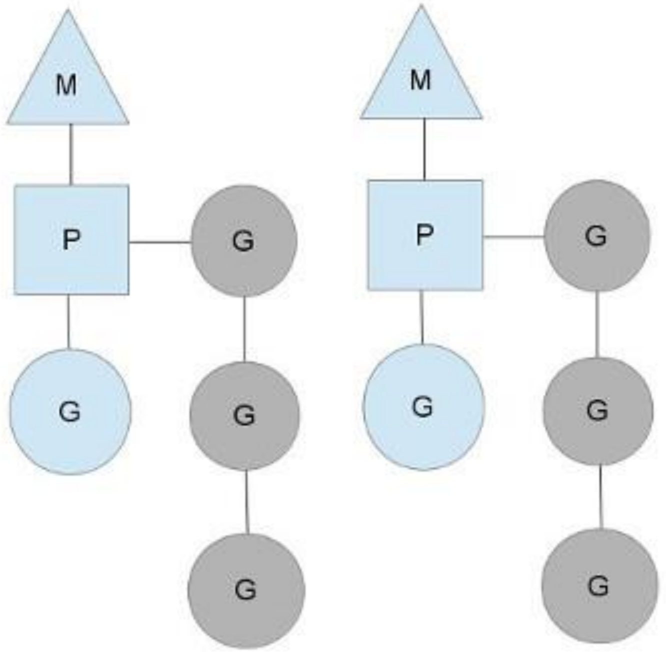
- M = “machine” → OS thread
- P = (processing) context



```
struct Sched {
  Lock;               // global sched lock.
                      // must be held to edit G or M queues

  G *gfree;           // available g's (status == Gdead)
  G *ghead;           // g's waiting to run queue
  G *gtail;           // tail of g's waiting to run queue
  int32 gwait;        // number of g's waiting to run
  int32 gcount;       // number of g's that are alive
  int32 grunning;     // number of g's running on cpu
                      // or in syscall

  M *mhead;           // m's waiting for work
  int32 mwait;        // number of m's waiting for work
  int32 mcount;       // number of m's that have been created
   ...
};
```

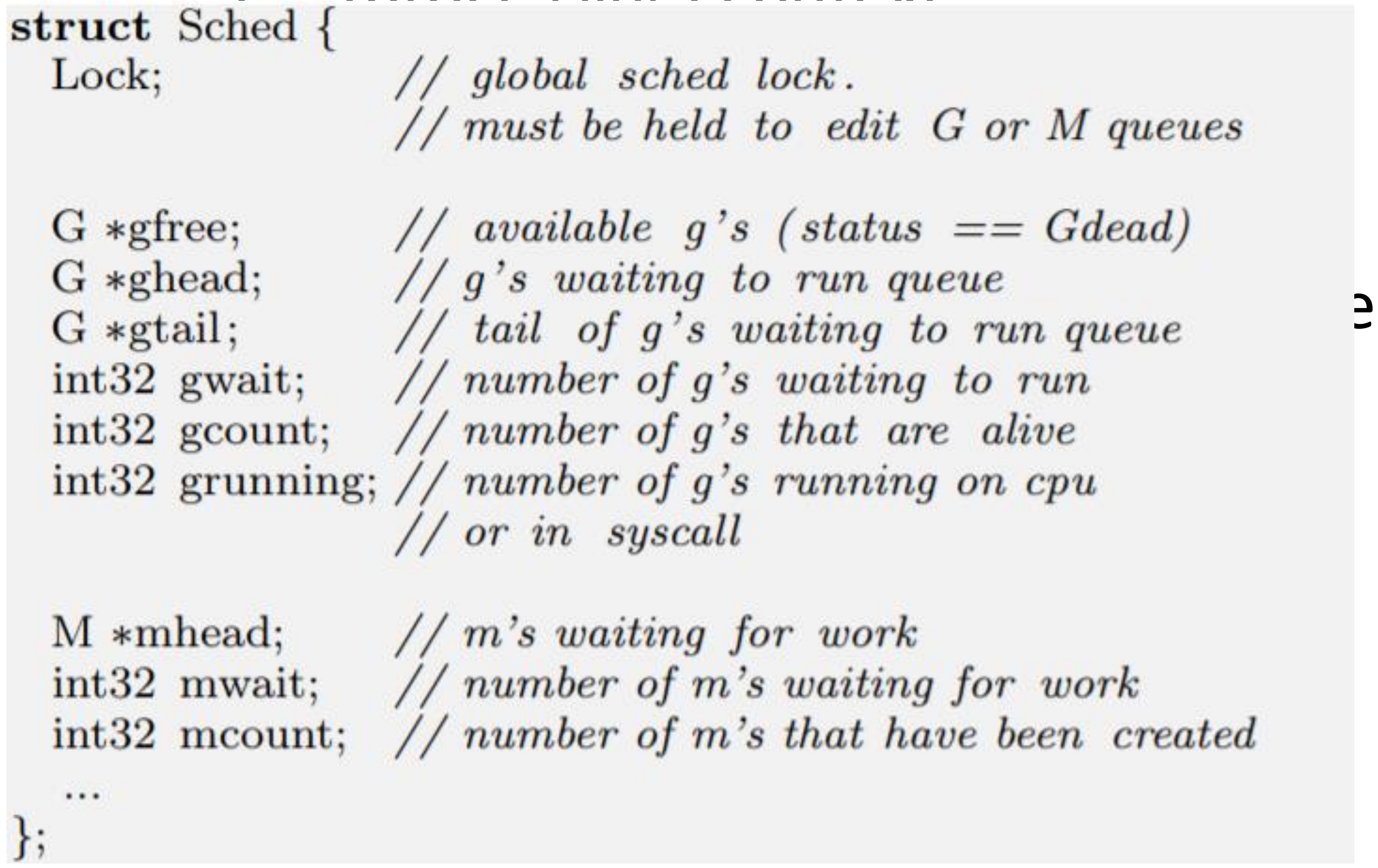
e

Go implementation details



- M = “machine” → OS thread
- P = (processing) context

e



```
struct Sched {
  Lock;              // global sched lock.
                     // must be held to edit G or M queues

  G *gfree;          // available g's (status == Gdead)
  G *ghead;          // g's waiting to run queue
  G *gtail;          // tail of g's waiting to run queue
  int32 gwait;       // number of g's waiting to run
  int32 gcount;      // number of g's that are alive
  int32 grunning;    // number of g's running on cpu
                     // or in syscall

  M *mhead;          // m's waiting for work
  int32 mwait;       // number of m's waiting for work
  int32 mcount;      // number of m's that have been created
  ...
};
```

1000s of go routines?

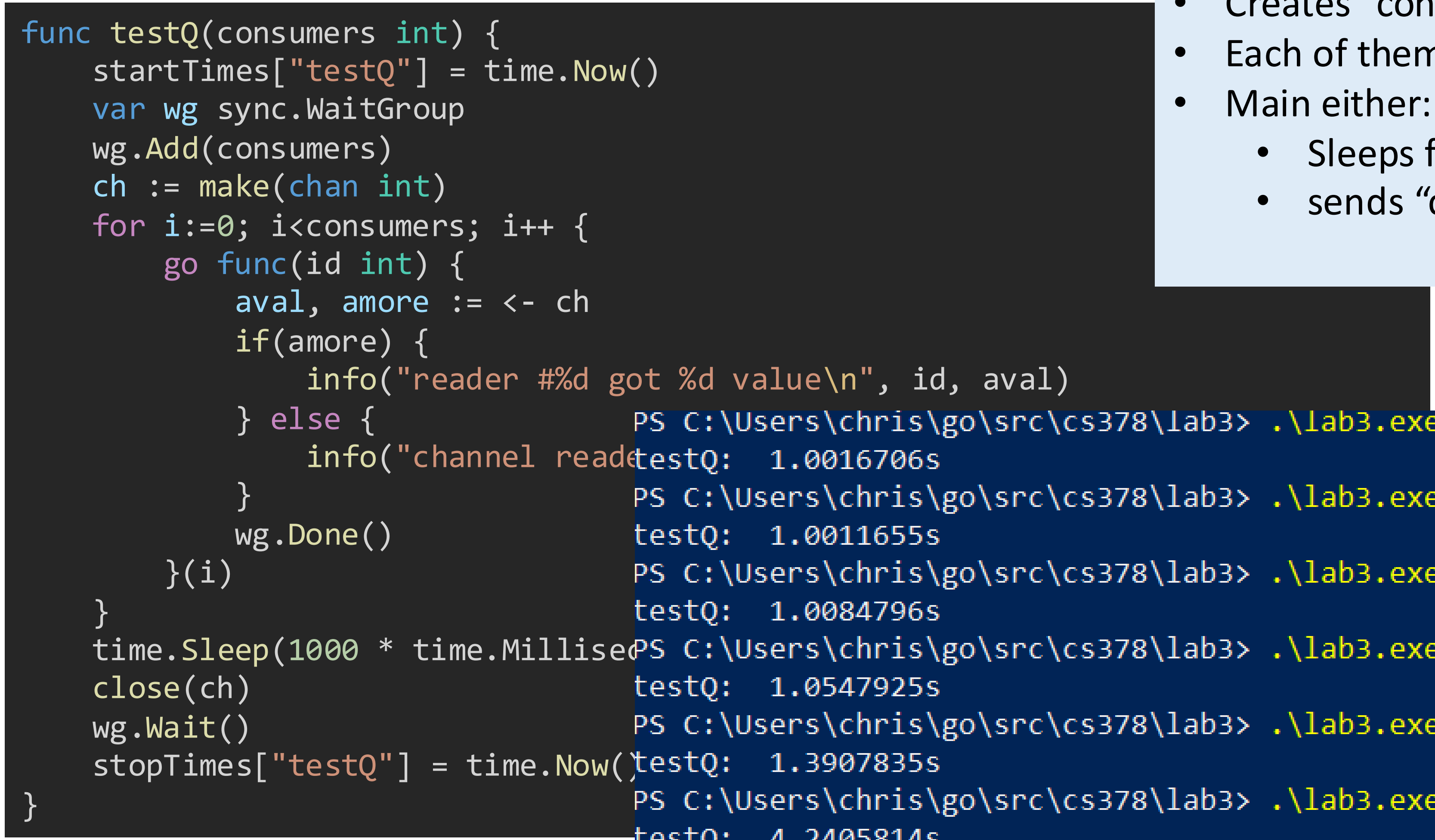
```go
func testQ(consumers int) {
    startTimes["testQ"] = time.Now()
    var wg sync.WaitGroup
    wg.Add(consumers)
    ch := make(chan int)
    for i:=0; i<consumers; i++ {
        go func(id int) {
            aval, amore := <- ch
            if(amore) {
                info("reader #%d got %d value\n", id, aval)
            } else {
                info("channel reader #%d terminated with nothing.\n", id)
            }
            wg.Done()
        }(i)
    }
    time.Sleep(1000 * time.Millisecond)
    close(ch)
    wg.Wait()
    stopTimes["testQ"] = time.Now()
}
```

1000s of go routines?

