Message Passing Concurrency

An alternative to shared memory

Hugues Evrard, Google

whoami

Hugues (“Hugh”) Evrard

Concurrency, Formal methods, GPU

Grenoble INP Ensimag

Inria

Imperial College London

GraphicsFuzz

Google

Opinions are my own and not the views of my employer.

Agenda

- Shared memory vs. message passing
- Taxonomy of message passing semantics
- Examples: bank account, barrier
- Concurrency: a very brief history
- Synchronous channels (CSP, Golang)
- Actor model (Erlang)
- Hardware

Definition of *process* for this talk

Process: *an instance executing a program*

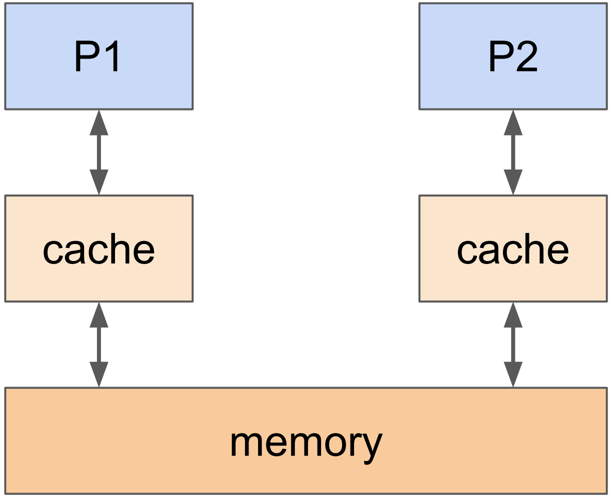
In practice: “a program counter and a stack”

- OS process, thread, programming language runtime routine, etc...

What is message passing?

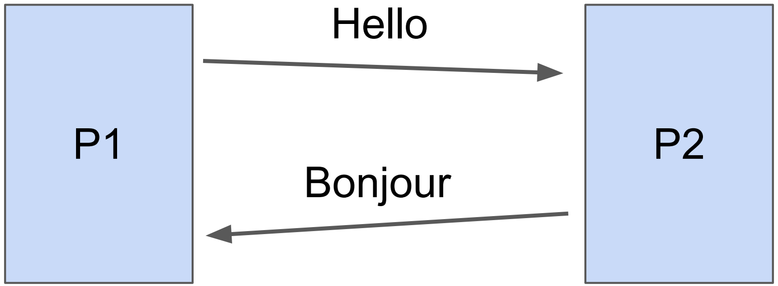
Inter-process communication & synchronization

Shared memory



primitives: **read / write**

Message Passing

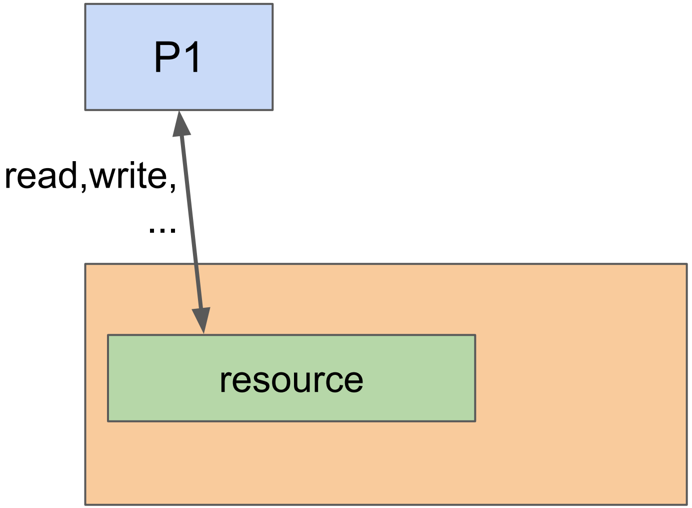


primitives: **send / receive**

Why use message passing?

Inter-process communication & synchronization

Shared memory



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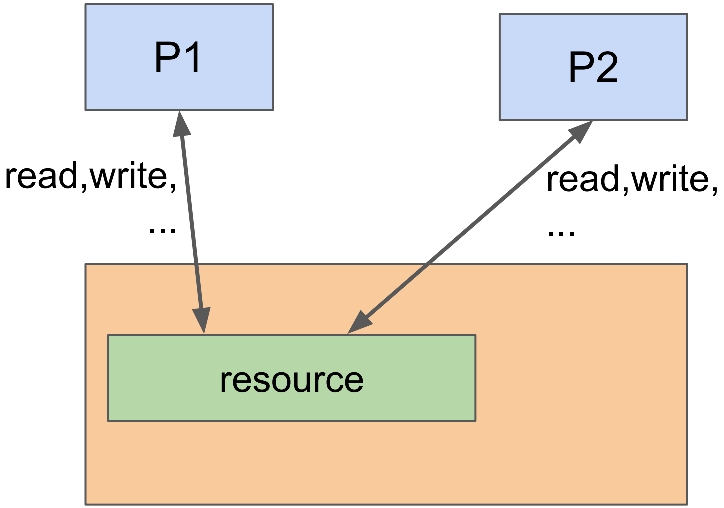

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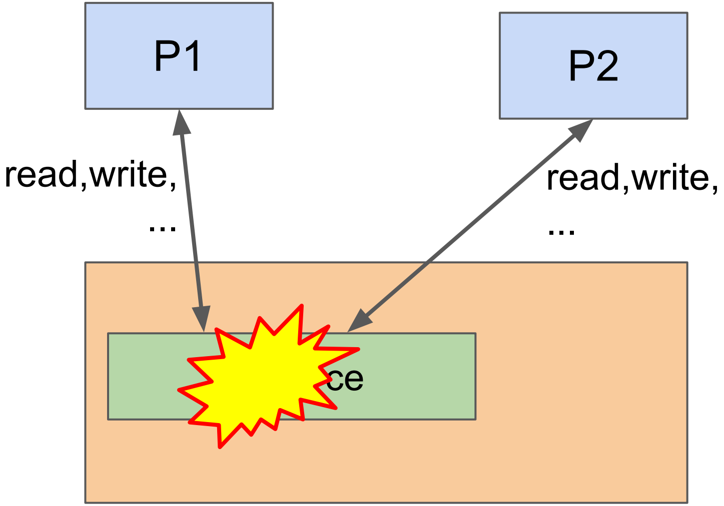

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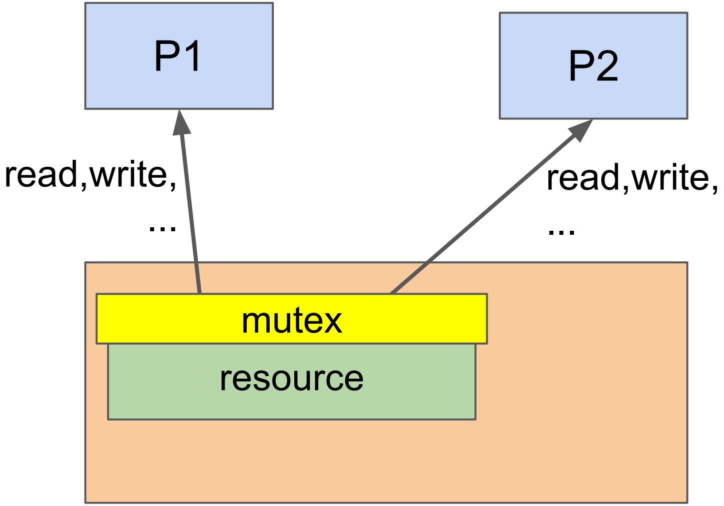

mutex mis-management:
deadlocks / data corruption

Inter-process communication & synchronization

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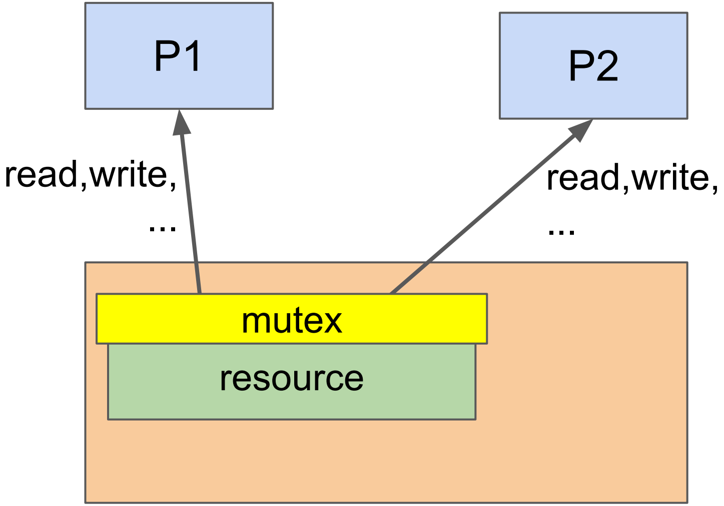

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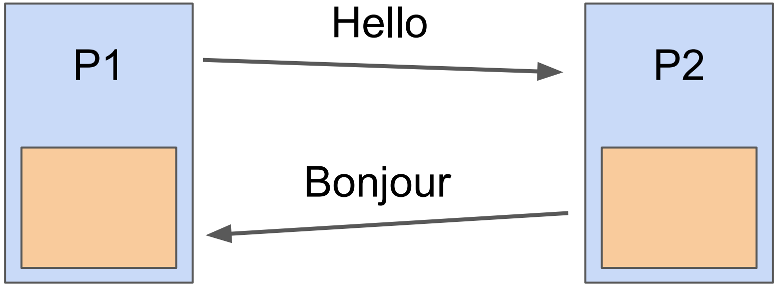
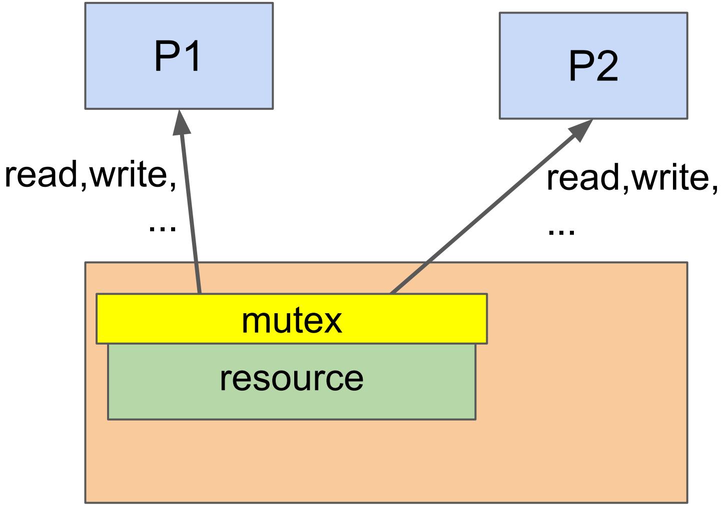


