Arrows and Reagents

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Advanced Functional Programming

March 3rd, 2016

Slides were borrowed and modified from Aaron Turon's PLDI 2012 talk: http://www.mpi-sws.org/~turon/pldi-2012-reagents.pdf

Arrows

```
module type Arrow =
sig
  type ('a,'b) t
  val arr   : ('a -> ‘b) -> ('a,'b) t
  val (>>>) : ('a,'b) t -> ('b,'c) t -> ('a,'c) t
  val first : ('a,'b) t -> ('a * 'c, 'b * 'c) t
end
```

Arrows

```
module type Arrow =
sig
  type ('a,'b) t
  val arr   : ('a -> ‘b) -> ('a,'b) t
  val (>>>) : ('a,'b) t -> ('b,'c) t -> ('a,'c) t
  val first : ('a,'b) t -> ('a * 'c, 'b * 'c) t
end
```

Laws

```
arr f >>> arr g ≡ arr (compose g f)
(f >>> g) >>> h ≡ f >>> (g >>> h)
    arr id >>> f ≡ f
            ... ...
```

Functions
as
Arrows

- https://gist.github.com/9eef070c232913121564

"If we think of a library as defining a domain specific '**language**', whose constructions are represented as **combinators**, then the idea is to implement the language via a combination of a **static analysis** and **an optimised dynamic semantics**."

John Huges, "Generalising Monads to Arrows"

“If we think of a library as defining a domain specific '**language**', whose constructions are represented as **combinators**, then the idea is to implement the language via a combination of a **static analysis** and **an optimised dynamic semantics**.”

John Huges, “Generalising Monads to Arrows”

```
val (>>=) : 'a Monad.t -> ('a -> 'b Monad.t) -> 'b Monad.t
val (>>>) : ('a, 'b) Arrow.t -> ('b,'c) Arrow.t -> ('a,'c) Arrow.t
```

Functions with *cost* as Arrows

- https://gist.github.com/66fcc8c01b563282ef42
- https://gist.github.com/644fbe3d36f90d98faa1

Reagents

- DSL for e*xpressing* and *composing* fine-grained concurrency libraries
- Aaron Turon, "Reagents: expressing and composing fine-grained concurrency", PLDI 2012
- Based on Arrows
  - Enable dynamic optimisations
- Built on k-compare-and-swap abstraction

Compare-and-swap (CAS)

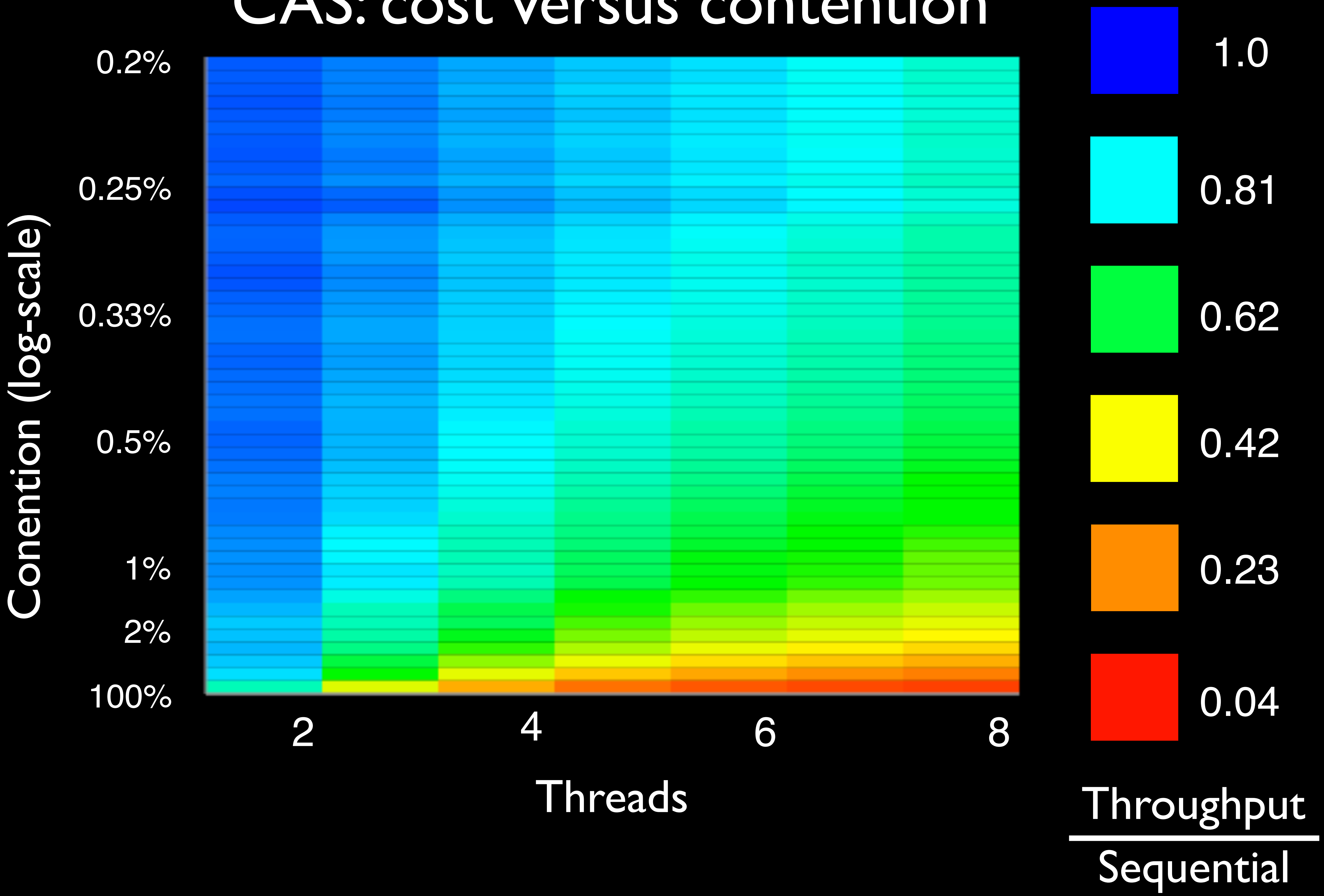
```
module CAS : sig
  val cas : 'a ref -> expect:'a -> update:'a -> bool
end = struct
 (* atomically... *)
 let cas r ~expect ~update =
    if !r = expect then
      (r:= update; true)
    else false
end
```

Compare-and-swap (CAS)

```
module CAS : sig
  val cas : 'a ref -> expect:'a -> update:'a -> bool
end = struct
 (* atomically... *)
 let cas r ~expect ~update =
    if !r = expect then
      (r:= update; true)
    else false
end
```

- Implemented *atomically* by processors
  - x86: CMPXCHG and friends
  - arm: LDREX, STREX, etc.
  - ppc: lwarx, stwcx, etc.

CAS: cost versus contention



java.util.concurrent

Synchronization

Reentrant locks
Semaphores
R/W locks
Reentrant R/W locks
Condition variables
Countdown latches
Cyclic barriers
Phasers
Exchangers

Data structures

- Queues
  - Nonblocking
  - Blocking (array & list)
  - Synchronous
  - Priority, nonblocking
  - Priority, blocking
- Deques
- Sets
- Maps (hash & skiplist)

java.util.concurrent

Synchronization

Reentrant locks
Semaphores
R/W locks
Reentrant R/W l
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Exc gers

Data s

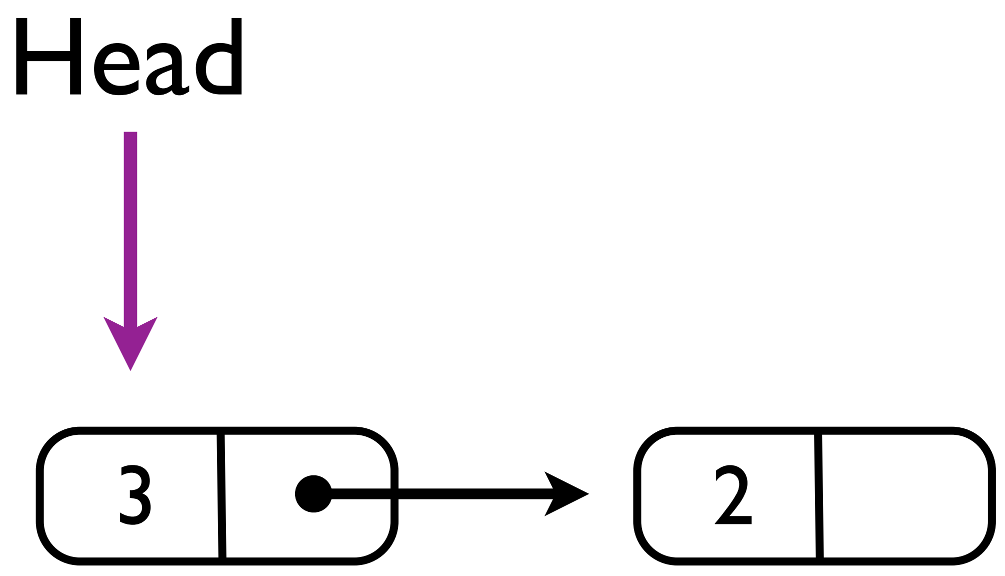
Q
cking
cking (array & list)
Synchronous
Priority, nonblocking
Priority, blocking
Deques
Sets
Maps (hash & skiplist)

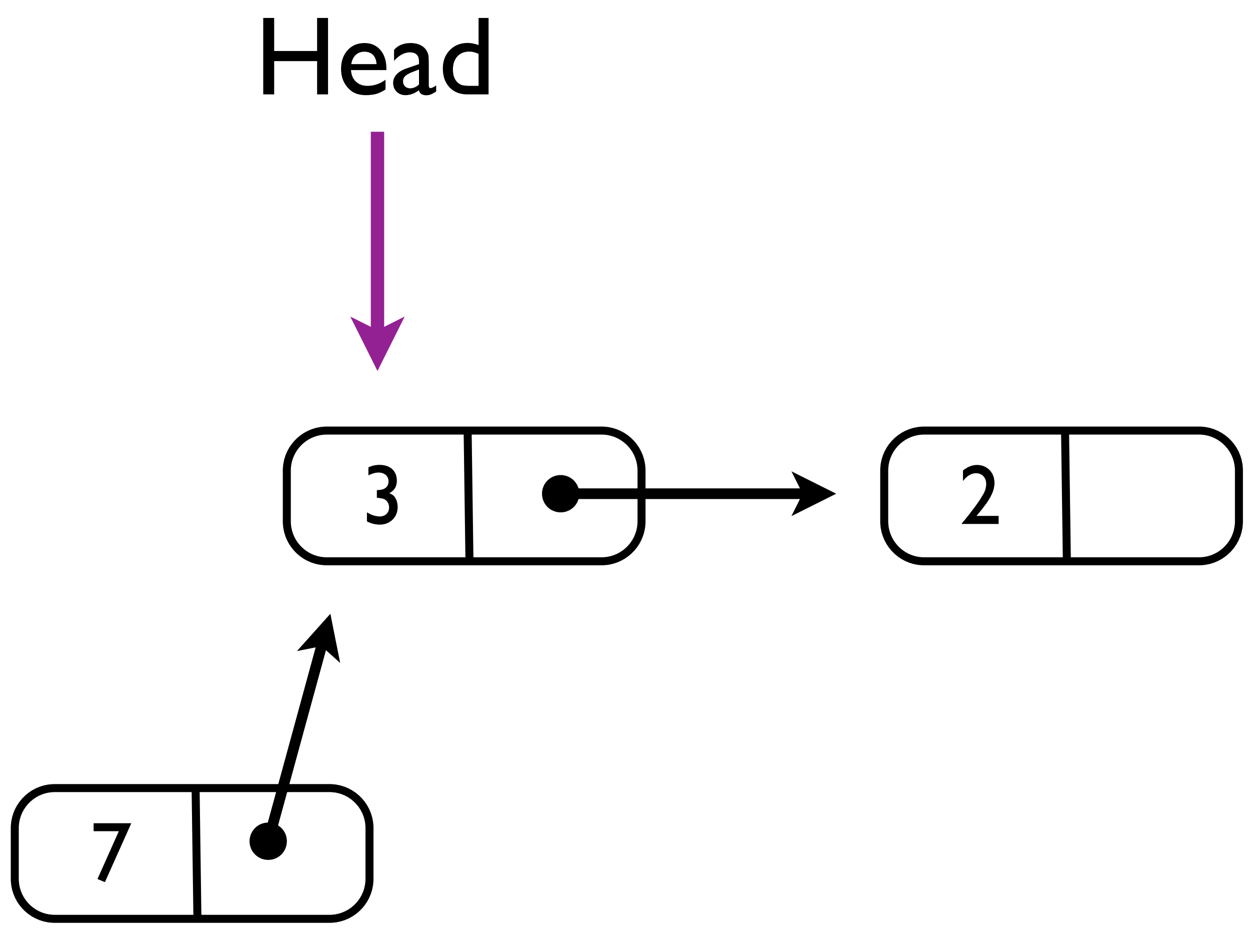
Not Composable

```
module type TREIBER_STACK = sig
  type 'a t
  val push : 'a t -> 'a -> unit
  ...
end

module Treiber_stack : TREIBER_STACK =
struct
  type 'a t = 'a list ref

  let rec push s t =
    let cur = !s in
    if CAS.cas s cur (t::cur) then ()
    else (backoff (); push s t)
end
```


