Language-Level Concurrency Support

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cs380p

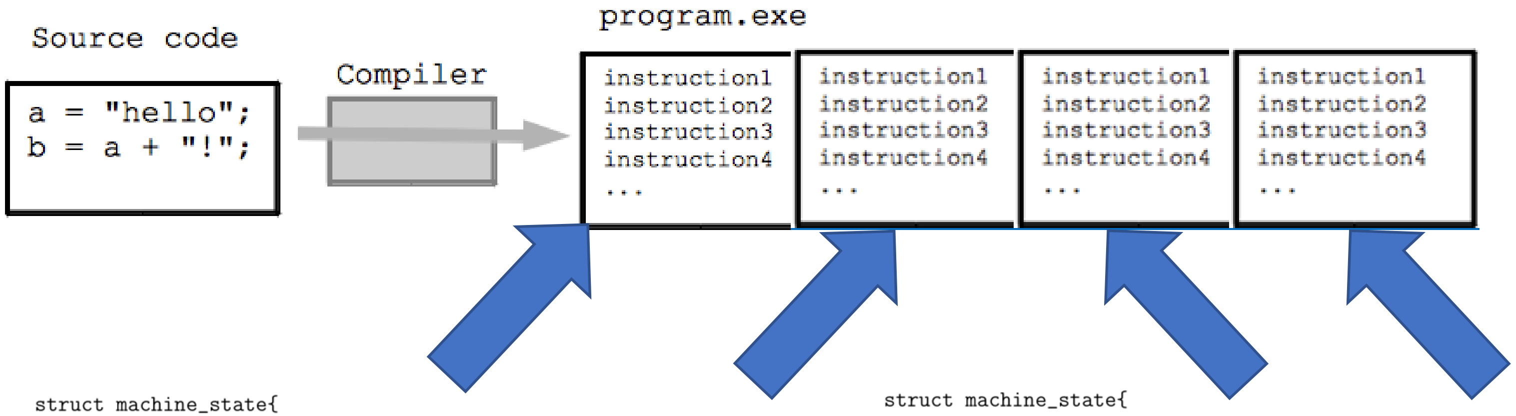
Outline

Message Passing background

Concurrency in Go

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

Review: Execution and Programming Models

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struct machine_state{
  uint64 pc;
  uint64 Registers[16];
  uint64 cr[6]; // control registers cr0-cr4 and EFER on AMD
...
} machine;
while(1) {
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  decode_instruction(machine.pc);
  execute_instruction(machine.pc);
}
void execute_instruction(i) {
  switch(opcode) {
  case add_rr:
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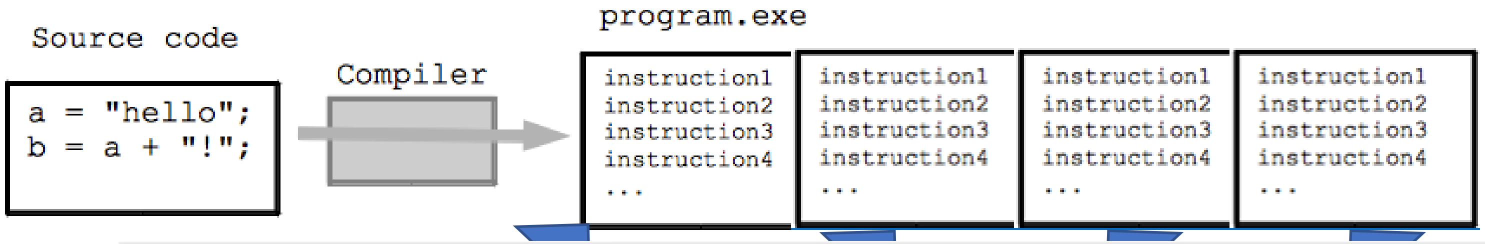


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   brea
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```

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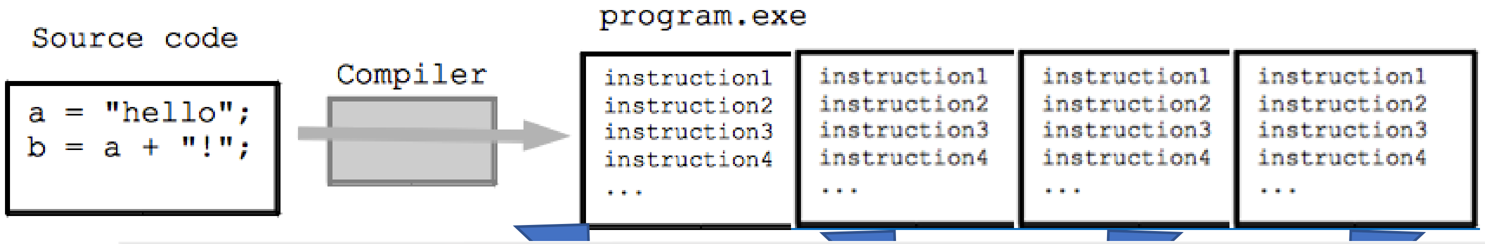


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Concrete execution model:

Multiple CPU(s) execute instructions sequentially

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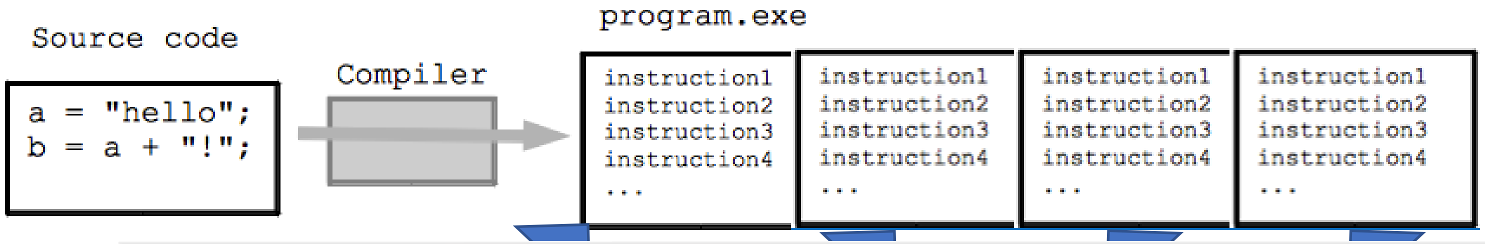


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Programming Model Dimensions:

- How to specify computation
- How to specify communication
- How to specify coordination/control transfer

