Concurrency is not Parallelism

Waza Jan 11, 2012

Rob Pike

Video

This talk was presented at Heroku's Waza conference in January 2012.

Watch the talk on Vimeo (http://vimeo.com/49718712)

The modern world is parallel

Multicore.

Networks.

Clouds of CPUs.

Loads of users.

Our technology should help.
That's where concurrency comes in.

Go supports concurrency

Go provides:

- concurrent execution (goroutines)
- synchronization and messaging (channels)
- multi-way concurrent control (select)

Concurrency is cool! Yay parallelism!!

NO! A fallacy.

When Go was announced, many were confused by the distinction.

"I ran the prime sieve with 4 processors and it got slower!"

Concurrency

Programming as the composition of independently executing processes.

(Processes in the general sense, not Linux processes. Famously hard to define.)

Parallelism

Programming as the simultaneous execution of (possibly related) computations. 7

Concurrency vs. parallelism

Concurrency is about dealing with lots of things at once.

Parallelism is about doing lots of things at once.

Not the same, but related.

Concurrency is about structure, parallelism is about execution.

Concurrency provides a way to structure a solution to solve a problem that may (but not necessarily) be parallelizable.

An analogy

Concurrent: Mouse, keyboard, display, and disk drivers.

Parallel: Vector dot product.

Concurrency plus communication

Concurrency is a way to structure a program by breaking it into pieces that can be executed independently.

Communication is the means to coordinate the independent executions.

This is the Go model and (like Erlang and others) it's based on CSP:

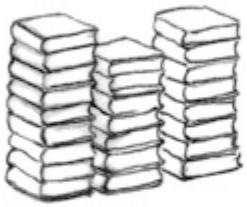
C. A. R. Hoare: Communicating Sequential Processes (CACM 1978)

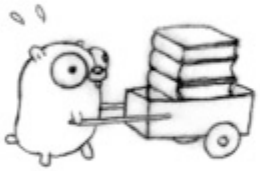
Gophers

This is too abstract. Let's get concrete. 11

Our problem

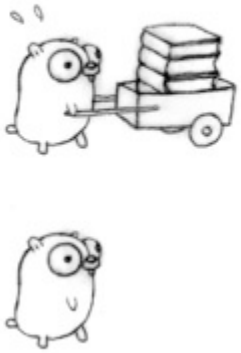
Move a pile of obsolete language manuals to the incinerator.





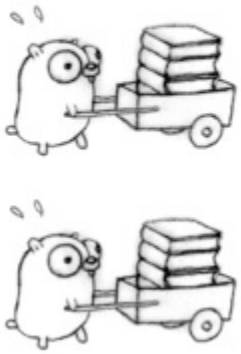
With only one gopher this will take too long.

More gophers!



More gophers are not enough; they need more carts.

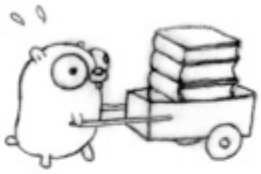
More gophers and more carts

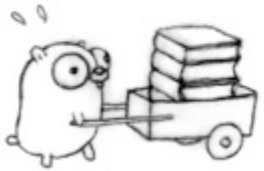


This will go faster, but there will be bottlenecks at the pile and incinerator.
Also need to synchronize the gophers.
A message (that is, a communication between the gophers) will do.

Double everything

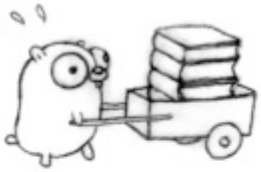
Remove the bottleneck; make them really independent.

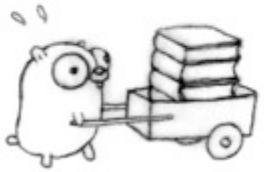




This will consume input twice as fast.

Concurrent composition


The concurrent composition of two gopher procedures.

Concurrent composition

This design is not automatically parallel!

