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!*

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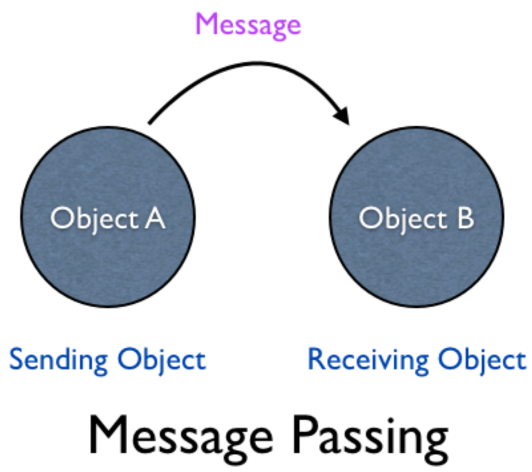
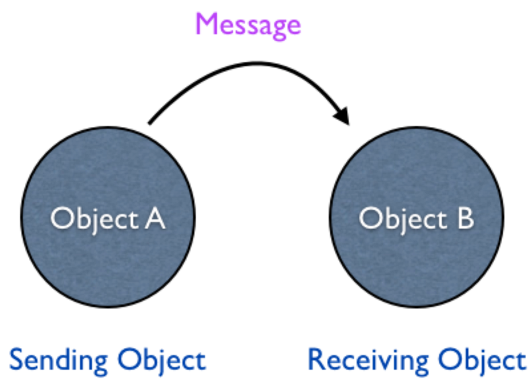
- Message passing:
  - *Threads aren’t the problem, shared memory is*
  - *restructure programming model to avoid communication through shared memory (and therefore locks)*

Message Passing



Message Passing

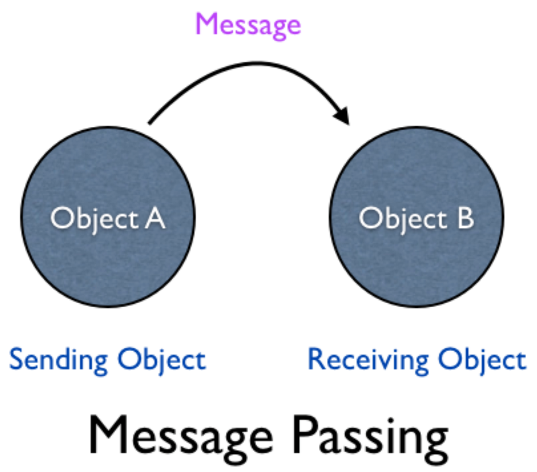
- Threads/Processes send/receive messages



Message Passing

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

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

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

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

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- Synchronous vs. Asynchronous
  - Blocking send: sender blocks until received
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  - 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

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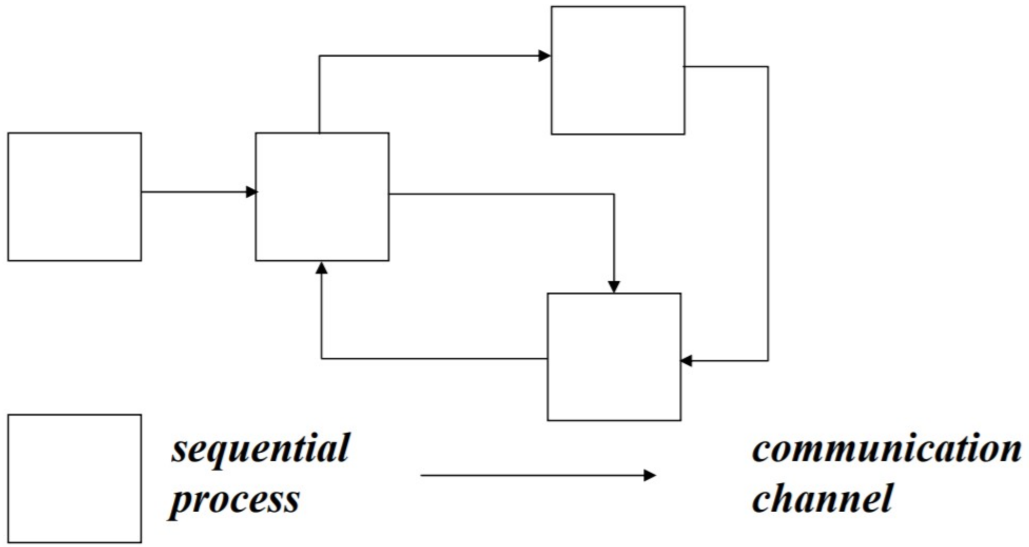
Communicating Sequential Processes
Hoare 1978

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



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- autonomous
- encapsulated
- named
- static