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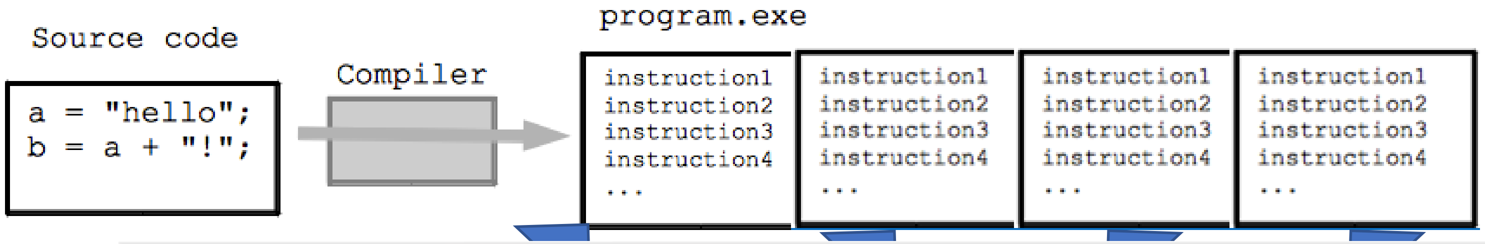

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Techniques/primitives

- Threads/Processes/Fibers/Events
- Message passing vs shared memory
- Preemption vs Non-preemption

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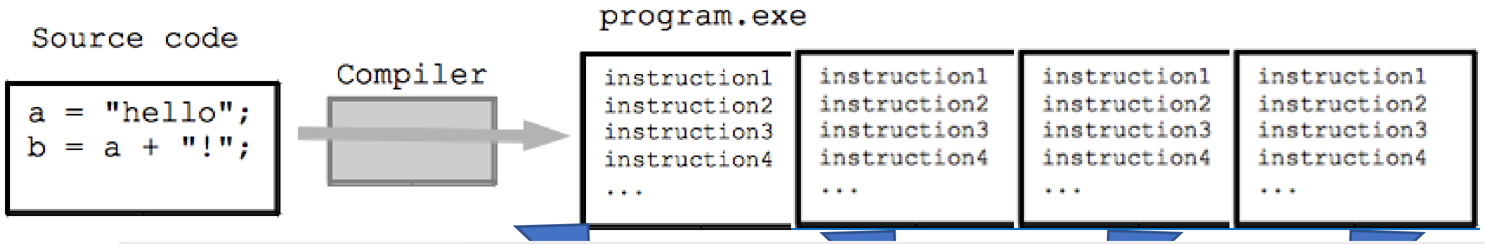


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Techniques/primitives

Threads/Processes/Fibers/Events

Message passing vs shared memory

Preemption vs Non-preemption

** *Dimensions/techniques not always orthogonal*

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
- …

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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)*

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Recurring theme

Message passing:

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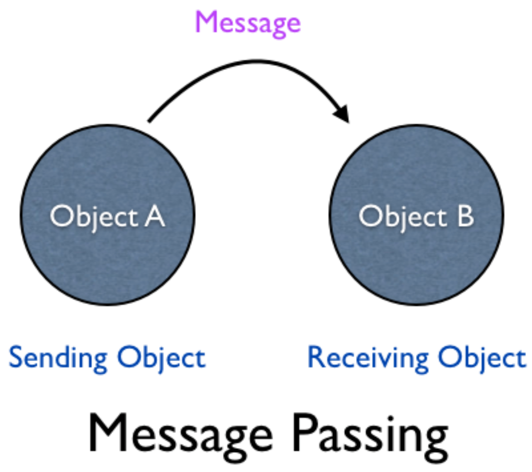
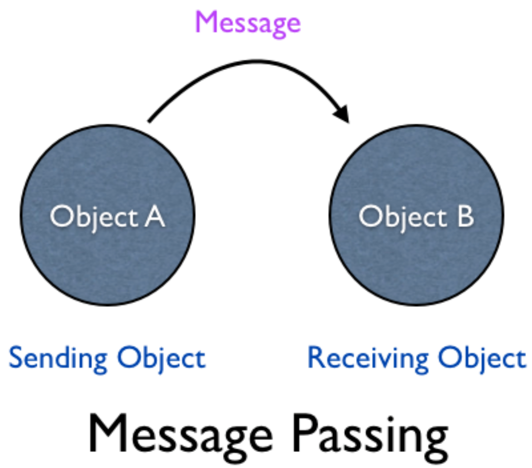
Message Passing



Message Passing

Threads/Processes send/receive messages

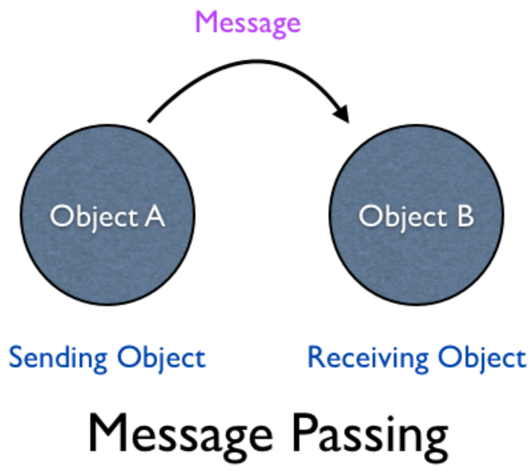


Message Passing

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

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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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Explicit Naming

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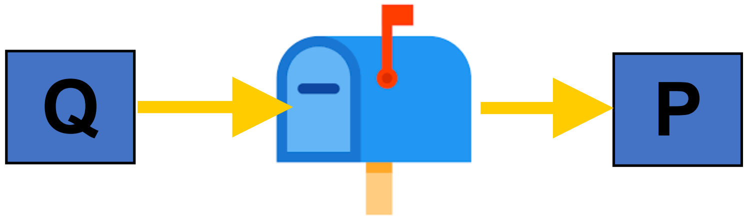
Implicit Naming

- 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*
Non-blocking receive:	*receiver gets a message or null*

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Synchronous vs. Asynchronous

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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

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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If ***both send and receive block***