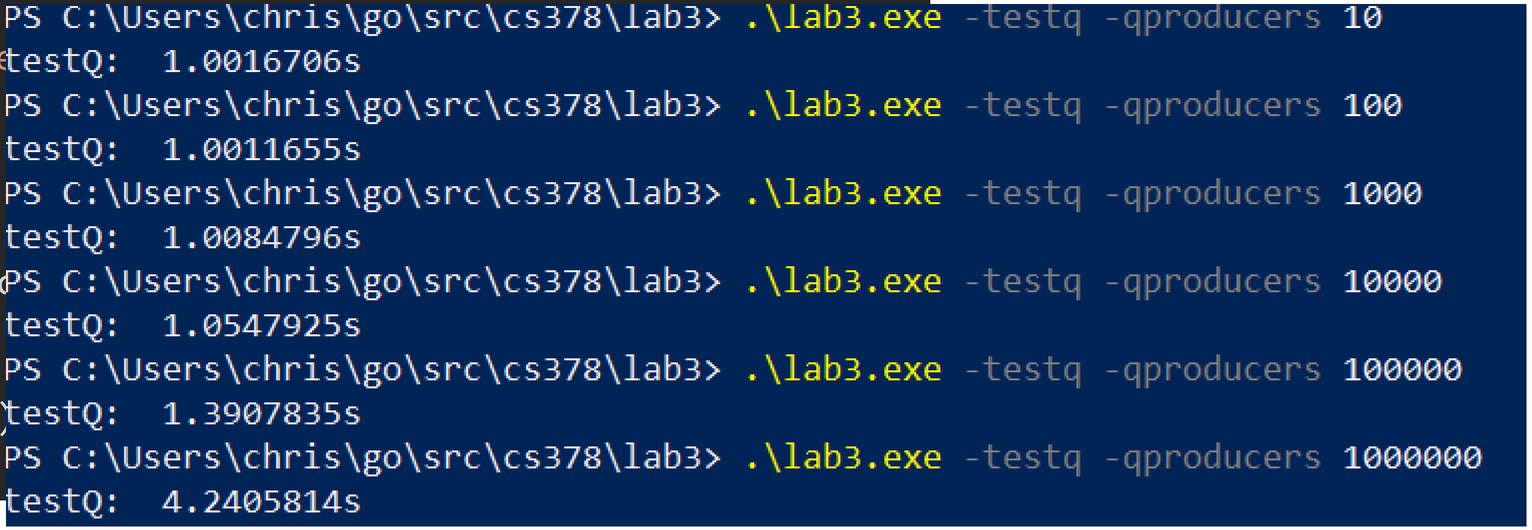
```go
func testQ(consumers int) {
    startTimes["testQ"] = time.Now()
    var wg sync.WaitGroup
    wg.Add(consumers)
    ch := make(chan int)
    for i:=0; i<consumers; i++ {
        go func(id int) {
            aval, amore := <- ch
            if(amore) {
                info("reader #%d got %d value\n", id, aval)
            } else {
                info("channel reader #%d terminated with nothing.\n", id)
            }
            wg.Done()
        }(i)
    }
    time.Sleep(1000 * time.Millisecond)
    close(ch)
    wg.Wait()
    stopTimes["testQ"] = time.Now()
}
```

- Creates a channel
- Creates “consumers” goroutines
- Each of them tries to read from the channel
- Main either:
  - Sleeps for 1 second, closes the channel
  - sends “consumers” values

1000s of go routines?



```
func testQ(consumers int) {
    startTimes["testQ"] = time.Now()
    var wg sync.WaitGroup
    wg.Add(consumers)
    ch := make(chan int)
    for i:=0; i<consumers; i++ {
        go func(id int) {
            aval, amore := <- ch
            if(amore) {
                info("reader #%d got %d value\n", id, aval)
            } else {
                info("channel reade
            }
            wg.Done()
        }(i)
    }
    time.Sleep(1000 * time.Millise
    close(ch)
    wg.Wait()
    stopTimes["testQ"] = time.Now(
}
```

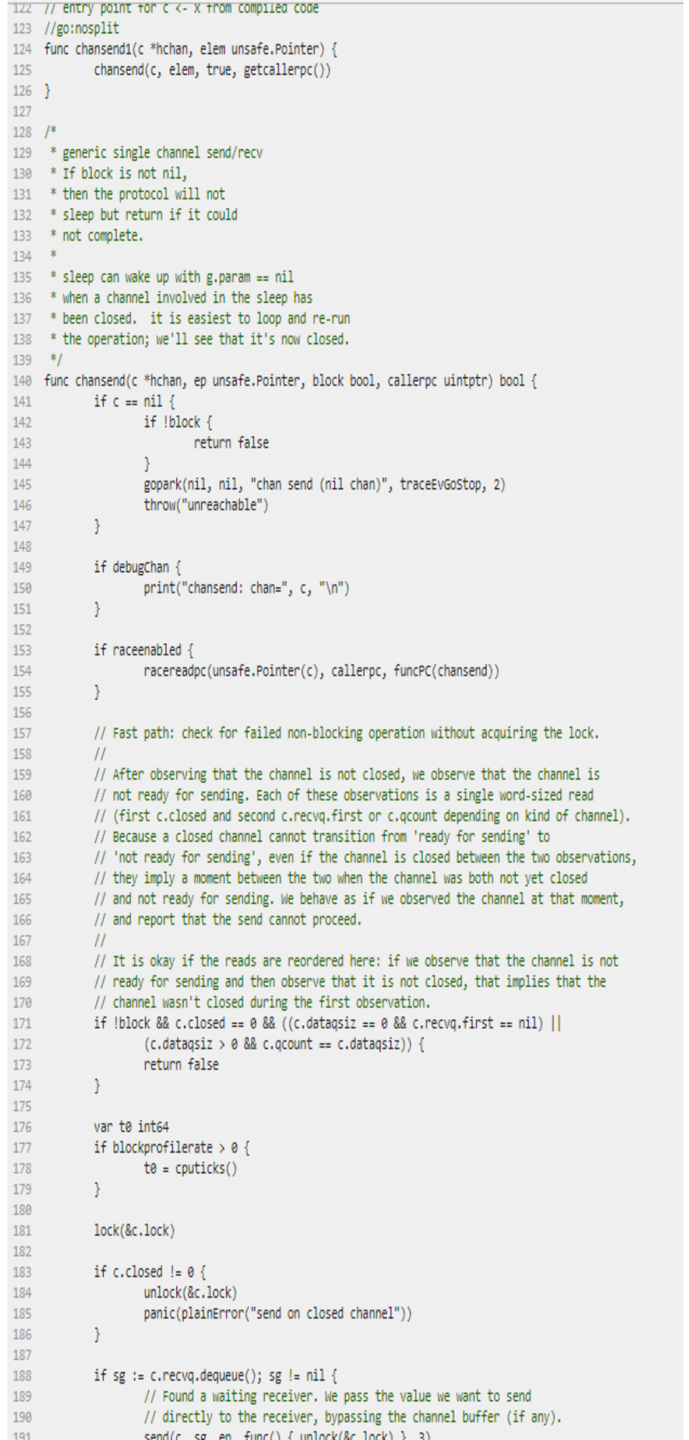


```
PS C:\Users\chris\go\src\cs378\lab3> .\lab3.exe -testq -qproducers 10
testQ:  1.0016706s
PS C:\Users\chris\go\src\cs378\lab3> .\lab3.exe -testq -qproducers 100
testQ:  1.0011655s
PS C:\Users\chris\go\src\cs378\lab3> .\lab3.exe -testq -qproducers 1000
testQ:  1.0084796s
PS C:\Users\chris\go\src\cs378\lab3> .\lab3.exe -testq -qproducers 10000
testQ:  1.0547925s
PS C:\Users\chris\go\src\cs378\lab3> .\lab3.exe -testq -qproducers 100000
testQ:  1.3907835s
PS C:\Users\chris\go\src\cs378\lab3> .\lab3.exe -testq -qproducers 1000000
testQ:  4.2405814s
```

- Creates a channel
- Creates "consumers" goroutines
- Each of them tries to read from the channel
- Main either:
    - Sleeps for 1 second, closes the channel
    - sends "consumers" values

Channel implementation

- You can just read it:
  - https://golang.org/src/runtime/chan.go
- Some highlights

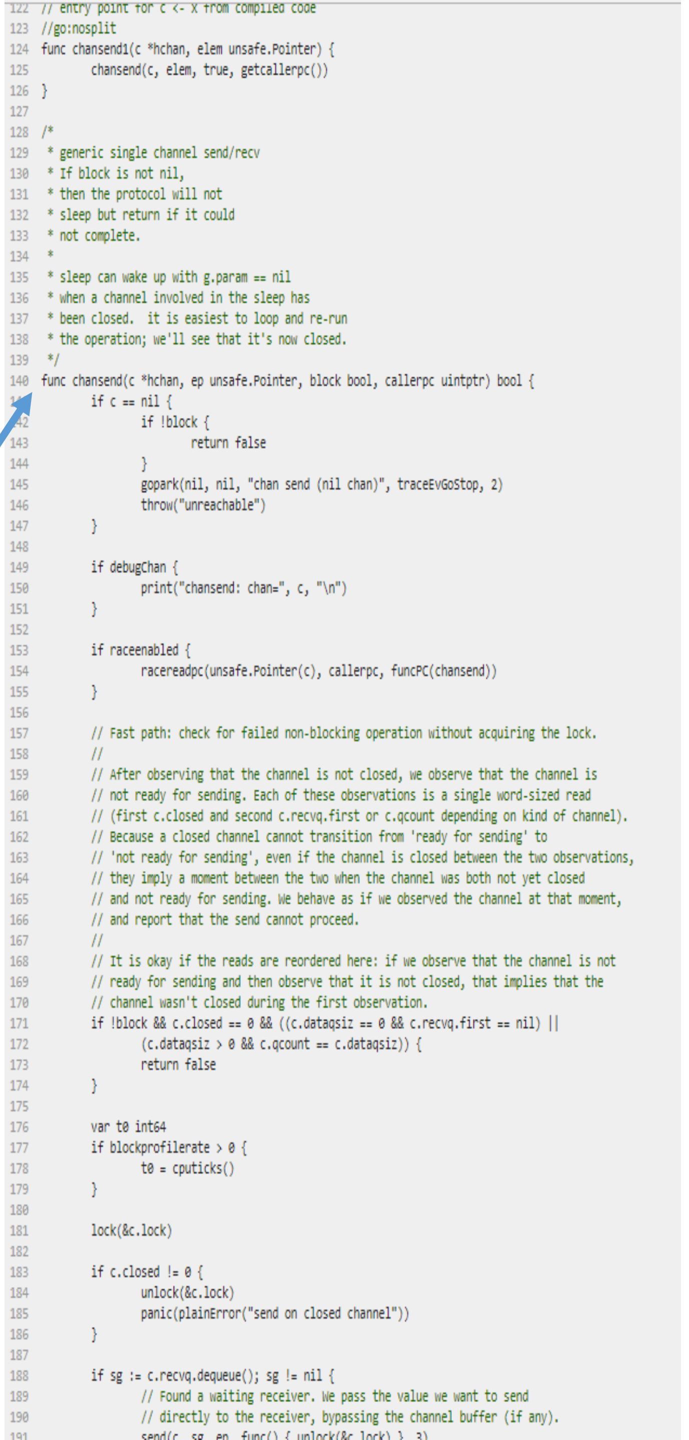


```go
// entry point for c <- x from compiled code
//go:nosplit
func chansend1(c *hchan, elem unsafe.Pointer) {
        chansend(c, elem, true, getcallerpc())
}

/*
 * generic single channel send/recv
 * If block is not nil,
 * then the protocol will not
 * sleep but return if it could
 * not complete.
 *
 * sleep can wake up with g.param == nil
 * when a channel involved in the sleep has
 * been closed.  it is easiest to loop and re-run
 * the operation; we'll see that it's now closed.
 */
func chansend(c *hchan, ep unsafe.Pointer, block bool, callerpc uintptr) bool {
        if c == nil {
                if !block {
                        return false
                }
                gopark(nil, nil, "chan send (nil chan)", traceEvGoStop, 2)
                throw("unreachable")
        }

        if debugChan {
                print("chansend: chan=", c, "\n")
        }

        if raceenabled {
                racereadpc(unsafe.Pointer(c), callerpc, funcPC(chansend))
        }

        // Fast path: check for failed non-blocking operation without acquiring the lock.
        //
        // After observing that the channel is not closed, we observe that the channel is
        // not ready for sending. Each of these observations is a single word-sized read
        // (first c.closed and second c.recvq.first or c.qcount depending on kind of channel).
        // Because a closed channel cannot transition from 'ready for sending' to
        // 'not ready for sending', even if the channel is closed between the two observations,
        // they imply a moment between the two when the channel was both not yet closed
        // and not ready for sending. We behave as if we observed the channel at that moment,
        // and report that the send cannot proceed.
        //
        // It is okay if the reads are reordered here: if we observe that the channel is not
        // ready for sending and then observe that it is not closed, that implies that the
        // channel wasn't closed during the first observation.
        if !block && c.closed == 0 && ((c.dataqsiz == 0 && c.recvq.first == nil) ||
                (c.dataqsiz > 0 && c.qcount == c.dataqsiz)) {
                return false
        }

        var t0 int64
        if blockprofilerate > 0 {
                t0 = cputicks()
        }

        lock(&c.lock)

        if c.closed != 0 {
                unlock(&c.lock)
                panic(plainError("send on closed channel"))
        }

        if sg := c.recvq.dequeue(); sg != nil {
                // Found a waiting receiver. We pass the value we want to send
                // directly to the receiver, bypassing the channel buffer (if any).
                send(c, sg, ep, func() { unlock(&c.lock) }, 3)
```