- Primitives: **send / receive**
- Memory is **isolated, per-process**

Inter-process communication & synchronization

Shared memory



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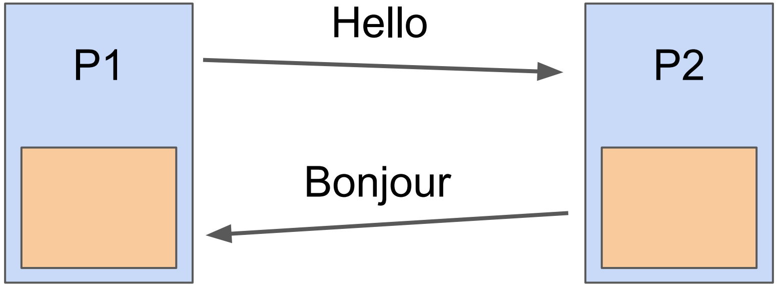

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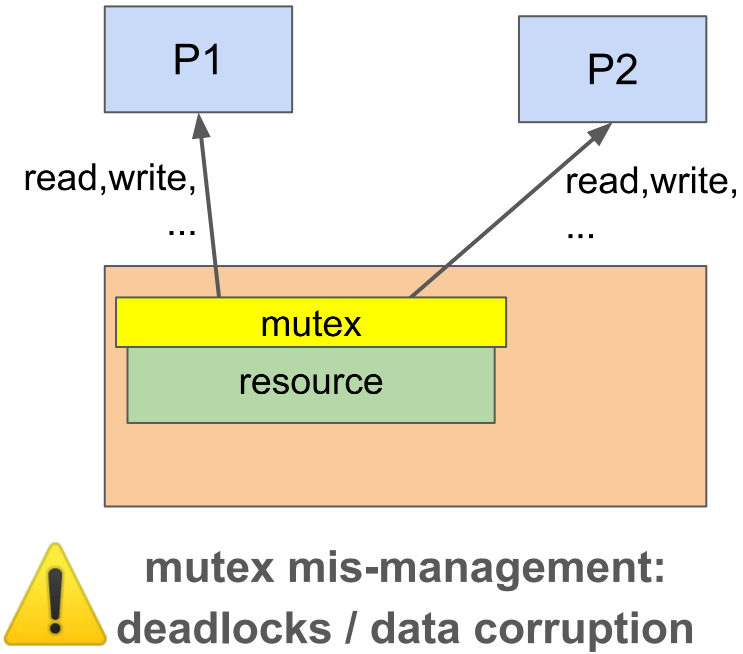
Inter-process communication & synchronization

Shared memory



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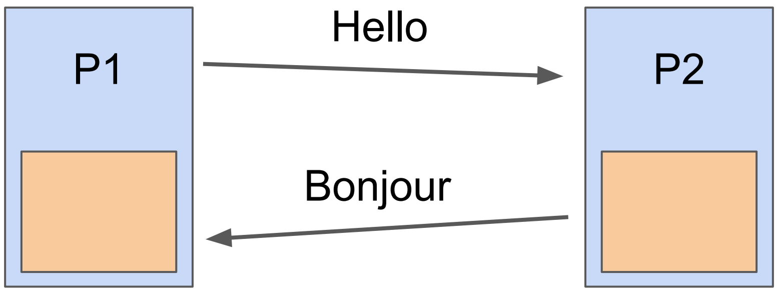


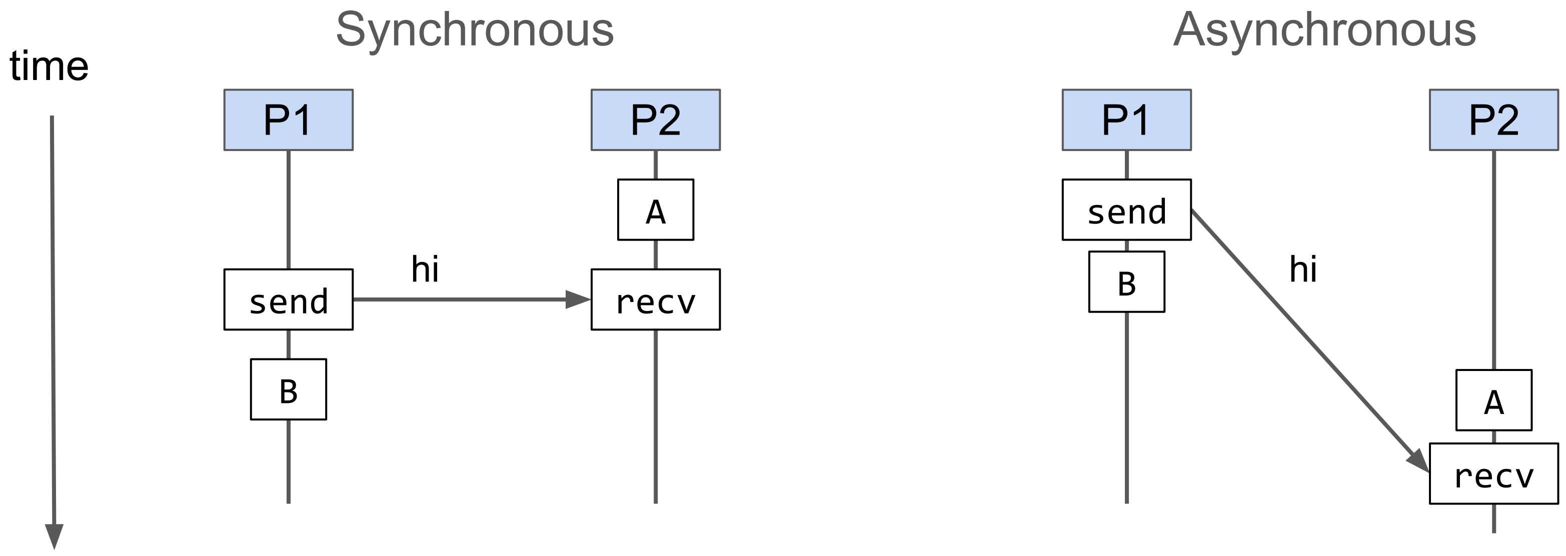
- Primitives: **send / receive**
- Memory is **isolated, per-process**
- Only possible interaction is MP
- **Cannot tamper a process without itself knowing it**

Message passing semantics taxonomy

Semantics: synchronous / asynchronous

```
P1 {
  send(P2, “hi”);
  B();
}
```

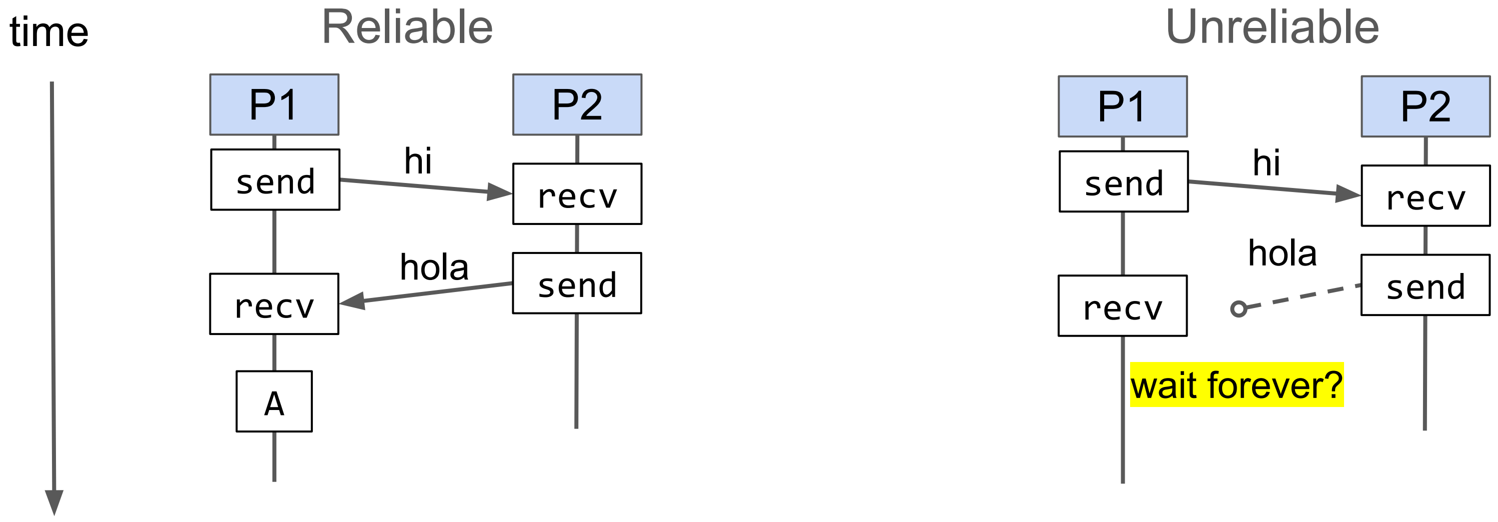
```
P2 {
  A();
  recv();
}
```



Semantics: asynchronous: reliable / unreliable

```
P1 {
  send(P2, “hi”);
  recv();
  A();
}
```