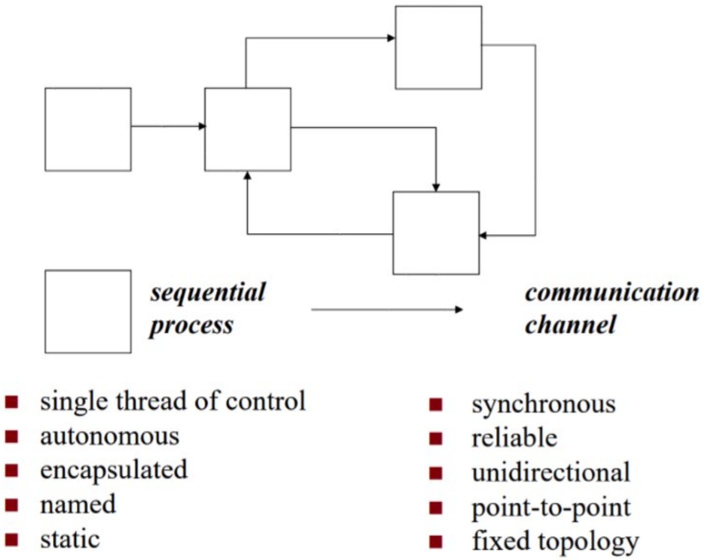
- “Rendezvouz”
- Operation acts as an ordering primitive
- Sender knows receiver succeeded
- Receiver knows sender succeeded
- Particularly appealing in distributed environment

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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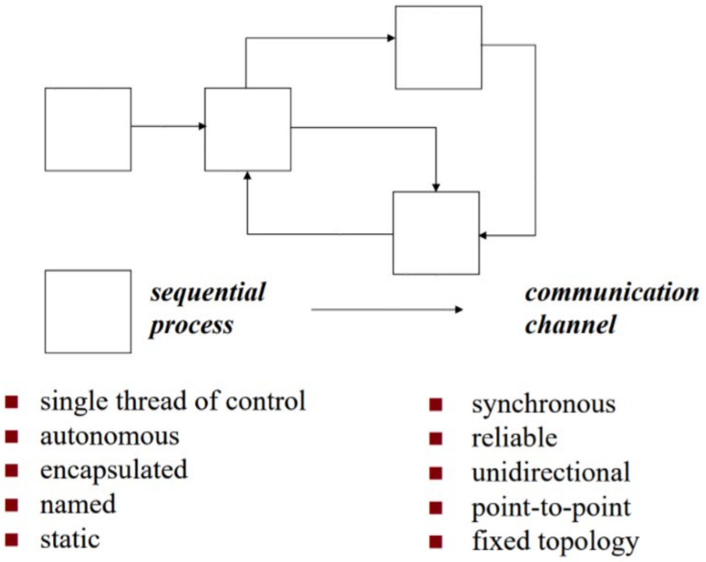

← Transputer!

An important problem in the CSP model

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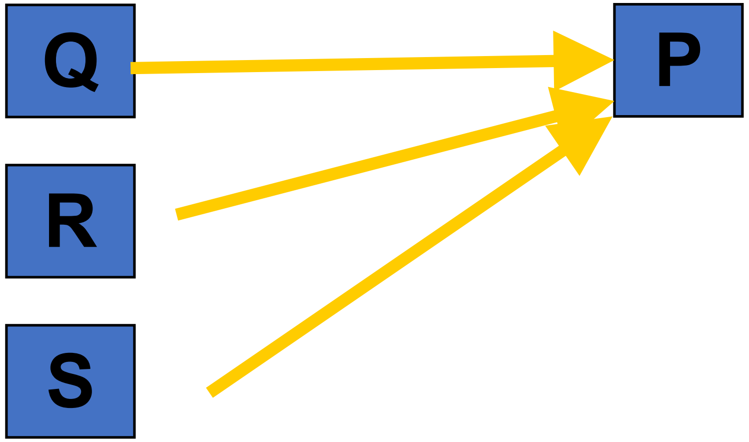