What if only one gopher is moving at a time?
Then it's still concurrent (that's in the design), just not parallel.

However, it's automatically parallelizable!

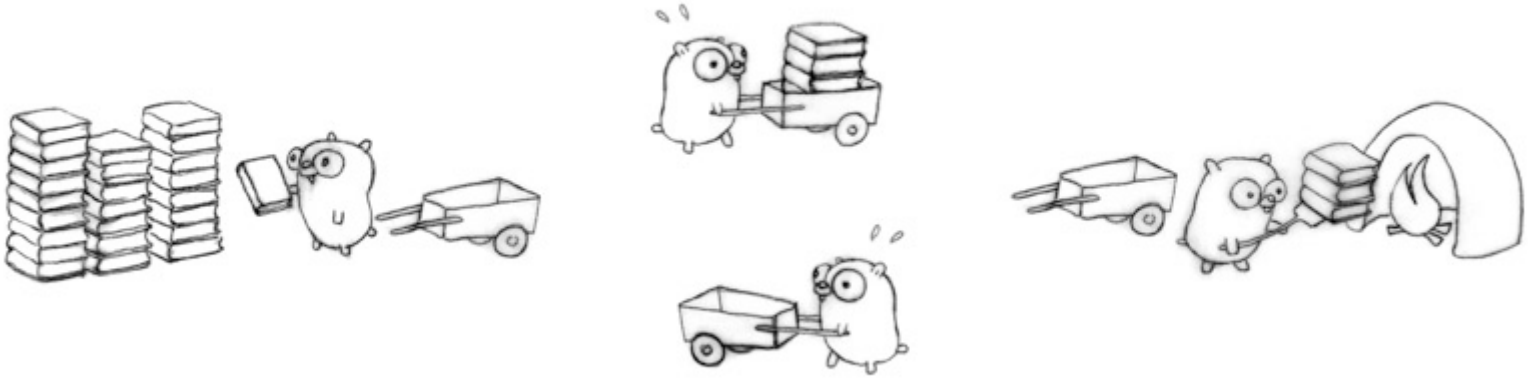
Moreover the concurrent composition suggests other models.

Another design

Three gophers in action, but with likely delays.
Each gopher is an independently executing procedure,
plus coordination (communication).

Finer-grained concurrency

Add another gopher procedure to return the empty carts.



Four gophers in action for better flow, each doing one simple task.

If we arrange everything right (implausible but not impossible), that's four times faster than our original one-gopher design.

Observation

We improved performance by adding a concurrent procedure to the existing design.

More gophers doing more work; it runs better.

This is a deeper insight than mere parallelism.