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

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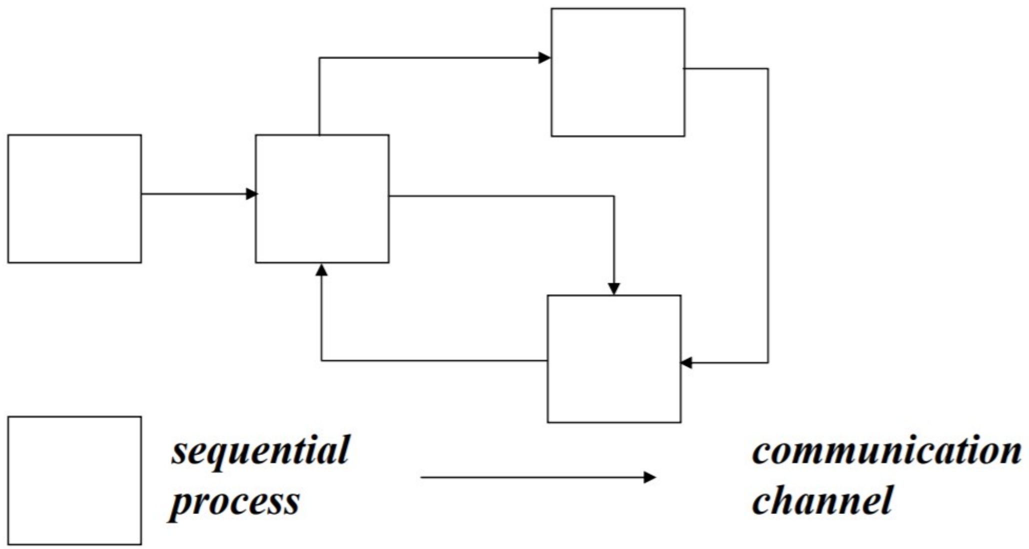

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← Transputer!

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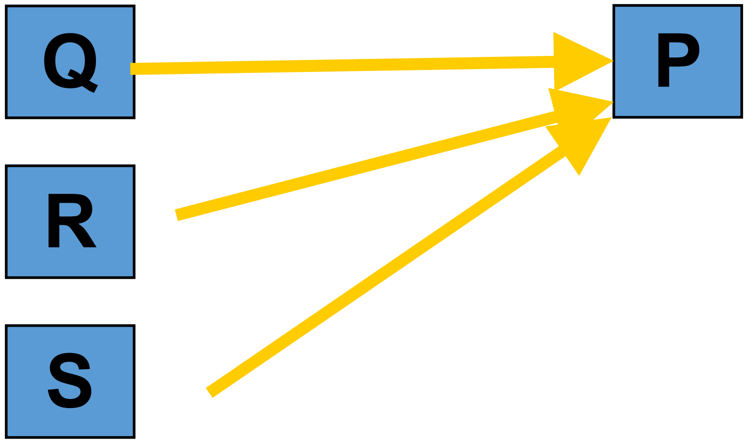

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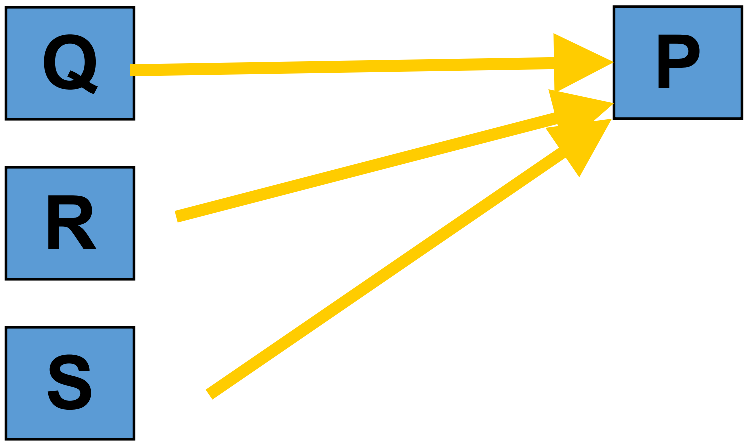


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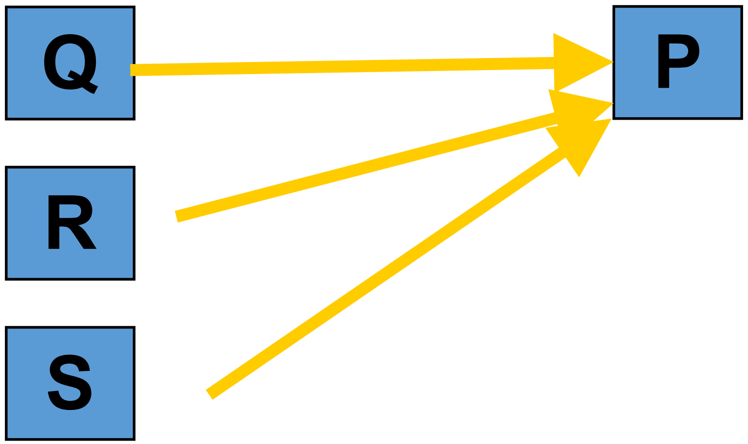


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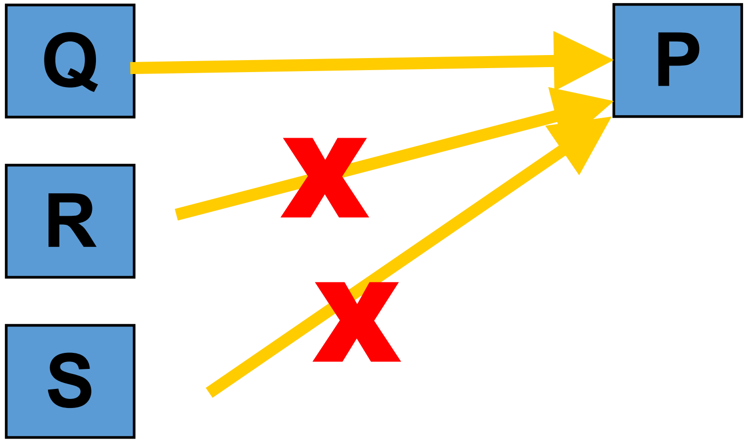


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- ***blocking receive*** with ***indirect naming***
  - Process waits on port, gets first message first message arriving at that port