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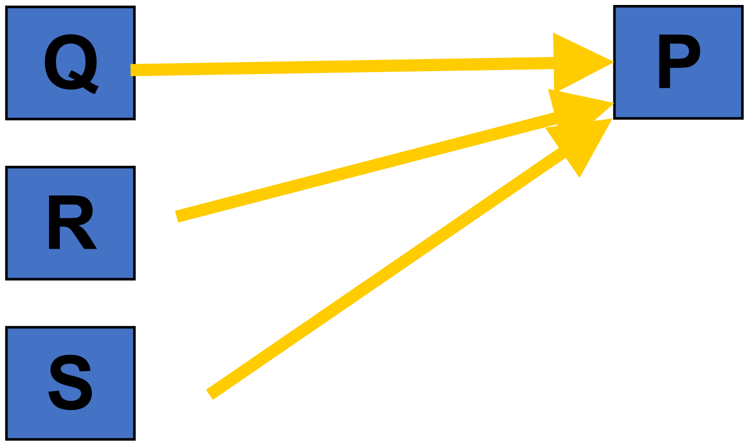


```
recv_multi(Q) {
  receive(Q, message)
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An important problem in the CSP model

Processes need to receive messages from different senders

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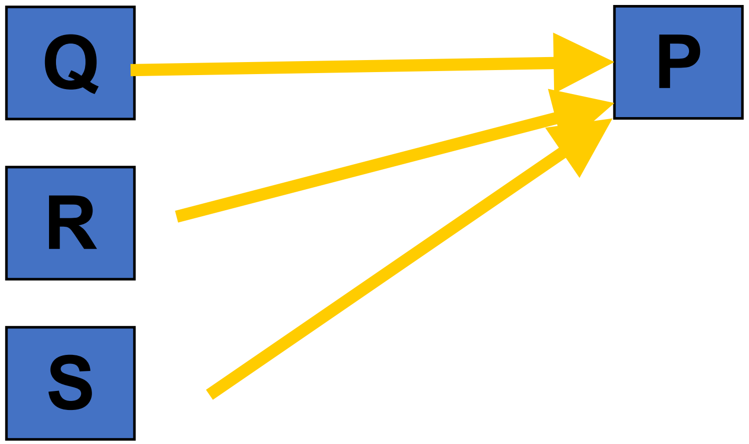


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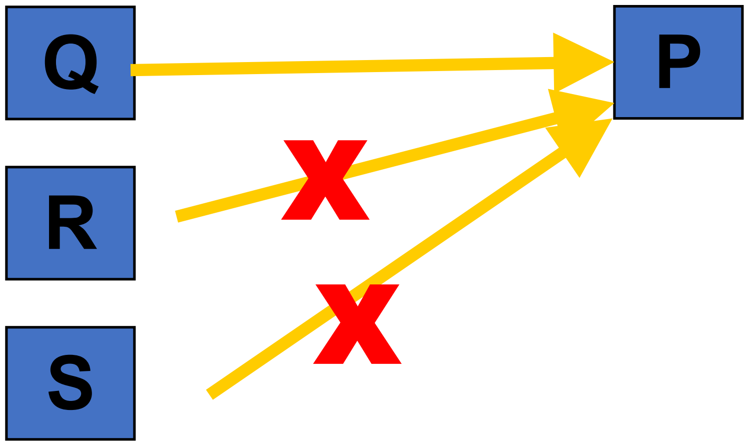


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Blocking with Indirect Naming

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blocking receive with ***indirect naming***

- Process waits on port, gets first message to arrive at that port

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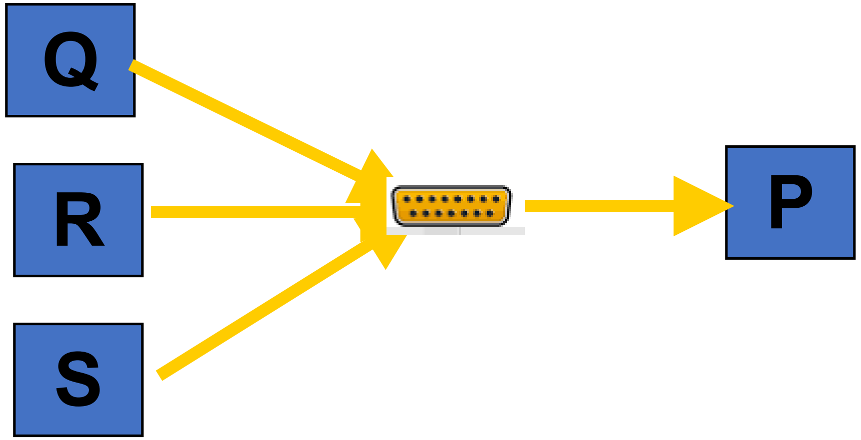

receive(port, message)

Blocking with Indirect Naming

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blocking receive with ***indirect naming***

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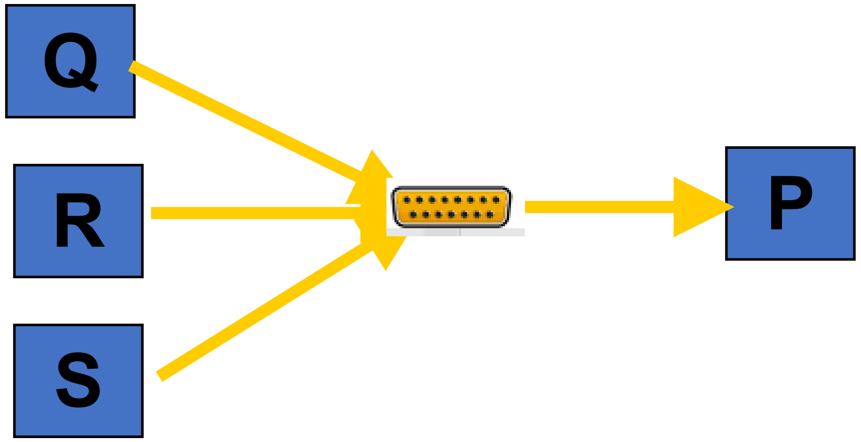

receive(port, message)

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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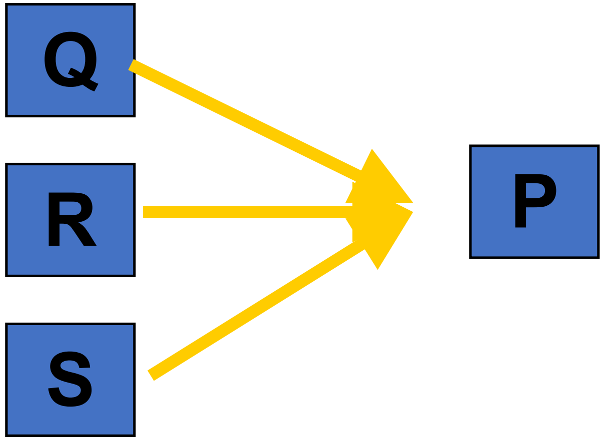

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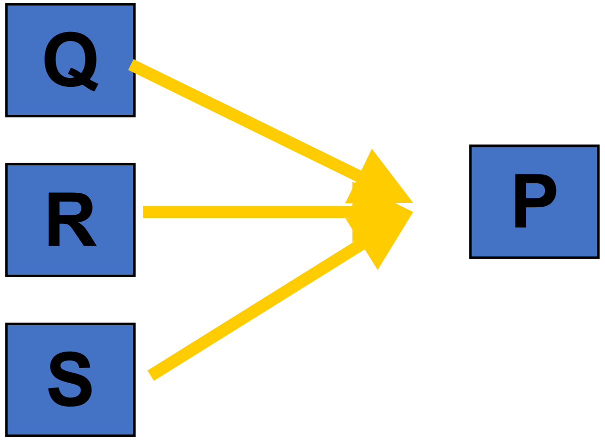


```
while(…) {
  try_receive(Q, message)
  try_receive(R, message)
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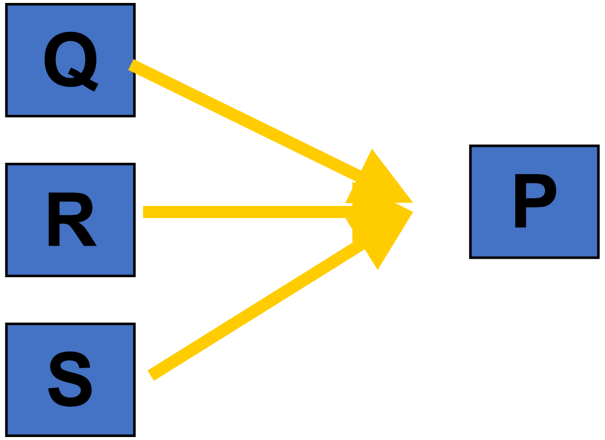
Non-blocking with Direct Naming