Head
3
2


Head
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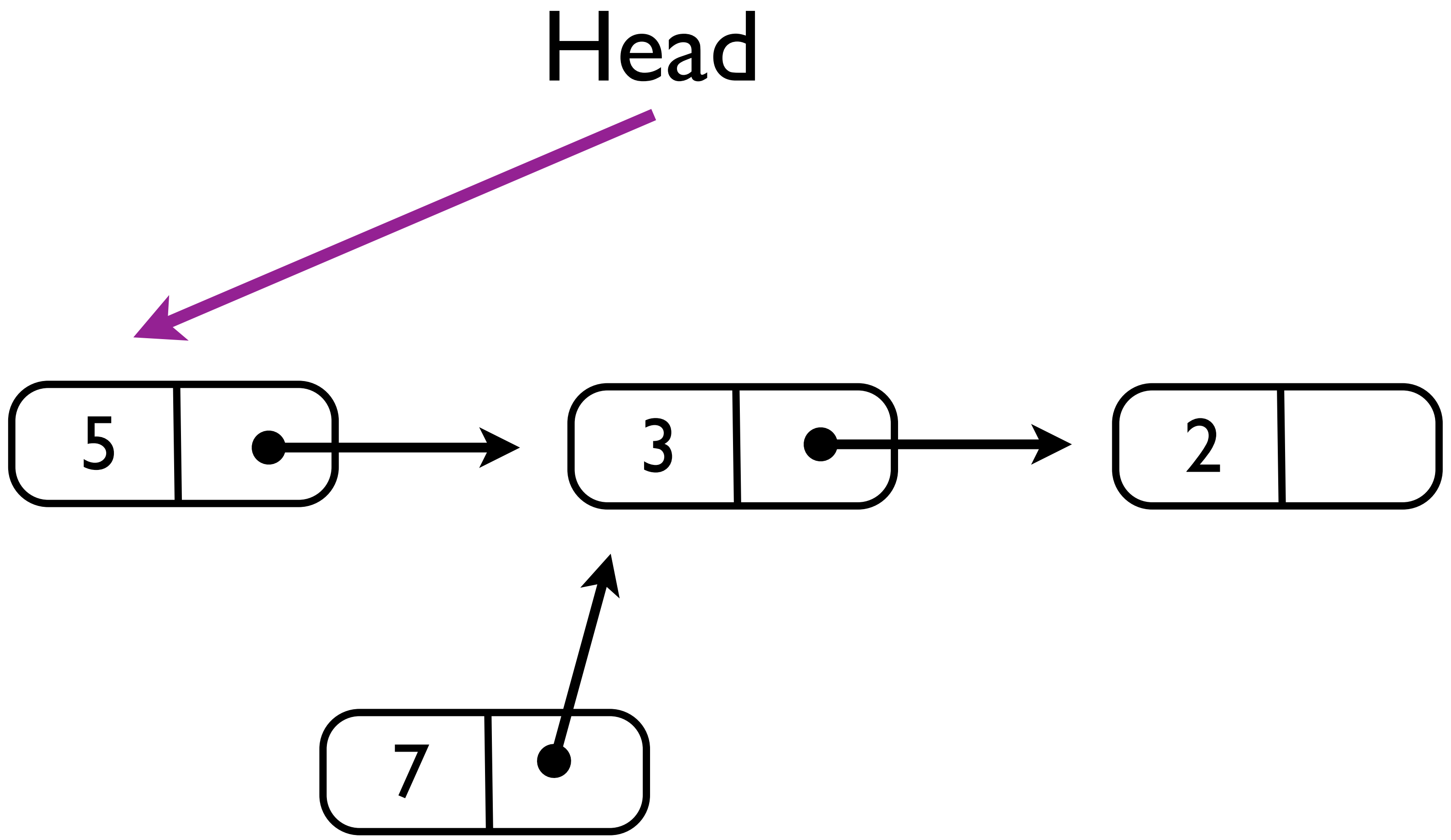
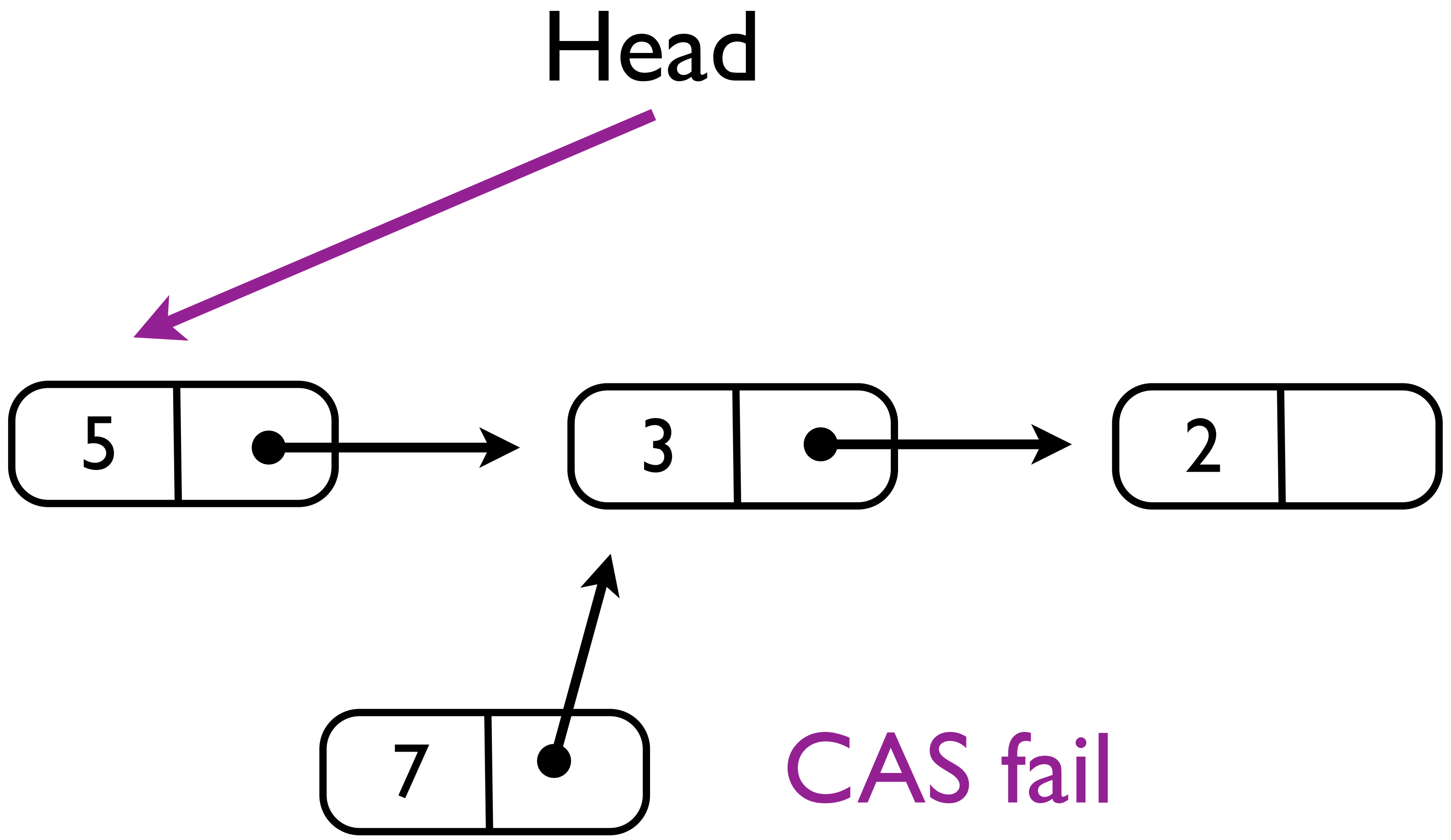

Head
5
3
2
7


Head
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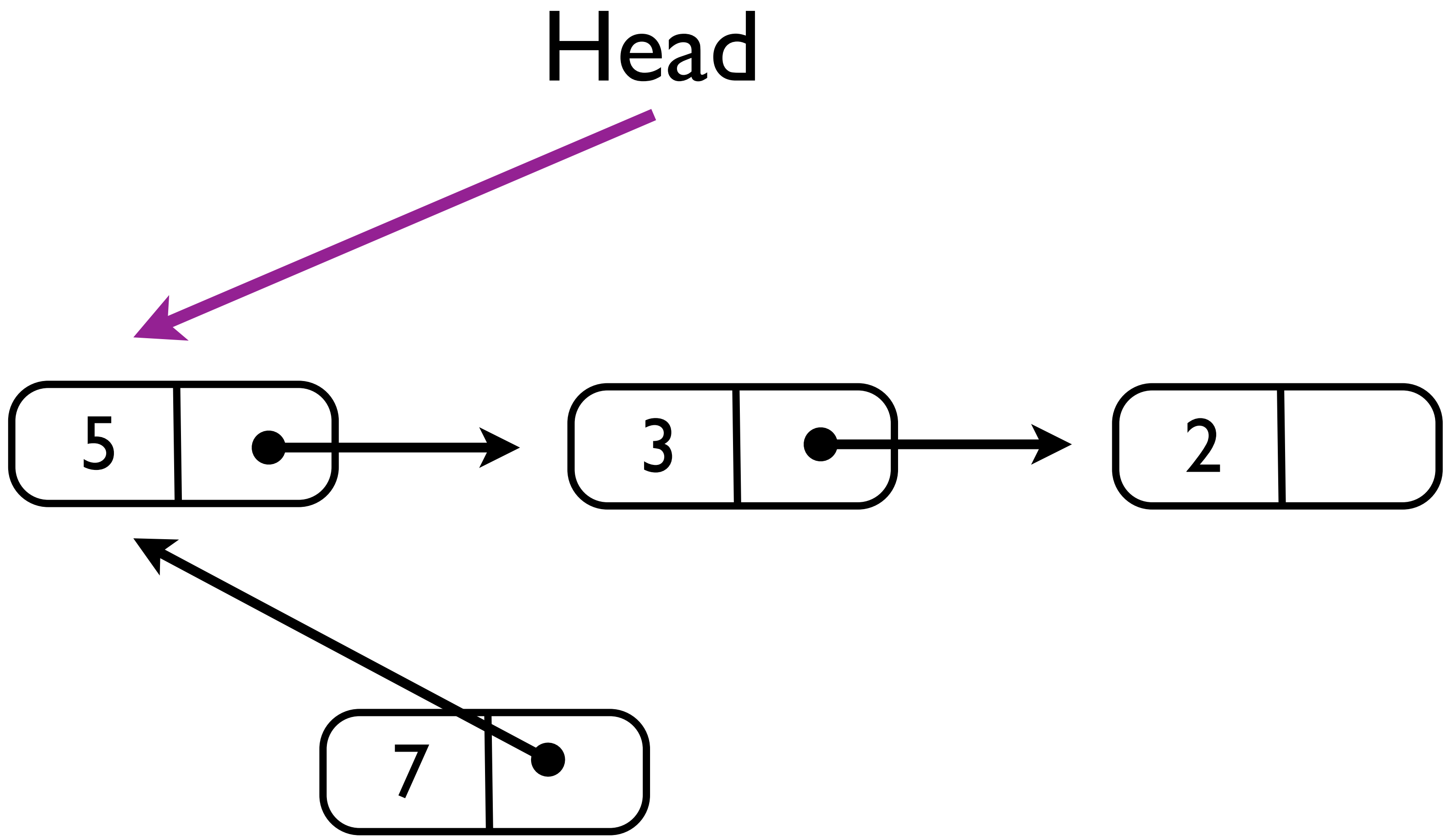
3
2
7
CAS fail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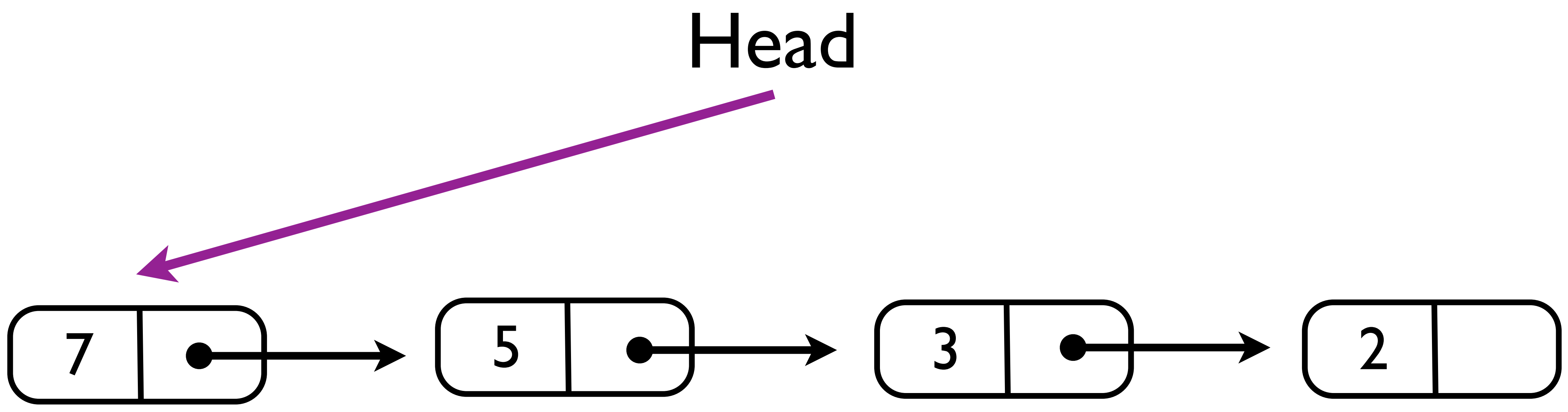

Head
7
5
3
2

```
module type TREIBER_STACK = sig
  type 'a t
  val push    : 'a t -> 'a -> unit
  val try_pop : 'a t -> 'a option
end

module Treiber_stack : TREIBER_STACK =
struct
  type 'a t = 'a list ref

  let rec push s t = ...

  let rec try_pop s =
    match !s with
    | [] -> None
    | (x::xs) as cur ->
        if CAS.cas s cur xs then Some x
        else (backoff (); try_pop s)
end
```

The Problem:

Concurrency libraries are indispensable, but hard to build and extend

```
let v = Treiber_stack.pop s1 in
Treiber_stack.push s2 v
```

is not ***atomic***

The Proposal:

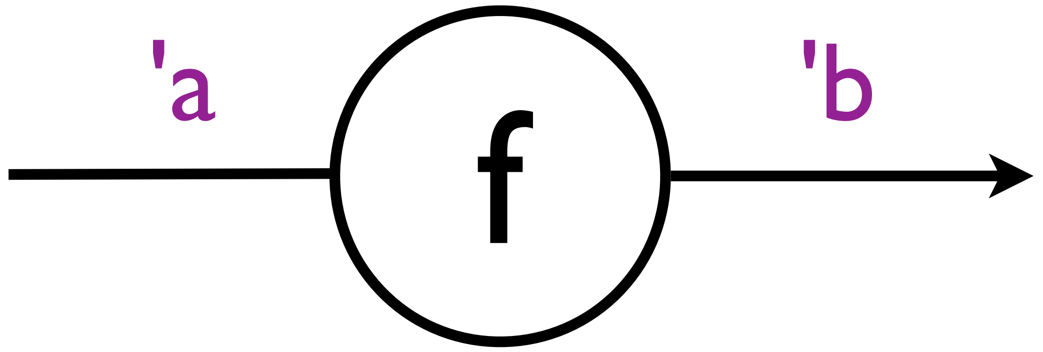
Scalable concurrent algorithms can be built and extended using abstraction and composition

```
Treiber_stack.pop s1 >>> Treiber_stack.push s2
```

is ***atomic***

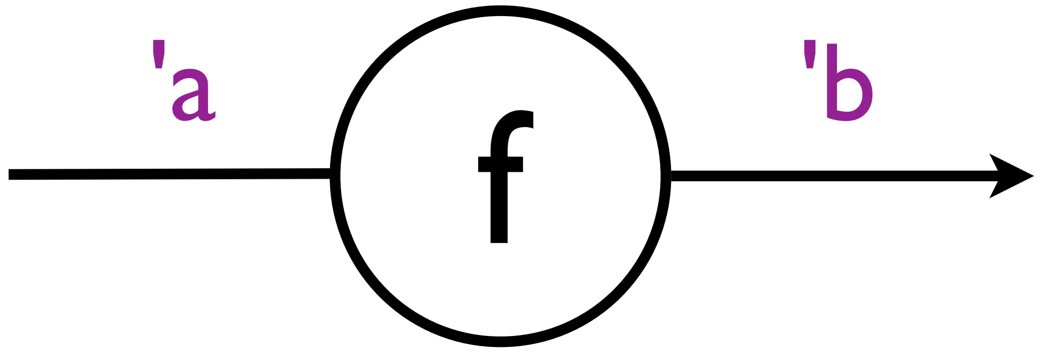
Design

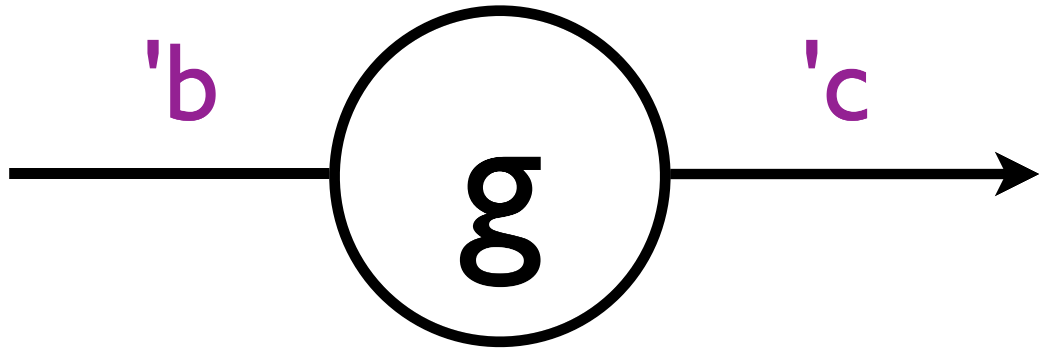
Lambda: the ultimate abstraction



```
val f : 'a -> 'b
```