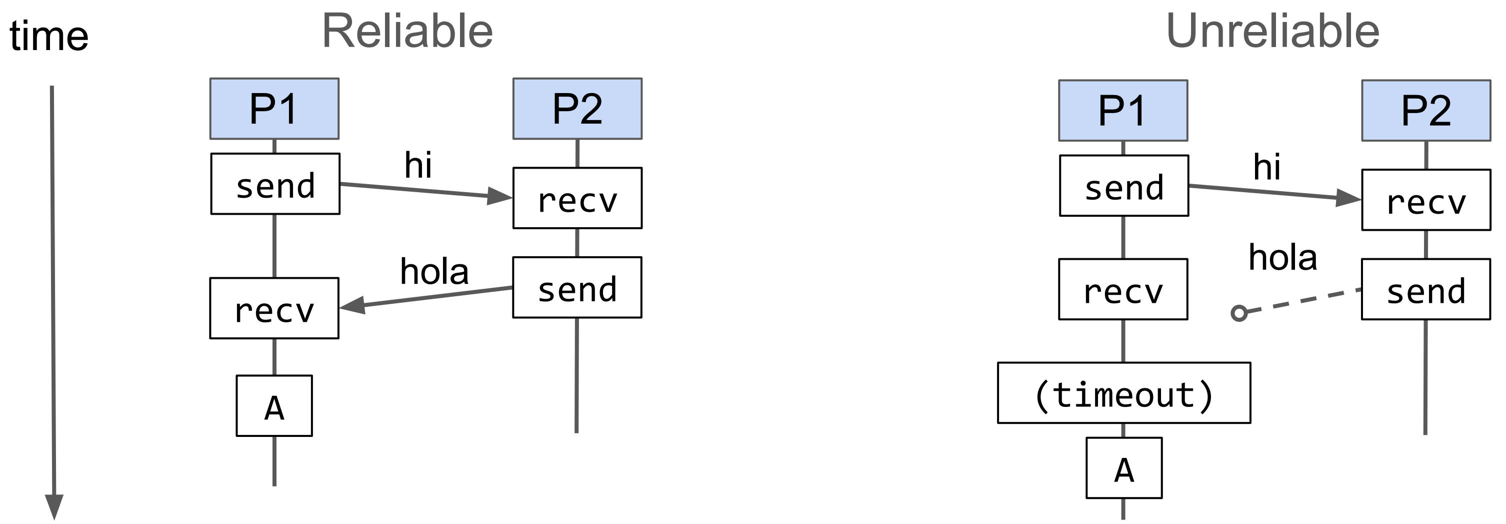
```
P2 {
  recv();
  send(P1, “hola”);
}
```



Semantics: asynchronous: reliable / unreliable

```
P1 {
  send(P2, “hi”);
  recv(timeout=1s);
  A();
}
```

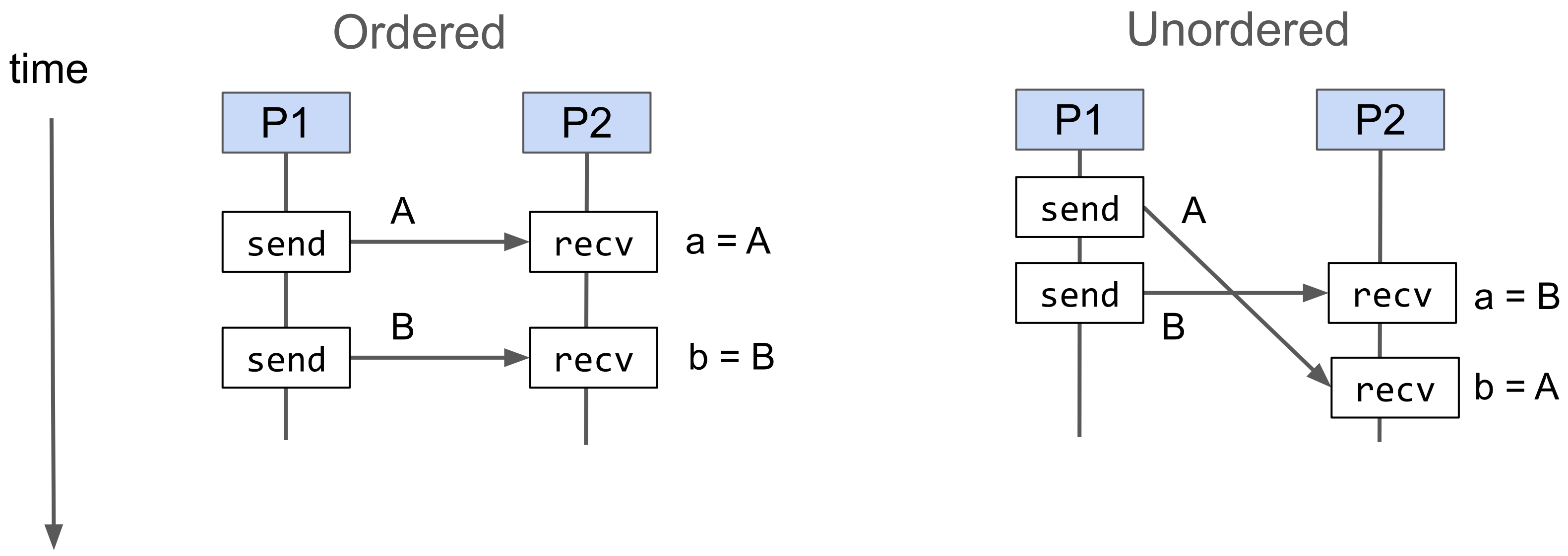
```
P2 {
  recv(timeout=1s);
  send(P1, “hola”);
}
```



Semantics: asynchronous: ordered / unordered

```
P1 {
  send(P2, "A");
  send(P2, "B");
}
```

```
P2 {
  a = recv();
  b = recv();
}
```

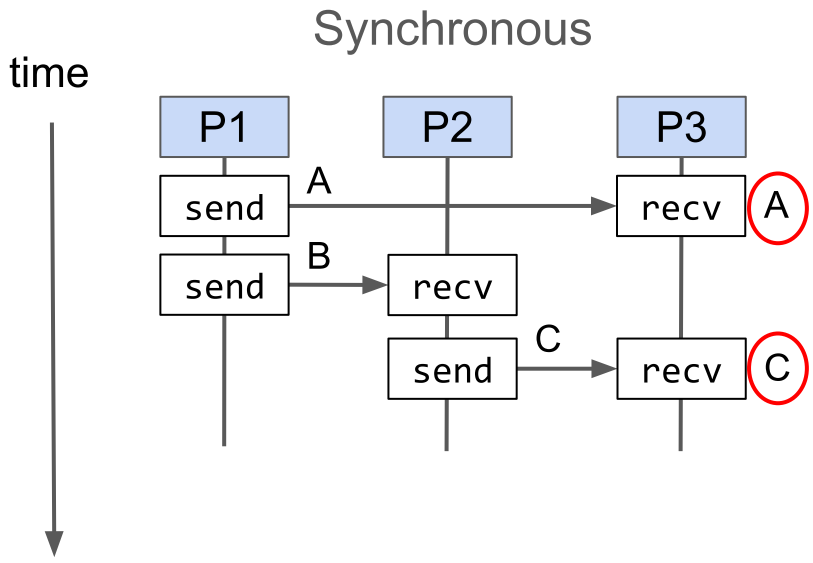


Message order with more than 2 processes

```
P1 {
  send(P3, “A”);
  send(P2, “B”);
}
```

```
P2 {
  recv();
  send(P3, “C”);
}
```

```
P3 {
  recv();
  recv();
}
```



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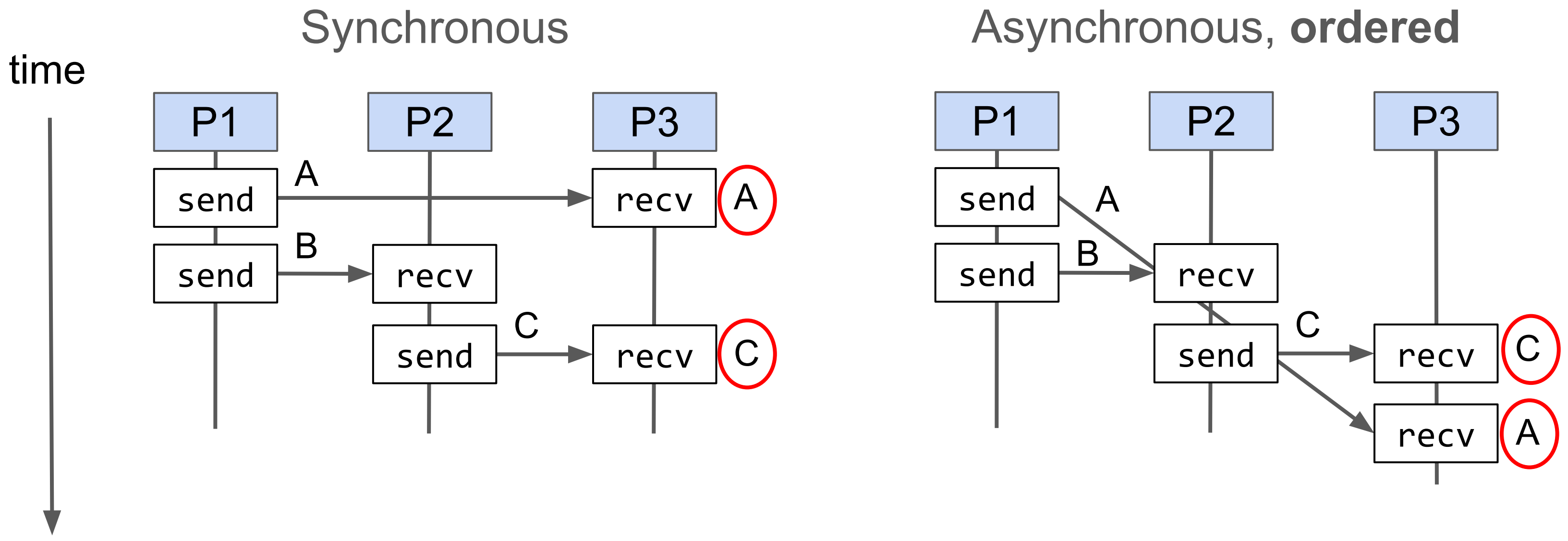

What to you send to?

So far, examples use a **process identifier**

```
P1 {
  send(P2, “foo”);
}
```

An alternative is to use **channels**

- named object to which you can send / receive
- channels can be **first-class citizens** (you can assign them to variables and pass them around)

```
P1 (ch: channel) {
  send(ch, “bar”);
  ch2 = recv(ch);
  send(ch2, “baz”);
}
```

What does recv() means?

- **Causality:** some process did a send() before
- If synchronous:
  - the sender has been blocking on send()
  - the sender is now aware of the reception

Can you selectively receive?

- General recv(): receive **any** message, from **any** process

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- Can you selectively receive:
  - From only a specific process / channel?

```
ch1, ch2, ch3

select {
case recv(ch1): …
case recv(ch2): …
}
recv(ch3);
```

Can you selectively receive?