Concurrent procedures

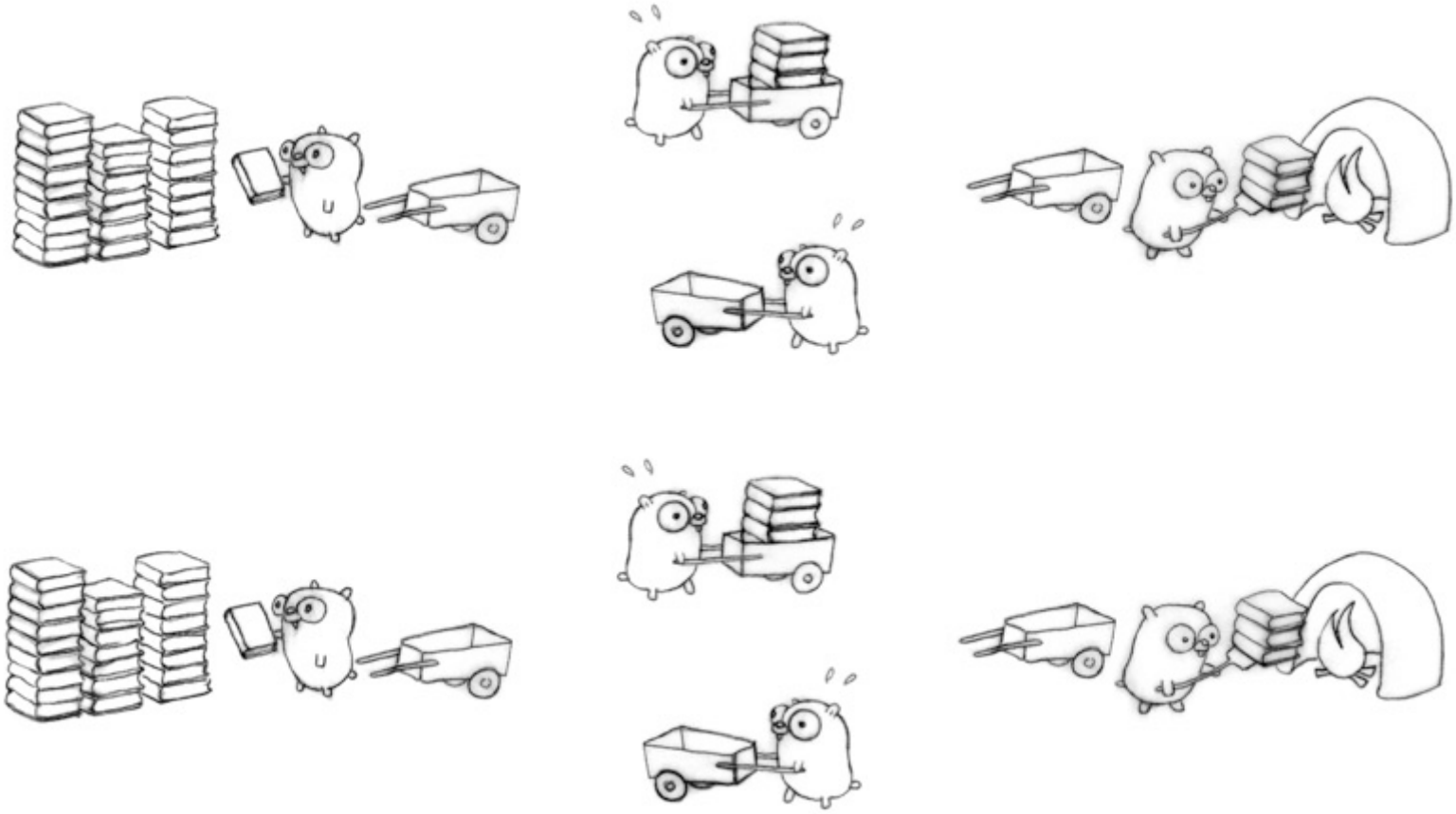
Four distinct gopher procedures:

- load books onto cart
- move cart to incinerator
- unload cart into incinerator
- return empty cart

Different concurrent designs enable different ways to parallelize.