Channel implementation

- Y
- S

```go
func chansend(c *hchan, ep unsafe.Pointer, block bool, callerpc uintptr) bool {
        if c == nil {
                if !block {
                        return false
                }
                gopark(nil, nil, "chan send (nil chan)", traceEvGoStop, 2)
                throw("unreachable")
        }

        if debugChan {
                print("chansend: chan=", c, "\n")
        }

        if raceenabled {
                racereadpc(unsafe.Pointer(c), callerpc, funcPC(chansend))
        }
```



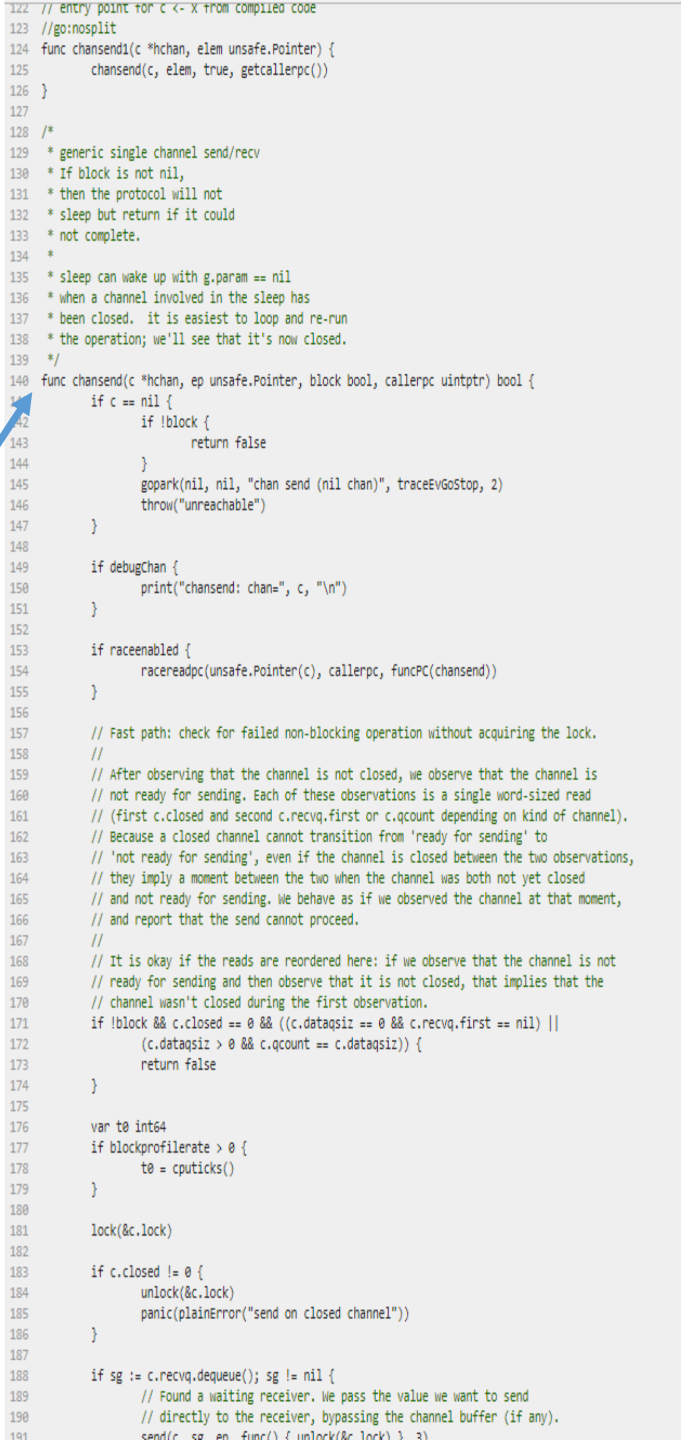
```go
// entry point for c <- x from compiled code
//go:nosplit
func chansend1(c *hchan, elem unsafe.Pointer) {
        chansend(c, elem, true, getcallerpc())
}

/*
 * generic single channel send/recv
 * If block is not nil,
 * then the protocol will not
 * sleep but return if it could
 * not complete.
 *
 * sleep can wake up with g.param == nil
 * when a channel involved in the sleep has
 * been closed.  it is easiest to loop and re-run
 * the operation; we'll see that it's now closed.
 */
func chansend(c *hchan, ep unsafe.Pointer, block bool, callerpc uintptr) bool {
        if c == nil {
                if !block {
                        return false
                }
                gopark(nil, nil, "chan send (nil chan)", traceEvGoStop, 2)
                throw("unreachable")
        }

        if debugChan {
                print("chansend: chan=", c, "\n")
        }

        if raceenabled {
                racereadpc(unsafe.Pointer(c), callerpc, funcPC(chansend))
        }

        // Fast path: check for failed non-blocking operation without acquiring the lock.
        //
        // After observing that the channel is not closed, we observe that the channel is
        // not ready for sending. Each of these observations is a single word-sized read
        // (first c.closed and second c.recvq.first or c.qcount depending on kind of channel).
        // Because a closed channel cannot transition from 'ready for sending' to
        // 'not ready for sending', even if the channel is closed between the two observations,
        // they imply a moment between the two when the channel was both not yet closed
        // and not ready for sending. We behave as if we observed the channel at that moment,
        // and report that the send cannot proceed.
        //
        // It is okay if the reads are reordered here: if we observe that the channel is not
        // ready for sending and then observe that it is not closed, that implies that the
        // channel wasn't closed during the first observation.
        if !block && c.closed == 0 && ((c.dataqsiz == 0 && c.recvq.first == nil) ||
                (c.dataqsiz > 0 && c.qcount == c.dataqsiz)) {
                return false
        }

        var t0 int64
        if blockprofilerate > 0 {
                t0 = cputicks()
        }

        lock(&c.lock)

        if c.closed != 0 {
                unlock(&c.lock)
                panic(plainError("send on closed channel"))
        }

        if sg := c.recvq.dequeue(); sg != nil {
                // Found a waiting receiver. We pass the value we want to send
                // directly to the receiver, bypassing the channel buffer (if any).
                send(c, sg, ep, func() { unlock(&c.lock) }, 3)
```

Channel implementation

- Y
- S

```go
func chansend(c *hchan, ep unsafe.Pointer, block bool, callerpc uintptr) bool {
	if c == nil {
		if !block {
			return false
		}
		gopark(nil, nil, "chan send (nil chan)", traceEvGoStop, 2)
		throw("unreachable")
	}

	if debugChan {
		print("chansend: chan=", c, "\n")
	}

	if raceenabled {
		racereadpc(unsafe.Pointer(c), callerpc, funcPC(chansend))
	}
```

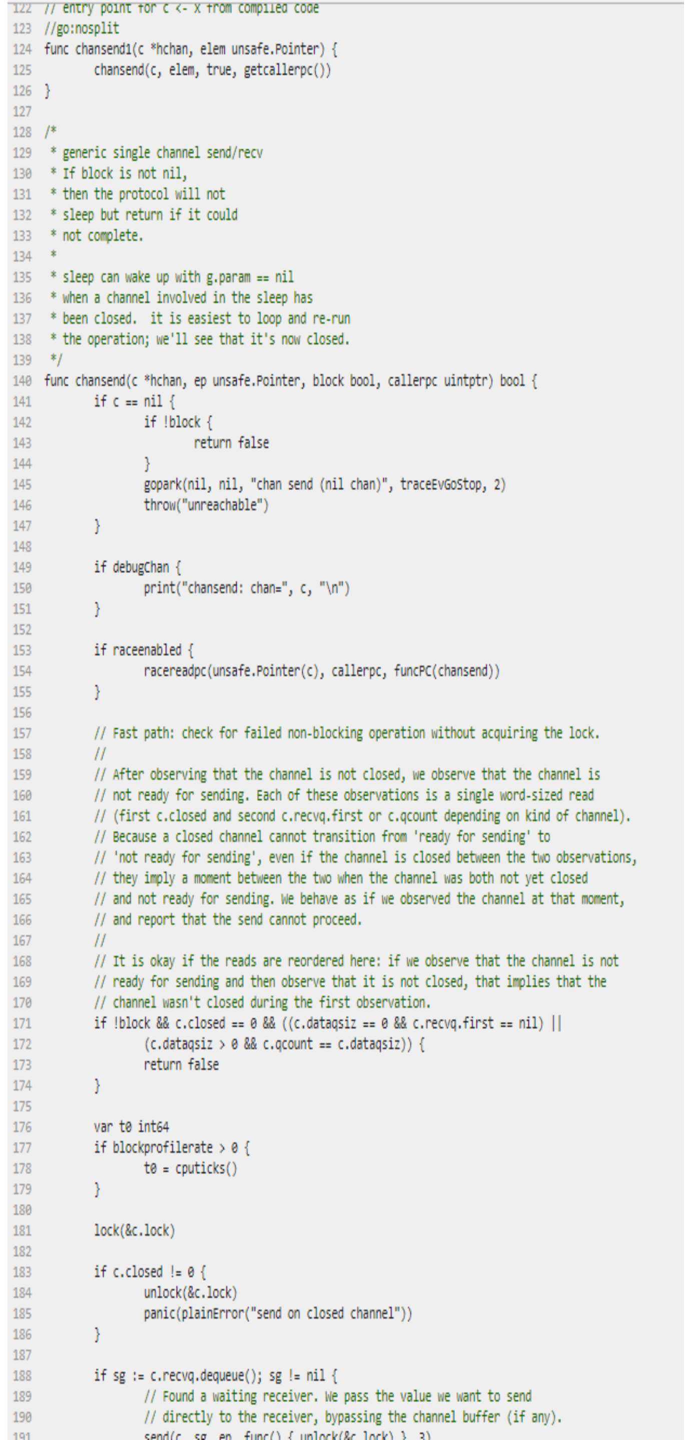
Race detection! Cool!



```go
// entry point for c <- x from compiled code
//go:nosplit
func chansend1(c *hchan, elem unsafe.Pointer) {
	chansend(c, elem, true, getcallerpc())
}

/*
 * generic single channel send/recv
 * If block is not nil,
 * then the protocol will not
 * sleep but return if it could
 * not complete.
 *
 * sleep can wake up with g.param == nil
 * when a channel involved in the sleep has
 * been closed.  it is easiest to loop and re-run
 * the operation; we'll see that it's now closed.
 */
func chansend(c *hchan, ep unsafe.Pointer, block bool, callerpc uintptr) bool {
	if c == nil {
		if !block {
			return false
		}
		gopark(nil, nil, "chan send (nil chan)", traceEvGoStop, 2)
		throw("unreachable")
	}

	if debugChan {
		print("chansend: chan=", c, "\n")
	}

	if raceenabled {
		racereadpc(unsafe.Pointer(c), callerpc, funcPC(chansend))
	}

	// Fast path: check for failed non-blocking operation without acquiring the lock.
	//
	// After observing that the channel is not closed, we observe that the channel is
	// not ready for sending. Each of these observations is a single word-sized read
	// (first c.closed and second c.recvq.first or c.qcount depending on kind of channel).
	// Because a closed channel cannot transition from 'ready for sending' to
	// 'not ready for sending', even if the channel is closed between the two observations,
	// they imply a moment between the two when the channel was both not yet closed
	// and not ready for sending. We behave as if we observed the channel at that moment,
	// and report that the send cannot proceed.
	//
	// It is okay if the reads are reordered here: if we observe that the channel is not
	// ready for sending and then observe that it is not closed, that implies that the
	// channel wasn't closed during the first observation.
	if !block && c.closed == 0 && ((c.dataqsiz == 0 && c.recvq.first == nil) ||
		(c.dataqsiz > 0 && c.qcount == c.dataqsiz)) {
		return false
	}

	var t0 int64
	if blockprofilerate > 0 {
		t0 = cputicks()
	}

	lock(&c.lock)

	if c.closed != 0 {
		unlock(&c.lock)
		panic(plainError("send on closed channel"))
	}

	if sg := c.recvq.dequeue(); sg != nil {
		// Found a waiting receiver. We pass the value we want to send
		// directly to the receiver, bypassing the channel buffer (if any).
		send(c, sg, ep, func() { unlock(&c.lock) }, 3)
```