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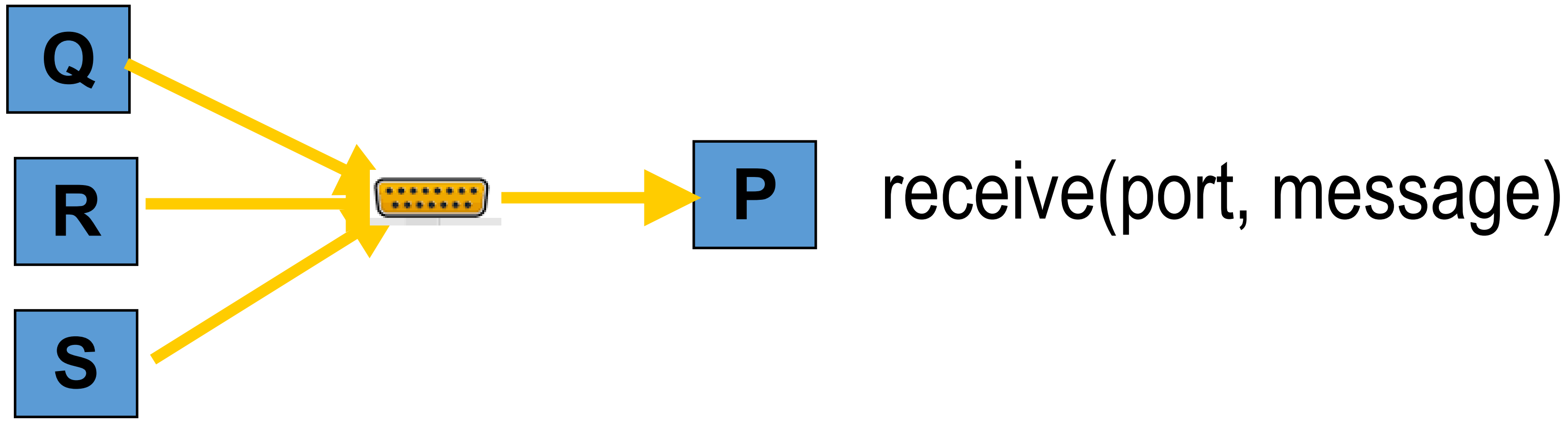

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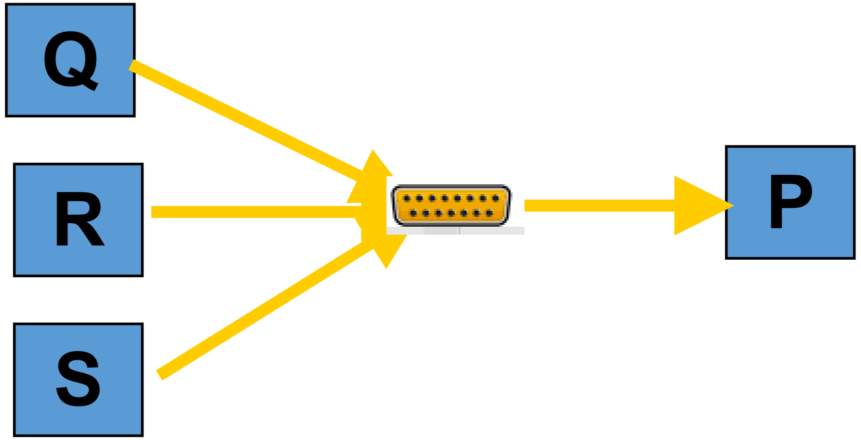

receive(port, message)

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

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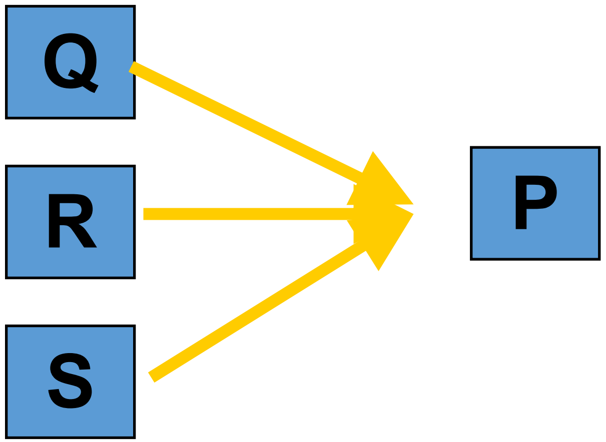

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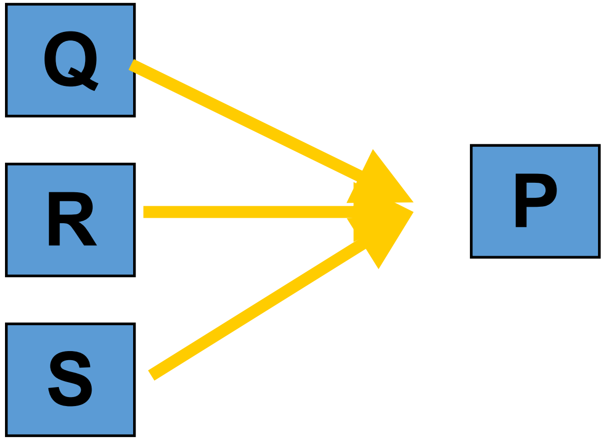