- General recv(): receive **any** message, from **any** process
- Can you selectively receive:
  - From only a specific process / channel?
  - Only receive certain values of messages? ("*guarded commands*")

```
ch1, ch2, ch3

select {
case recv(ch1): …
case recv(ch2): …
}
recv(ch3);
```

```
ch1, ch2, ch3

select {
case i := recv(ch1) where i > 5: // send(ch1, 2) would block
  …
case recv(ch2):
  …
}
recv(ch3);
```

Message passing semantics: recap

Message passing can be:

- Synchronous
  - Sender/receiver both blocks waiting for the other one
- Asynchronous
  - reliable or not
  - ordered or not
- Send to process identifiers or first-class citizen channels
- Ability to selectively receive, or not

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- Also
  - unidirectional / bidirectional, whole/partial message, …
  - can express asynchronous on top of synchronous (easy) and vice-versa (harder)

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Network protocols:
- UDP: asynchronous, unordered, unreliable
- TCP: asynchronous, ordered, reliable (🤞)

Examples

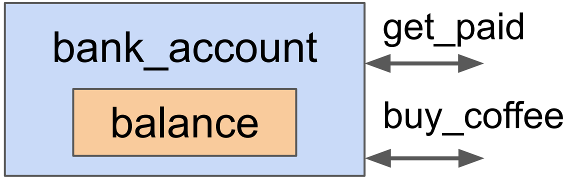
Example: bank account

```
bank_account (get_paid, buy_coffee: channel int) {
  balance = 0
  for {
    select {

    case i = recv(get_paid):
      balance += i

    case i = recv(buy_coffee):
      balance -= i

    }
  }
}
```



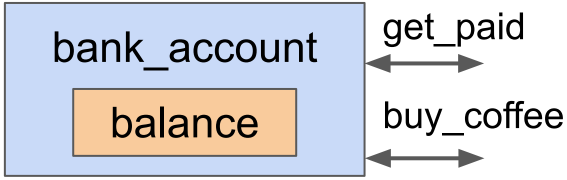
Example: bank account with guarded reception

```
bank_account (get_paid, buy_coffee: channel int) {
  balance = 0
  for {
    select {

    case i = recv(get_paid):
      balance += i

    case i = recv(buy_coffee) where i <= balance:
      balance -= i

    }
  }
}
```

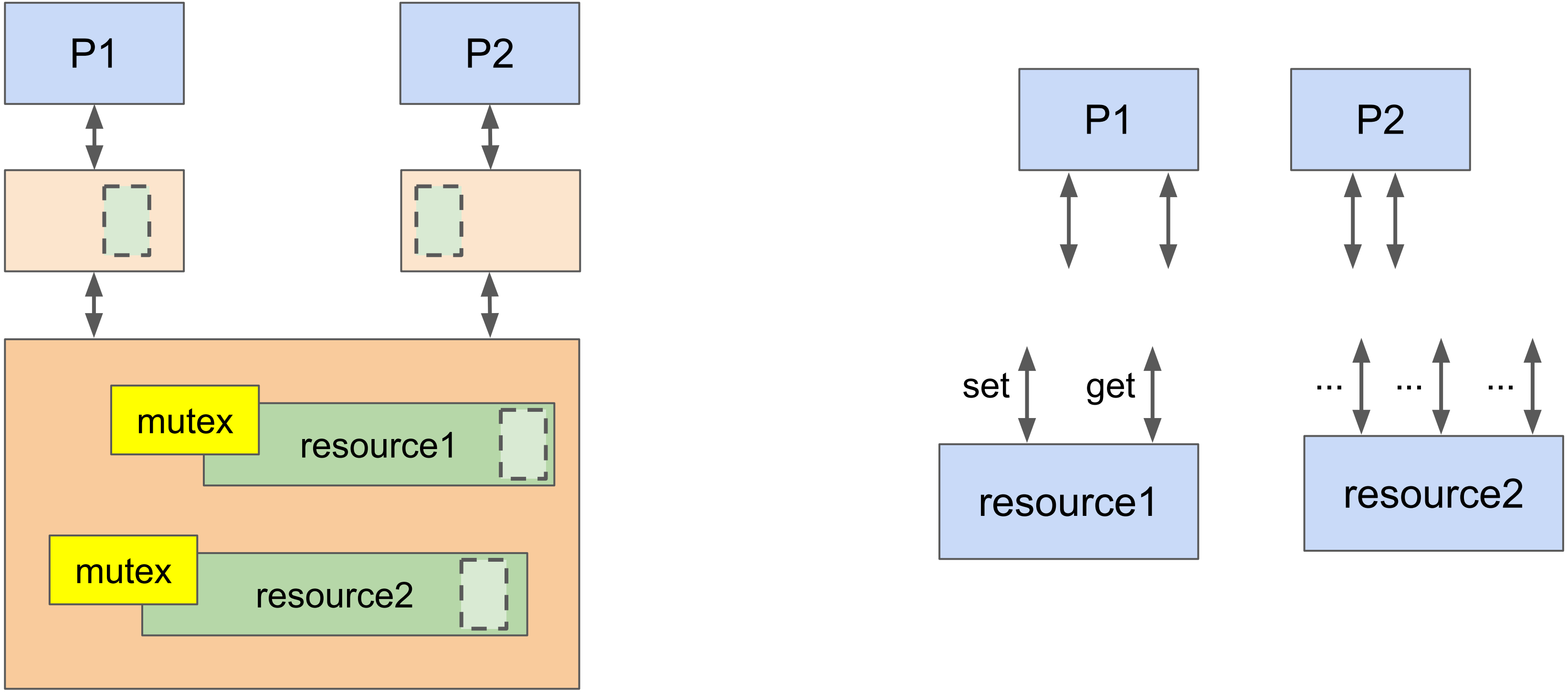


Avoids negative balance

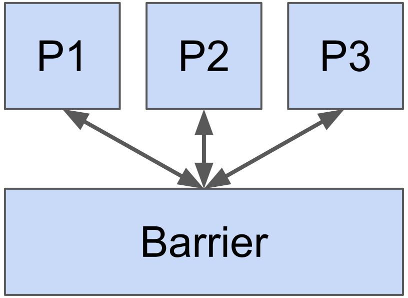
But: if synchronous, sender will block!

It may be OK, as it will block until get_paid adds enough money to unblock.

Shared resources become processes



Example: barrier




```
P (ch: channel) {
  ...
  // barrier synchronization
  send(ch)
  recv(ch)
  ...
}
```

```
Barrier (n: int, ch: channel) {
  for (i = 0; i < n; i++) {
    recv(ch)
  }
  for (i = 0; i < n; i++) {
    send(ch)
  }
}
```

Step back:
Why concurrent programming?

Why concurrent programming? A very brief history

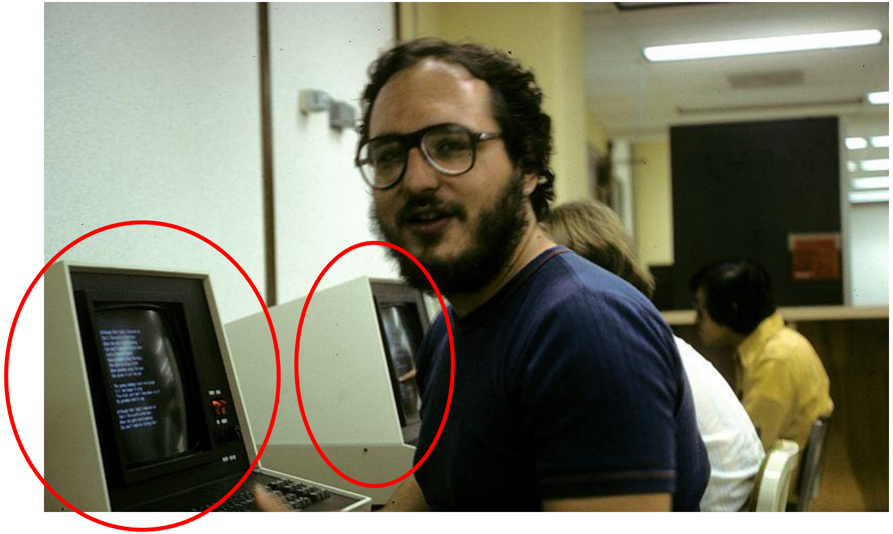
- 40s: single processor, “batch” execution of single program

IBM 1401, http://ed-thelen.org/comp-hist/BRL61-0526.jpg

Why concurrent programming? A very brief history

- 40s: single processor, “batch” execution of single program
- 60s: ***time sharing*** on a single processor

Terminals to the same server



Dave Winer, https://en.wikipedia.org/wiki/File:Unix_Timesharing_UW-Madison_1978.jpeg

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- 65: Dijkstra’s *Solution of a problem in concurrent programming control*

Why concurrent programming? A very brief history

- 40s: single processor, “batch” execution of single program
- 60s: ***time sharing*** on a single processor
- 65: Dijkstra’s *Solution of a problem in concurrent programming control*
- 70s: single processors talk over networks
- 78: Hoare’s *Communicating Sequential Processes*
- 87: Erlang
- 2000s: multi-core processors with shared memory

Decades before shared-memory multi-core processors, concurrency mattered as **a way to design programs**.

Synchronous channels

Programming languages with synchronous channels

- Incomplete timeline:
  - ...
  - 78, Tony Hoare: *CSP*
  - 83, David May: *occam*
  - (83, Jean Ichbiah: *Ada)*
  - 88, Rob Pike: *Newsqueak*
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"Bell Labs" family

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- As a library:
  - mid-90s: Java CSP
  - 2013: Clojure core.async
  - …

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***The roots of this style** go back at least as far as Hoare's Communicating Sequential Processes (**CSP**), followed by realizations and extensions in e.g. occam, Java CSP and the Go programming language.*

*[...] the notion of a channel becomes **first class** [...]*

*A key characteristic of channels is that they are **blocking**. [...]*

https://clojure.org/news/2013/06/28/clojure-clore-async-channels

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"Bell Labs" family

- Golang channels: bidirectional, typed, optionally buffered (i.e. asynchronous), selectively receive (no guards).

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- Golang channels: bidirectional, typed, optionally buffered (i.e. asynchronous), selectively receive (no guards).