Processes need to receive messages from different senders

Non-blocking receive with ***direct naming***

  Requires receiver to poll senders

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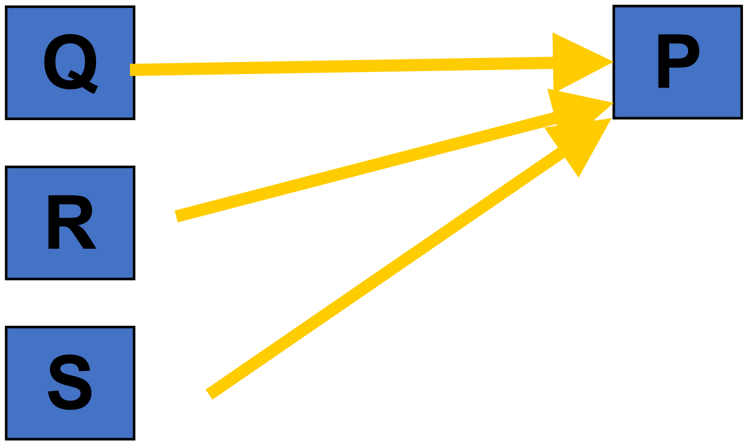
```

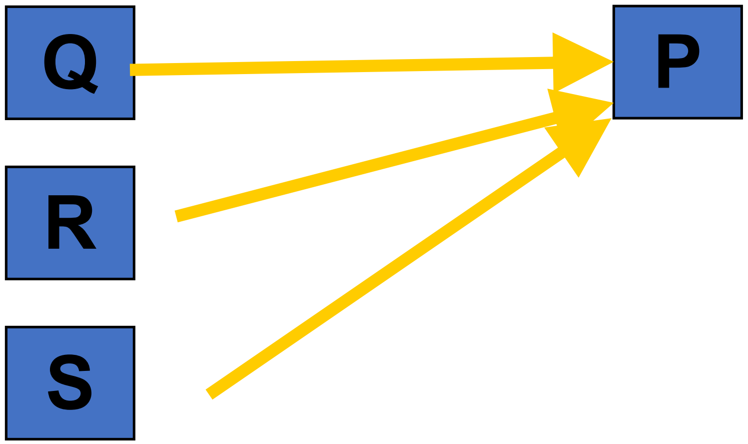
Polling (bad)
No indirection (good)

Blocking and Direct Naming



Blocking and Direct Naming

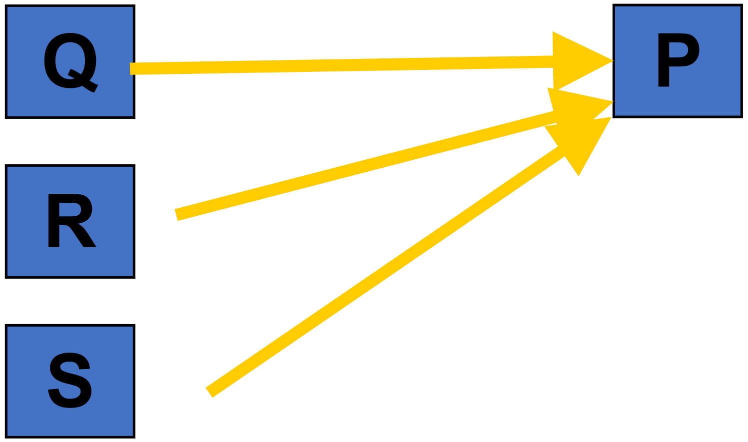
How to achieve ***it?***



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);

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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)
    }
}
```

```
func main() {
    boring("boring!")
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```
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"
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- Keep main() around a while
- See goroutine actually running

```
func main() {
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    fmt.Println("I'm listening.")
    time.Sleep(2 * time.Second)
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I'm listening.
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Program exited.
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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
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```
You say: "boring! 0"
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You say: "boring! 3"
You say: "boring! 4"
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Program exited.
```

Channels

Connect goroutines allowing them to communicate

- 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

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```
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")
}
```

Implementing 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

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!

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:
        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:
        fmt.Println("timed out")
        return
    }
}
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

Note the *absence of locks* in previous examples!

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

```
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("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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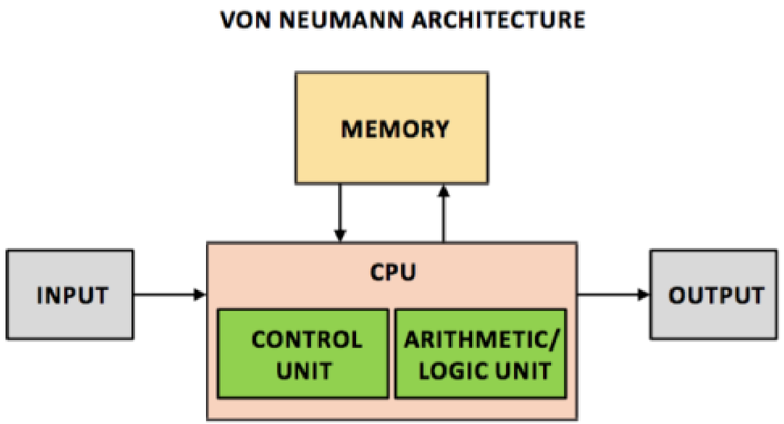
            if(amore) {
                fmt.Printf("reader #%d got %d value\n", id, aval)
            } else {
                fmt.Printf("reader #%d terminated with nothing.\n", id)
            }
            wg.Done()
        }(i)
    }
    time.Sleep(1000 * time.Millisecond)
    close(ch)
    wg.Wait()
}
```

WaitGroups

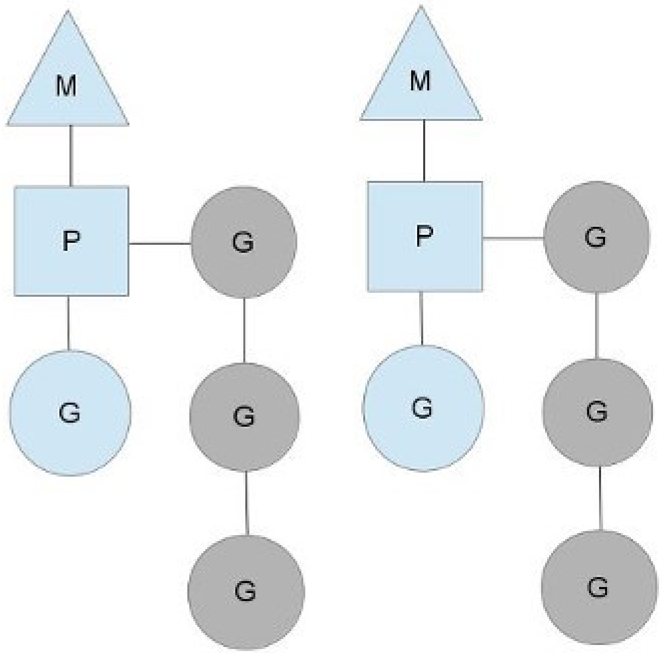
```
func test0() {
[illegible]
    ch := [illegible]int)
    for i:=0; i<4; i++ {
        go func(id int) {
            aval, amore := <- ch
            if(amore) {
                fmt.Printf("reader #%d got %d value\n", id, aval)
            } else {
                fmt.Printf("reader #%d terminated with nothing.\n", id)
[illegible]
        }([illegible]
    }
    time.Sleep(1000 * time.Millisecond)
[illegible]
}
```