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while(…) {
  try_receive(Q, message)
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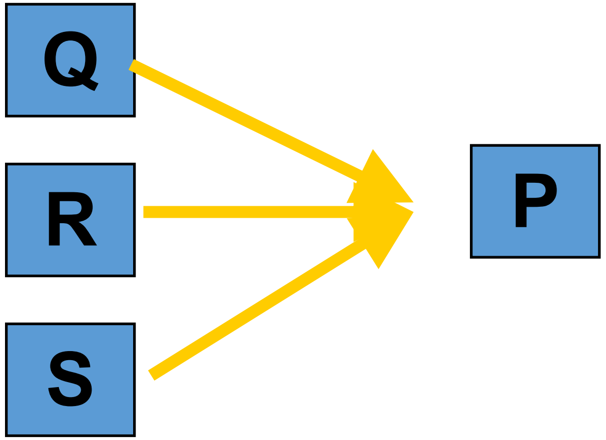


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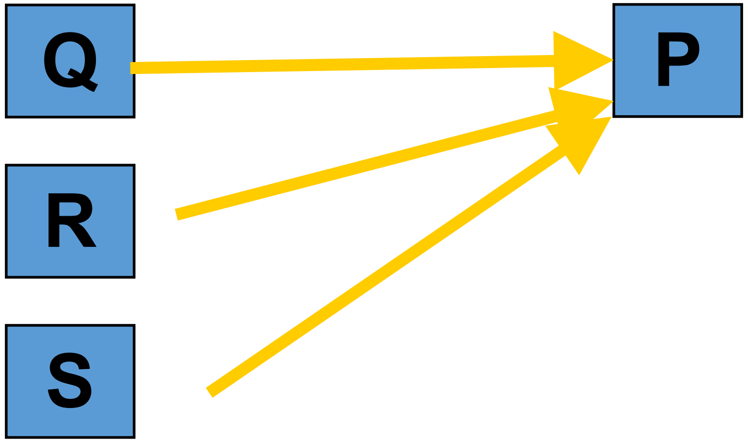
Polling (bad)
No indirection (good)

Blocking and Direct Naming



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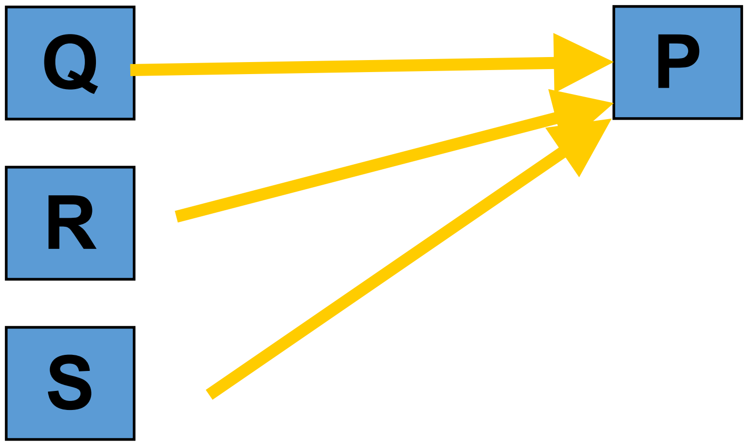
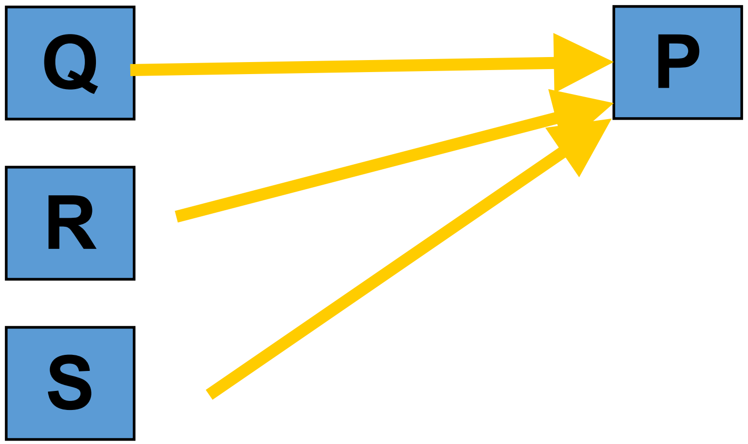
- How to achieve ***it?***



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

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 command:

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

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

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

```go
package main

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

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func main() {
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    time.Sleep(2 * time.Second)
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Program exited.
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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
```

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```
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.
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Program exited.
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Channels

- Connect goroutines allowing th

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

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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")
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```go
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

```
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

```
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!

```
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:
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    }
}
return
```

```
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