Channel implementation

- You can just read it:
  - https://golang.org/src/runtime/chan.go
- Some highlights

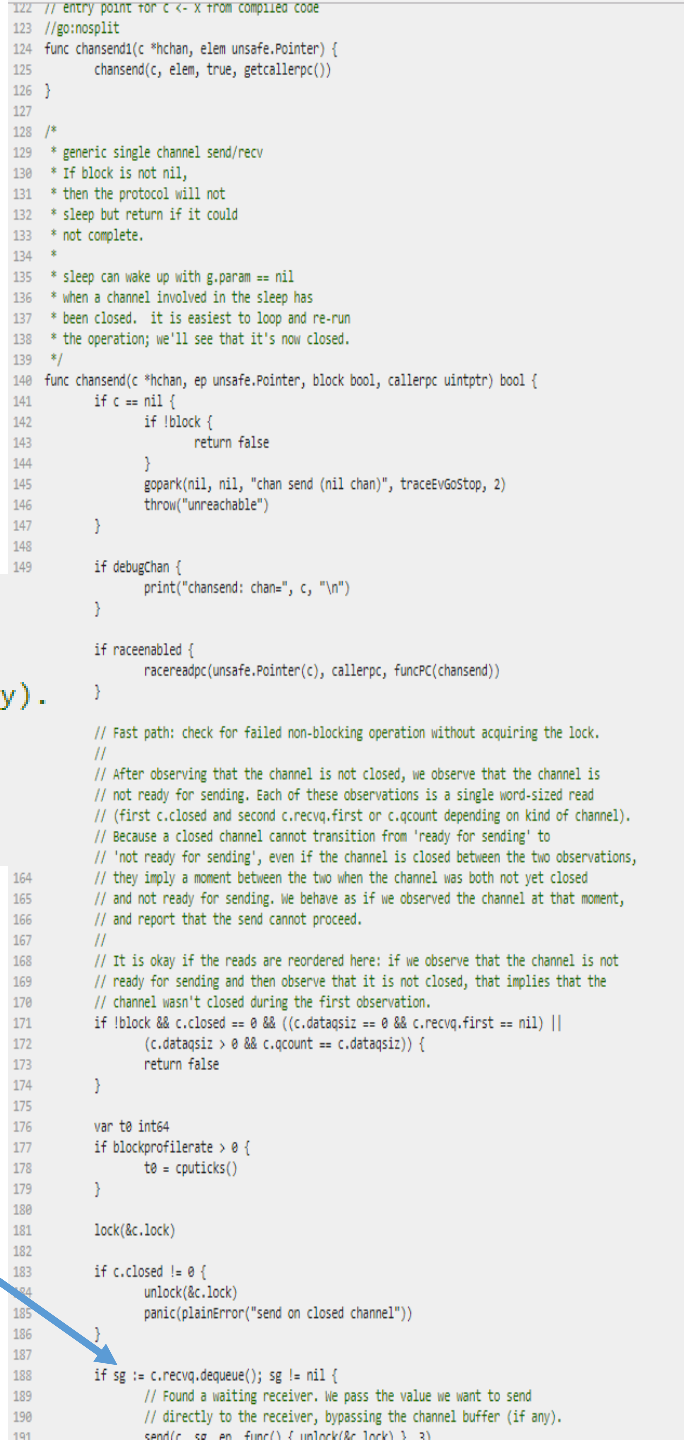


```go
// entry point for c <- x from compiled code
//go:nosplit
func chansend1(c *hchan, elem unsafe.Pointer) {
	chansend(c, elem, true, getcallerpc())
}

/*
 * generic single channel send/recv
 * If block is not nil,
 * then the protocol will not
 * sleep but return if it could
 * not complete.
 *
 * sleep can wake up with g.param == nil
 * when a channel involved in the sleep has
 * been closed.  it is easiest to loop and re-run
 * the operation; we'll see that it's now closed.
 */
func chansend(c *hchan, ep unsafe.Pointer, block bool, callerpc uintptr) bool {
	if c == nil {
		if !block {
			return false
		}
		gopark(nil, nil, "chan send (nil chan)", traceEvGoStop, 2)
		throw("unreachable")
	}

	if debugChan {
		print("chansend: chan=", c, "\n")
	}

	if raceenabled {
		racereadpc(unsafe.Pointer(c), callerpc, funcPC(chansend))
	}

	// Fast path: check for failed non-blocking operation without acquiring the lock.
	//
	// After observing that the channel is not closed, we observe that the channel is
	// not ready for sending. Each of these observations is a single word-sized read
	// (first c.closed and second c.recvq.first or c.qcount depending on kind of channel).
	// Because a closed channel cannot transition from 'ready for sending' to
	// 'not ready for sending', even if the channel is closed between the two observations,
	// they imply a moment between the two when the channel was both not yet closed
	// and not ready for sending. We behave as if we observed the channel at that moment,
	// and report that the send cannot proceed.
	//
	// It is okay if the reads are reordered here: if we observe that the channel is not
	// ready for sending and then observe that it is not closed, that implies that the
	// channel wasn't closed during the first observation.
	if !block && c.closed == 0 && ((c.dataqsiz == 0 && c.recvq.first == nil) ||
		(c.dataqsiz > 0 && c.qcount == c.dataqsiz)) {
		return false
	}

	var t0 int64
	if blockprofilerate > 0 {
		t0 = cputicks()
	}

	lock(&c.lock)

	if c.closed != 0 {
		unlock(&c.lock)
		panic(plainError("send on closed channel"))
	}

	if sg := c.recvq.dequeue(); sg != nil {
		// Found a waiting receiver. We pass the value we want to send
		// directly to the receiver, bypassing the channel buffer (if any).
		send(c, sg, ep, func() { unlock(&c.lock) }, 3)
```

Channel implementation

- You can just read it:
  - https://golang.org/src/runtime/chan.go
- Some highlig

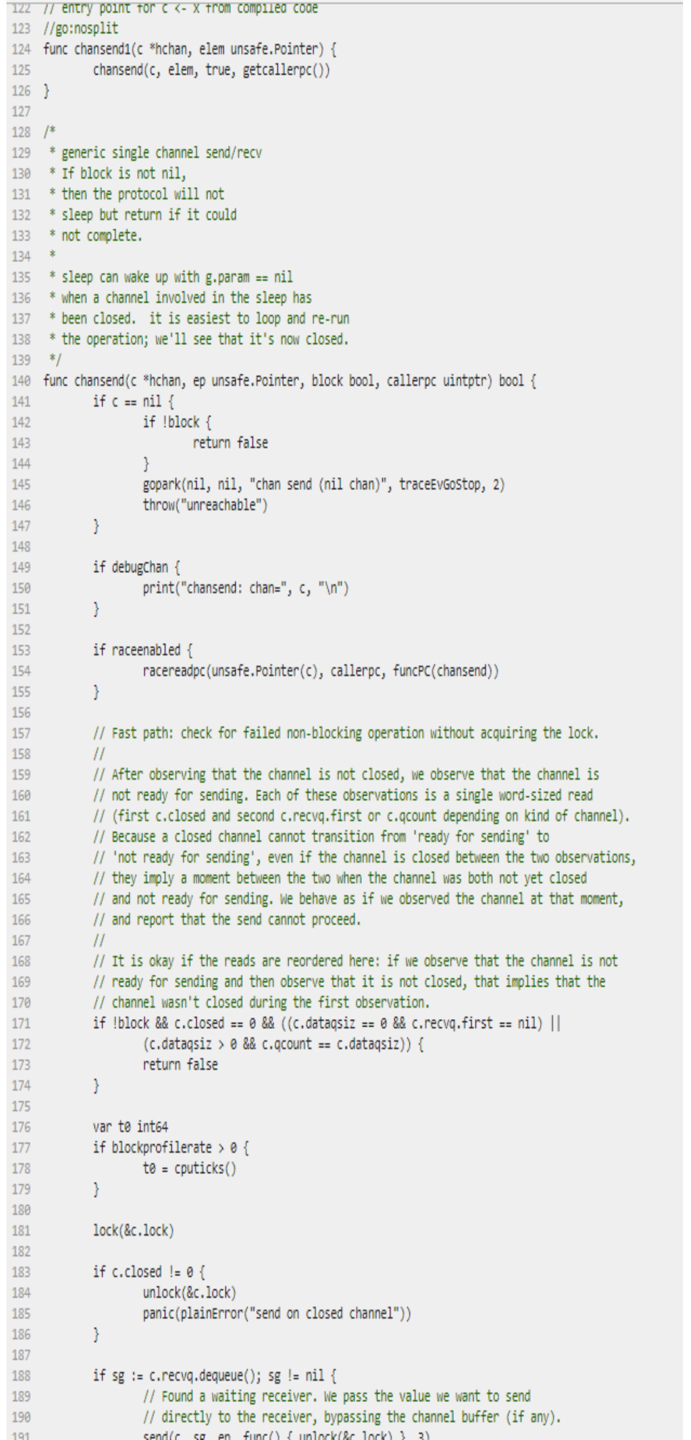
```go
if sg := c.recvq.dequeue(); sg != nil {
        // Found a waiting receiver. We pass the value we want to send
        // directly to the receiver, bypassing the channel buffer (if any).
        send(c, sg, ep, func() { unlock(&c.lock) }, 3)
        return true
}
```



```go
// entry point for c <- x from compiled code
//go:nosplit
func chansend1(c *hchan, elem unsafe.Pointer) {
        chansend(c, elem, true, getcallerpc())
}

/*
 * generic single channel send/recv
 * If block is not nil,
 * then the protocol will not
 * sleep but return if it could
 * not complete.
 *
 * sleep can wake up with g.param == nil
 * when a channel involved in the sleep has
 * been closed.  it is easiest to loop and re-run
 * the operation; we'll see that it's now closed.
 */
func chansend(c *hchan, ep unsafe.Pointer, block bool, callerpc uintptr) bool {
        if c == nil {
                if !block {
                        return false
                }
                gopark(nil, nil, "chan send (nil chan)", traceEvGoStop, 2)
                throw("unreachable")
        }

        if debugChan {
                print("chansend: chan=", c, "\n")
        }

        if raceenabled {
                racereadpc(unsafe.Pointer(c), callerpc, funcPC(chansend))
        }

        // Fast path: check for failed non-blocking operation without acquiring the lock.
        //
        // After observing that the channel is not closed, we observe that the channel is
        // not ready for sending. Each of these observations is a single word-sized read
        // (first c.closed and second c.recvq.first or c.qcount depending on kind of channel).
        // Because a closed channel cannot transition from 'ready for sending' to
        // 'not ready for sending', even if the channel is closed between the two observations,
        // they imply a moment between the two when the channel was both not yet closed
        // and not ready for sending. We behave as if we observed the channel at that moment,
        // and report that the send cannot proceed.
        //
        // It is okay if the reads are reordered here: if we observe that the channel is not
        // ready for sending and then observe that it is not closed, that implies that the
        // channel wasn't closed during the first observation.
        if !block && c.closed == 0 && ((c.dataqsiz == 0 && c.recvq.first == nil) ||
                (c.dataqsiz > 0 && c.qcount == c.dataqsiz)) {
                return false
        }

        var t0 int64
        if blockprofilerate > 0 {
                t0 = cputicks()
        }

        lock(&c.lock)

        if c.closed != 0 {
                unlock(&c.lock)
                panic(plainError("send on closed channel"))
        }

        if sg := c.recvq.dequeue(); sg != nil {
                // Found a waiting receiver. We pass the value we want to send
                // directly to the receiver, bypassing the channel buffer (if any).
                send(c, sg, ep, func() { unlock(&c.lock) }, 3)
```