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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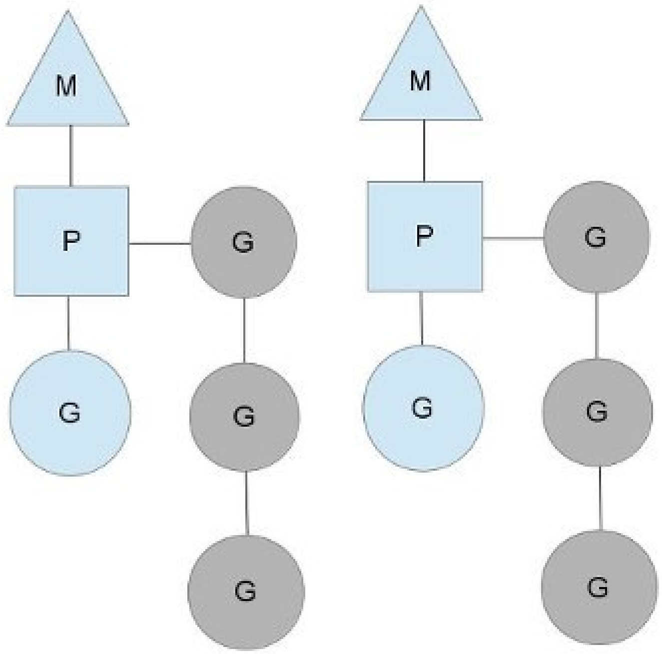
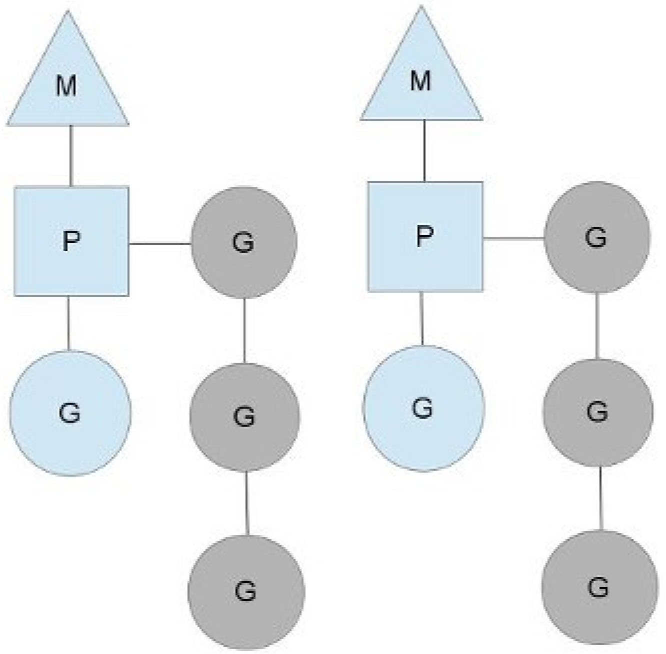


M = “machine” → OS thread

Go implementation details



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

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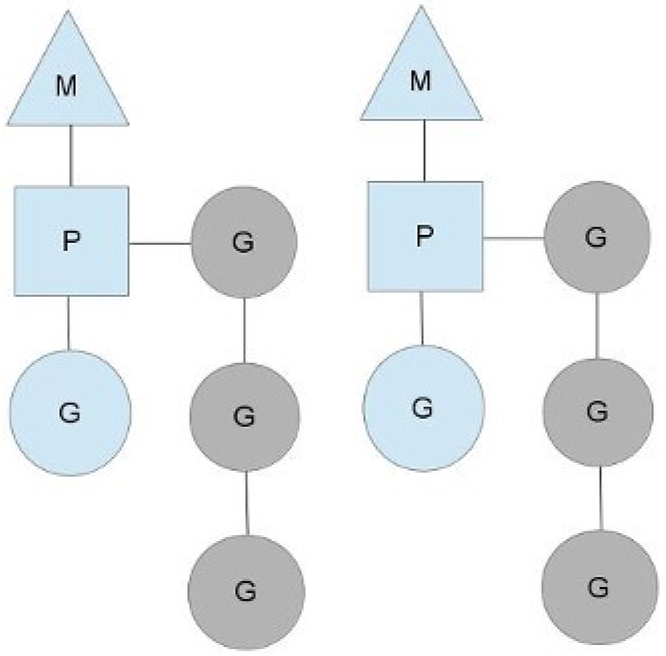

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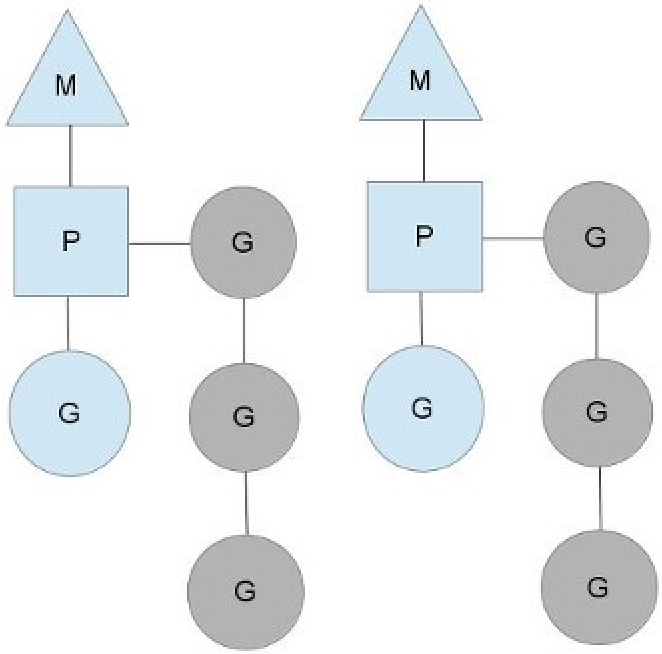

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Each ‘M’ has a queue of goroutines