```
func testQ() {
    var wg sync.WaitGroup
    wg.Add(4)
    ch := make(chan int)
    for i:=0; i<4; i++ {
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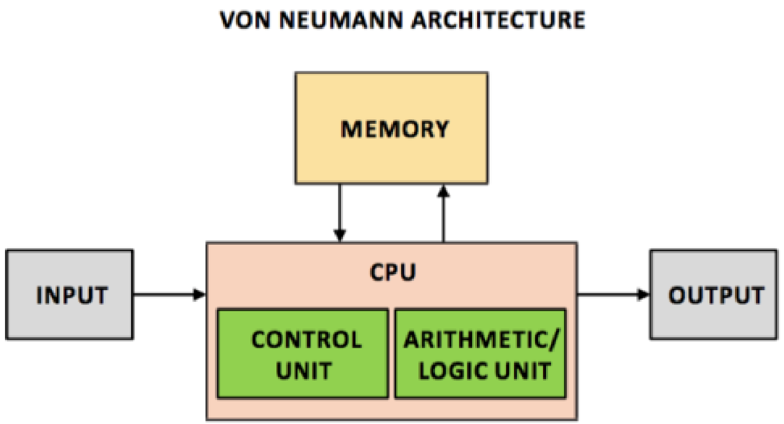
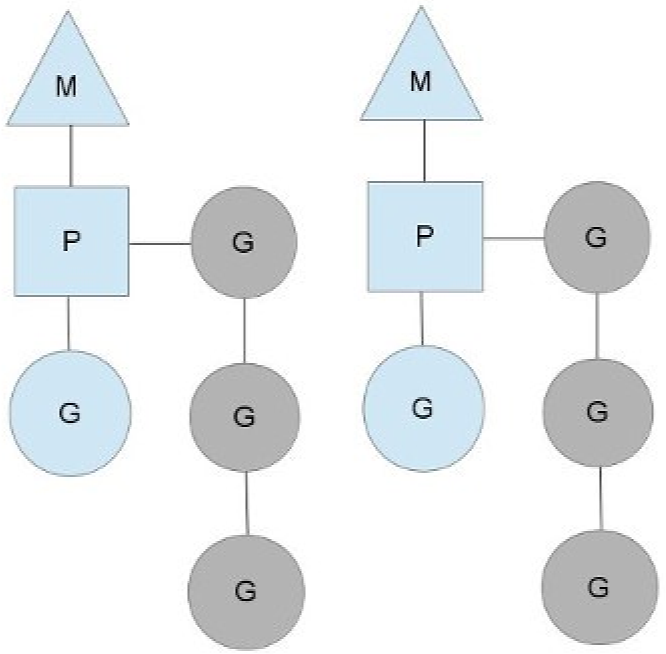
    time.Sleep(1000 * time.Millisecond)
    close(ch)
    wg.Wait()
}
```

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



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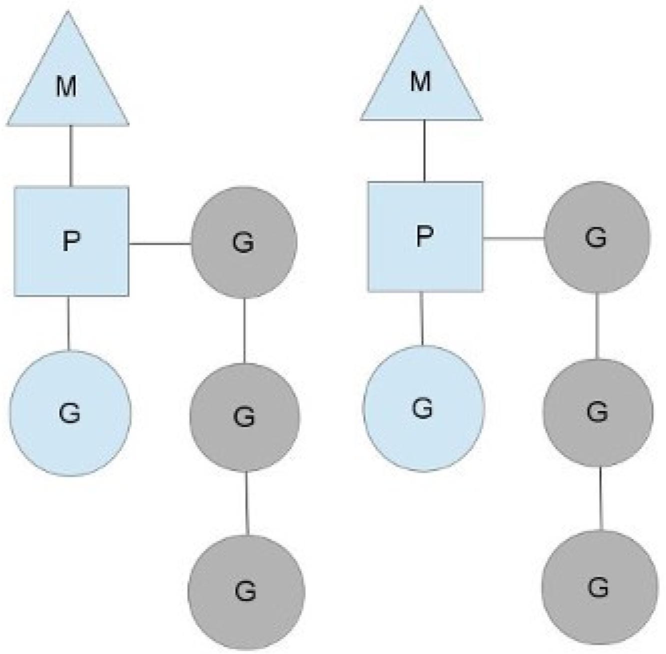
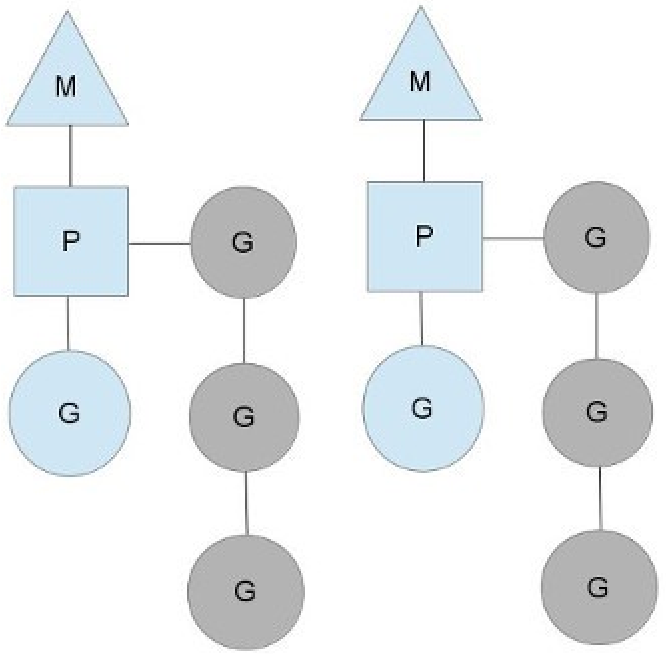


- M = “machine” → OS thread

Go implementation details



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

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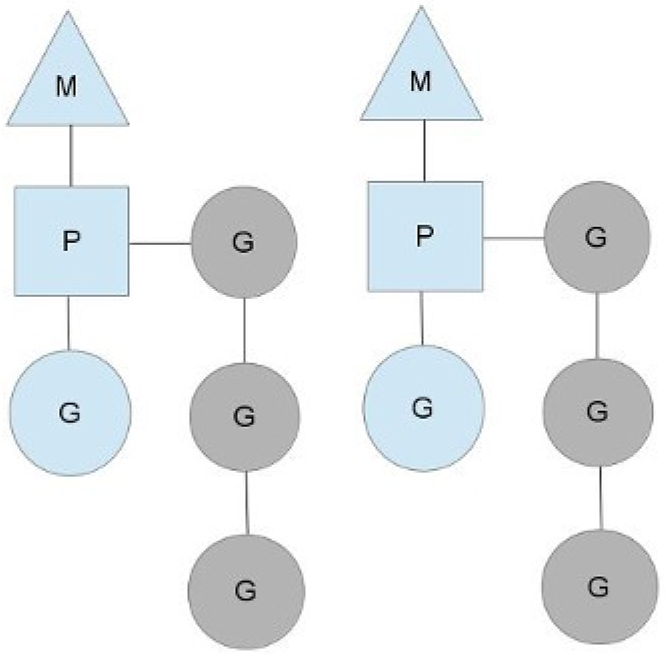