Channel implementation

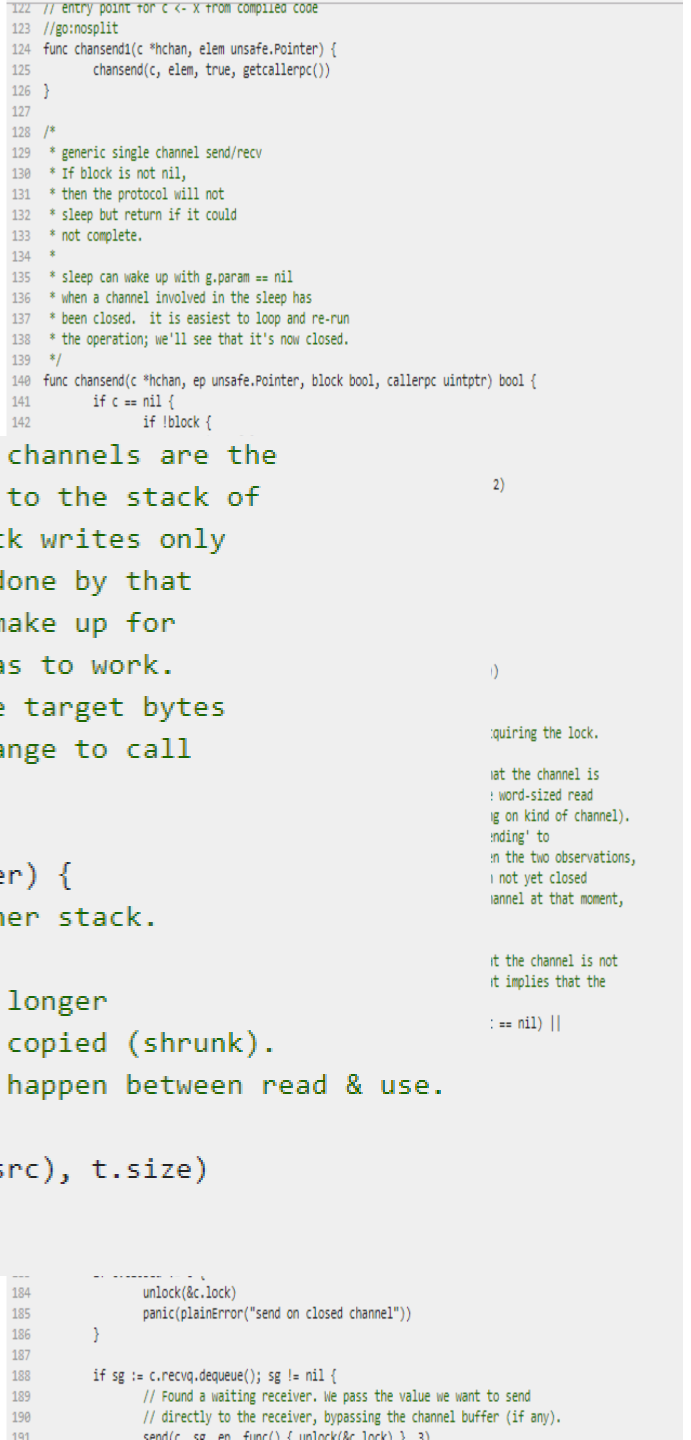
- You can just read it:
  - https://golang.org/src/runtime/chan.go
- Some highlights



```go
// entry point for c <- x from compiled code
//go:nosplit
func chansend1(c *hchan, elem unsafe.Pointer) {
        chansend(c, elem, true, getcallerpc())
}

/*
 * generic single channel send/recv
 * If block is not nil,
 * then the protocol will not
 * sleep but return if it could
 * not complete.
 *
 * sleep can wake up with g.param == nil
 * when a channel involved in the sleep has
 * been closed.  it is easiest to loop and re-run
 * the operation; we'll see that it's now closed.
 */
func chansend(c *hchan, ep unsafe.Pointer, block bool, callerpc uintptr) bool {
        if c == nil {
                if !block {
                        return false
                }
                gopark(nil, nil, "chan send (nil chan)", traceEvGoStop, 2)
                throw("unreachable")
        }

        if debugChan {
                print("chansend: chan=", c, "\n")
        }

        if raceenabled {
                racereadpc(unsafe.Pointer(c), callerpc, funcPC(chansend))
        }

        // Fast path: check for failed non-blocking operation without acquiring the lock.
        //
        // After observing that the channel is not closed, we observe that the channel is
        // not ready for sending. Each of these observations is a single word-sized read
        // (first c.closed and second c.recvq.first or c.qcount depending on kind of channel).
        // Because a closed channel cannot transition from 'ready for sending' to
        // 'not ready for sending', even if the channel is closed between the two observations,
        // they imply a moment between the two when the channel was both not yet closed
        // and not ready for sending. We behave as if we observed the channel at that moment,
        // and report that the send cannot proceed.
        //
        // It is okay if the reads are reordered here: if we observe that the channel is not
        // ready for sending and then observe that it is not closed, that implies that the
        // channel wasn't closed during the first observation.
        if !block && c.closed == 0 && ((c.dataqsiz == 0 && c.recvq.first == nil) ||
                (c.dataqsiz > 0 && c.qcount == c.dataqsiz)) {
                return false
        }

        var t0 int64
        if blockprofilerate > 0 {
                t0 = cputicks()
        }

        lock(&c.lock)

        if c.closed != 0 {
                unlock(&c.lock)
                panic(plainError("send on closed channel"))
        }

        if sg := c.recvq.dequeue(); sg != nil {
                // Found a waiting receiver. We pass the value we want to send
                // directly to the receiver, bypassing the channel buffer (if any).
                send(c, sg, ep, func() { unlock(&c.lock) }, 3)
```

Channel implementation

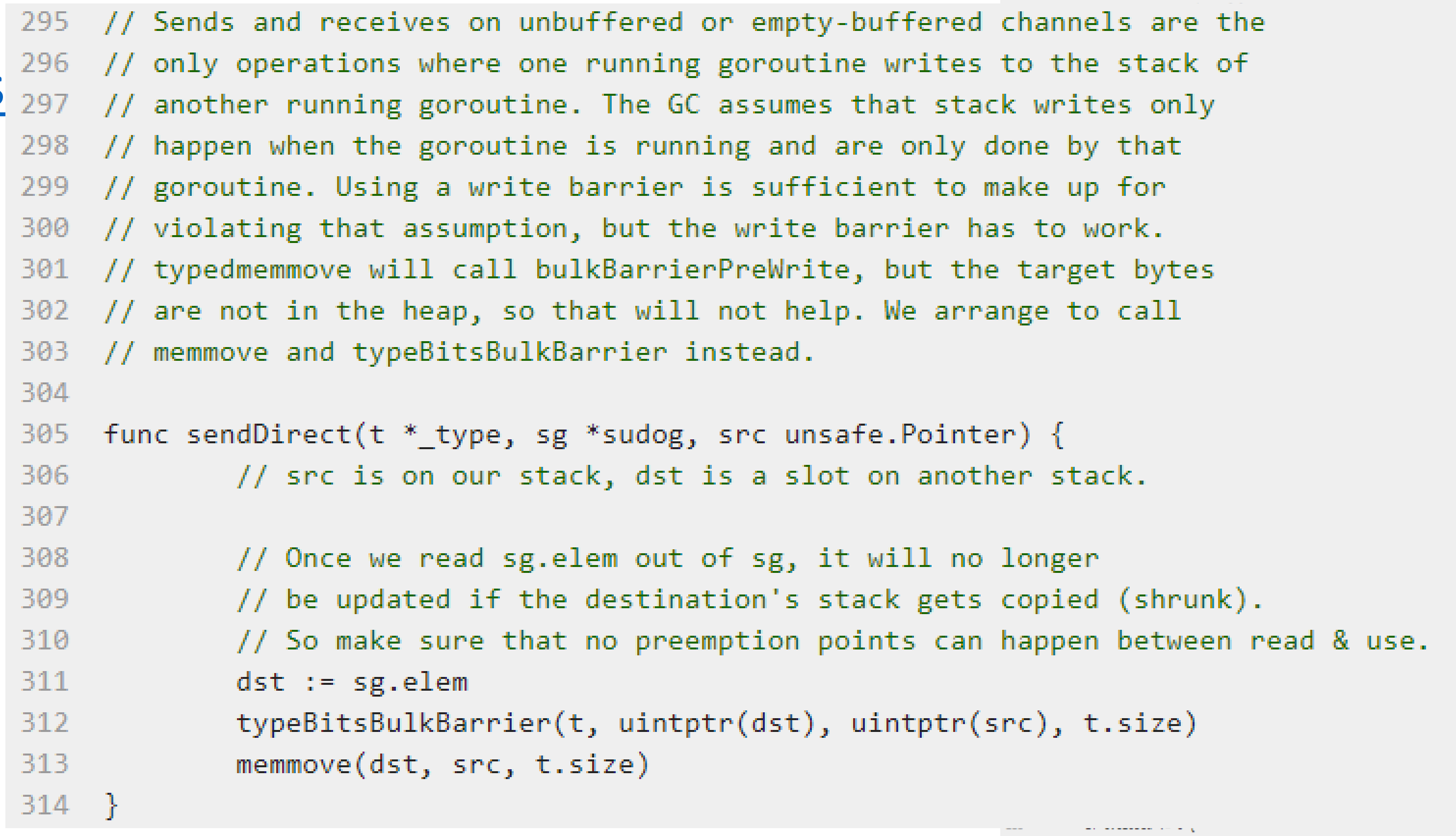
- You can just read it:
  - https://golang.org/s
- Some highlights



```
// entry point for c <- x from compiled code
//go:nosplit
func chansend1(c *hchan, elem unsafe.Pointer) {
        chansend(c, elem, true, getcallerpc())
}

/*
 * generic single channel send/recv
 * If block is not nil,
 * then the protocol will not
 * sleep but return if it could
 * not complete.
 *
 * sleep can wake up with g.param == nil
 * when a channel involved in the sleep has
 * been closed.  it is easiest to loop and re-run
 * the operation; we'll see that it's now closed.
 */
func chansend(c *hchan, ep unsafe.Pointer, block bool, callerpc uintptr) bool {
        if c == nil {
                if !block {
```

```
2)
)
quiring the lock.
at the channel is
 word-sized read
g on kind of channel).
nding' to
n the two observations,
 not yet closed
annel at that moment,
t the channel is not
t implies that the
 == nil) ||
```

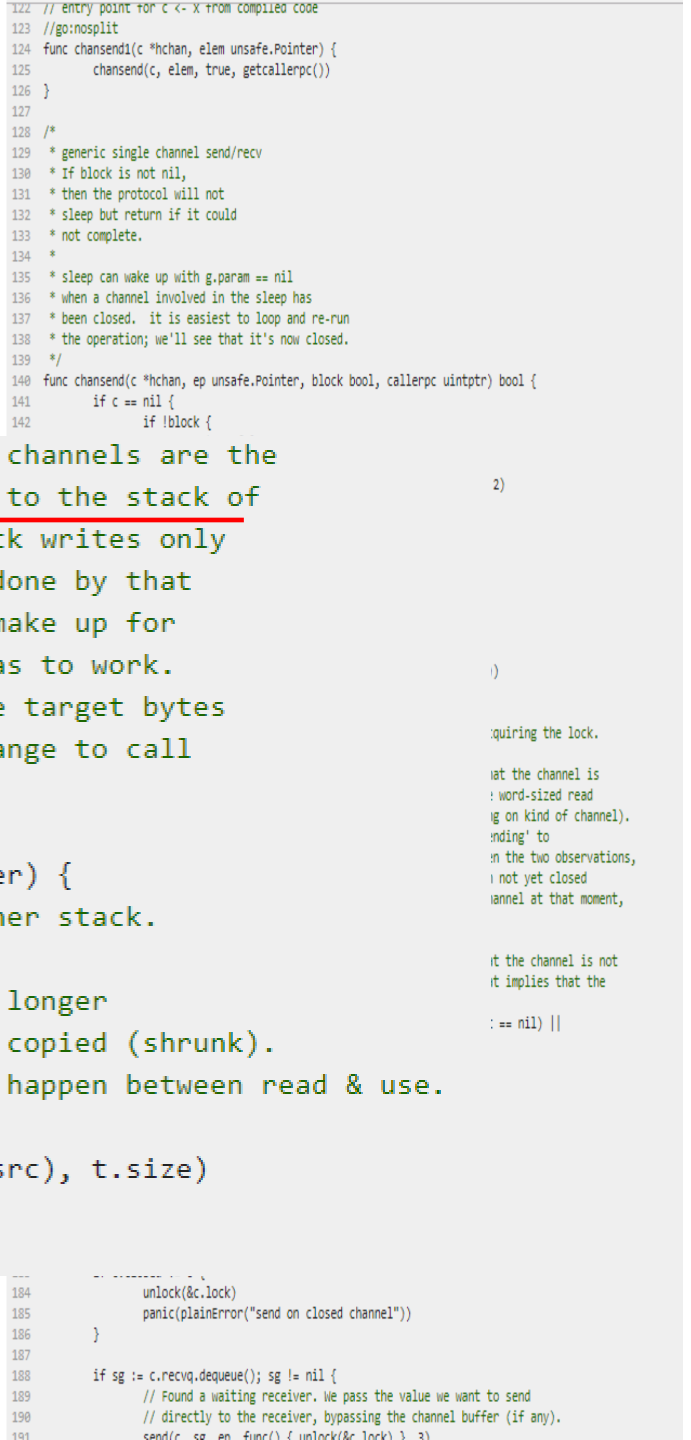
```
                unlock(&c.lock)
                panic(plainError("send on closed channel"))
        }

        if sg := c.recvq.dequeue(); sg != nil {
                // Found a waiting receiver. We pass the value we want to send
                // directly to the receiver, bypassing the channel buffer (if any).
                send(c, sg, ep, func() { unlock(&c.lock) }, 3)
```



```
// Sends and receives on unbuffered or empty-buffered channels are the
// only operations where one running goroutine writes to the stack of
// another running goroutine. The GC assumes that stack writes only
// happen when the goroutine is running and are only done by that
// goroutine. Using a write barrier is sufficient to make up for
// violating that assumption, but the write barrier has to work.
// typedmemmove will call bulkBarrierPreWrite, but the target bytes
// are not in the heap, so that will not help. We arrange to call
// memmove and typeBitsBulkBarrier instead.

func sendDirect(t *_type, sg *sudog, src unsafe.Pointer) {
        // src is on our stack, dst is a slot on another stack.

        // Once we read sg.elem out of sg, it will no longer
        // be updated if the destination's stack gets copied (shrunk).
        // So make sure that no preemption points can happen between read & use.
        dst := sg.elem
        typeBitsBulkBarrier(t, uintptr(dst), uintptr(src), t.size)
        memmove(dst, src, t.size)
}
```