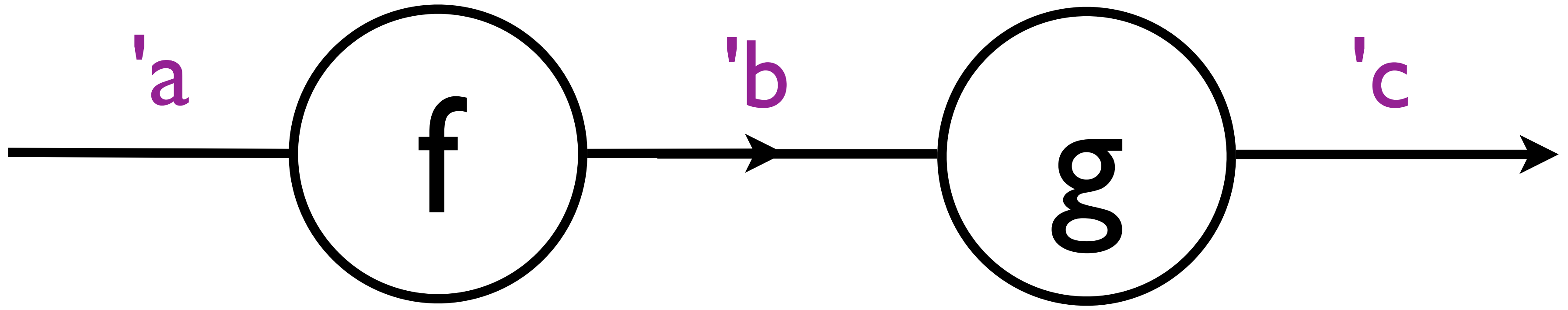
Lambda: the ultimate abstraction





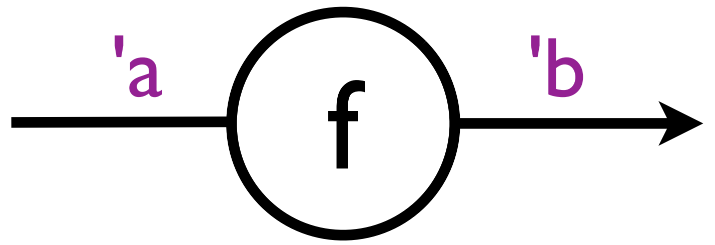
```
val f : 'a -> 'b          val g : 'b -> 'c
```

Lambda: the ultimate abstraction

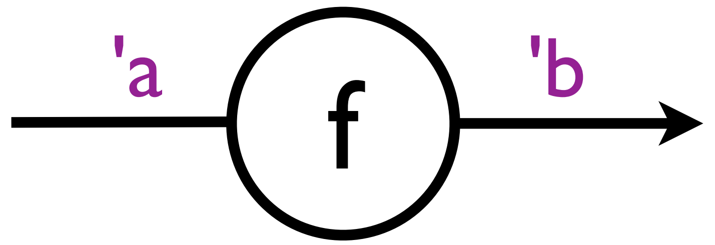


```
(compose g f): 'a -> 'c
```

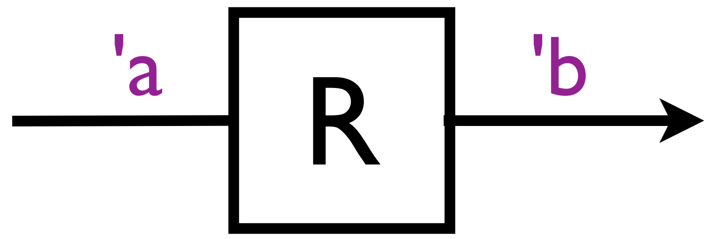
Lambda abstraction:



Lambda abstraction:



Reagent abstraction:



```
('a,'b) Reagent.t
```

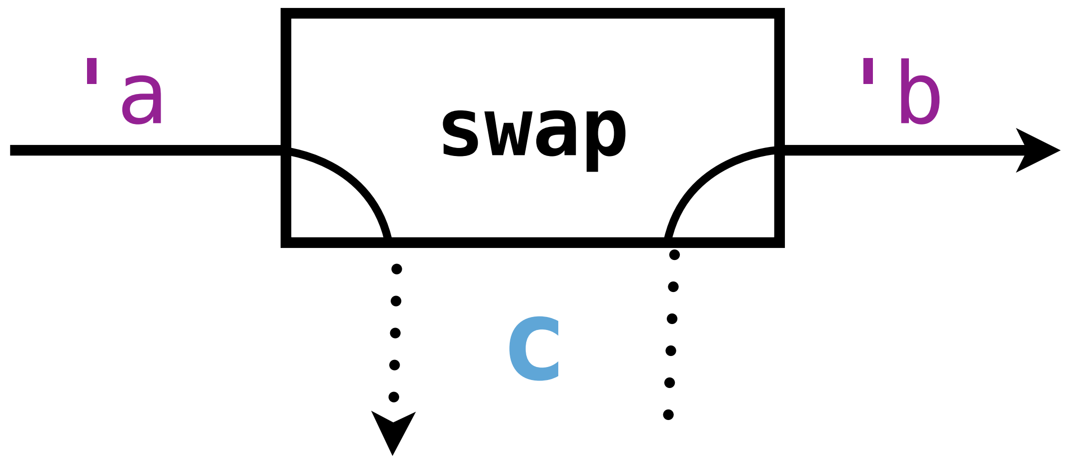
Reagent combinators

```
module type Reagents = sig
  type ('a,'b) t
  val never         : ('a,'b) t
  val constant      : 'a -> ('b,'a) t
  val (>>>)         : ('a,'b) t -> ('b,'c) t -> ('a,'c) t

  module Ref : Ref.S with type ('a,'b) reagent = ('a,'b) t
  module Channel : Channel.S with type ('a,'b) reagent = ('a,'b) t

  val run           : ('a,'b) t -> 'a -> ‘b
  ...
end
```

```
module type Channel = sig
  type ('a,'b) endpoint
  type ('a,'b) reagent

  val mk_chan : unit -> ('a,'b) endpoint * ('b,'a) endpoint
  val swap    : ('a,'b) endpoint -> ('a,'b) reagent
end
```

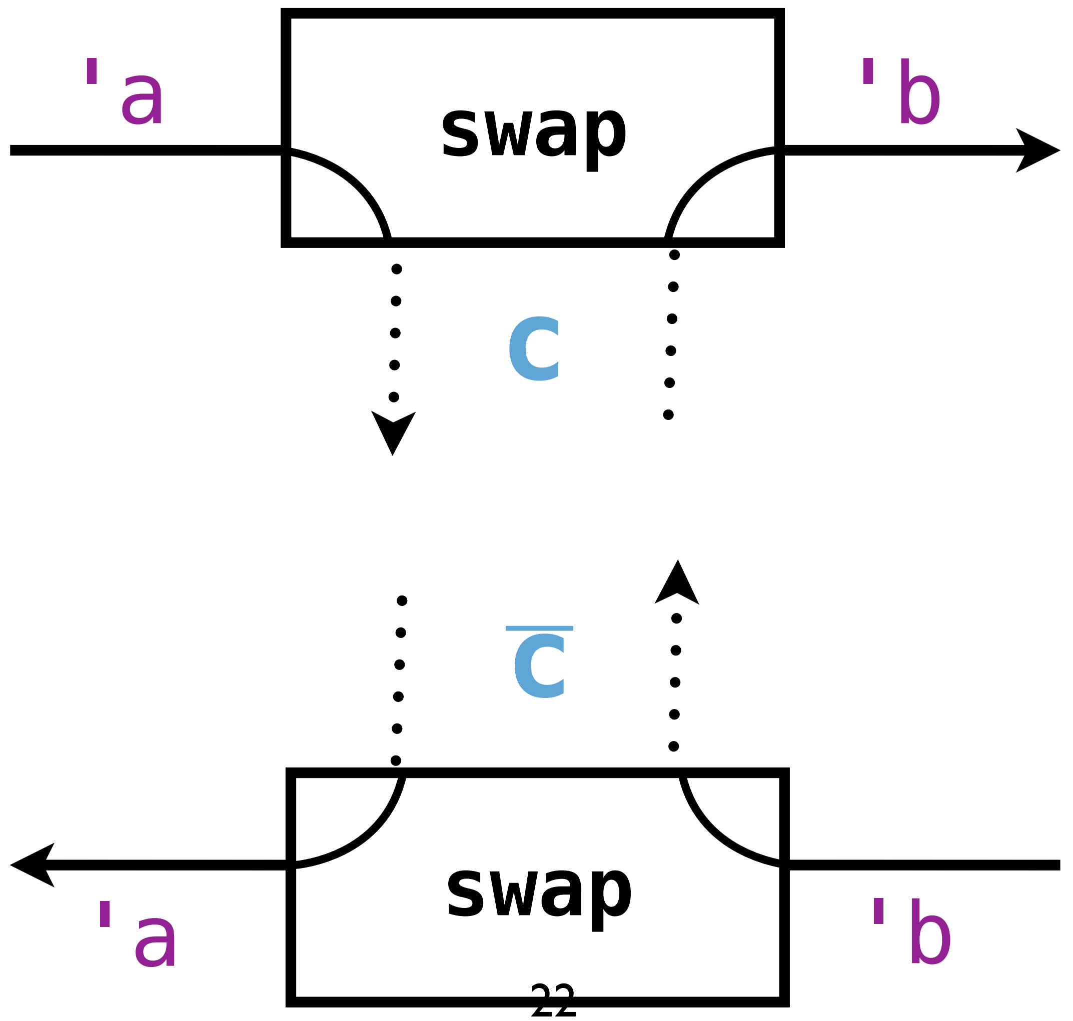
```
module type Channel = sig
  type ('a,'b) endpoint
  type ('a,'b) reagent

  val mk_chan : unit -> ('a,'b) endpoint * ('b,'a) endpoint
  val swap    : ('a,'b) endpoint -> ('a,'b) reagent
end
```

c: ('a,'b) endpoint

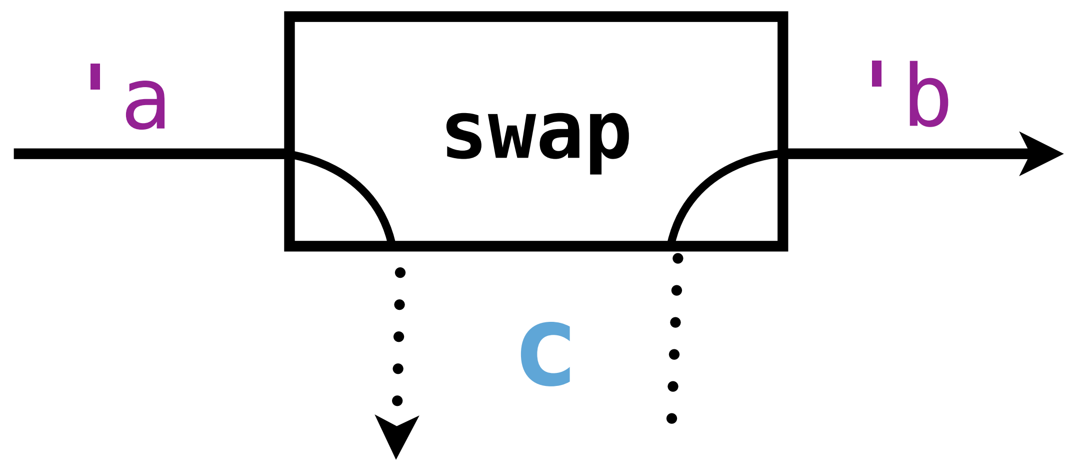


```
module type Channel = sig
  type ('a,'b) endpoint
  type ('a,'b) reagent

  val mk_chan : unit -> ('a,'b) endpoint * ('b,'a) endpoint
  val swap    : ('a,'b) endpoint -> ('a,'b) reagent
end
```

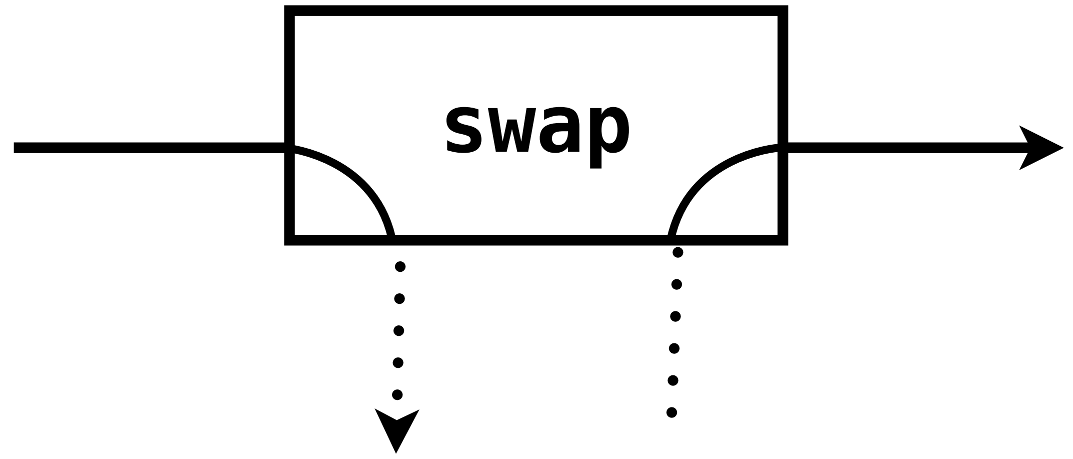
```
c: ('a,'b) endpoint
```



```
c: ('a,'b) endpoint
```