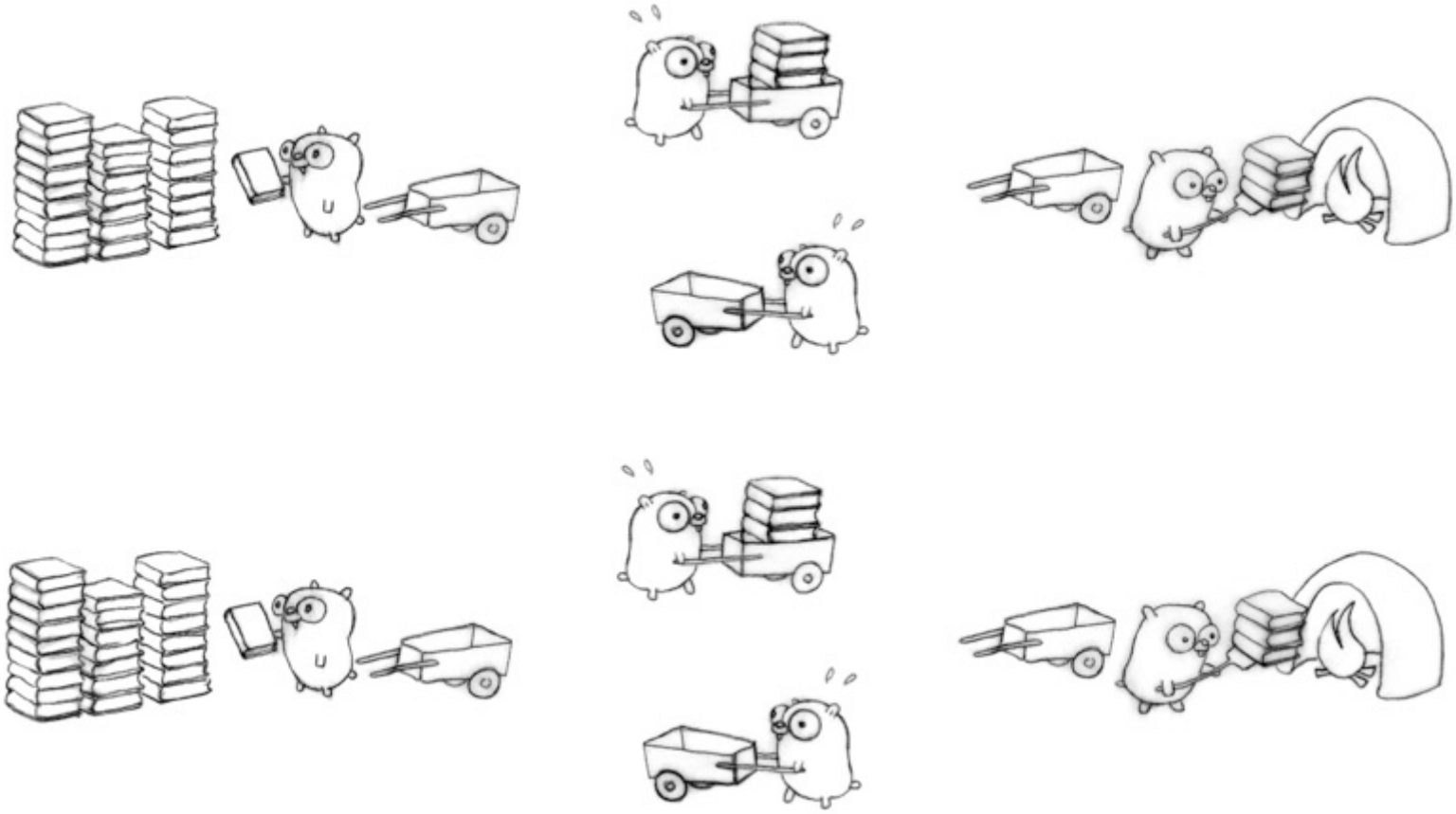
More parallelization!

We can now parallelize on the other axis; the concurrent design makes it easy. Eight gophers, all busy.



Or maybe no parallelization at all

Keep in mind, even if only one gopher is active at a time (zero parallelism), it's still a correct and concurrent solution.



Another design

Here's another way to structure the problem as the concurrent composition of gopher procedures.

Two gopher procedures, plus a staging pile.