Channel implementation

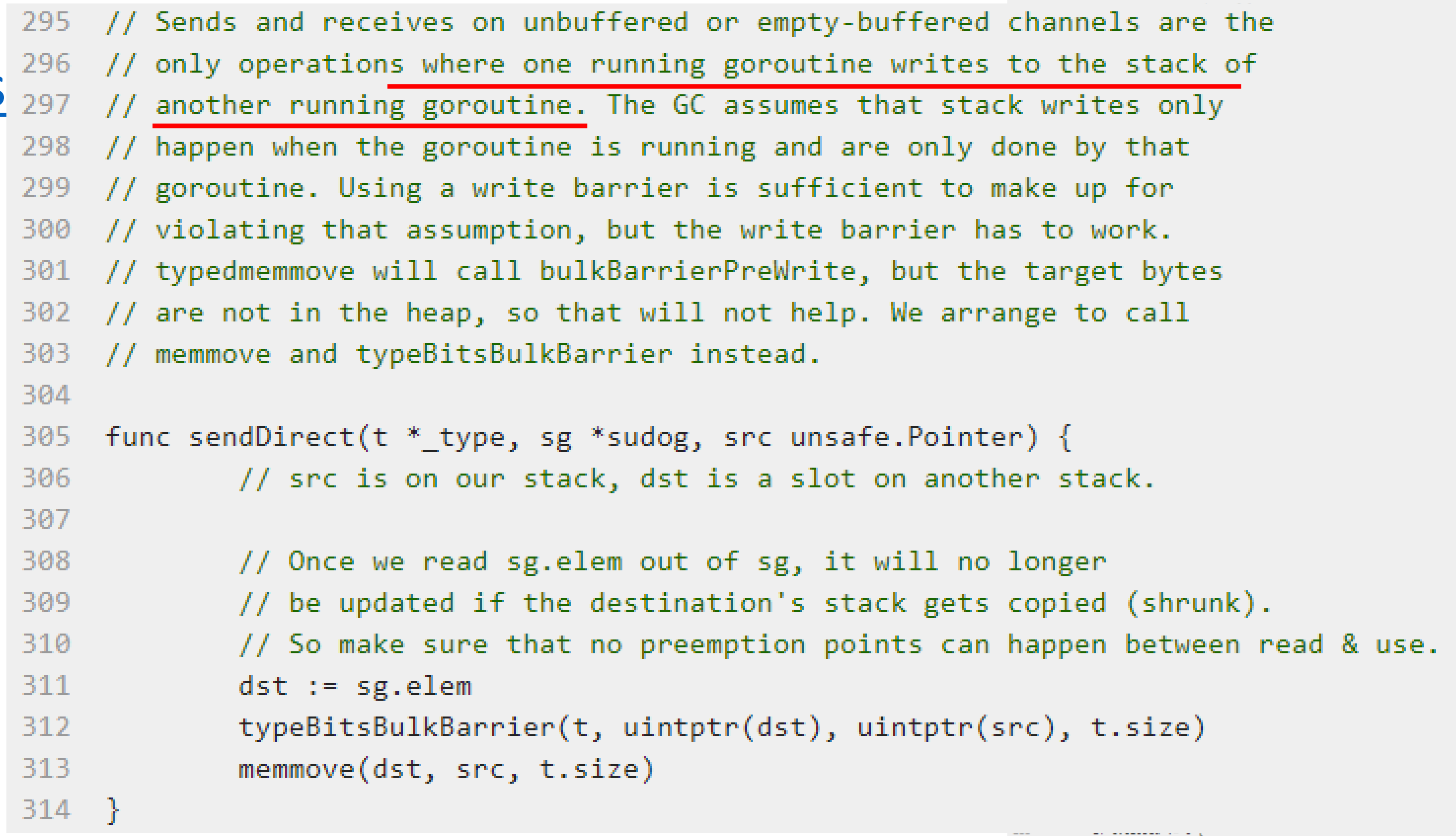
- You can just read it:
  - https://golang.org/s
- Some highlights



```
// entry point for c <- x from compiled code
//go:nosplit
func chansend1(c *hchan, elem unsafe.Pointer) {
        chansend(c, elem, true, getcallerpc())
}

/*
 * generic single channel send/recv
 * If block is not nil,
 * then the protocol will not
 * sleep but return if it could
 * not complete.
 *
 * sleep can wake up with g.param == nil
 * when a channel involved in the sleep has
 * been closed.  it is easiest to loop and re-run
 * the operation; we'll see that it's now closed.
 */
func chansend(c *hchan, ep unsafe.Pointer, block bool, callerpc uintptr) bool {
        if c == nil {
                if !block {
```

```
2)

)

quiring the lock.

at the channel is
 word-sized read
g on kind of channel).
nding' to
n the two observations,
 not yet closed
annel at that moment,

t the channel is not
t implies that the

 == nil) ||
```

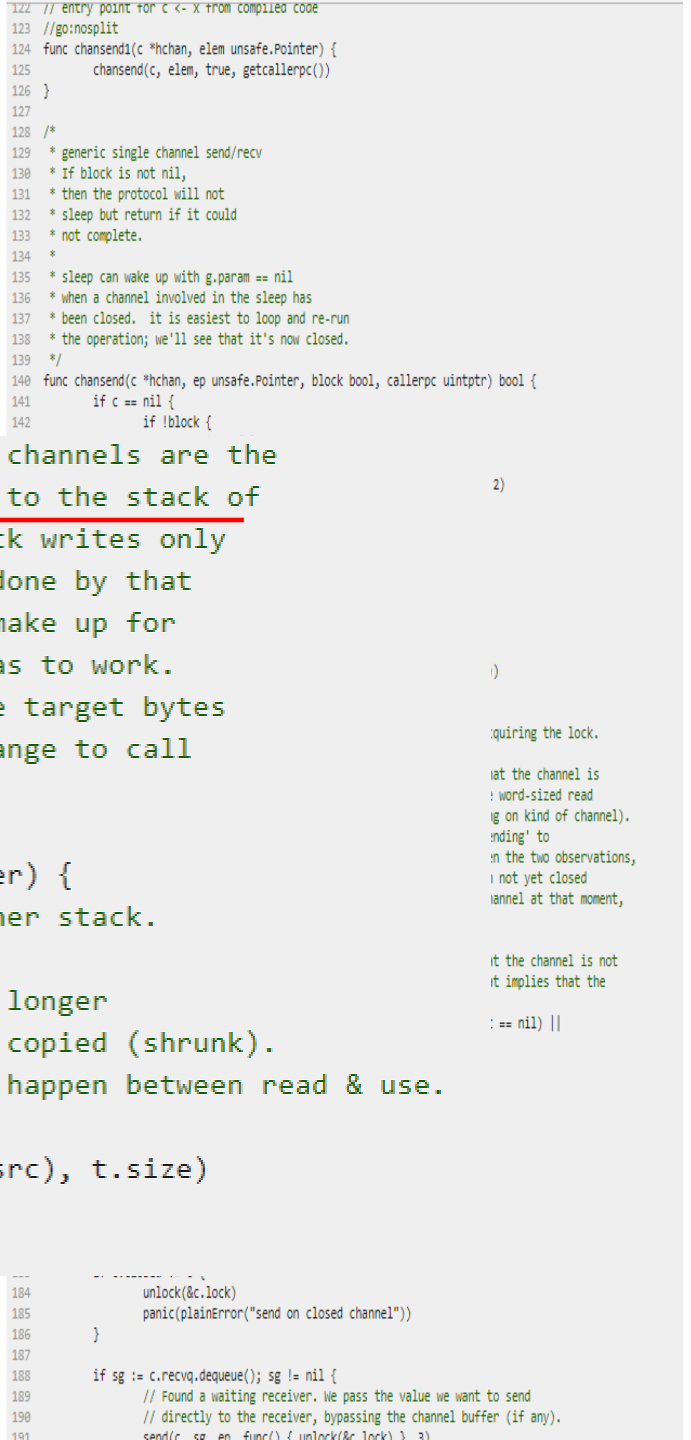
```
                unlock(&c.lock)
                panic(plainError("send on closed channel"))
        }

        if sg := c.recvq.dequeue(); sg != nil {
                // Found a waiting receiver. We pass the value we want to send
                // directly to the receiver, bypassing the channel buffer (if any).
                send(c, sg, ep, func() { unlock(&c.lock) }, 3)
```



```
// Sends and receives on unbuffered or empty-buffered channels are the
// only operations where one running goroutine writes to the stack of
// another running goroutine. The GC assumes that stack writes only
// happen when the goroutine is running and are only done by that
// goroutine. Using a write barrier is sufficient to make up for
// violating that assumption, but the write barrier has to work.
// typedmemmove will call bulkBarrierPreWrite, but the target bytes
// are not in the heap, so that will not help. We arrange to call
// memmove and typeBitsBulkBarrier instead.

func sendDirect(t *_type, sg *sudog, src unsafe.Pointer) {
        // src is on our stack, dst is a slot on another stack.

        // Once we read sg.elem out of sg, it will no longer
        // be updated if the destination's stack gets copied (shrunk).
        // So make sure that no preemption points can happen between read & use.
        dst := sg.elem
        typeBitsBulkBarrier(t, uintptr(dst), uintptr(src), t.size)
        memmove(dst, src, t.size)
}
```