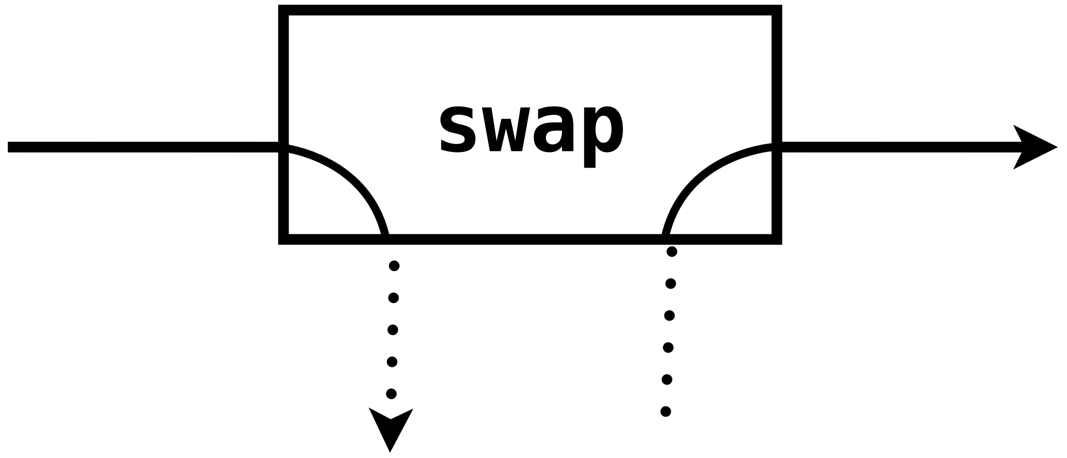


Message passing

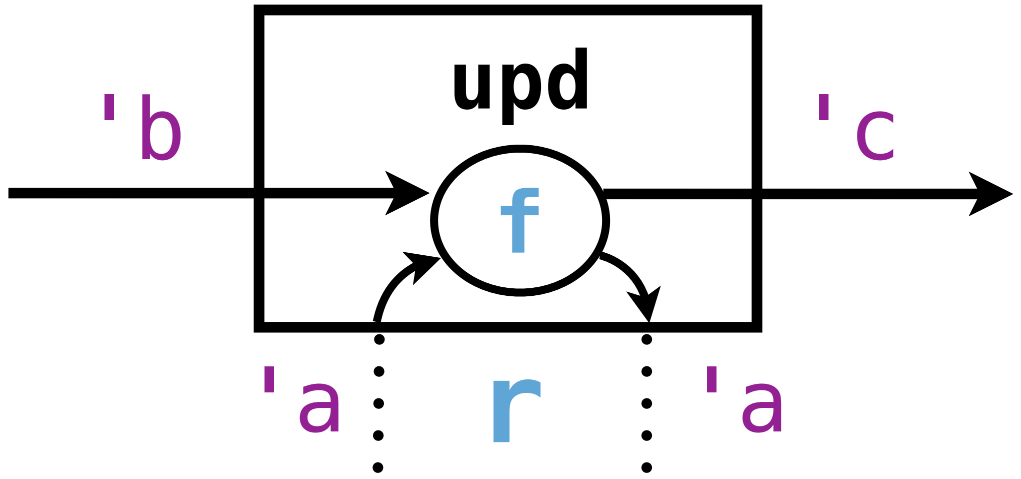


```
type 'a ref
val upd : 'a ref
  -> f:(‘a -> 'b -> ('a * ‘c) option)
  -> ('b, 'c) Reagent.t
```

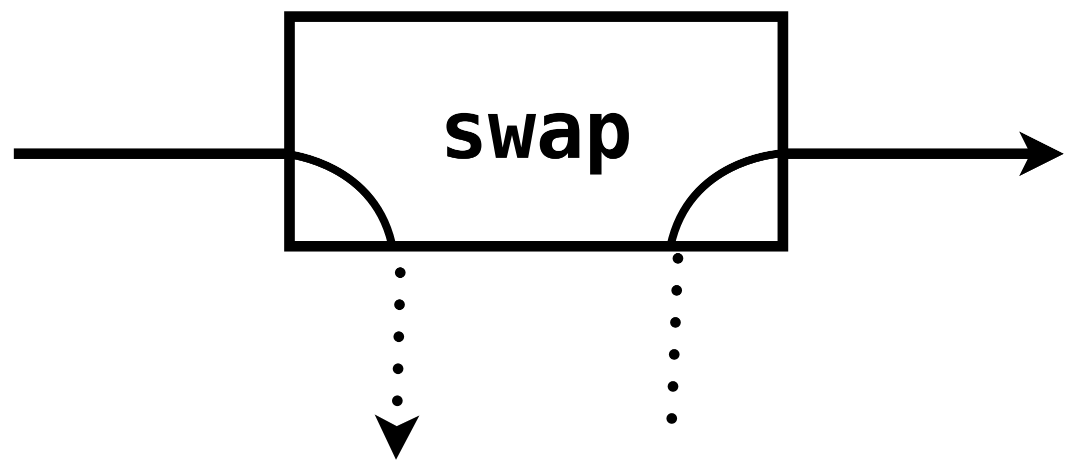
Message passing



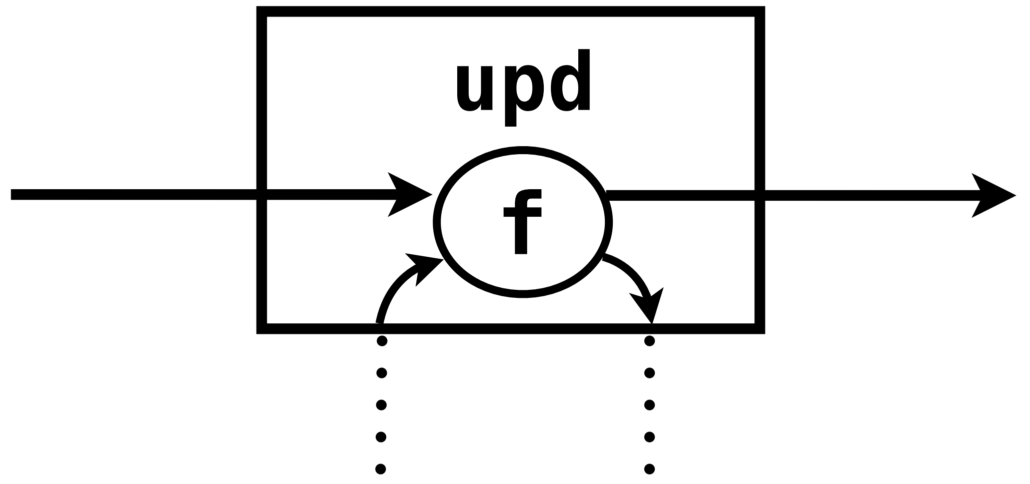
```
type 'a ref
val upd : 'a ref
   -> f:('a -> 'b -> ('a * 'c) option)
   -> ('b, 'c) Reagent.t
```