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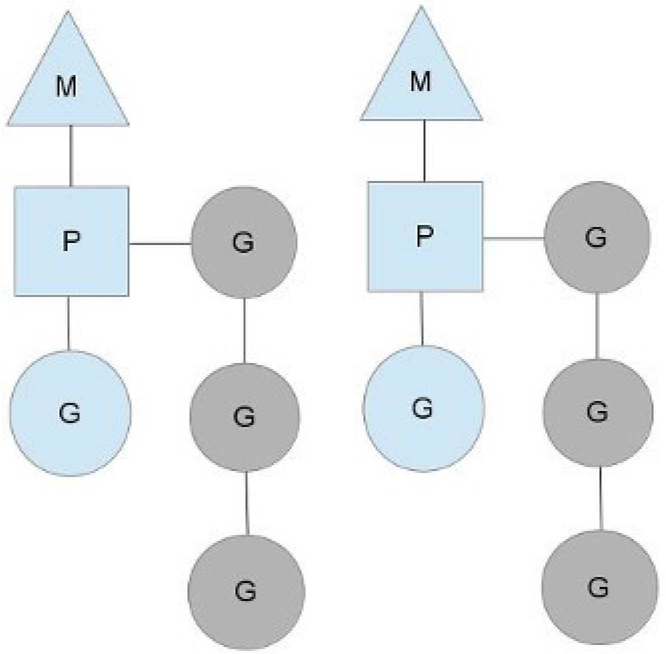

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- Each ‘M’ has a queue of goroutines

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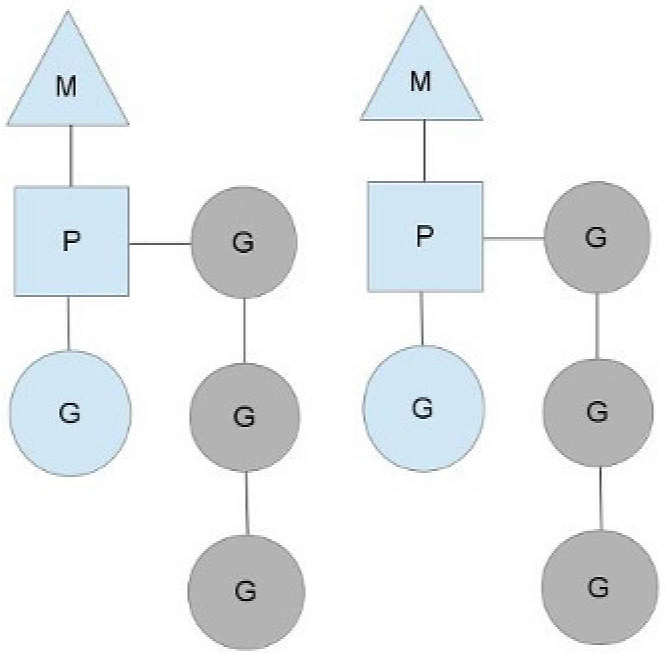

- M = “machine” → OS thread
- P = (processing) context
- G = goroutines
- Each ‘M’ has a queue of goroutines
- Goroutine scheduling is cooperative
  - Switch out on complete or block
  - Very light weight (fibers!)
  - Scheduler does work-stealing

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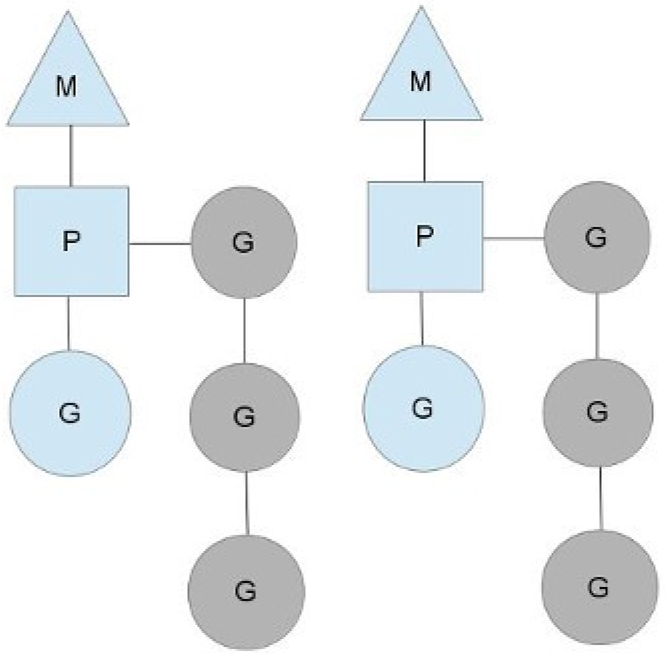
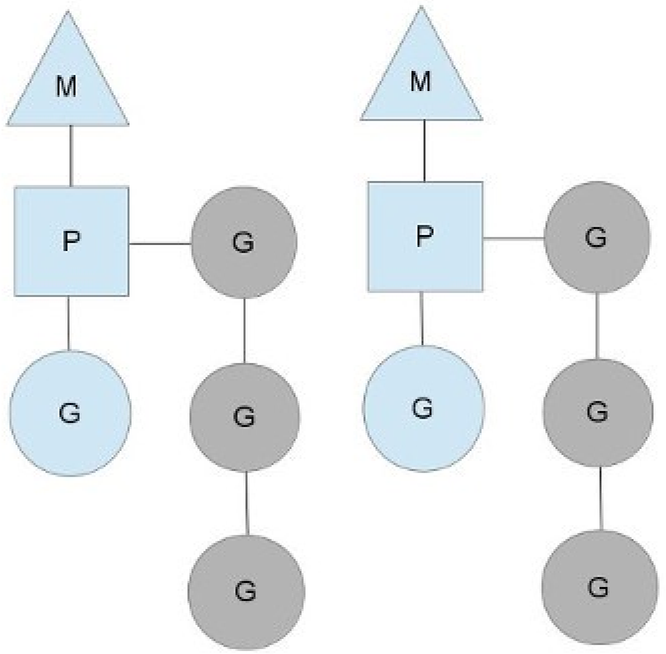


- M = “machine” → OS thread
- P = (processing) context
- G = goroutines