24

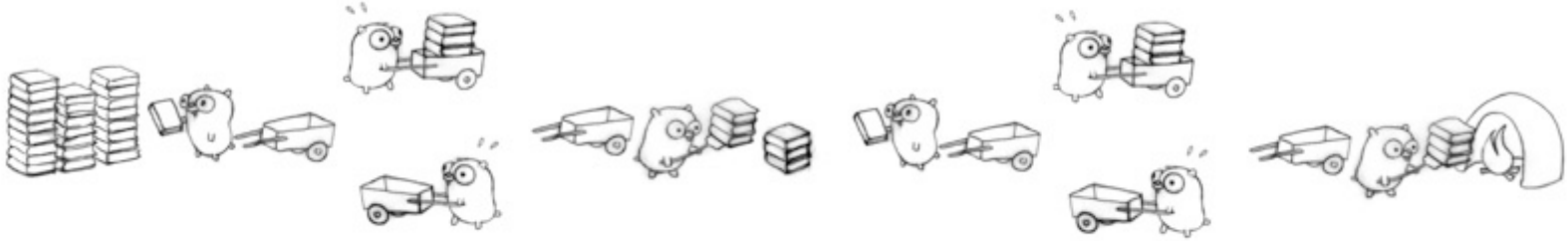
Parallelize the usual way

Run more concurrent procedures to get more throughput.

25

Or a different way

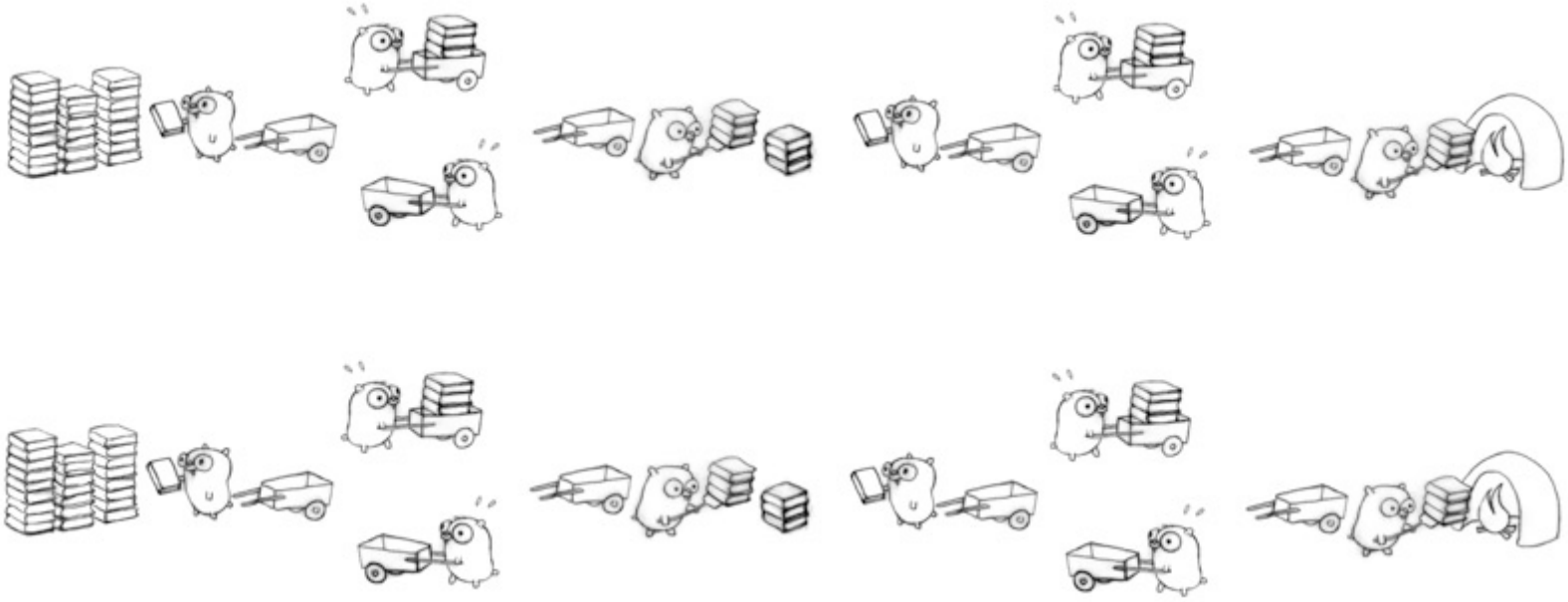
Bring the staging pile to the multi-gopher concurrent model:



26

Full on optimization

Use all our techniques. Sixteen gophers hard at work!