Channel implementation

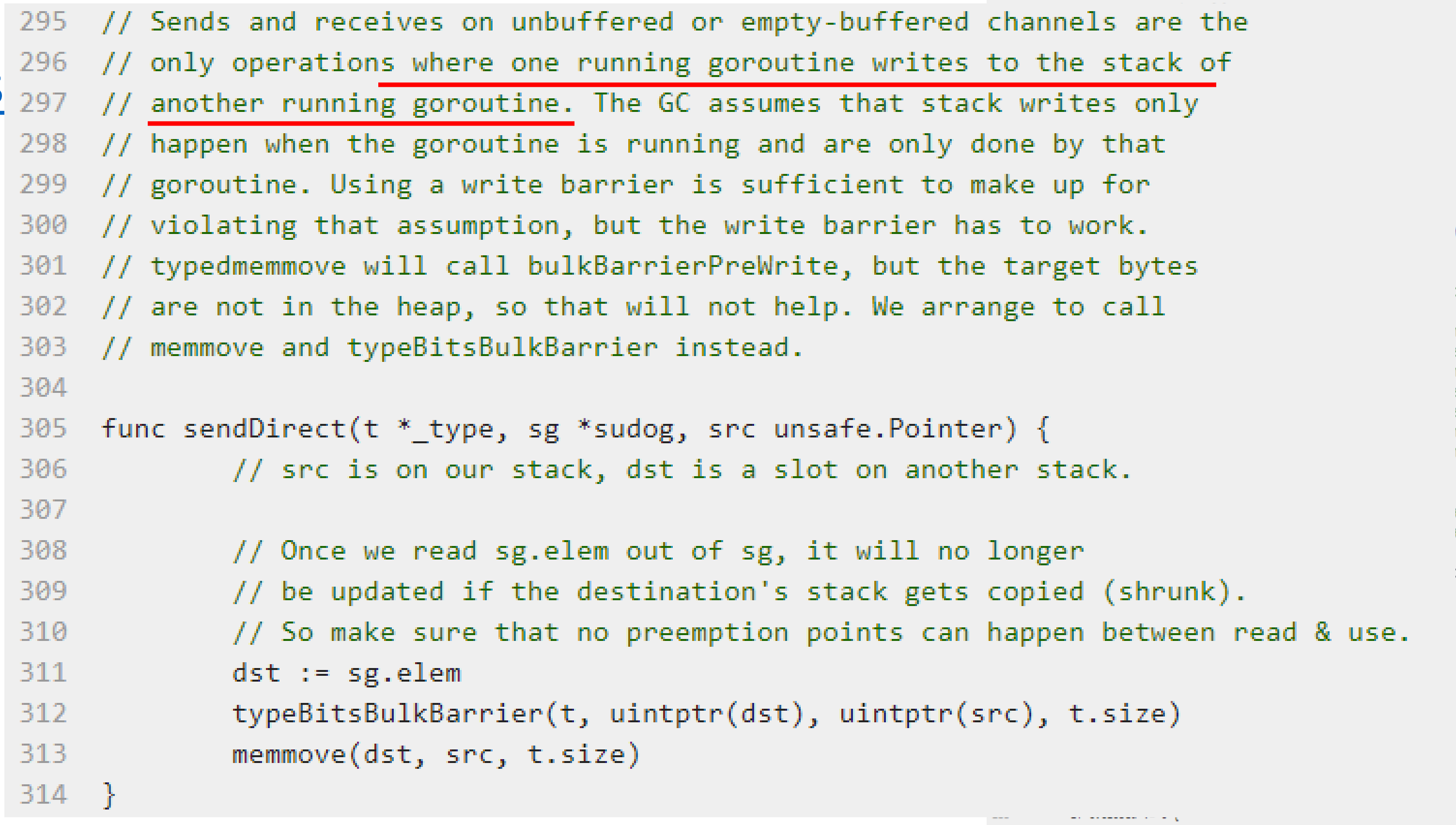
- You can just read it:
  - https://golang.org/s
- Some highlights



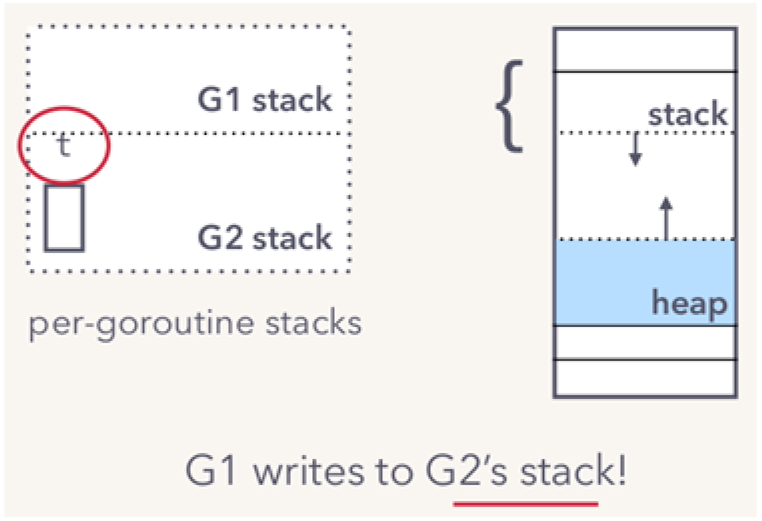
```
// entry point for c <- x from compiled code
//go:nosplit
func chansend1(c *hchan, elem unsafe.Pointer) {
        chansend(c, elem, true, getcallerpc())
}

/*
 * generic single channel send/recv
 * If block is not nil,
 * then the protocol will not
 * sleep but return if it could
 * not complete.
 *
 * sleep can wake up with g.param == nil
 * when a channel involved in the sleep has
 * been closed.  it is easiest to loop and re-run
 * the operation; we'll see that it's now closed.
 */
func chansend(c *hchan, ep unsafe.Pointer, block bool, callerpc uintptr) bool {
        if c == nil {
                if !block {
```

```
2)
)
quiring the lock.
at the channel is
word-sized read
g on kind of channel).
nding' to
n the two observations,
not yet closed
annel at that moment,
t the channel is not
t implies that the
== nil) ||
```

```
                unlock(&c.lock)
                panic(plainError("send on closed channel"))
        }

        if sg := c.recvq.dequeue(); sg != nil {
                // Found a waiting receiver. We pass the value we want to send
                // directly to the receiver, bypassing the channel buffer (if any).
```

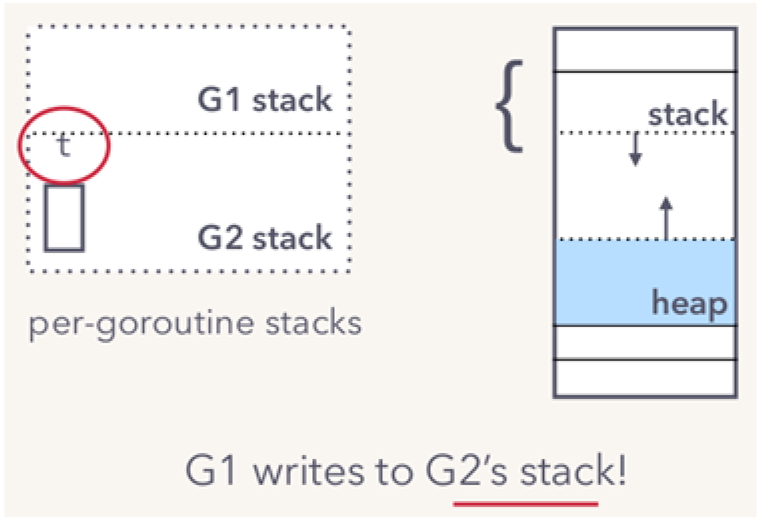


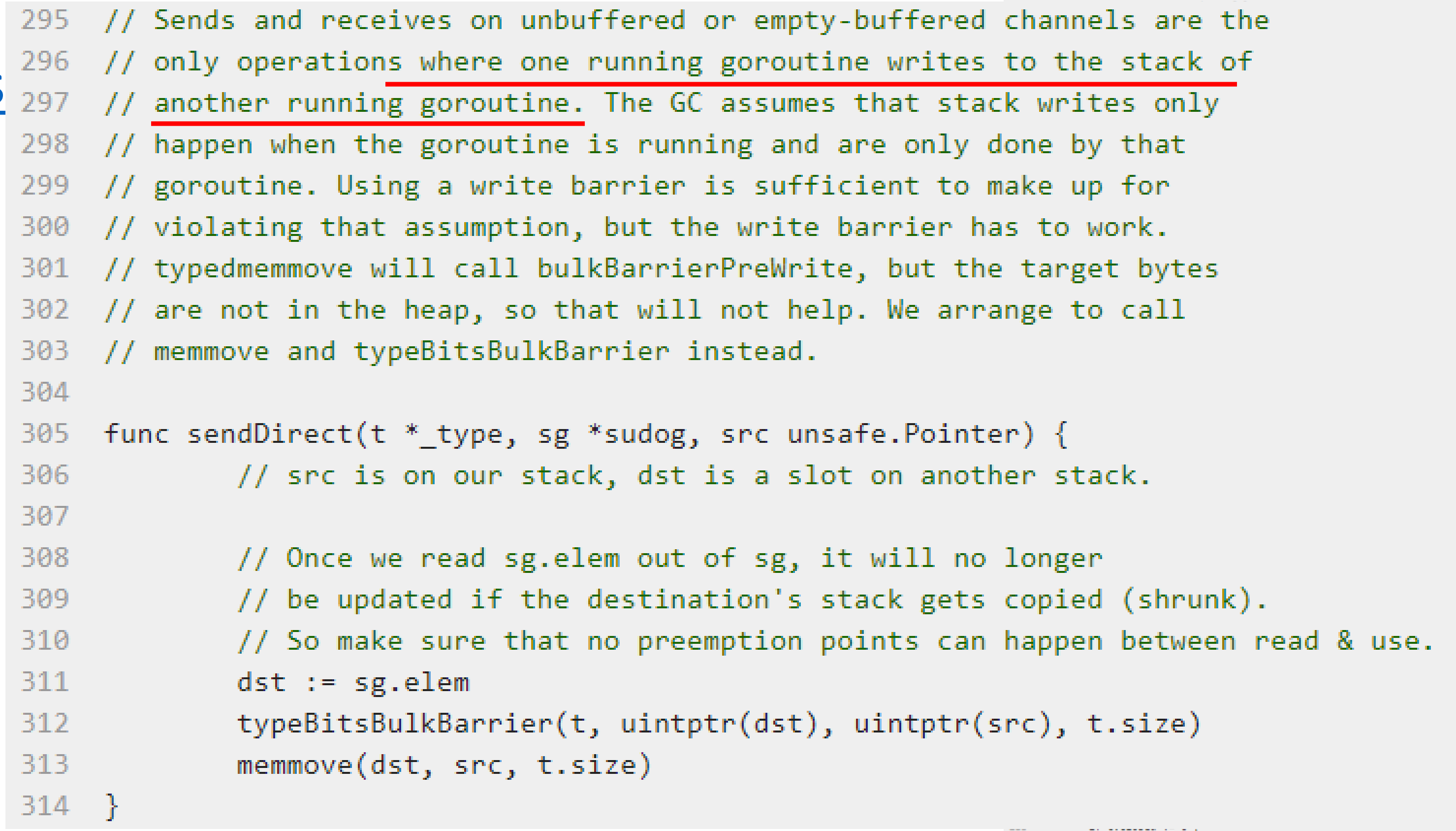
```
// Sends and receives on unbuffered or empty-buffered channels are the
// only operations where one running goroutine writes to the stack of
// another running goroutine. The GC assumes that stack writes only
// happen when the goroutine is running and are only done by that
// goroutine. Using a write barrier is sufficient to make up for
// violating that assumption, but the write barrier has to work.
// typedmemmove will call bulkBarrierPreWrite, but the target bytes
// are not in the heap, so that will not help. We arrange to call
// memmove and typeBitsBulkBarrier instead.

func sendDirect(t *_type, sg *sudog, src unsafe.Pointer) {
        // src is on our stack, dst is a slot on another stack.

        // Once we read sg.elem out of sg, it will no longer
        // be updated if the destination's stack gets copied (shrunk).
        // So make sure that no preemption points can happen between read & use.
        dst := sg.elem
        typeBitsBulkBarrier(t, uintptr(dst), uintptr(src), t.size)
        memmove(dst, src, t.size)
}
```