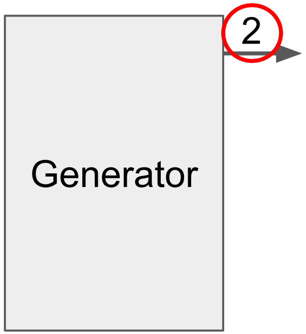
```
// This is Golang code

func counter(ch chan int) {
  i := 1;
  for {
    i++;
    ch <- i  // send
  }
}

func main() {
  ch := make(chan int) // create a channel
  go counter(ch);      // launch a process
  j := <-ch            // recv, j == 2
  j  = <-ch            // j == 3
  j  = <-ch            // j == 4
}
```

https://play.golang.org/p/1PE4jTg1tNa

Example: prime sieve (McIlroy)



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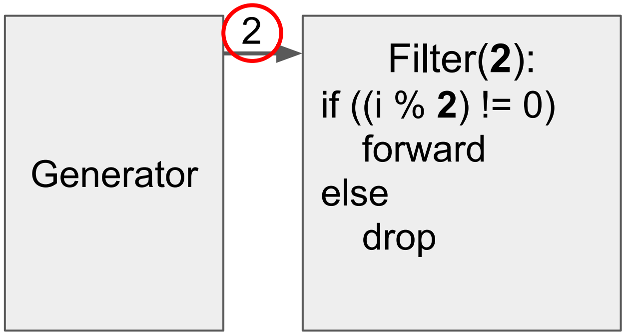

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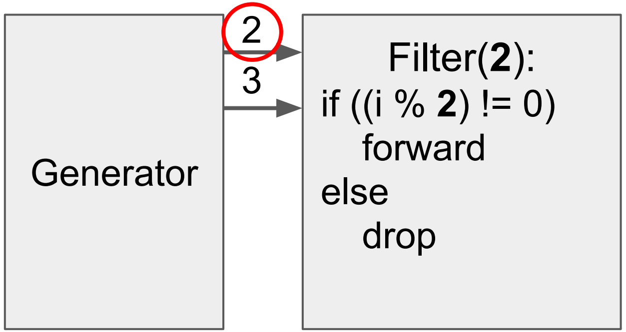

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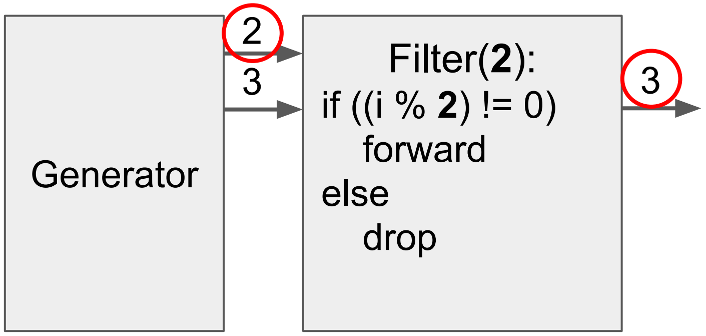

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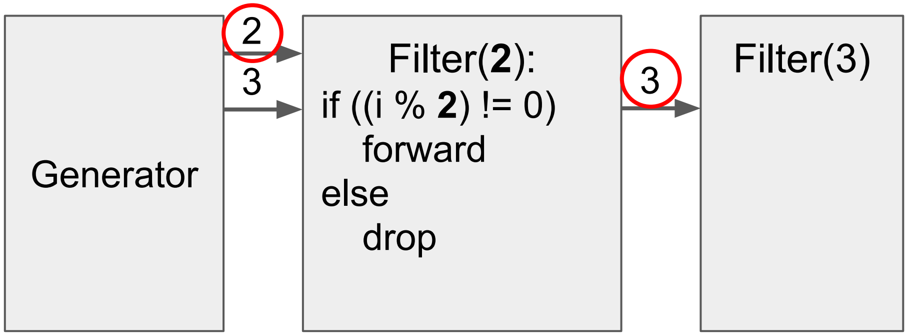

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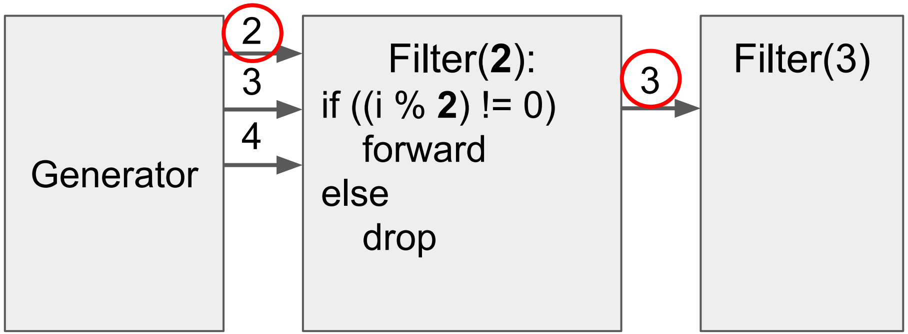

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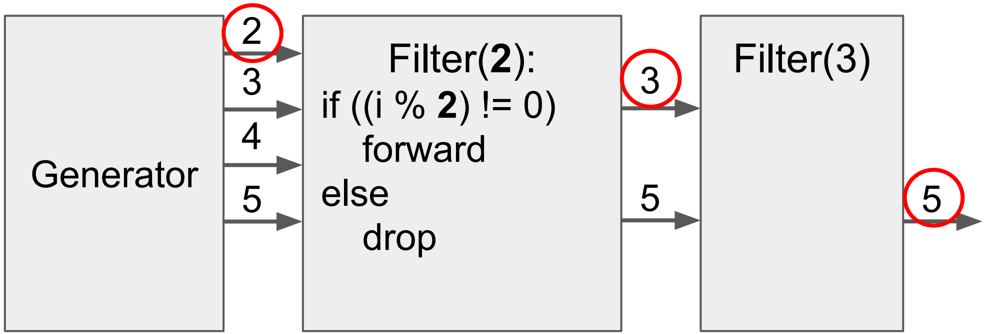

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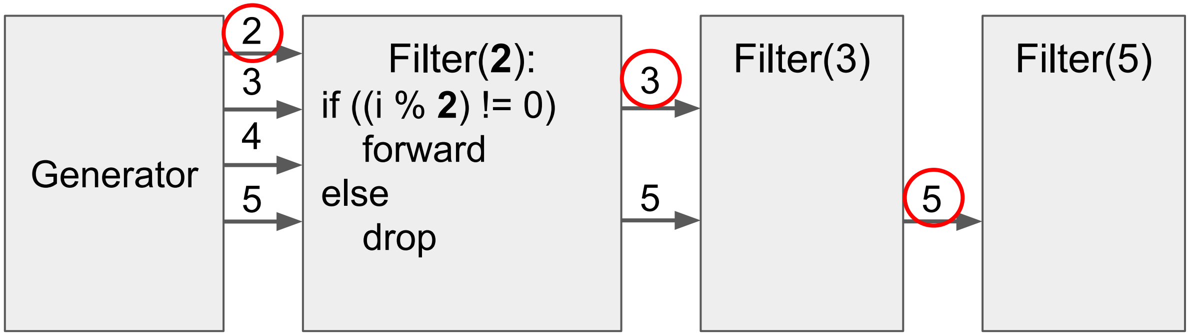

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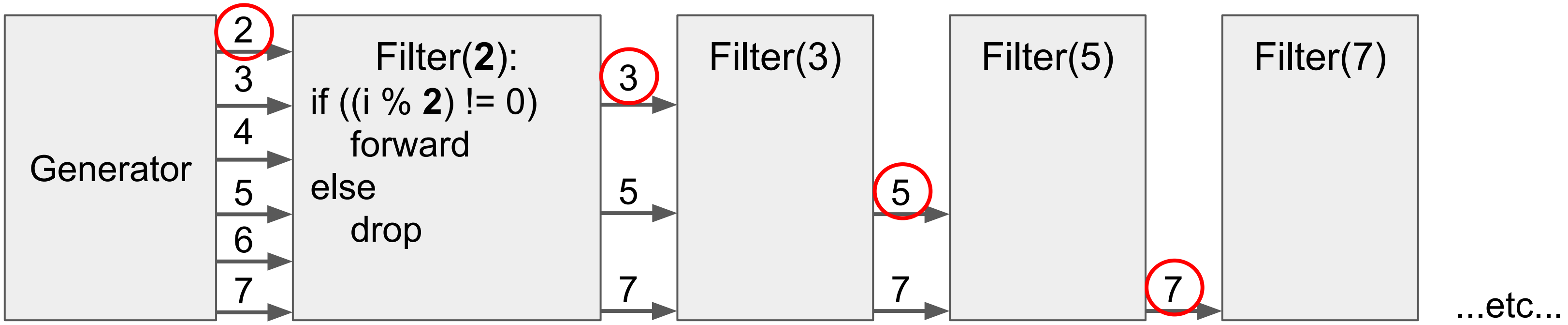

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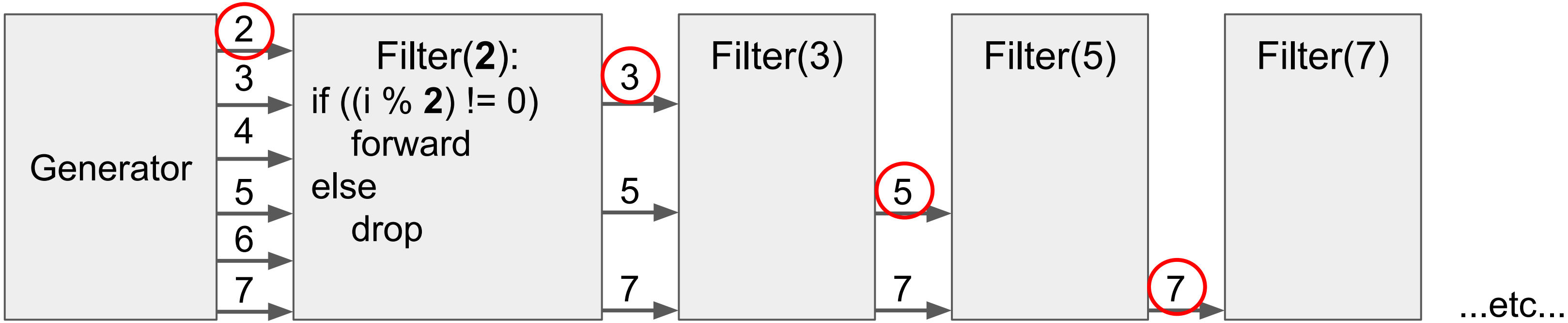


```
func filter(prime int,
            src, next chan int) {
  for {
    i := <-src
    if (i % prime) != 0 {
      next <- i
    }
  }
}
```