27

Lesson

There are many ways to break the processing down.

That's concurrent design.

Once we have the breakdown, parallelization can fall out and correctness is easy. 28

Back to Computing

In our book transport problem, substitute:

- book pile => web content
- gopher => CPU
- cart => marshaling, rendering, or networking
- incinerator => proxy, browser, or other consumer

It becomes a concurrent design for a scalable web service.
Gophers serving web content.

A little background about Go

Not the place for a tutorial, just quick highlights.

30

Goroutines

A goroutine is a function running independently in the same address space as other goroutines

```
f("hello", "world") // f runs; we wait
```

```
go f("hello", "world") // f starts running
g() // does not wait for f to return
```

Like launching a function with shell's & notation.

Goroutines are not threads

(They're a bit like threads, but they're much cheaper.)

Goroutines are multiplexed onto OS threads as required.

When a goroutine blocks, that thread blocks but no other goroutine blocks.

Channels

Channels are typed values that allow goroutines to synchronize and exchange information.

```
timerChan := make(chan time.Time)
go func() {
    time.Sleep(deltaT)
    timerChan <- time.Now() // send time on timerChan
}()
// Do something else; when ready, receive.
// Receive will block until timerChan delivers.
// Value sent is other goroutine's completion time.
completedAt := <-timerChan
```

33

Select

The `select` statement is like a `switch`, but the decision is based on ability to communicate rather than equal values.

```
select {
case v := <-ch1:
    fmt.Println("channel 1 sends", v)
case v := <-ch2:
    fmt.Println("channel 2 sends", v)
default: // optional
    fmt.Println("neither channel was ready")
}
```

Go really supports concurrency

Really.

It's routine to create thousands of goroutines in one program.
(Once debugged a program after it had created 1.3 million.)

Stacks start small, but grow and shrink as required.

Goroutines aren't free, but they're very cheap.

Closures are also part of the story

Make some concurrent calculations easier to express.

They are just local functions.
Here's a non-concurrent example:

```
func Compose(f, g func(x float) float)
                  func(x float) float {
     return func(x float) float {
        return f(g(x))
    }
}

print(Compose(sin, cos)(0.5))
```

Some examples

Learn concurrent Go by osmosis. 37

Launching daemons

Use a closure to wrap a background operation.

This copies items from the input channel to the output channel:

```
go func() { // copy input to output
    for val := range input {
        output <- val
    }
}()
```

The `for range` operation runs until channel is drained.

A simple load balancer (1)

A unit of work:

```
type Work struct {
    x, y, z int
}
```

39

A simple load balancer (2)

A worker task

```
func worker(in <-chan *Work, out chan<- *Work) {
   for w := range in {
      w.z = w.x * w.y
      Sleep(w.z)
      out <- w
   }
}
```

Must make sure other workers can run when one blocks.

A simple load balancer (3)

The runner

```
func Run() {
   in, out := make(chan *Work), make(chan *Work)
   for i := 0; i < NumWorkers; i++ {
       go worker(in, out)
   }
   go sendLotsOfWork(in)
   receiveLotsOfResults(out)
}
```

Easy problem but also hard to solve concisely without concurrency.

Concurrency enables parallelism

The load balancer is implicitly parallel and scalable.

`NumWorkers` could be huge.

The tools of concurrency make it almost trivial to build a safe, working, scalable, parallel design.