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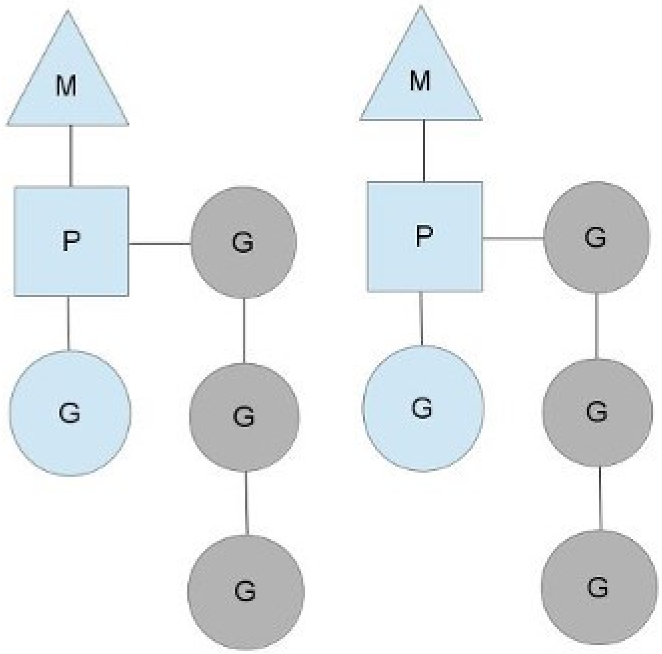

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Each ‘M’ has a queue of goroutines

Goroutine scheduling is cooperative

- Switch out on complete or block
- Very light weight (fibers!)
- Scheduler does work-stealing

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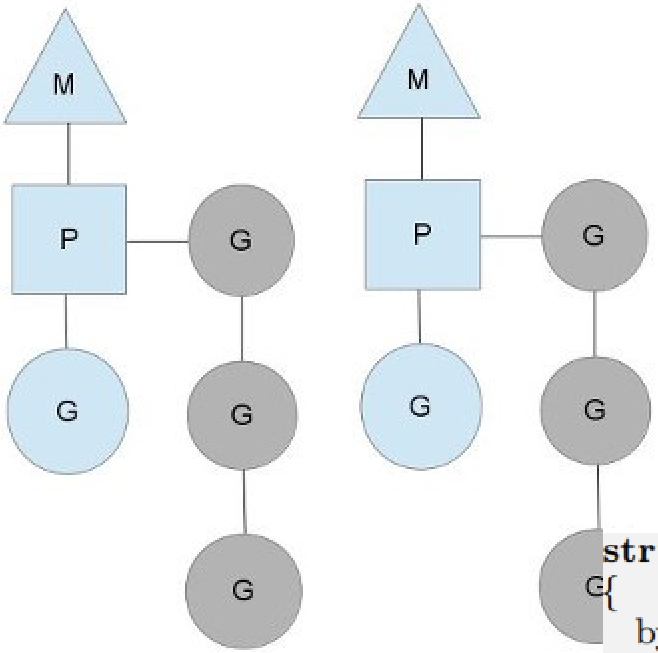

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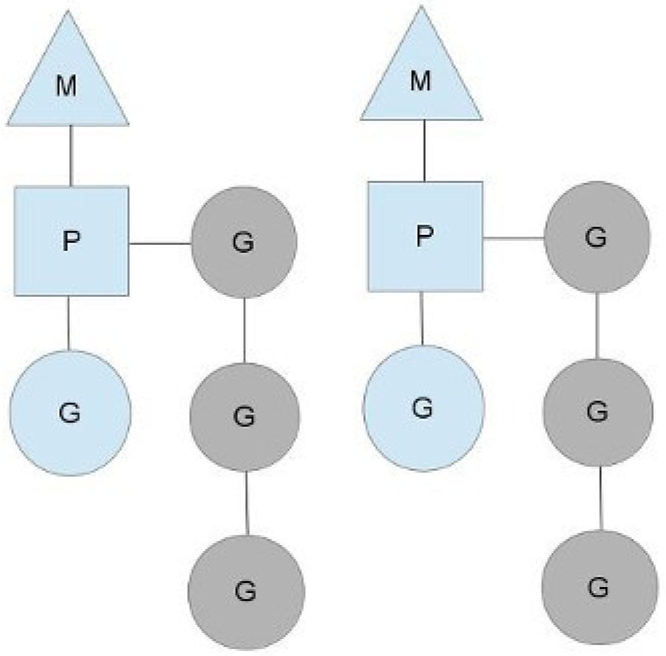
Each ‘M’ has a queue of goroutines

Goroutine scheduling is cooperative

- Switch out on complete or block
- Very light weight (fibers!)
- Scheduler does work-stealing

```
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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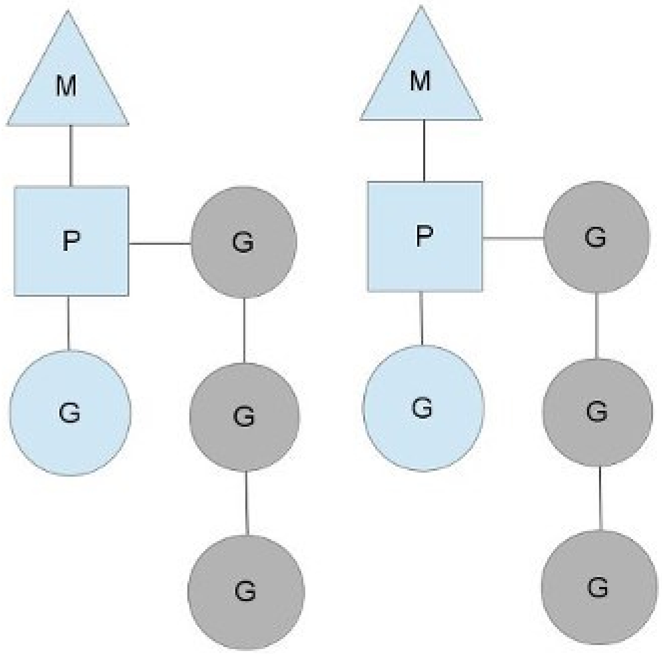

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G = goroutines

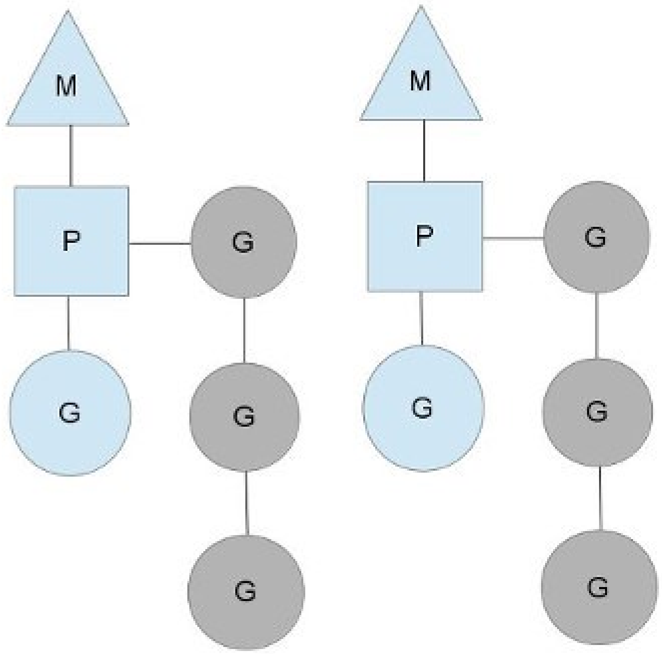
Each ‘M’ has a queue of goroutines

Goroutine scheduling is cooperative

- Switch out on complete or block
- Very light weight (fibers!)
- Scheduler does work-stealing