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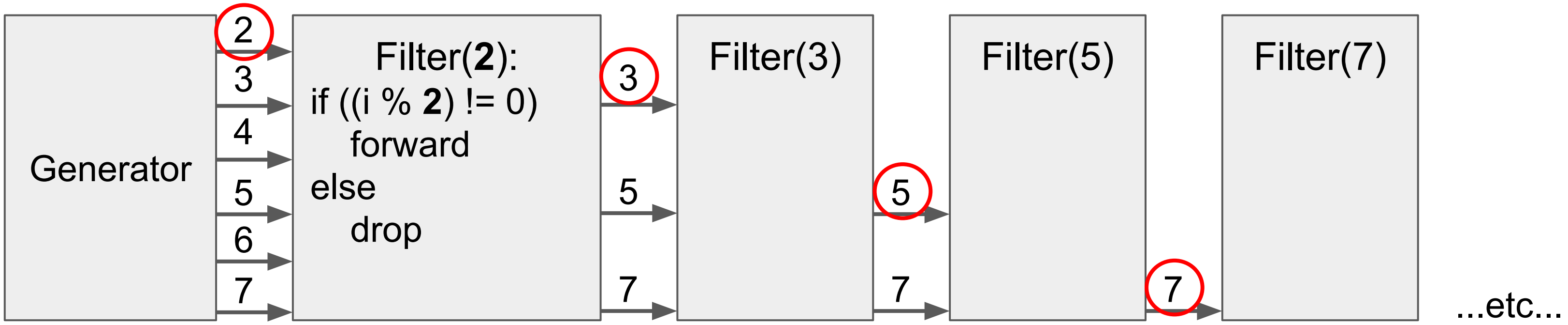


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}
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```
func sieve(result chan int) {
  ch := make(chan int)
  go counter(ch)
  for {
    i := <-ch
    result <- i
    next := make(chan int)
    go filter(i, ch, next)
    ch = next
  }
}
```

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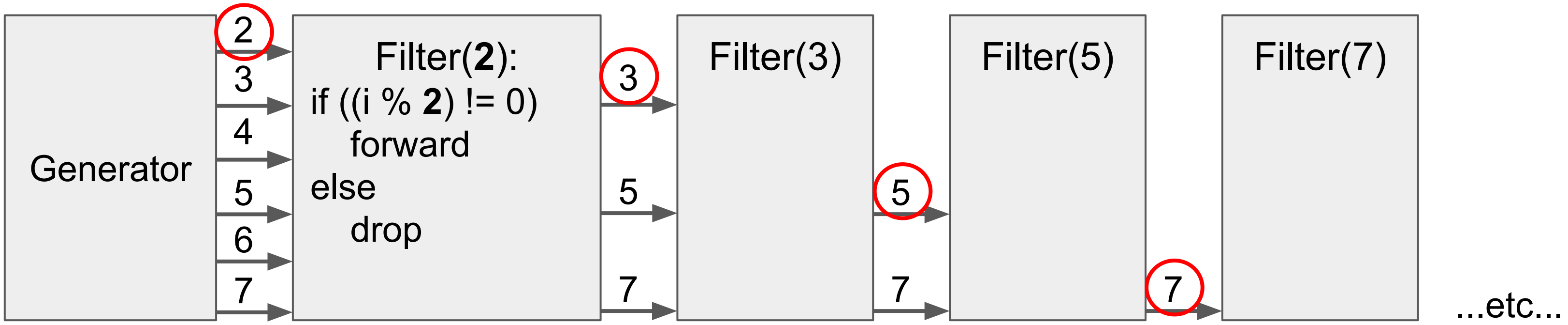


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  }
}
```

```go
func main() {
  r := make(chan int)
  go sieve(r)
  <-r // 2
  <-r // 3
  <-r // 5
  <-r // 7
  <-r // 11
  <-r // 13
}
```

https://play.golang.org/p/xDKhkm6ZDIa

Golang is not "purely" message passing

- You can have shared memory, mutexes, etc
- This is discouraged

Do not communicate by sharing memory; instead, share memory by communicating.

https://blog.golang.org/codelab-share

Asynchronous, “pure” message passing

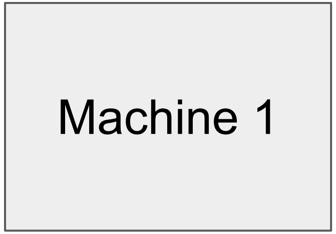
(Actor model)
Concurrency for reliability

Asynchronous, “pure” message passing

(Actor model)
Concurrency for reliability

Origin: ***reliability***

Thesis: “Making reliable distributed systems in the presence of software errors”



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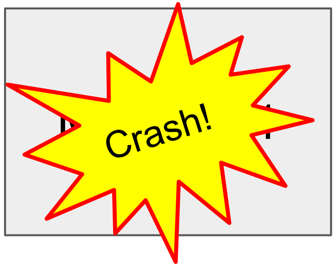

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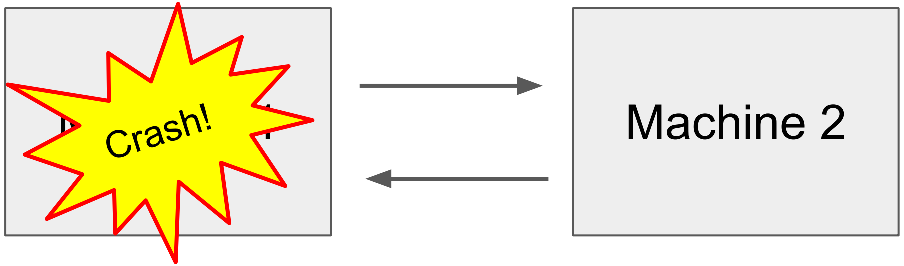

- Need at least 2 separate machines

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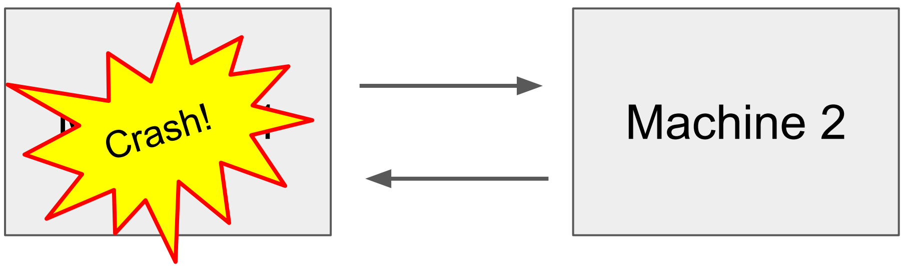

- Need at least 2 separate machines
- Do not share memory
- Send messages over a network

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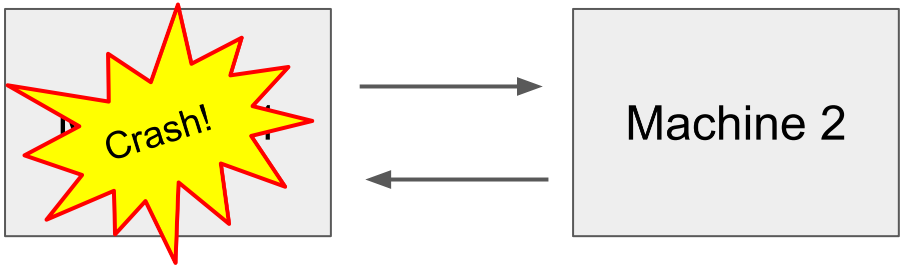

- Need at least 2 separate machines
- Do not share memory
- Send messages over a network
- Synchronous? No! If sender/receiver crashes, the other deadlocks
- *Asynchronous message passing between isolated processes*

Origin: ***reliability***

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> *The process provides a clean unit of modularity, service, fault containment and failure. Fault containment through fail-fast software modules. The process achieves fault containment by sharing no state with other processes; its only contact with other processes is via messages carried by a kernel message system.*
>
> 1985, Jim Gray: Why do computers stop and what can be done about it?

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A taste of Erlang

- Sequential part: functional programming

```
foo() -> …          // define func foo with arity 0
```

A taste of Erlang

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- MP is only possible interaction, strictly no shared memory
- MP: asynchronous, ordered, unreliable
  - *“Send and pray”*

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Pid = spawn(foo/0)  // launch a process, get its ID

Pid ! msg           // send a message to Pid
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  - Timeout

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   after timeout -> …
end
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A taste of ~~Erlang~~ Elixir

The new cool kid on top of Erlang VM!
(nicer syntax, similar concepts)

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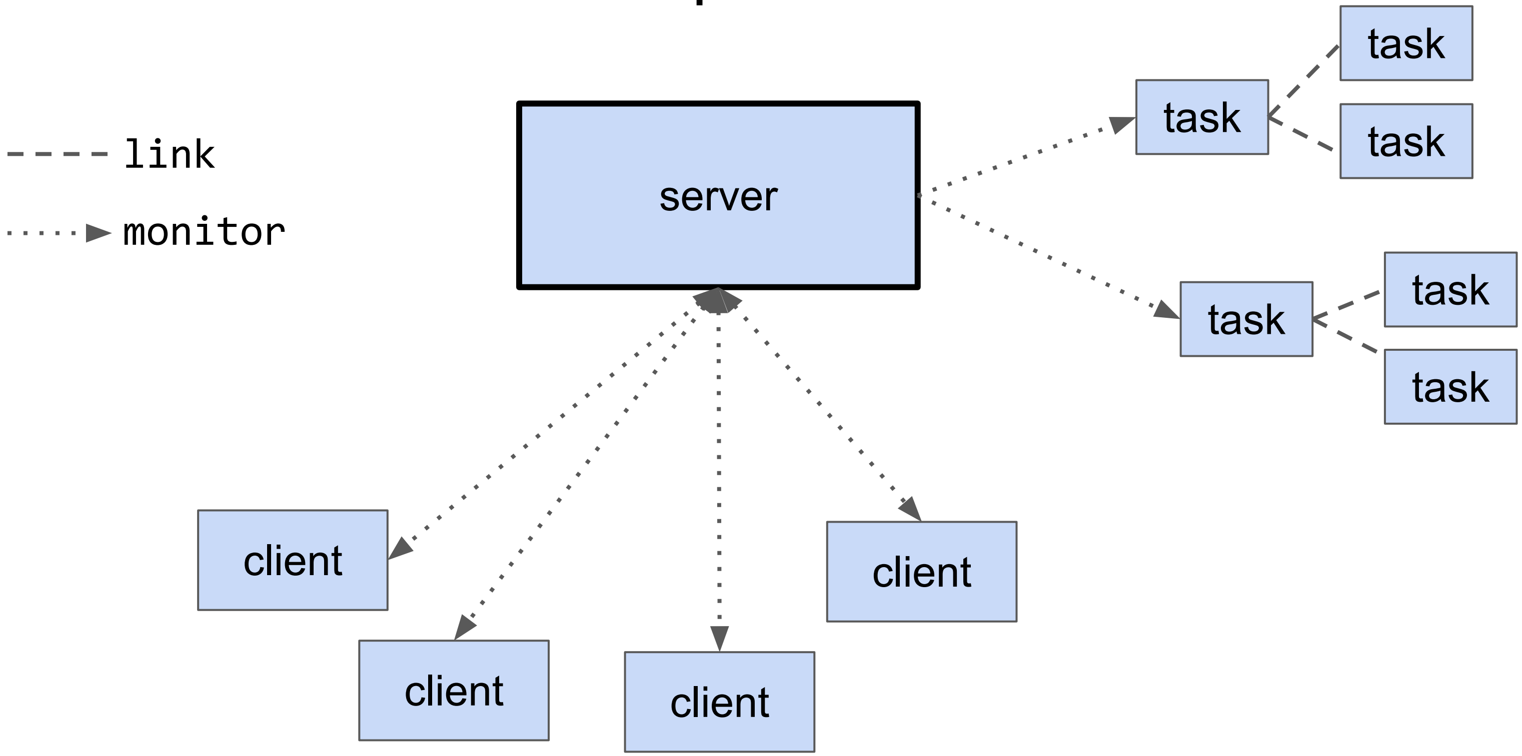
Error containment: supervision trees