Concurrency simplifies synchronization

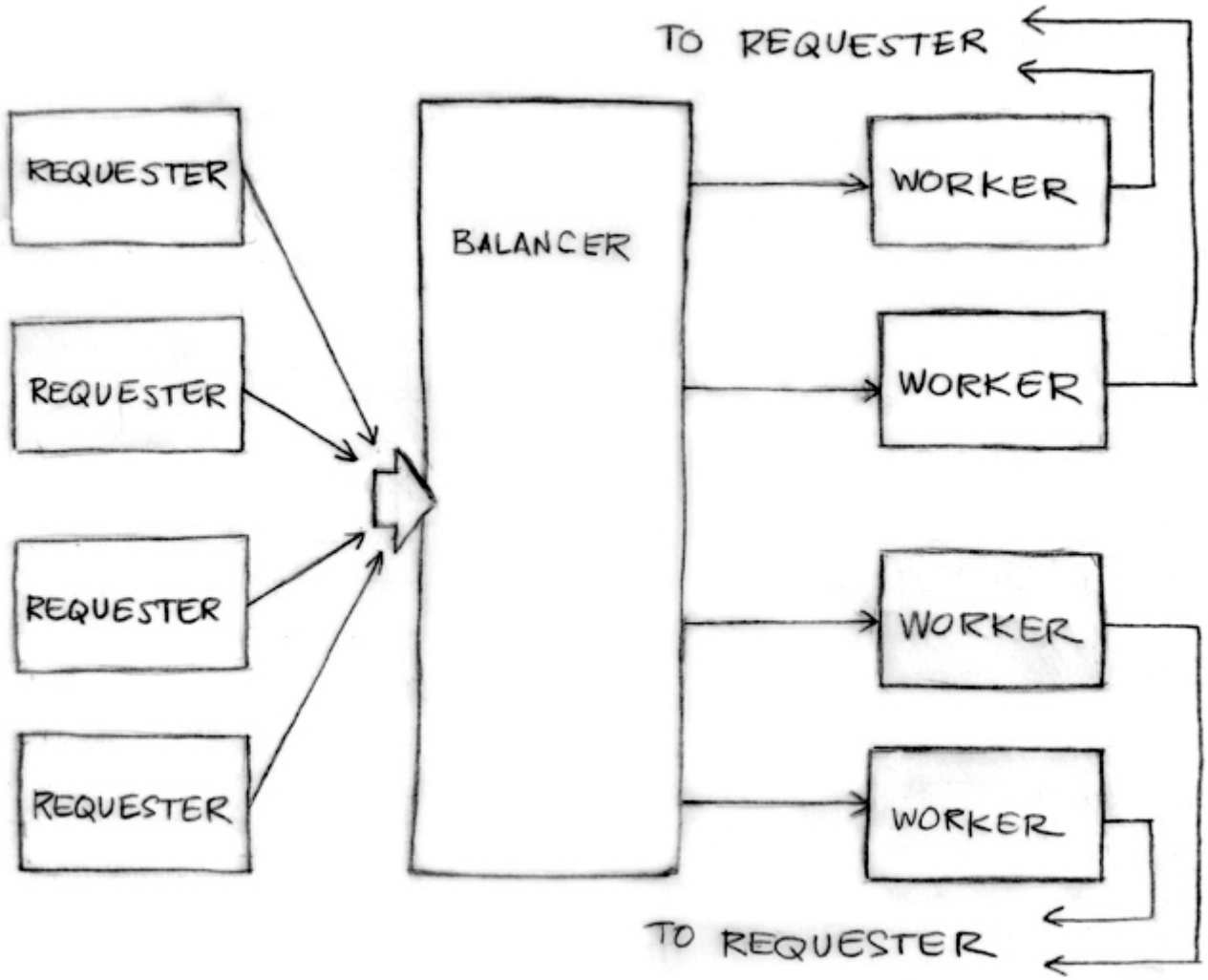
No explicit synchronization needed.

The structure of the program is implicitly synchronized.

That was too easy

Let's do a more realistic load balancer.

Load balancer



Request definition

The requester sends Requests to the balancer

```
type Request struct {
    fn func() int  // The operation to perform.
    c  chan int    // The channel to return the result.
}
```

Note the return channel inside the request.
Channels are first-class values.