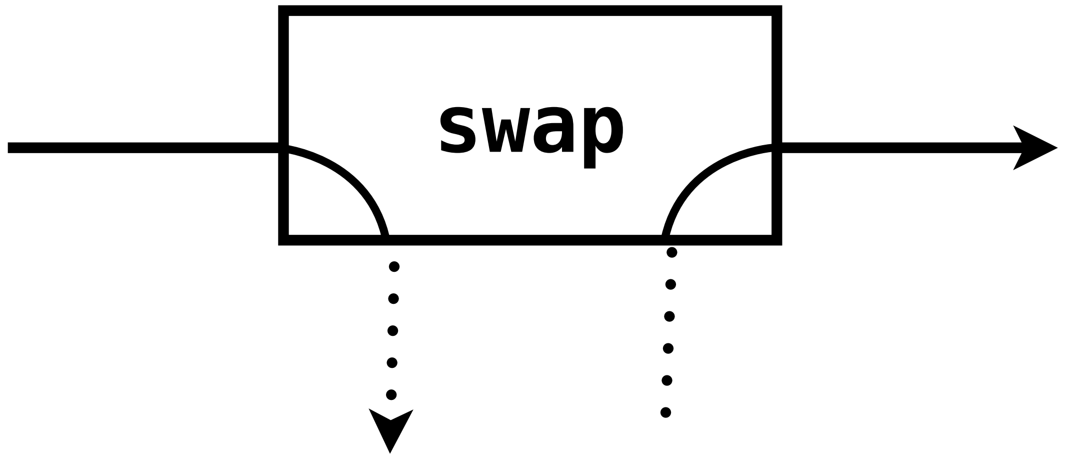
Message passing



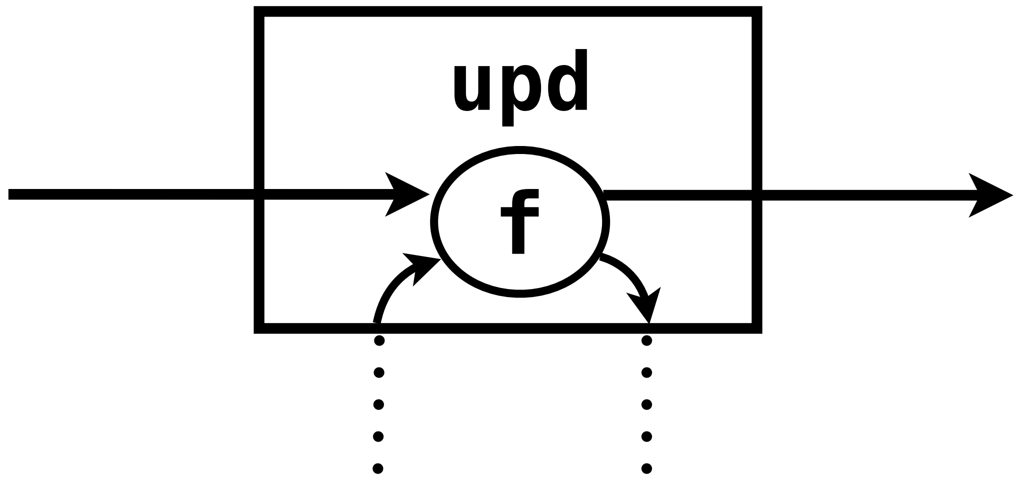
Shared state

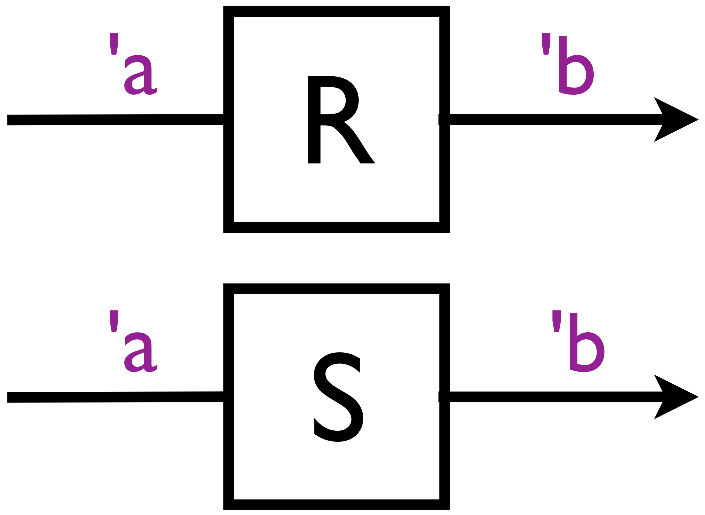


Message passing



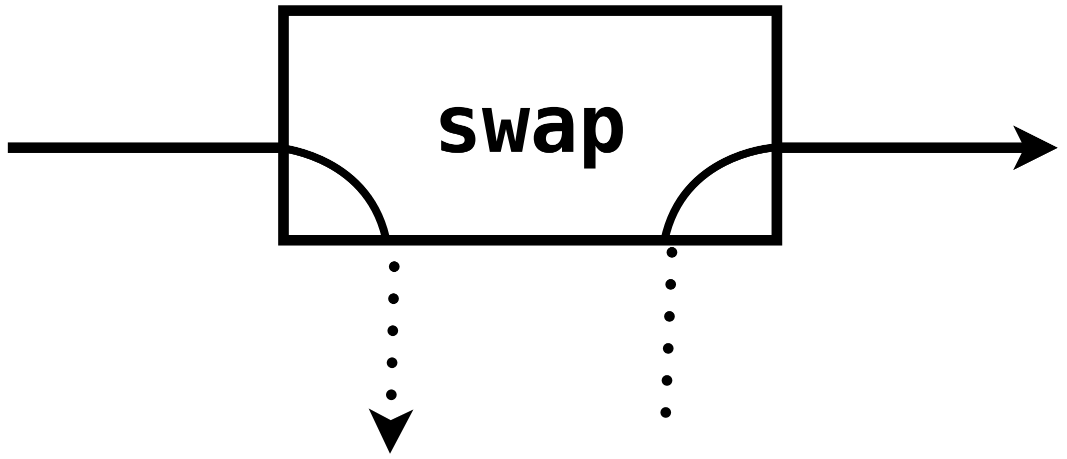
Shared state

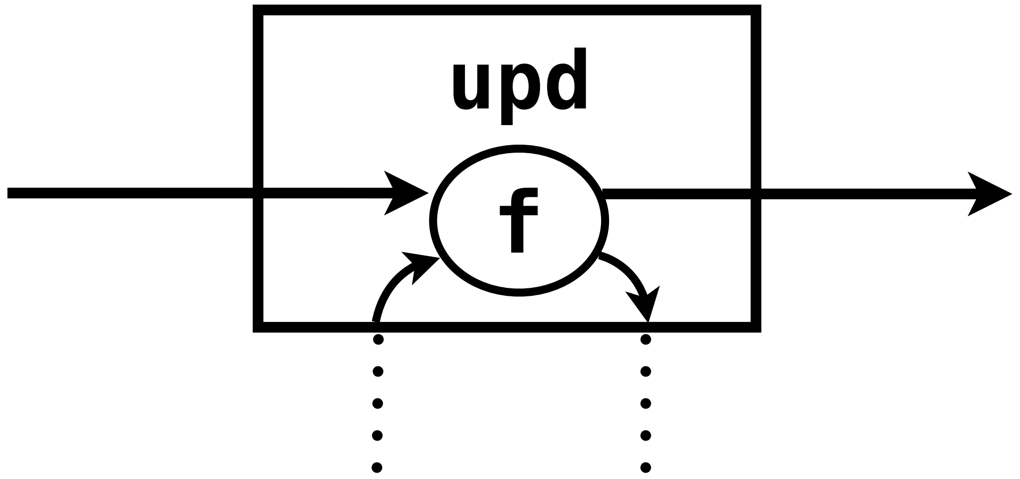


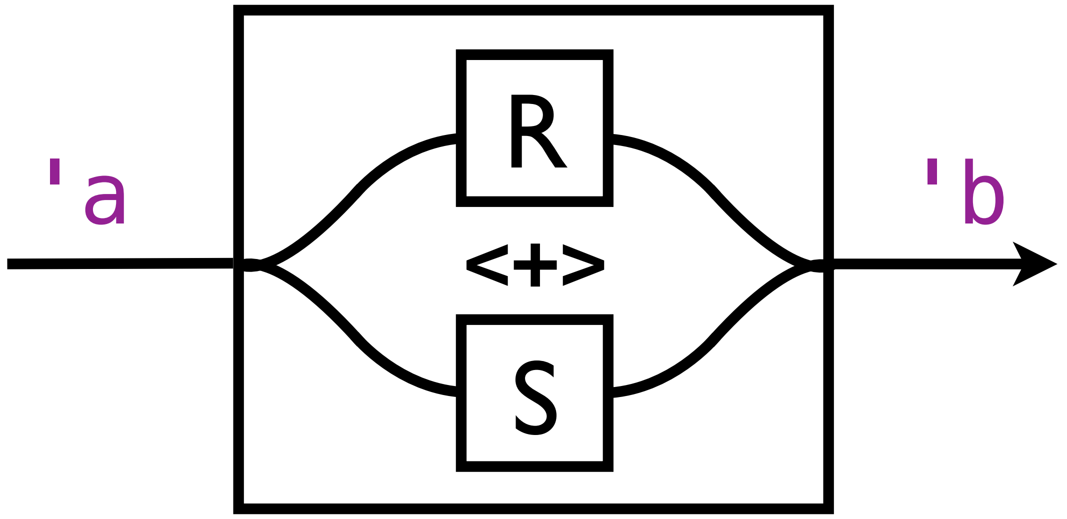


Message passing

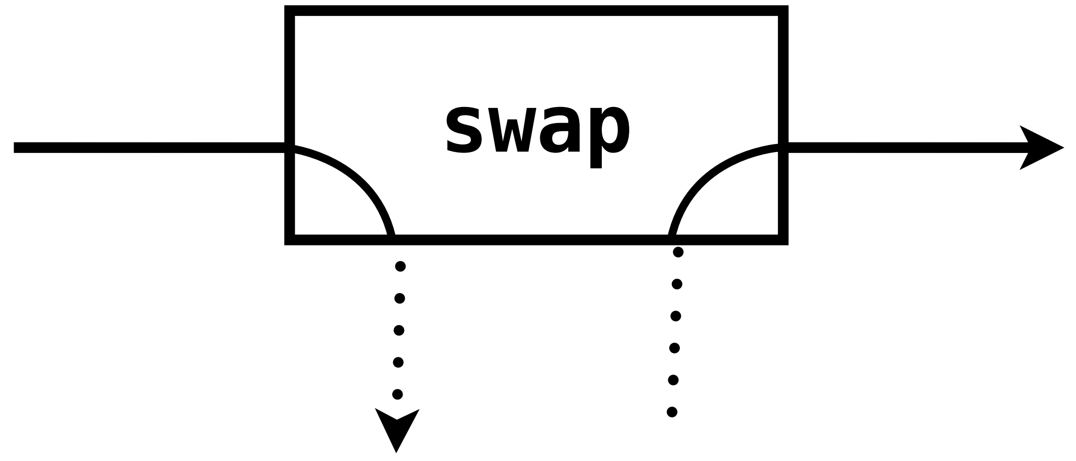
Shared state



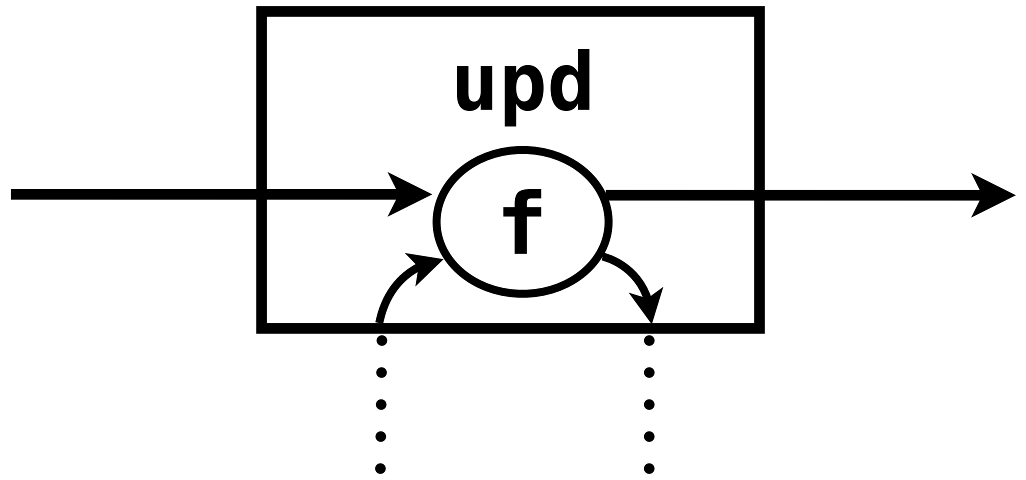




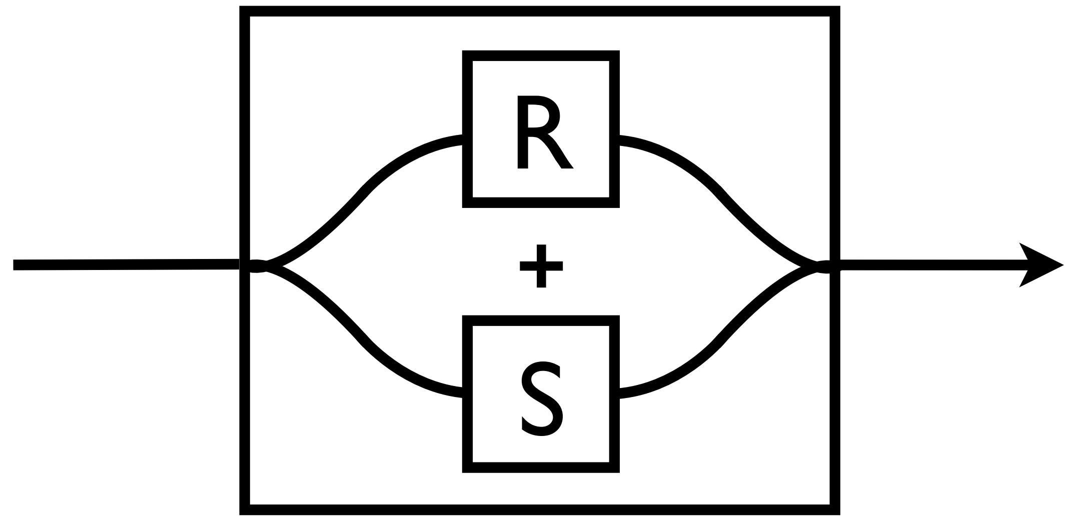
Message passing



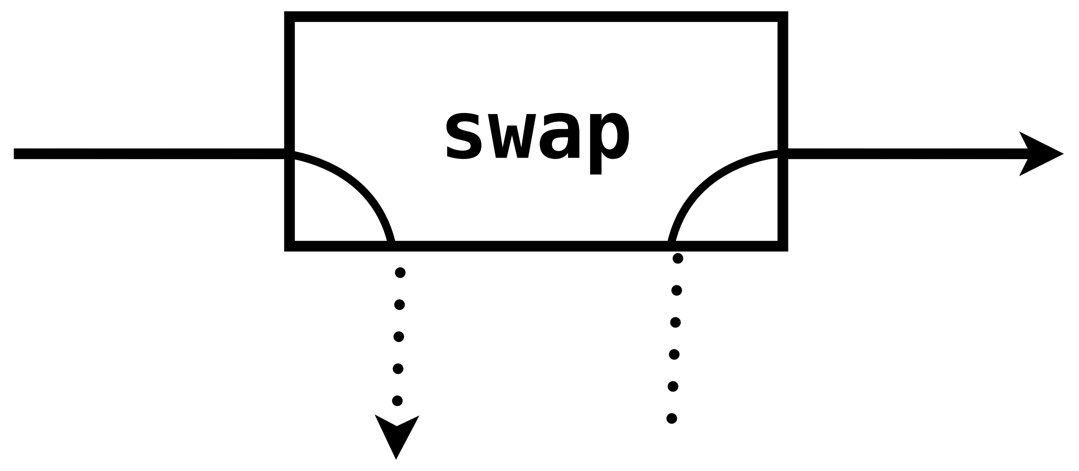
Shared state



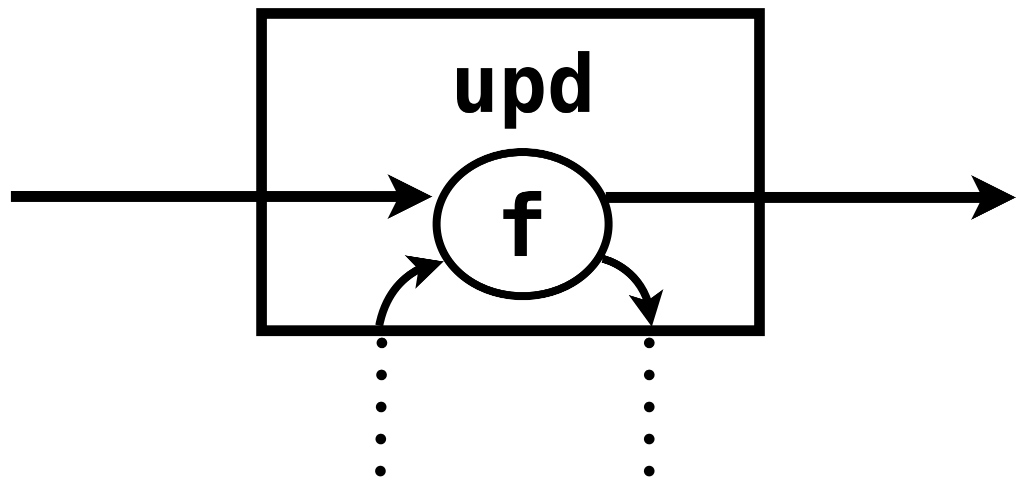
Disjunction



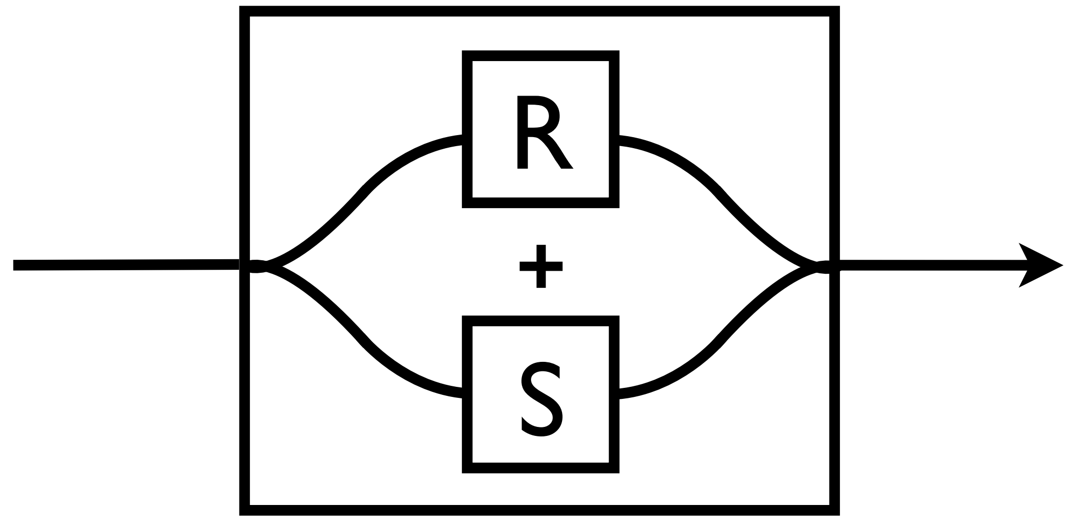
Message passing

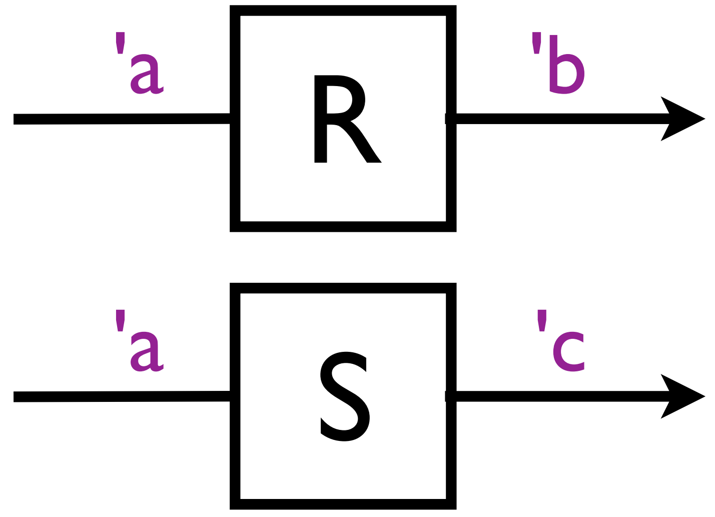


Shared state

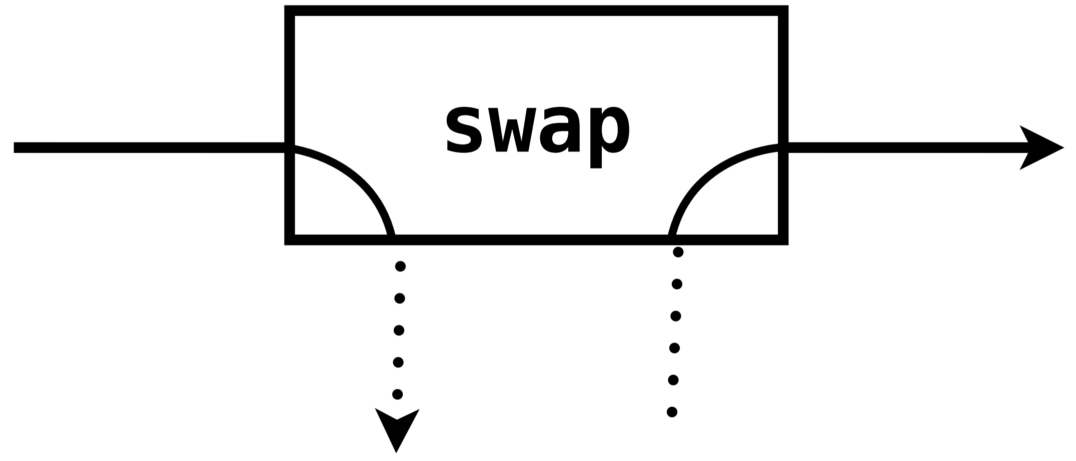


Disjunction

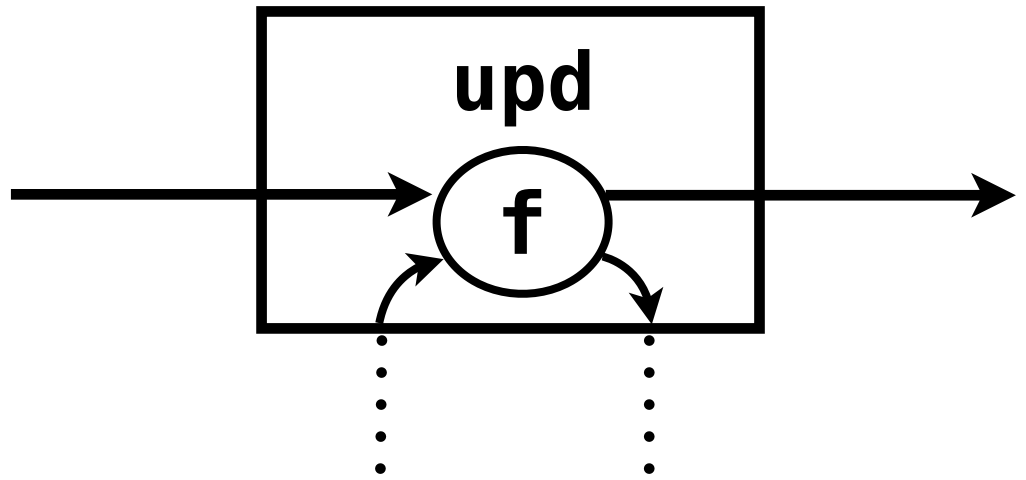




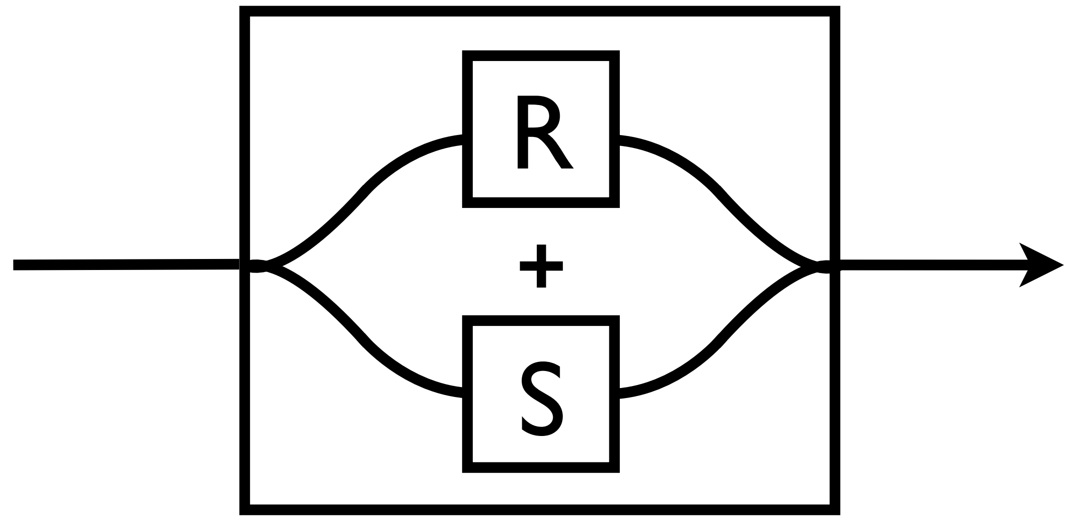
Message passing

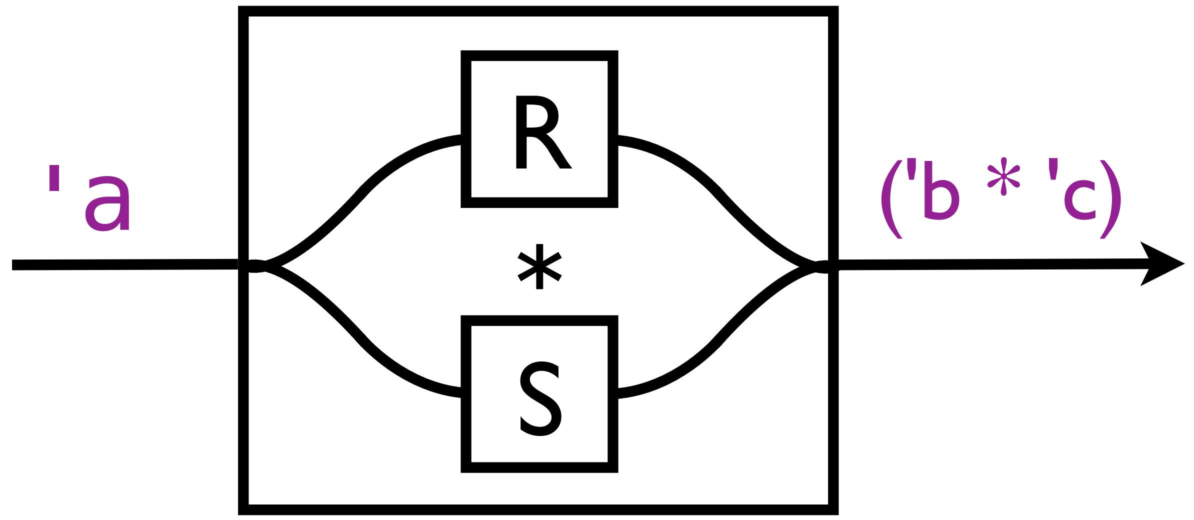


Shared state

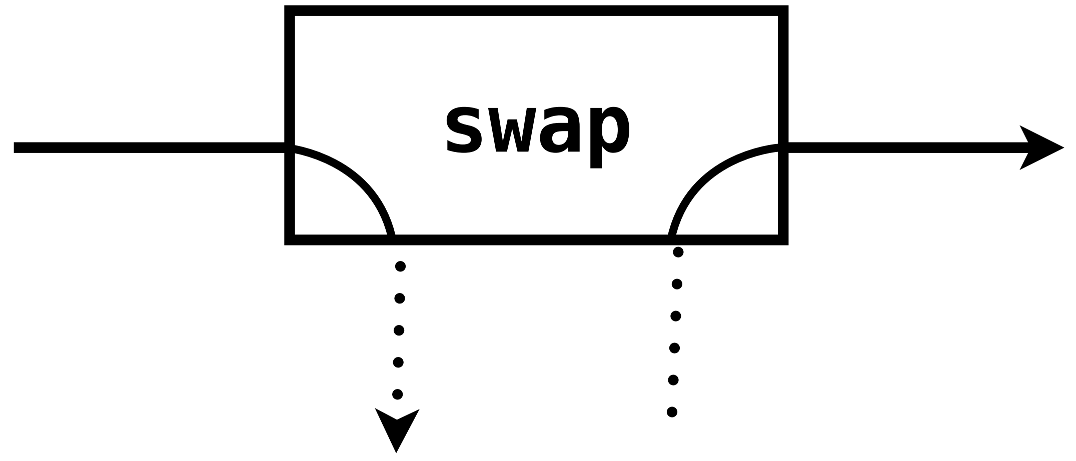


Disjunction

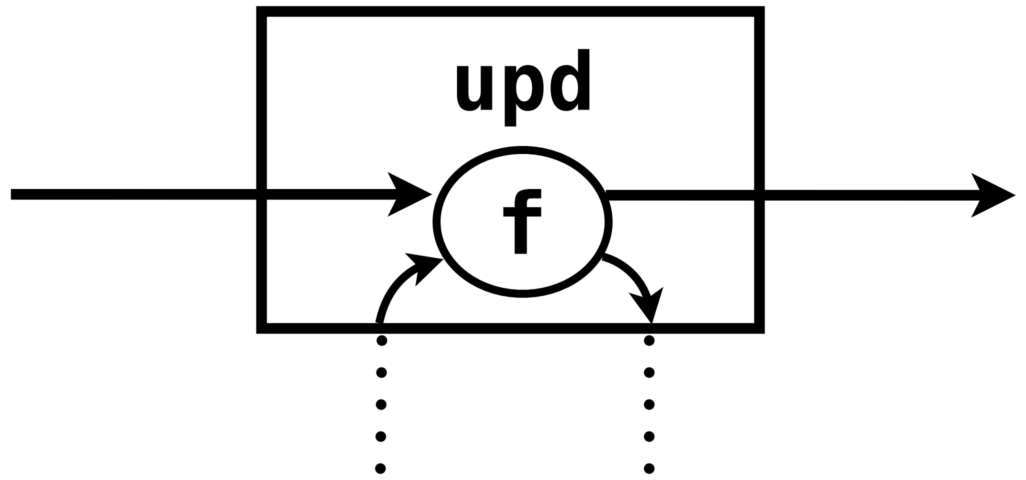




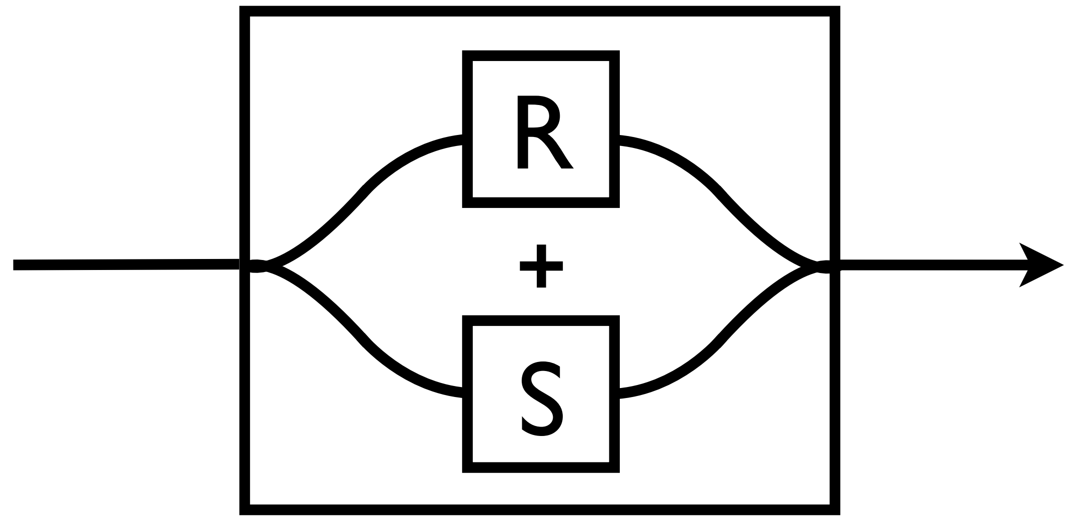
Message passing