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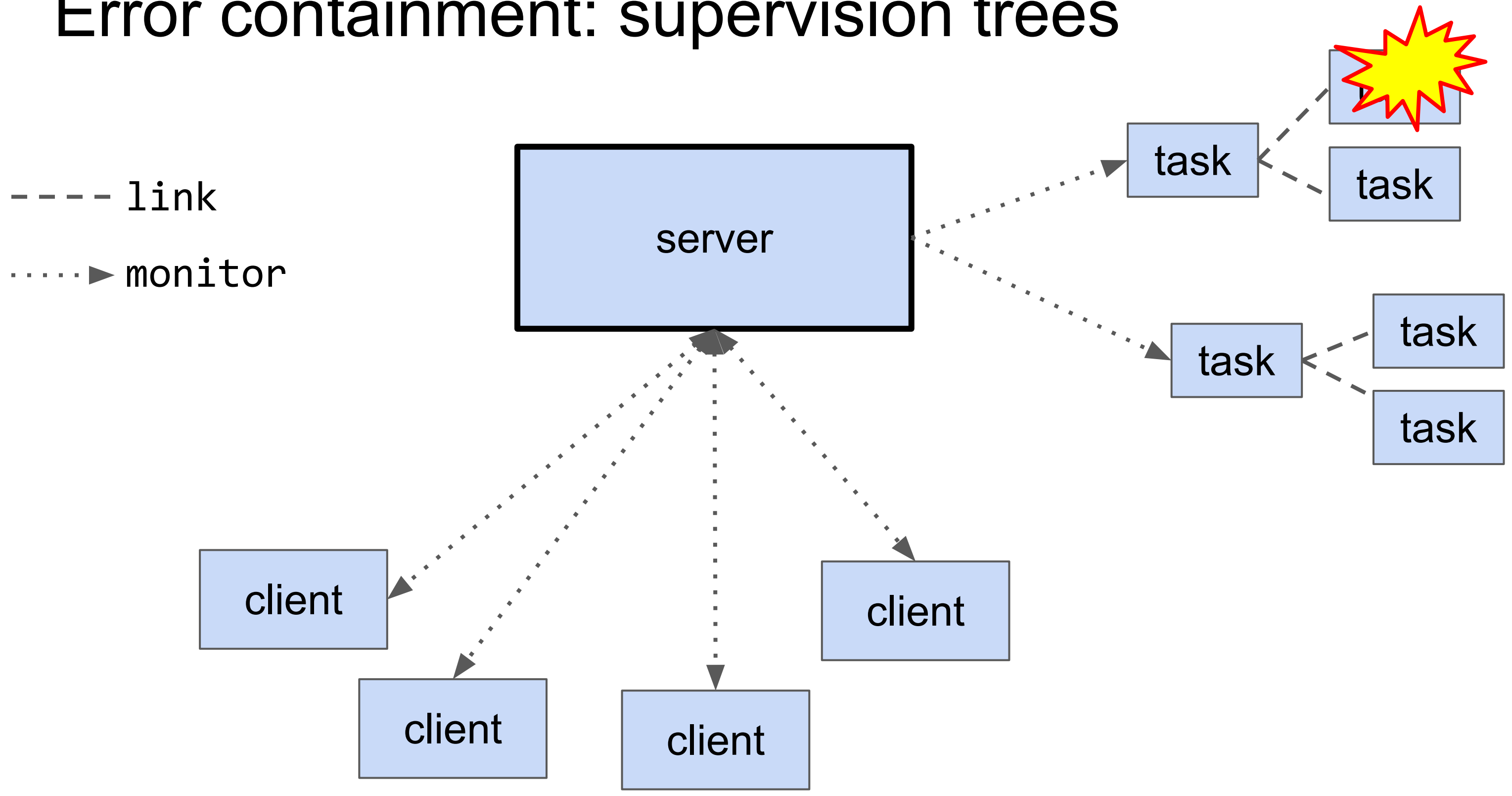
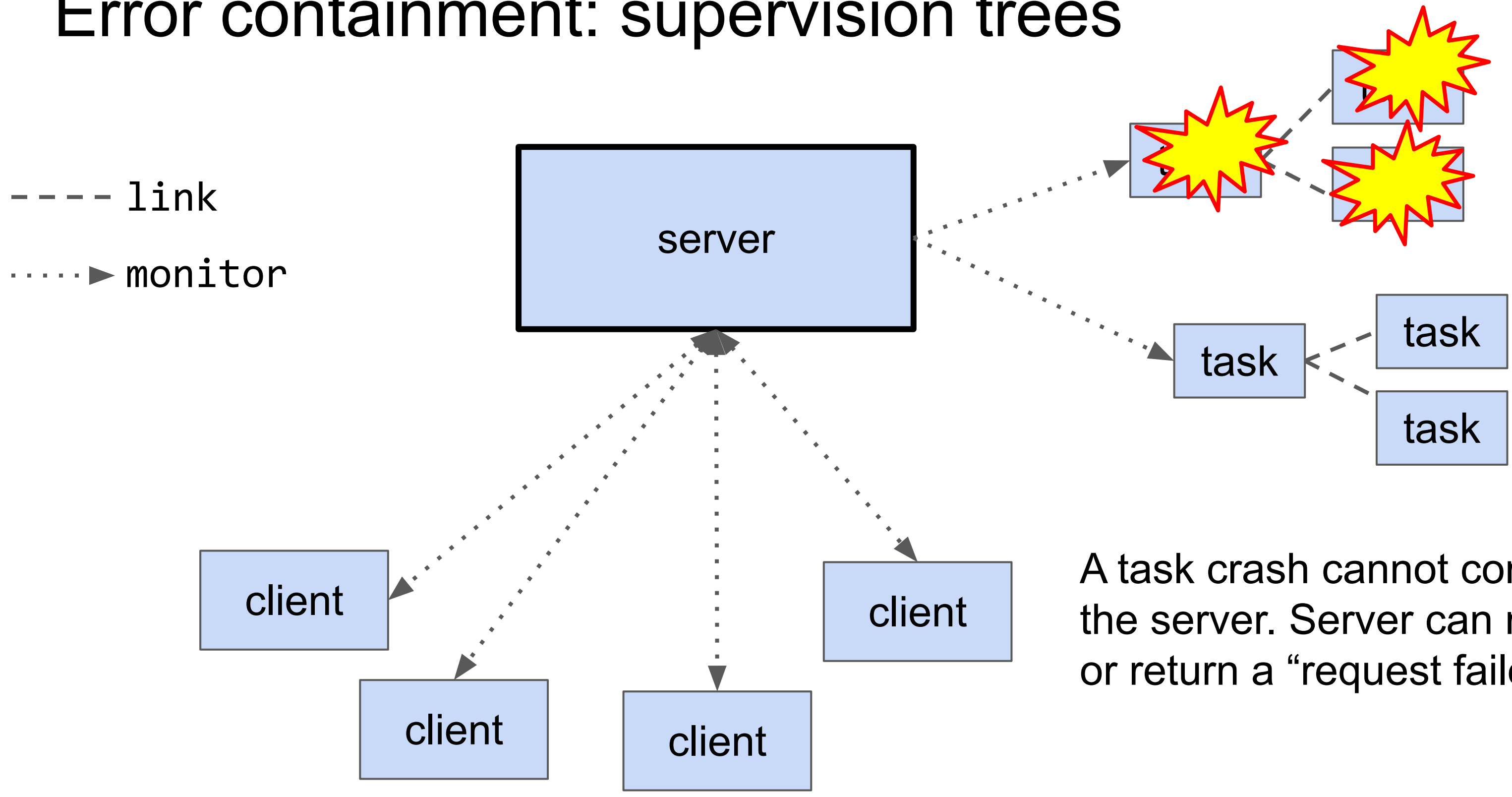


Error containment: supervision trees



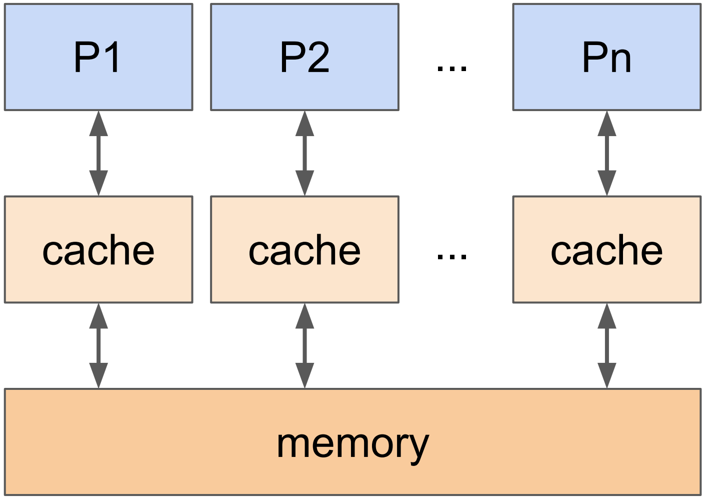
A task crash cannot corrupt the state of the server. Server can restart the task, or return a “request failed” to the client.

Is Erlang used in industry?

- Telecom companies
  - **Ericsson** (this is where it started! **Er**icsson **Lang**uage)
  - **Nortel**, **T-Mobile**, …
  - Reliability first! 99,999% uptime needed
  - Erlang VM can do hot code reload, no downtime
- **WhatsApp**, 2015: 50 engineers, 900 millions users (Wired article)
- **Heroku**
- **Discord** (elixir)
- **AliBaba**
- **EaseMob** (Chinese comm framework, reportedly 1 billion users)
- **RabbitMQ**
- ...