```
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

G = goroutines

Each ‘M’ has a queue of goroutines

Goroutine scheduling is cooperative

- Switch out on complete or block

```
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
  ...
};
```

Scaling to 1000s of goroutines

```
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("reader #%d terminated with nothing.\n", id)
            }
            wg.Done()
        }(i)
    }
    time.Sleep(1000 * time.Millisecond)
    close(ch)
    wg.Wait()
    stopTimes["testQ"] = time.Now()
}
```

Scaling to 1000s of goroutines

- 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

```
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++ {
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            aval, amore := <- ch
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            }
            wg.Done()
        }(i)
    }
    time.Sleep(1000 * time.Millisecond)
    close(ch)
    wg.Wait()
    stopTimes["testQ"] = time.Now()
}
```

Scaling to 1000s of goroutines

- Creates a channel
- Creates "consumers" goroutines
- Each of them tries to read from the channel
- Main either:
  - Sleeps for 1 second, closes the channel
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    startTimes["testQ"] = time.Now()
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    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("reader #%d terminated with nothing.\n", id)
            }

    }
    time
    clos
    wg.W
    stop
}
```

```
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

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

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

	if raceenabled {
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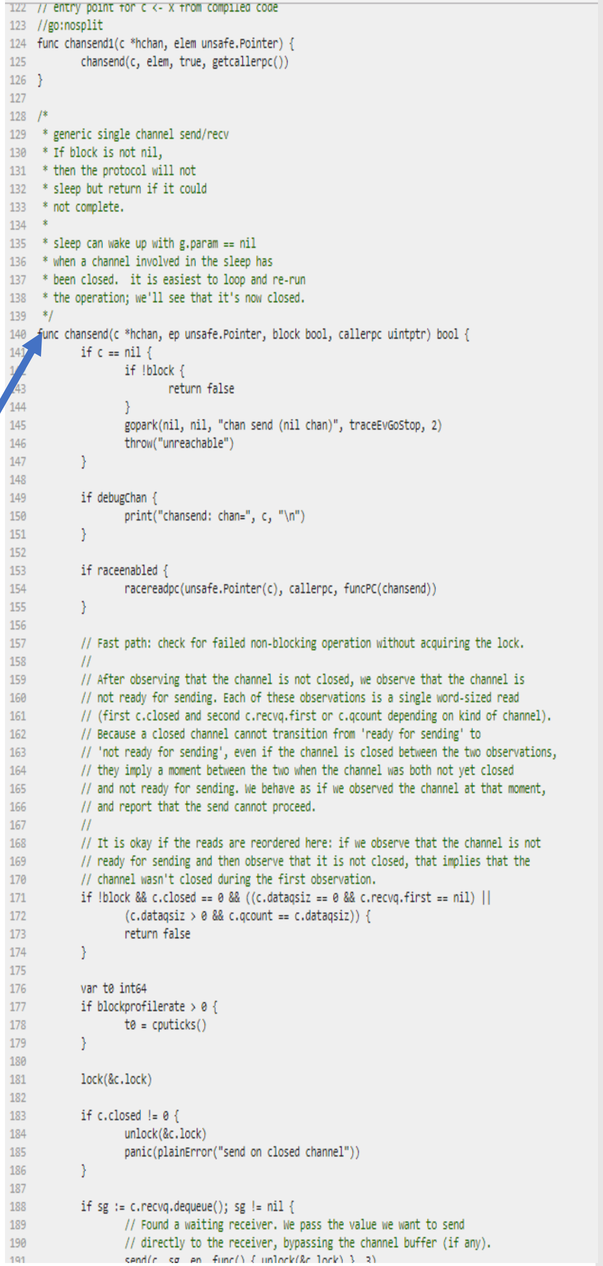
```



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

/*
 * 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
 * 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.
 */
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		}
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	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
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	// Because a closed channel cannot transition from 'ready for sending' to
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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)) {
		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)
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        }

        if debugChan {
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        }

                            callerpc, funcPC(chansend))
        }
```

Race detection! Cool!

```
// entry point for c <- x from compiled code
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func chansend1(c *hchan, elem unsafe.Pointer) {
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                return false
        }

        var t0 int64
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	if blockprofilerate > 0 {
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Some highlights

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	dst := sg.elem
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	memmove(dst, src, t.size)
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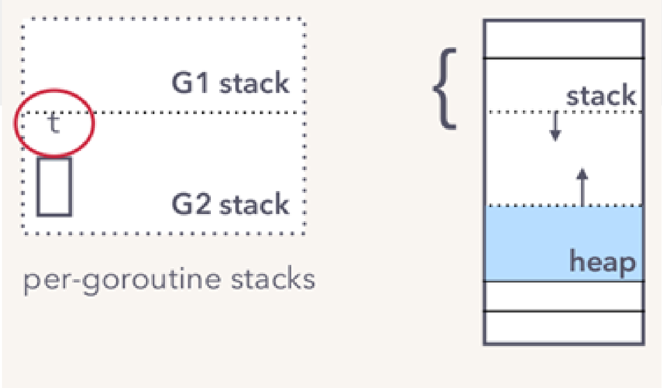

G1 writes to G2's stack!

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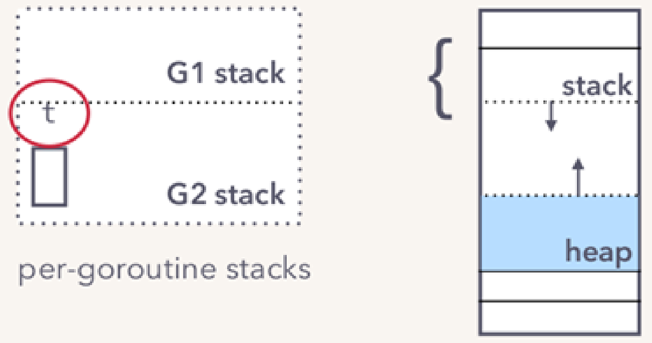

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Transputers did this in hardware in the 90s btw.

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- *Right tradeoffs? None of these problems have to do with concurrency!*