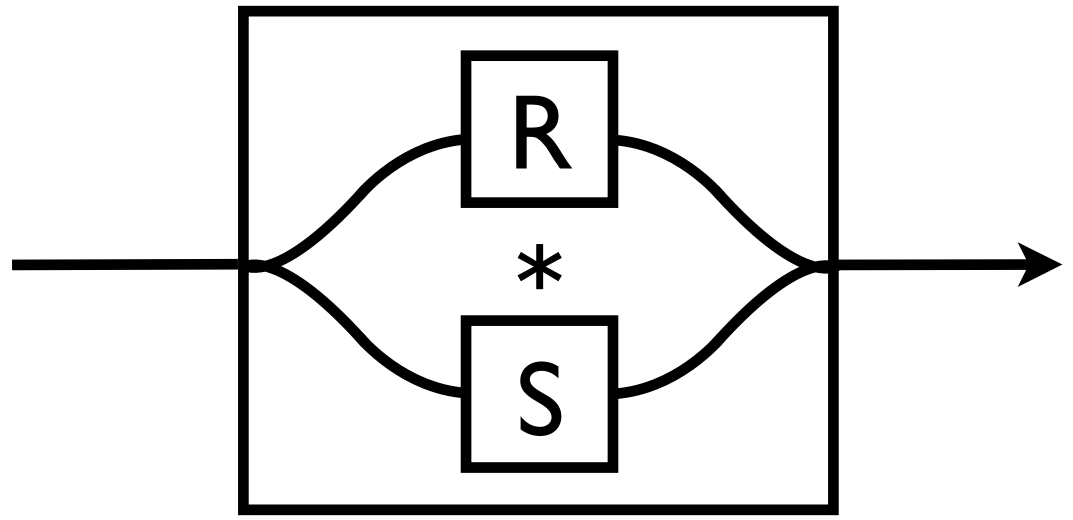
Shared state



Disjunction



Conjunction



```
module type TREIBER_STACK = sig
  type 'a t
  val create  : unit -> 'a t
  val push    : 'a t -> ('a, unit) Reagent.t
  val pop     : 'a t -> (unit, 'a) Reagent.t
  val try_pop : 'a t -> (unit, 'a option) Reagent.t
end

module Treiber_stack : TREIBER_STACK = struct
  type 'a t = 'a list Ref.ref

  let create () = Ref.mk_ref []

  let push r x = Ref.upd r (fun xs x -> Some (x::xs,()))

  let try_pop r = Ref.upd r (fun l () ->
    match l with
    | [] -> Some ([], None)
    | x::xs -> Some (xs, Some x))

  let pop r = Ref.upd r (fun l () ->
    match l with
    | [] -> None
    | x::xs -> Some (xs,x))
end
```

Composability

Transfer elements atomically

```
Treiber_stack.pop s1 >>> Treiber_stack.push s2
```

Composability

Transfer elements atomically

```
Treiber_stack.pop s1 >>> Treiber_stack.push s2
```

Consume elements atomically

```
Treiber_stack.pop s1 <*> Treiber_stack.pop s2
```

Composability

Transfer elements atomically

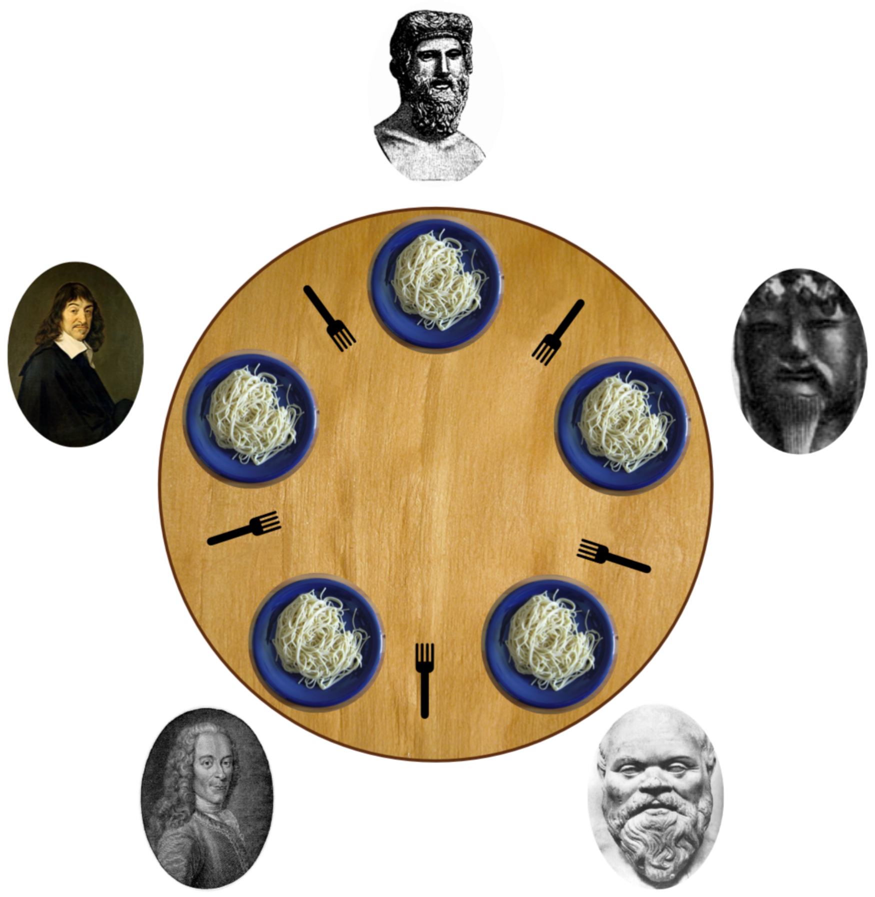
```
Treiber_stack.pop s1 >>> Treiber_stack.push s2
```