```
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



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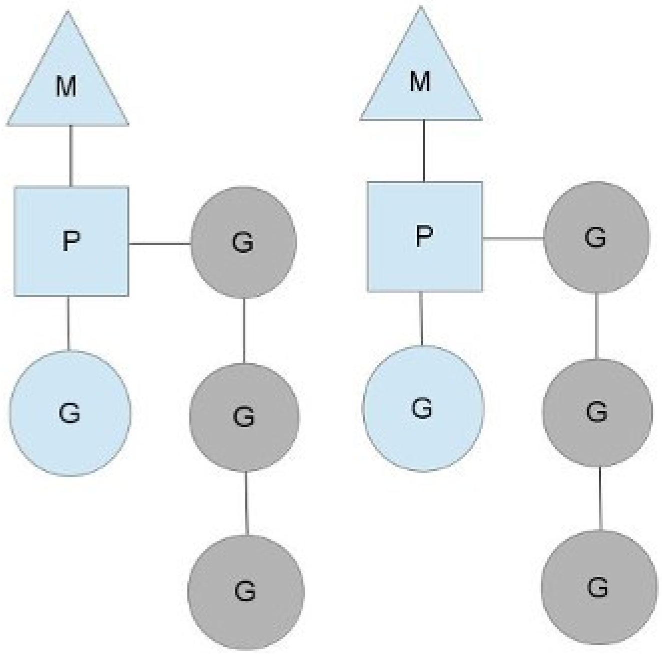
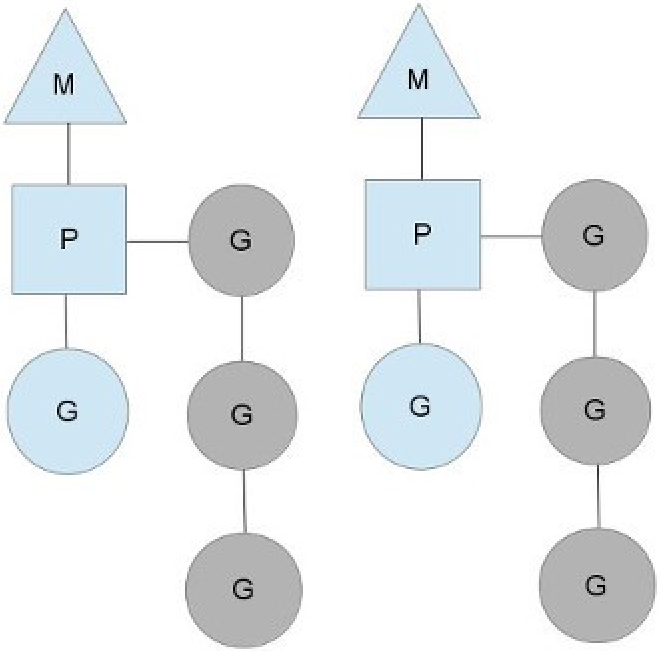


- M = “machine” → OS thread
- P = (processing) context
- G = goroutines

```
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

```
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
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```

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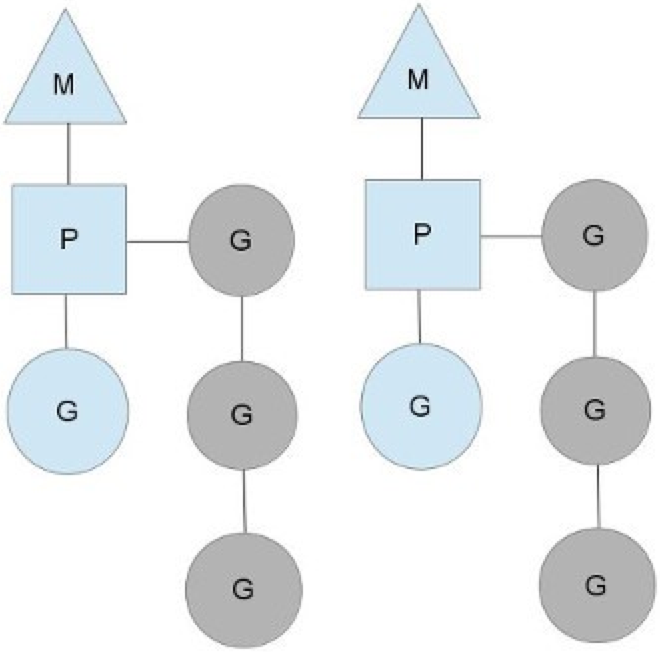