Hardware

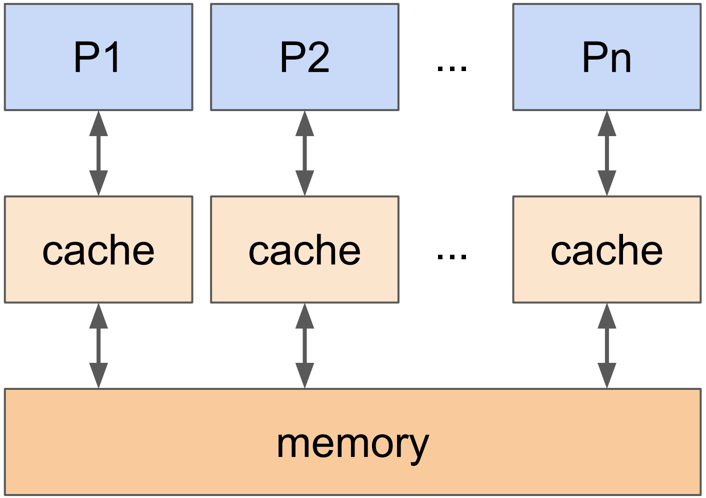
Message passing at the hardware level



Memory coherency: *hard to scale!*

Nowadays, **n < 100**

Message passing at the hardware level



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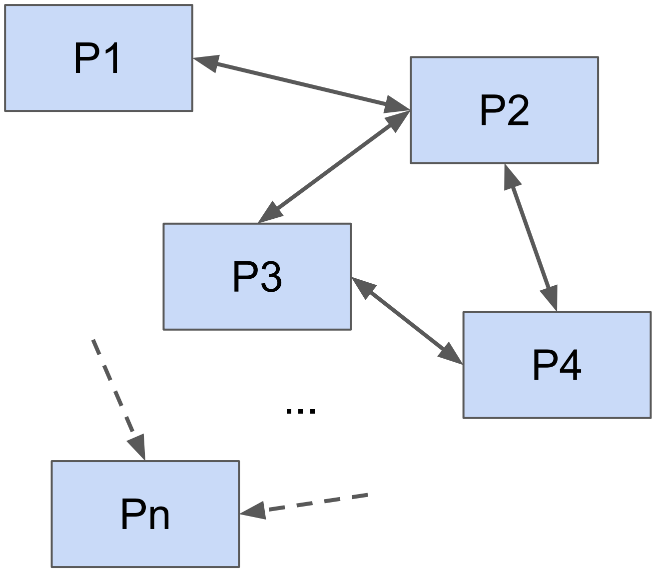
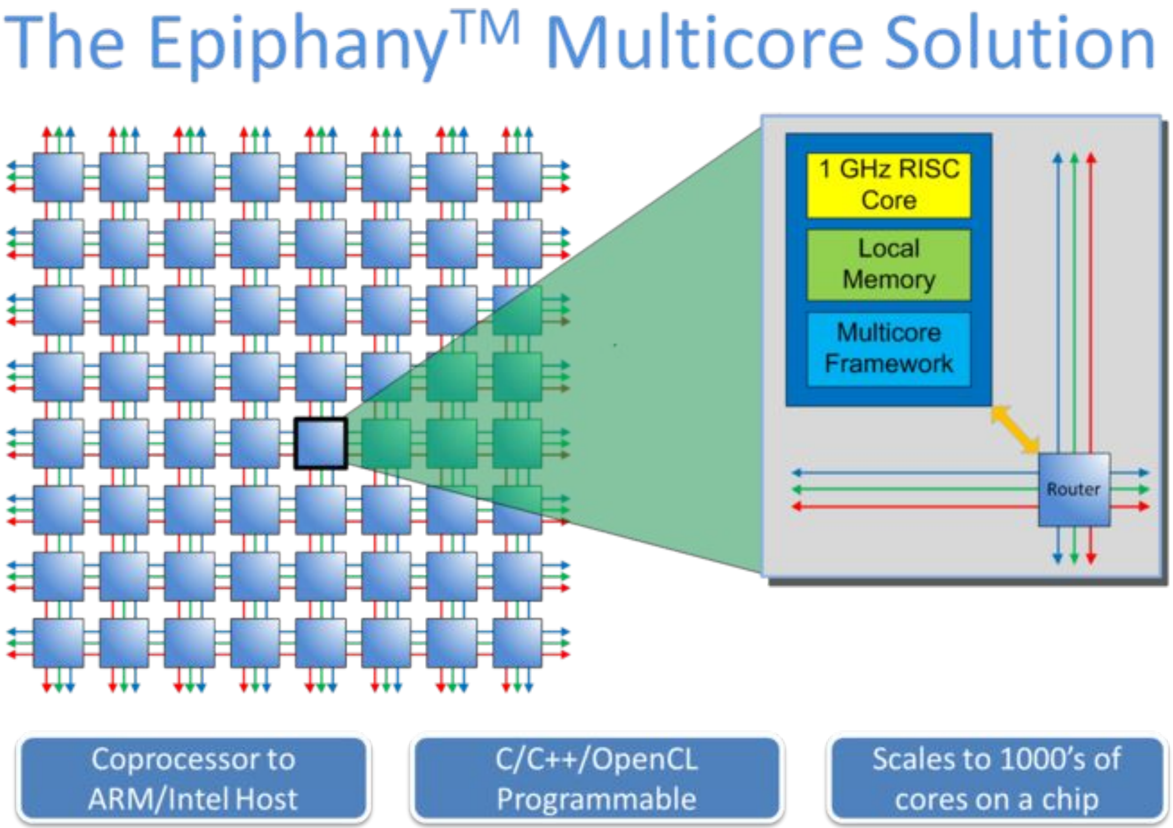


On the same chip / over a network
n > 100

Massively parallel processor array (MPPA)



https://spellfoundry.com/wp/wp-content/uploads/2013/05/Parallela.png

Hardware with non-shared memory

An non-exhaustive list:

- 80’s: Inmos Transputer (programmed in occam, ?? cores)
- 90’s, Intel: Paragon (2048 cores “in a 2D grid”)
- 2000’s, IBM & Rapport: Kilocore (1024 cores)
- 2010’s, Tilera: TileGx (72 cores)
- 2010’s Adapteva: Epiphany (up to 4096 cores in theory, Parallela board 64 cores)
- 2006-2015, UC Davis: AsAP (36, then 167 cores)
- since 2008, Kalray: MPPA (256 cores)
- since 2012, Green Arrays: GA144 (144 cores) - asynchronous, no clock signal!
- 2018, Sunway: SW26010 (260 cores) (TaihuLight supercomputer #1 in 2018)

The elephant in the room

Processes interacting by sending messages over a network… 🤔

The elephant in the room

Processes interacting by sending messages over a network…

The internet!

Distributed systems. “The cloud.”

A software **designed** using isolated process & MP can **scale**.

The elephant in the room

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Distributed systems. “The cloud.”
A software **designed** using isolated process & MP can **scale**.

High performance computing (HPC): Open MPI (*Message Passing Interface*)

Bonus:
OS-level message passing

OS: isolate processes, but let them communicate

Unix:

- Processes do not share memory (in general)
- `man 7 pipe:` *“Pipes provide a unidirectional interprocess comm channel.”*
    - semantics: asynchronous, ordered, reliable, unidirectional

```
pipe()    // create a pipe, returns 2 file descriptors to write & read

write(fd1, …)       // send
read(fd2, …)        // recv
select(<set of FDs>) // recv from one of the file descriptors (see also poll/epoll)

fork()  // create a new process
SIGCHLD // signal received by parent with child process crashes
```

Who designs software using OS-level processes?

Introducing Site Isolation in Firefox

Anny Gakhokidze and Neha Kochar | May 18, 2021

When two major vulnerabilities known as Meltdown and Spectre were disclosed by security researchers in early 2018, Firefox promptly added security mitigations to keep you safe. Going forward, however, it

Isolating each site into a separate operating system process makes it even harder for malicious sites to read another site's secret or private data.

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https://blog.mozilla.org/security/2021/05/18/introducing-site-isolation-in-firefox/

Who designs software using OS-level processes?

- Mozilla
- …
- Prof. D J Bernstein: qmail (email), djbdns (DNS)
  - Used by millions
  - **Final** versions released ~20 years ago
  - Handful of non-security holes found
  - **20+ years ongoing bug bounty to find a security hole**

Who (

- Mo
- …
- Pro
  -
  -
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  -

D. J. Bernstein Mon, May 17, 6:28 PM (3 days ago)

to me

There were already many more message-passing systems at the time. UNIX pipes---and pipelines, showing how usable the notation can be to express a common communication pattern---predate CSP and Erlang. There were several competing RPC APIs for clusters, plus RPC on top of email across the Internet. Microkernels were emphasizing message passing. Nowadays the buzzword would be "microservices".

Obviously it's good for fault tolerance to keep spinning up workers that each try to get something done, obviously it's good for performance to have these workers able to run in parallel (even if there's just one core, since there are other bottlenecks such as disks and networks), and obviously non-persistent per-worker storage tends to be much easier to reason about than storage that's temporally and spatially shared.

---Dan

Conclusion

Conclusion

- Message passing semantics
- Use MP concurrency for software *design*
- Use isolated processes for software *reliability*
- Not mainstream (yet?), but used in the industry
- Scalability of isolated processes + message passing design

- Not a silver bullet!
- Try it yourself :)

Further reading / watching

- Videos
  - **Joe Armstrong: How we program multicores** https://youtu.be/bo5WL5IQAd0
  - **Rob Pike: Concurrency/message passing Newsqueak** https://youtu.be/hB05UFqOtFA
  - (Both are good speakers, check out their other talks!)
- Russ Cox: ”Bell Labs and CSP Threads” https://swtch.com/~rsc/thread/
- Joe Armstrong’s PhD thesis (2003): http://erlang.org/download/armstrong_thesis_2003.pdf
- Fred Hébert (Heroku): https://learnyousomeerlang.com/ https://www.erlang-in-anger.com/
- Actor model as a library in Java: Akka https://akka.io
- Formal reasoning on concurrent programs using CSP, CCS, process calculus, etc…
- Multiway rendezvous: synchronous message passing between N processes
  - Garavel, Serwe: The Unheralded Value of the Multiway Rendezvous hal.archives-ouvertes.fr/hal-01511847
- More generally: “Coders at Work” by Peter Seibel, interviews of famous programmers

Thanks!

Questions?