Consume elements atomically

```
Treiber_stack.pop s1 <*> Treiber_stack.pop s2
```

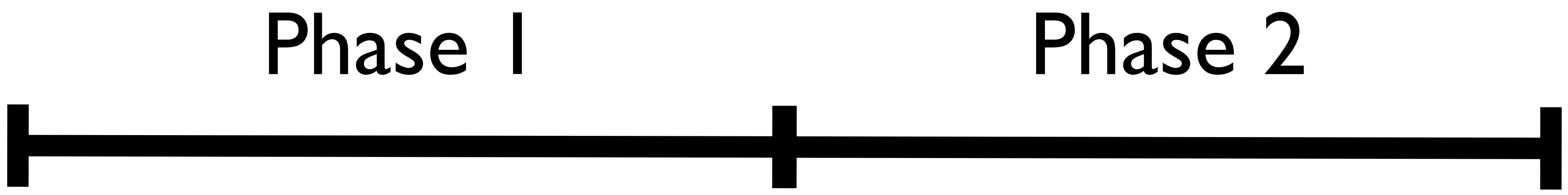
Consume elements from either

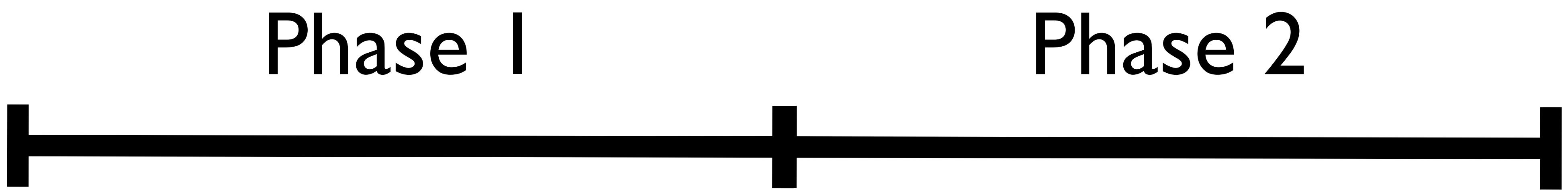
```
Treiber_stack.pop s1 <+> Treiber_stack.pop s2
```



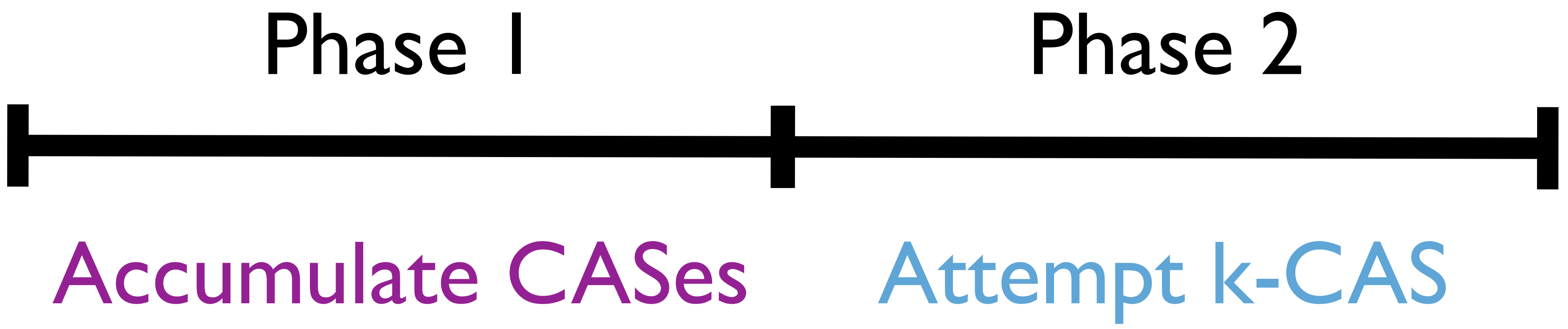
```
type fork =
  {drop : (unit,unit) endpoint;
   take : (unit,unit) endpoint}

let mk_fork () =
  let drop, take = mk_chan () in
  {drop; take}

let drop f = swap f.drop
let take f = swap f.take

let init forks =
  List.iter (fun fork ->
    Thread.spawn @@ run (drop fork)) forks

let eat l_fork r_fork =
  run (take l_fork <*> take r_fork) ();
  (* ...
   * eat
   * ... *)
  run (drop l_fork) ();
  run (drop r_fork) ()
```

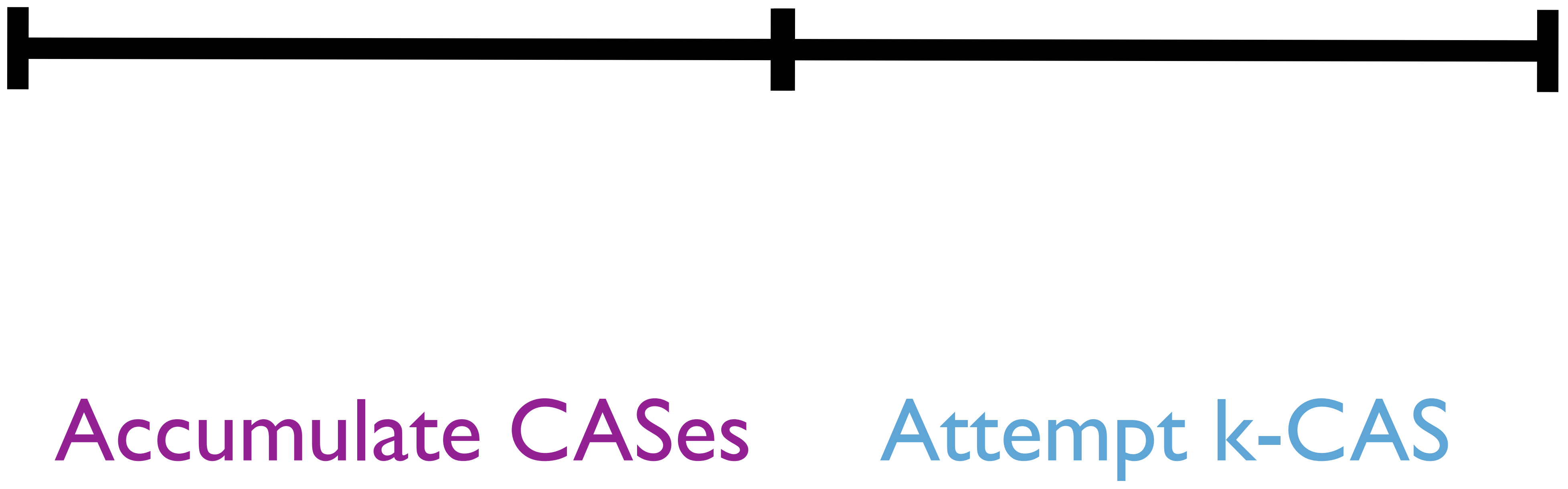
Implementation

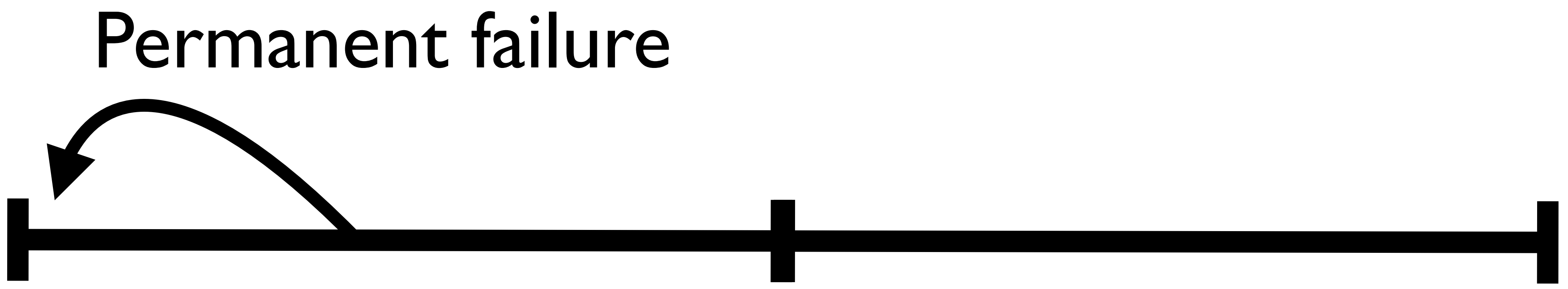

Phase 1
Phase 2



Accumulate CASes


Phase 1
Phase 2
Accumulate CASes
Attempt k-CAS


Accumulate CASes
Attempt k-CAS



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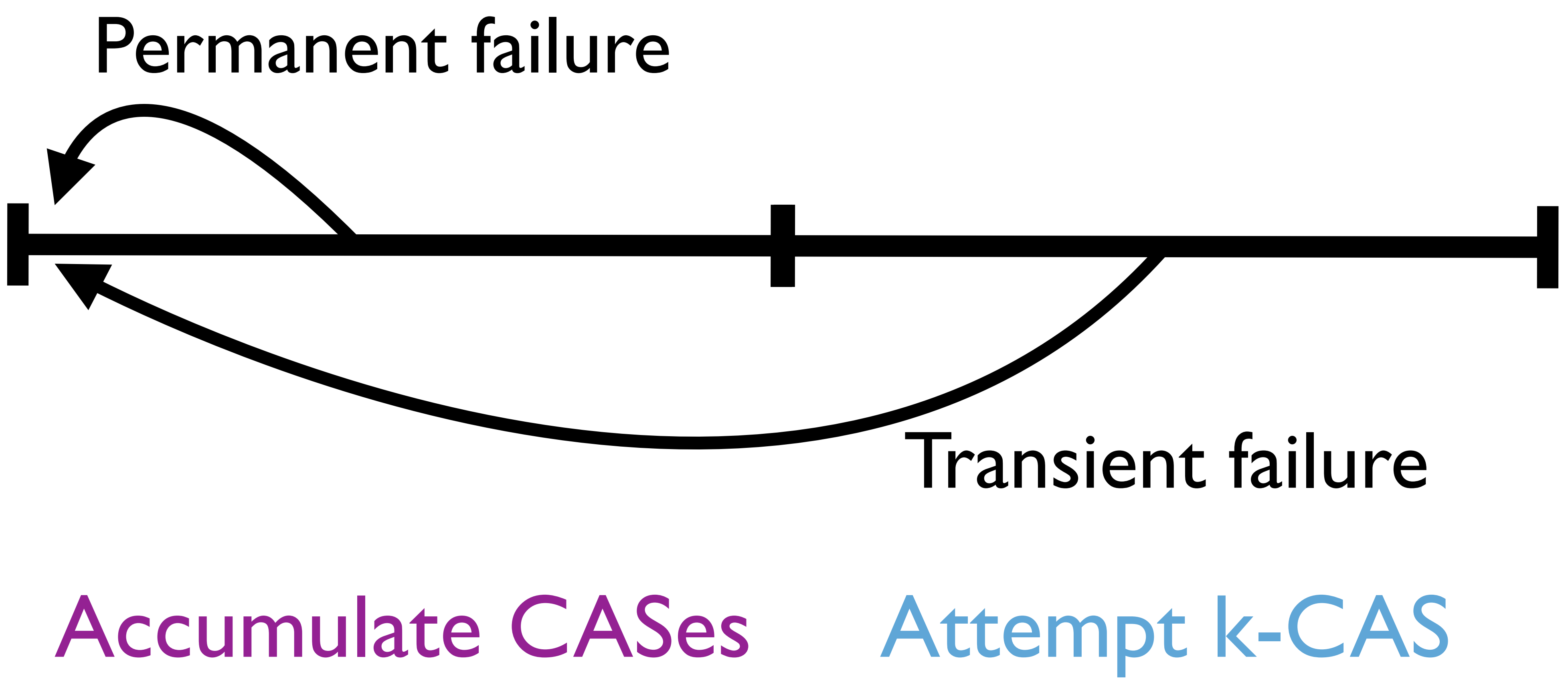
Permanent failure
Transient failure
Accumulate CASes
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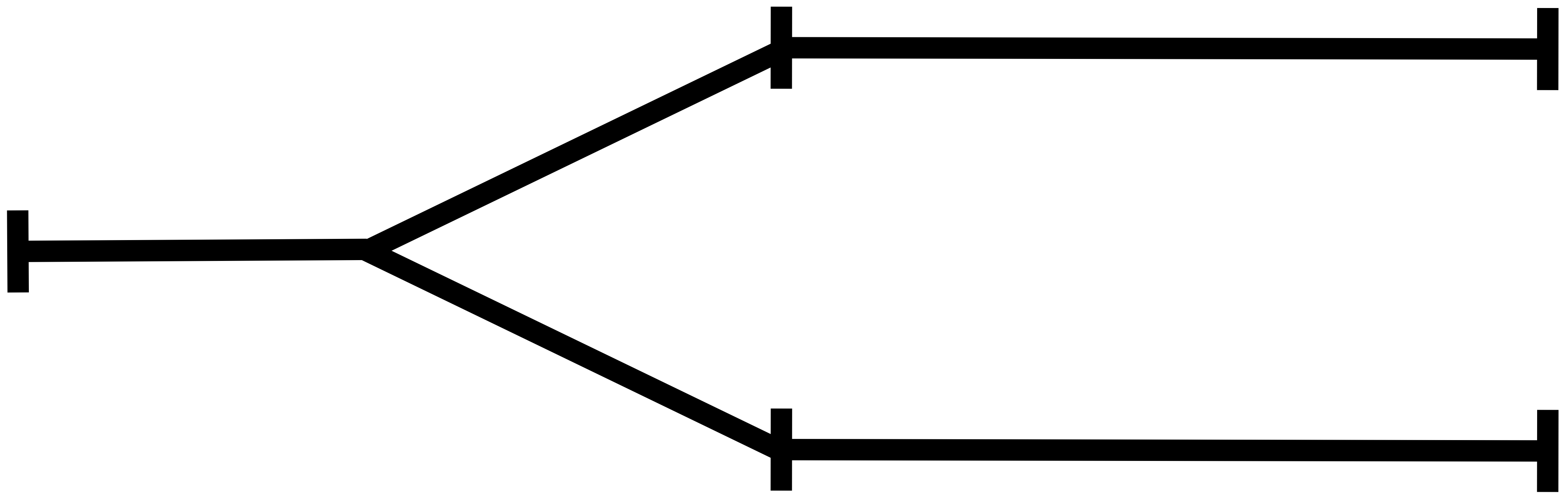
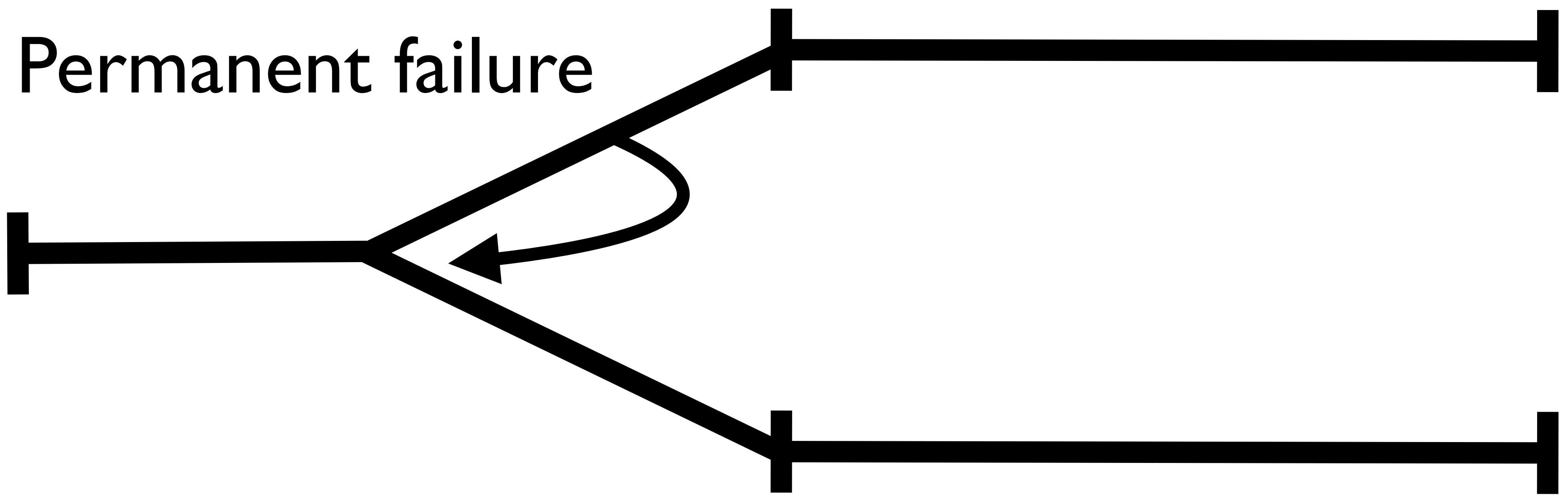
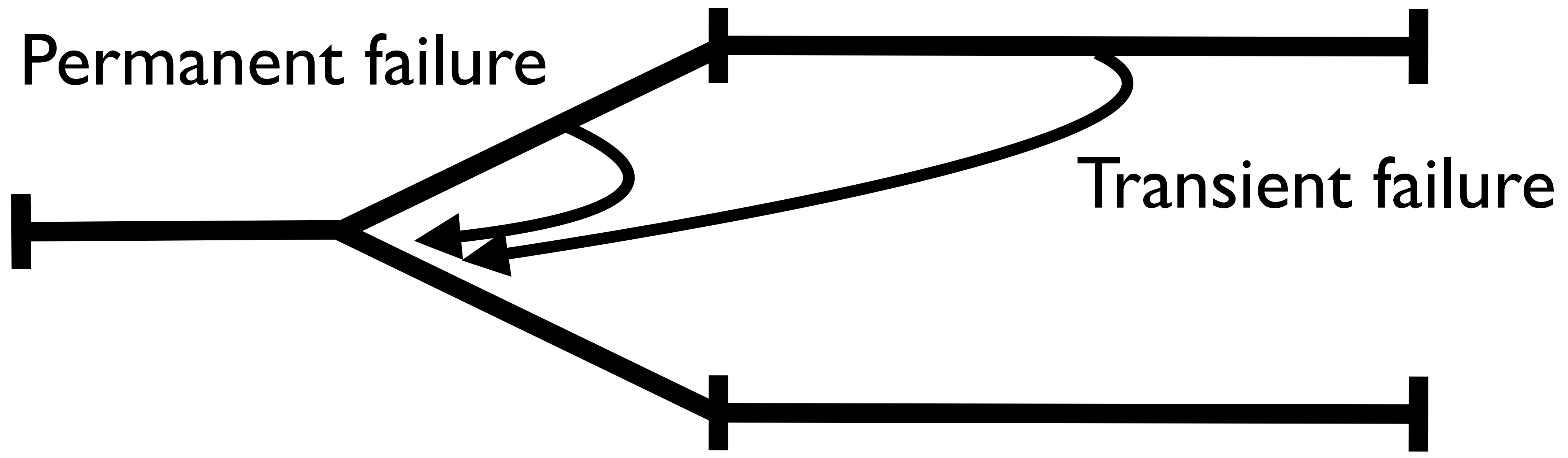