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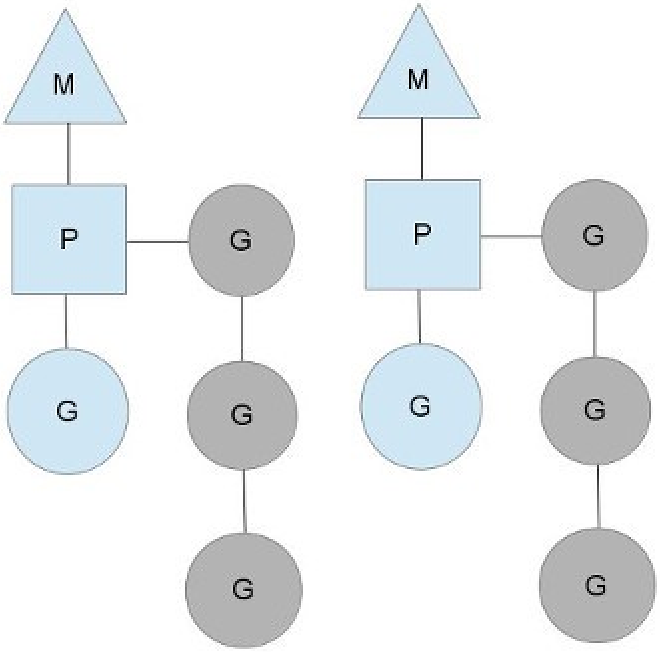

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};
```

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?

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    close(ch)
    wg.Wait()
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```

- 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

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```

- 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

```
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
```

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 {
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```go
// entry point for c <- x from compiled code
//go:nosplit
func chansend1(c *hchan, elem unsafe.Pointer) {
	chansend(c, elem, true, getcallerpc())
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/*
 * generic single channel send/recv
 * If block is not nil,
 * then the protocol will not
 * sleep but return if it could
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 * sleep can wake up with g.param == nil
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	// 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).
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	// they imply a moment between the two when the channel was both not yet closed
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	// 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)) {
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	}

	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
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```

Race detection! Cool!

```
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	if sg := c.recvq.dequeue(); sg != nil {
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func chansend(c *hchan, ep unsafe.Pointer, block bool, callerpc uintptr) bool {
        if c == nil {
                if !block {
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                }
                gopark(nil, nil, "chan send (nil chan)", traceEvGoStop, 2)
                throw("unreachable")
        }

        if debugChan {
                print("chansend: chan=", c, "\n")
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        var t0 int64
        if blockprofilerate > 0 {
                t0 = cputicks()
        }

        lock(&c.lock)

        if c.closed != 0 {
                unlock(&c.lock)
                panic(plainError("send on closed channel"))
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        if sg := c.recvq.dequeue(); sg != nil {
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                send(c, sg, ep, func() { unlock(&c.lock) }, 3)
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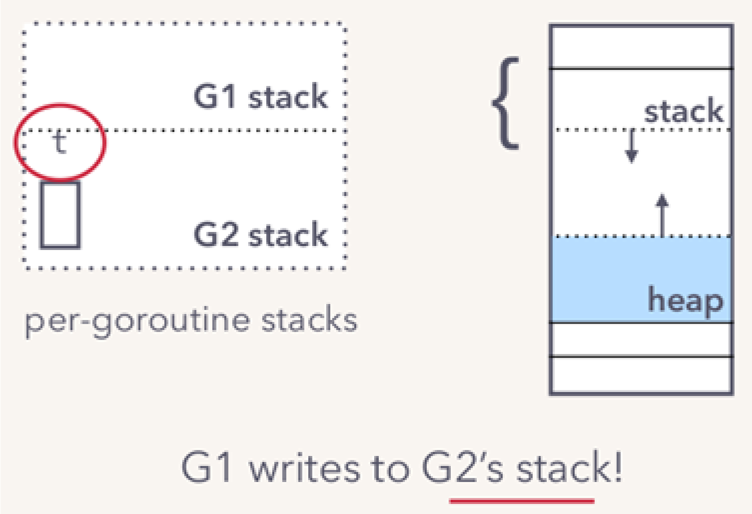


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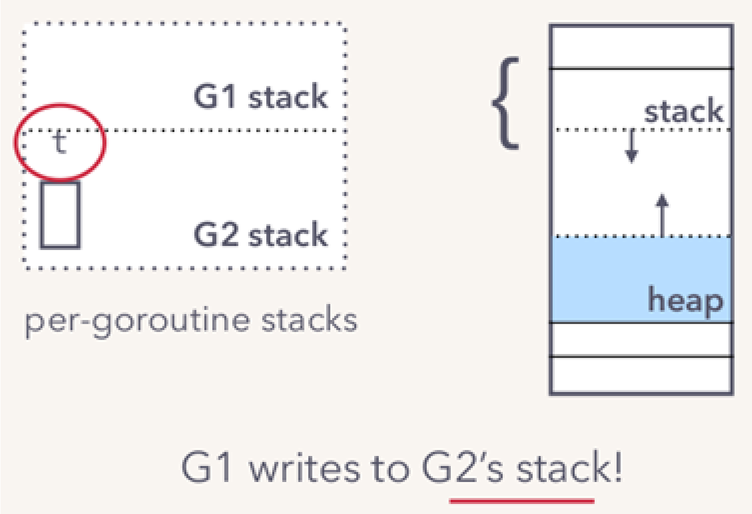


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Transputers did this in hardware in the 90s btw.

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

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	if debugChan {
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	if raceenabled {
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	// Fast path: check for failed non-blocking operation without acquiring the lock.
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  - 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?