Requester function

An artificial but illustrative simulation of a requester, a load generator.

```
func requester(work chan<- Request) {
    c := make(chan int)
    for {
        // Kill some time (fake load).
        Sleep(rand.Int63n(nWorker * 2 * Second))
        work <- Request{workFn, c} // send request
        result := <-c              // wait for answer
        furtherProcess(result)
    }
}
```

Worker definition

A channel of requests, plus some load tracking data.

```
type Worker struct {
    requests chan Request // work to do (buffered channel)
    pending  int          // count of pending tasks
    index     int         // index in the heap
}
```

48

Worker

Balancer sends request to most lightly loaded worker

```
func (w *Worker) work(done chan *Worker) {
    for {
        req := <-w.requests // get Request from balancer
        req.c <- req.fn()   // call fn and send result
        done <- w           // we've finished this request
    }
}
```

The channel of requests (`w.requests`) delivers requests to each worker. The balancer tracks the number of pending requests as a measure of load.
Each response goes directly to its requester.

Could run the loop body as a goroutine for parallelism.

Balancer definition

The load balancer needs a pool of workers and a single channel to which requesters can report task completion.

```
type Pool []*Worker

type Balancer struct {
    pool Pool
    done chan *Worker
}
```

50

Balancer function

Easy!

```
func (b *Balancer) balance(work chan Request) {
    for {
        select {
        case req := <-work: // received a Request...
            b.dispatch(req) // ...so send it to a Worker
        case w := <-b.done: // a worker has finished ...
            b.completed(w)  // ...so update its info
        }
    }
}
```

Just need to implement dispatch and completed.

A heap of channels

Make Pool an implementation of the Heap interface by providing a few methods such as:

```
func (p Pool) Less(i, j int) bool {
    return p[i].pending < p[j].pending
}
```

Now we balance by making the `Pool` a heap tracked by load.

Dispatch

All the pieces are in place.

```
// Send Request to worker
func (b *Balancer) dispatch(req Request) {
    // Grab the least loaded worker...
    w := heap.Pop(&b.pool).(*Worker)
    // ...send it the task.
    w.requests <- req
    // One more in its work queue.
    w.pending++
    // Put it into its place on the heap.
    heap.Push(&b.pool, w)
}
```

Completed

```
// Job is complete; update heap
func (b *Balancer) completed(w *Worker) {
    // One fewer in the queue.
    w.pending--
    // Remove it from heap.
    heap.Remove(&b.pool, w.index)
    // Put it into its place on the heap.
    heap.Push(&b.pool, w)
}
```

Lesson

A complex problem can be broken down into easy-to-understand components.

The pieces can be composed concurrently.

The result is easy to understand, efficient, scalable, and correct.

Maybe even parallel.

One more example

We have a replicated database and want to minimize latency by asking them all and returning the first response to arrive.

Query a replicated database

```
func Query(conns []Conn, query string) Result {
    ch := make(chan Result, len(conns))  // buffered
    for _, conn := range conns {
        go func(c Conn) {
            ch <- c.DoQuery(query):
        }(conn)
    }
    return <-ch
}
```

Concurrent tools and garbage collection make this an easy solution to a subtle problem.

(Teardown of late finishers is left as an exercise.) 57

Conclusion

Concurrency is powerful.

Concurrency is not parallelism.

Concurrency enables parallelism.

Concurrency makes parallelism (and scaling and everything else) easy. 58

For more information

Go: golang.org

Some history: swtch.com/~rsc/thread/

A previous talk (video): tinyurl.com/newsqueak1

Parallelism is not concurrency (Harper): tinyurl.com/pincharper

A concurrent window system (Pike): tinyurl.com/pikecws

Concurrent power series (McIlroy): tinyurl.com/powser

And finally, parallel but not concurrent:
research.google.com/archive/sawzall.html

Thank you

Rob Pike
r@golang.org (mailto:r@golang.org)