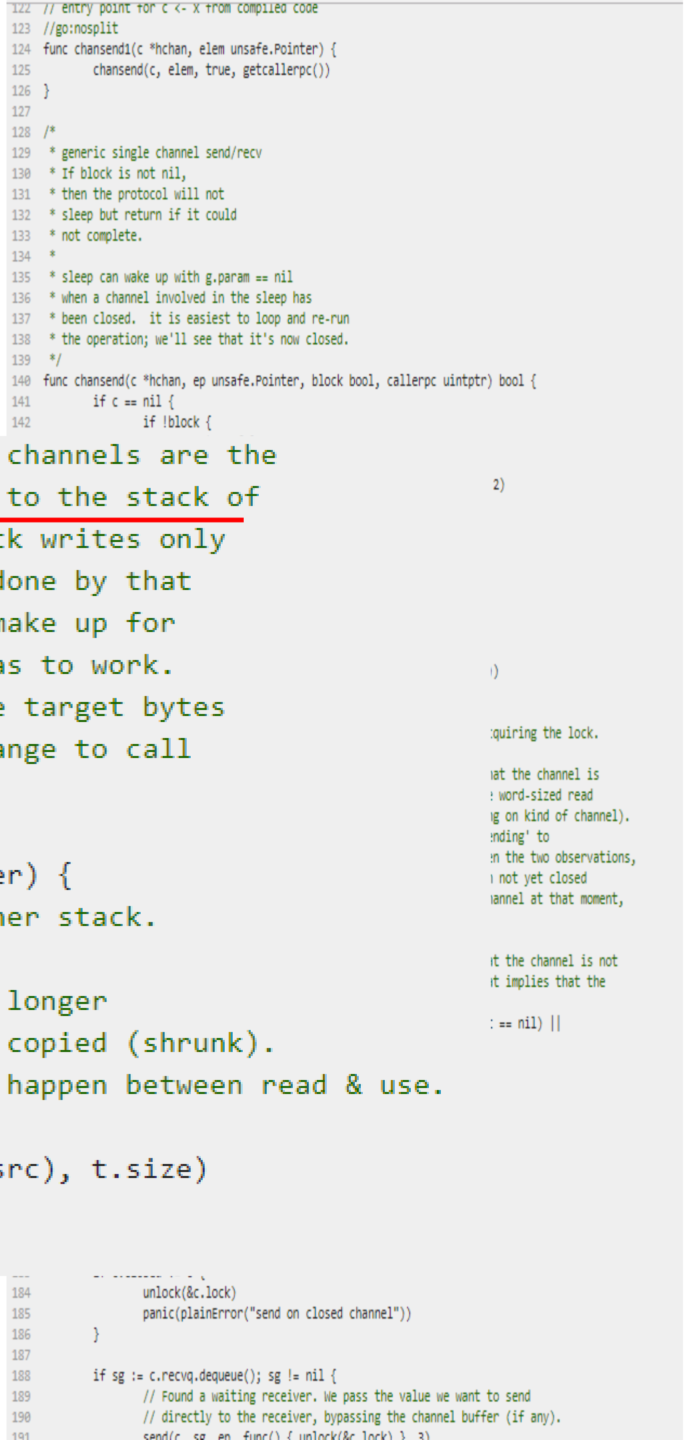
Channel implementation

- You can just read it:
  - https://golang.org/s
- Some highlights





```go
// Sends and receives on unbuffered or empty-buffered channels are the
// only operations where one running goroutine writes to the stack of
// another running goroutine. The GC assumes that stack writes only
// happen when the goroutine is running and are only done by that
// goroutine. Using a write barrier is sufficient to make up for
// violating that assumption, but the write barrier has to work.
// typedmemmove will call bulkBarrierPreWrite, but the target bytes
// are not in the heap, so that will not help. We arrange to call
// memmove and typeBitsBulkBarrier instead.

func sendDirect(t *_type, sg *sudog, src unsafe.Pointer) {
	// src is on our stack, dst is a slot on another stack.

	// Once we read sg.elem out of sg, it will no longer
	// be updated if the destination's stack gets copied (shrunk).
	// So make sure that no preemption points can happen between read & use.
	dst := sg.elem
	typeBitsBulkBarrier(t, uintptr(dst), uintptr(src), t.size)
	memmove(dst, src, t.size)
}
```



```go
// entry point for c <- x from compiled code
//go:nosplit
func chansend1(c *hchan, elem unsafe.Pointer) {
	chansend(c, elem, true, getcallerpc())
}

/*
 * generic single channel send/recv
 * If block is not nil,
 * then the protocol will not
 * sleep but return if it could
 * not complete.
 *
 * sleep can wake up with g.param == nil
 * when a channel involved in the sleep has
 * been closed.  it is easiest to loop and re-run
 * the operation; we'll see that it's now closed.
 */
func chansend(c *hchan, ep unsafe.Pointer, block bool, callerpc uintptr) bool {
	if c == nil {
		if !block {
```

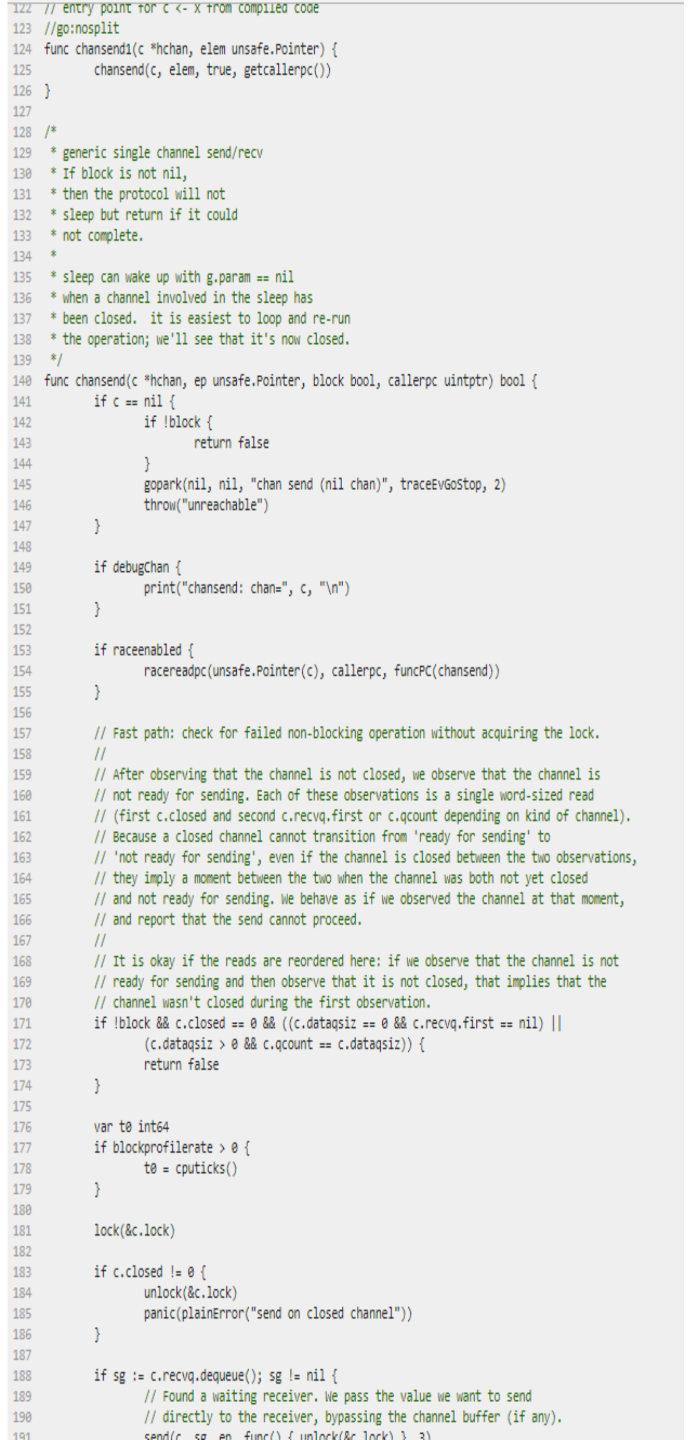
```
2)
)
quiring the lock.
at the channel is
 word-sized read
g on kind of channel).
nding' to
n the two observations,
 not yet closed
annel at that moment,
t the channel is not
t implies that the
 == nil) ||
```

```go
			unlock(&c.lock)
			panic(plainError("send on closed channel"))
		}

		if sg := c.recvq.dequeue(); sg != nil {
			// Found a waiting receiver. We pass the value we want to send
			// directly to the receiver, bypassing the channel buffer (if any).
```

Transputers did this in hardware in the 90s btw.

Channel implementation

- You can just read it:
  - https://golang.org/src/runtime/chan.go
- Some highlights:
  - Race detection built in
  - Fast path just write to receiver stack
  - Often has no capacity → scheduler hint!
  - Buffered channel implementation fairly standard



```go
// entry point for c <- x from compiled code
//go:nosplit
func chansend1(c *hchan, elem unsafe.Pointer) {
        chansend(c, elem, true, getcallerpc())
}

/*
 * generic single channel send/recv
 * If block is not nil,
 * then the protocol will not
 * sleep but return if it could
 * not complete.
 *
 * sleep can wake up with g.param == nil
 * when a channel involved in the sleep has
 * been closed.  it is easiest to loop and re-run
 * the operation; we'll see that it's now closed.
 */
func chansend(c *hchan, ep unsafe.Pointer, block bool, callerpc uintptr) bool {
        if c == nil {
                if !block {
                        return false
                }
                gopark(nil, nil, "chan send (nil chan)", traceEvGoStop, 2)
                throw("unreachable")
        }

        if debugChan {
                print("chansend: chan=", c, "\n")
        }

        if raceenabled {
                racereadpc(unsafe.Pointer(c), callerpc, funcPC(chansend))
        }

        // Fast path: check for failed non-blocking operation without acquiring the lock.
        //
        // After observing that the channel is not closed, we observe that the channel is
        // not ready for sending. Each of these observations is a single word-sized read
        // (first c.closed and second c.recvq.first or c.qcount depending on kind of channel).
        // Because a closed channel cannot transition from 'ready for sending' to
        // 'not ready for sending', even if the channel is closed between the two observations,
        // they imply a moment between the two when the channel was both not yet closed
        // and not ready for sending. We behave as if we observed the channel at that moment,
        // and report that the send cannot proceed.
        //
        // It is okay if the reads are reordered here: if we observe that the channel is not
        // ready for sending and then observe that it is not closed, that implies that the
        // channel wasn't closed during the first observation.
        if !block && c.closed == 0 && ((c.dataqsiz == 0 && c.recvq.first == nil) ||
                (c.dataqsiz > 0 && c.qcount == c.dataqsiz)) {
                return false
        }

        var t0 int64
        if blockprofilerate > 0 {
                t0 = cputicks()
        }

        lock(&c.lock)

        if c.closed != 0 {
                unlock(&c.lock)
                panic(plainError("send on closed channel"))
        }

        if sg := c.recvq.dequeue(); sg != nil {
                // Found a waiting receiver. We pass the value we want to send
                // directly to the receiver, bypassing the channel buffer (if any).
                send(c, sg, ep, func() { unlock(&c.lock) }, 3)
```

Go: Sliced Bread 2.0?

Go: Sliced Bread 2.0?

- Has compile-time generics

Go: Sliced Bread 2.0?

- Has compile-time generics
  - Results in no code duplication

Go: Sliced Bread 2.0?

- Has compile-time generics
    - Results in no code duplication
    - Metaprogramming can be statically checked

Go: Sliced Bread 2.0?

- Has compile-time generics
  - Results in no code duplication
  - Metaprogramming can be statically checked
  - Standard library can offer generic algorithms

Go: Sliced Bread 2.0?

- Has compile-time generics
  - Results in no code duplication
  - Metaprogramming can be statically checked
  - Standard library can offer generic algorithms
- Lack of language extensibility makes certain tasks more verbose

Go: Sliced Bread 2.0?

- Has compile-time generics
  - Results in no code duplication
  - Metaprogramming can be statically checked
  - Standard library can offer generic algorithms
- Lack of language extensibility makes certain tasks more verbose
  - Lacks operator overloading (Java)

Go: Sliced Bread 2.0?

- Has compile-time generics
  - Results in no code duplication
  - Metaprogramming can be statically checked
  - Standard library can offer generic algorithms
- Lack of language extensibility makes certain tasks more verbose
  - Lacks operator overloading (Java)
- Pauses and overhead of garbage collection

Go: Sliced Bread 2.0?

- Has compile-time generics
  - Results in no code duplication
  - Metaprogramming can be statically checked
  - Standard library can offer generic algorithms
- Lack of language extensibility makes certain tasks more verbose
  - Lacks operator overloading (Java)
- Pauses and overhead of garbage collection
  - Limit Go’s use in systems programming compared to languages with manual memory management

Go: Sliced Bread 2.0?

- Has compile-time generics
  - Results in no code duplication
  - Metaprogramming can be statically checked
  - Standard library can offer generic algorithms
- Lack of language extensibility makes certain tasks more verbose
  - Lacks operator overloading (Java)
- Pauses and overhead of garbage collection
  - Limit Go's use in systems programming compared to languages with manual memory management
- *Right tradeoffs? None of these problems have to do with concurrency!*

Questions?