Permanent failure


Permanent failure
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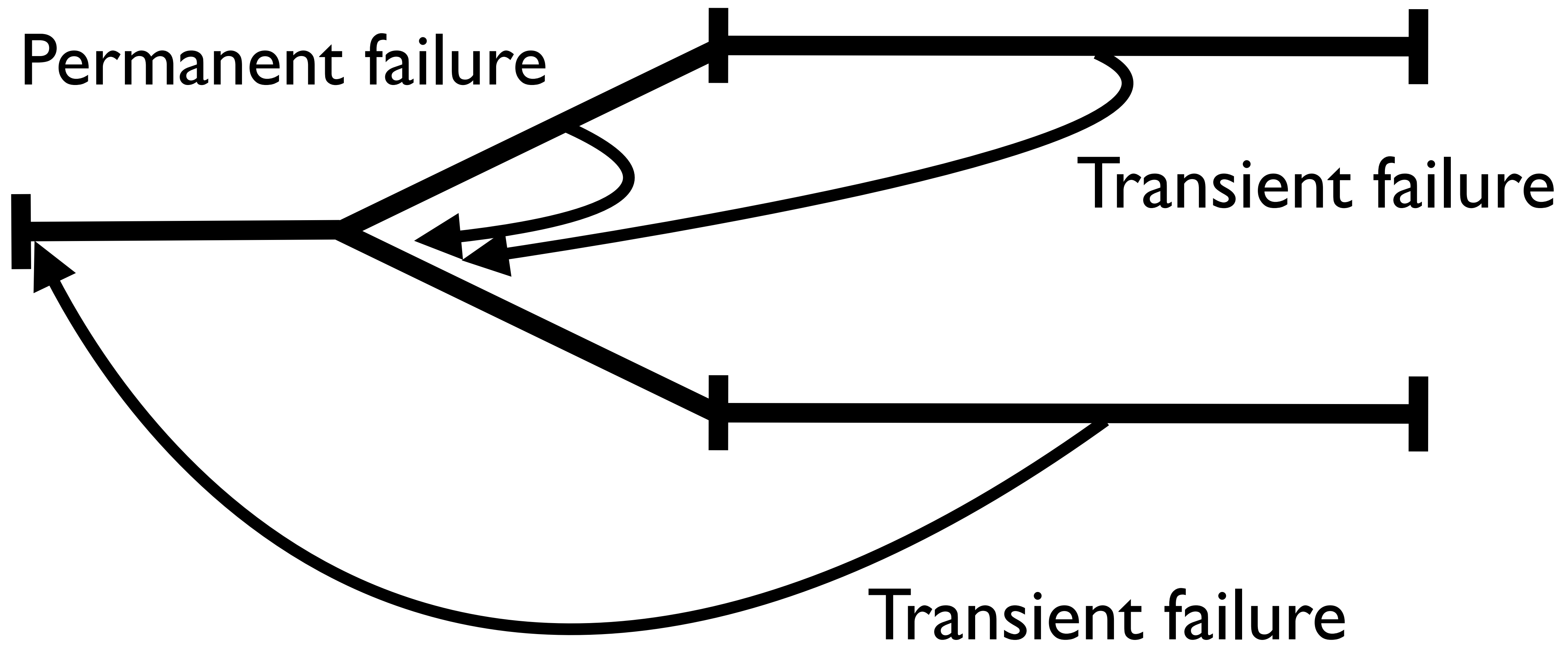
Permanent failure
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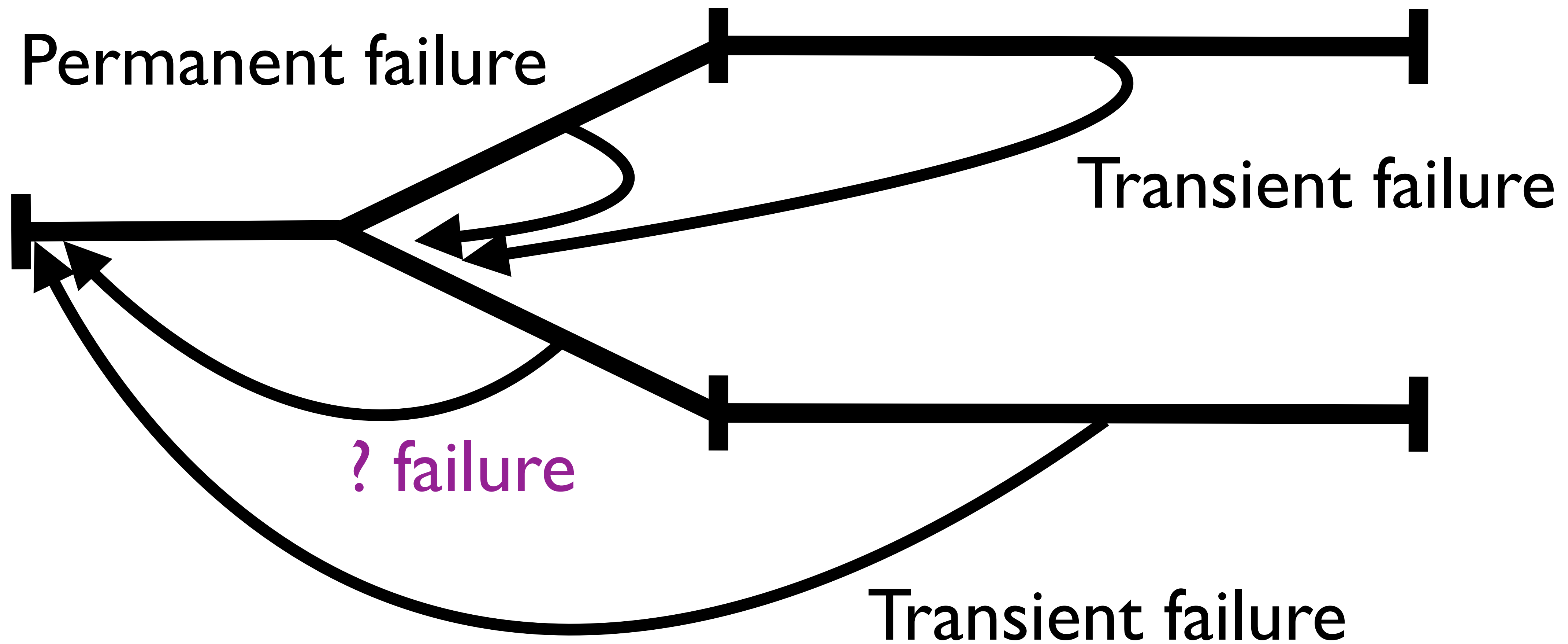
Permanent failure
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? failure
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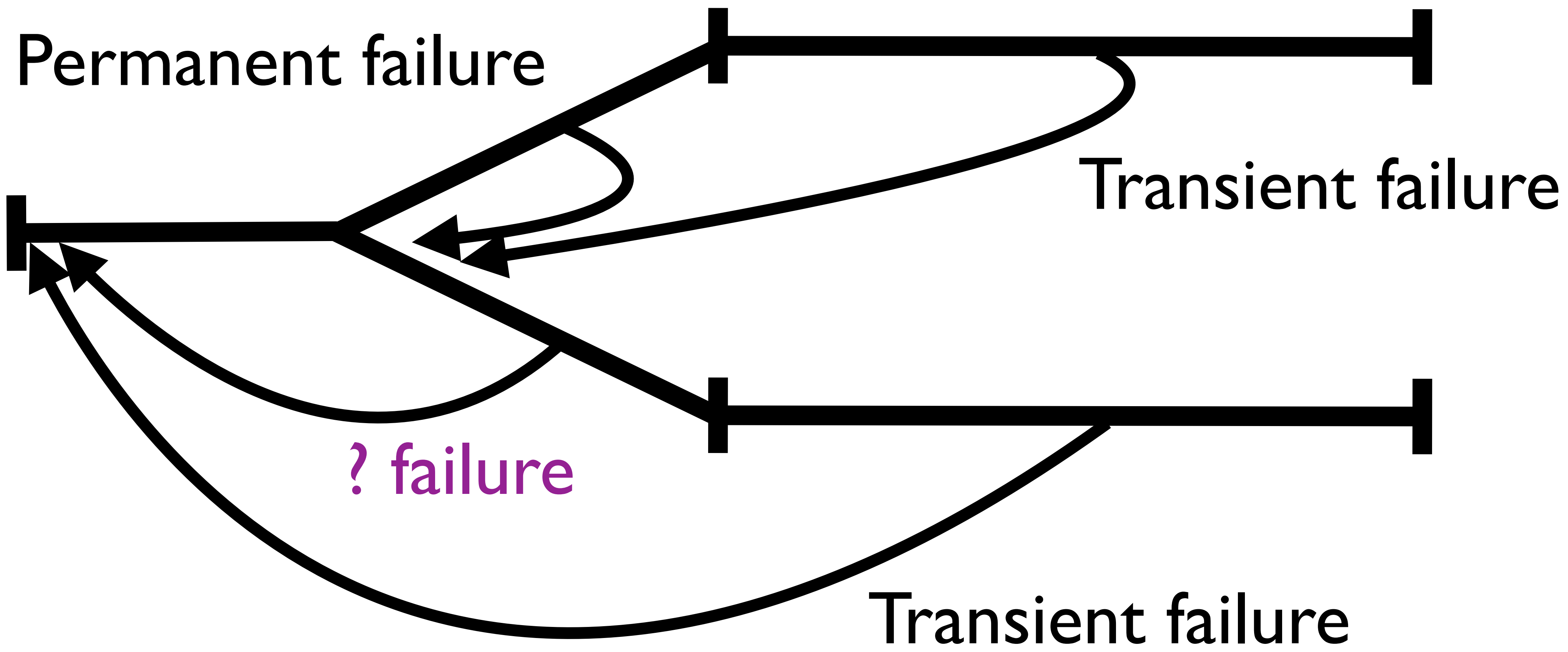

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Trouble with k-CAS

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    1. Sort refs
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- Additional book-keeping required
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- Common case is *just a single CAS*
    - *Identify and optimise with Arrows*

Reagent type

```
type 'a result = Block | Retry | Done of 'a

type ('a,'b) t =
  { try_react : 'a -> Reaction.t -> 'b Offer.t option -> 'b result;
    compose : 'r. ('b,'r) t -> ('a,'r) t;
    always_commits : bool;
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+
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```

No CASes

No channel communication

```
let rec never : 'a 'b. ('a,'b) t =
  { try_react = (fun _ _ _ -> Block);
    may_sync = false;
    always_commits = false;
    compose = fun _ -> never }
```

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  { try_react = (fun _ _ _ -> Block);
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    compose = fun _ -> never }
```

```
let rec constant : 'a 'b 'r. 'a -> ('a,'r) t -> ('b, 'r) t =
  fun x k (* continuation *) ->
    { may_sync = k.may_sync;
      always_commits = k.always_commits;
      try_react = (fun _ rx o -> k.try_react x rx o);
      compose = (fun next -> constant x (k.compose next)) }
```

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let rec never : 'a 'b. ('a,'b) t =
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      try_react = (fun _ rx o -> k.try_react x rx o);
      compose = (fun next -> constant x (k.compose next)) }
```
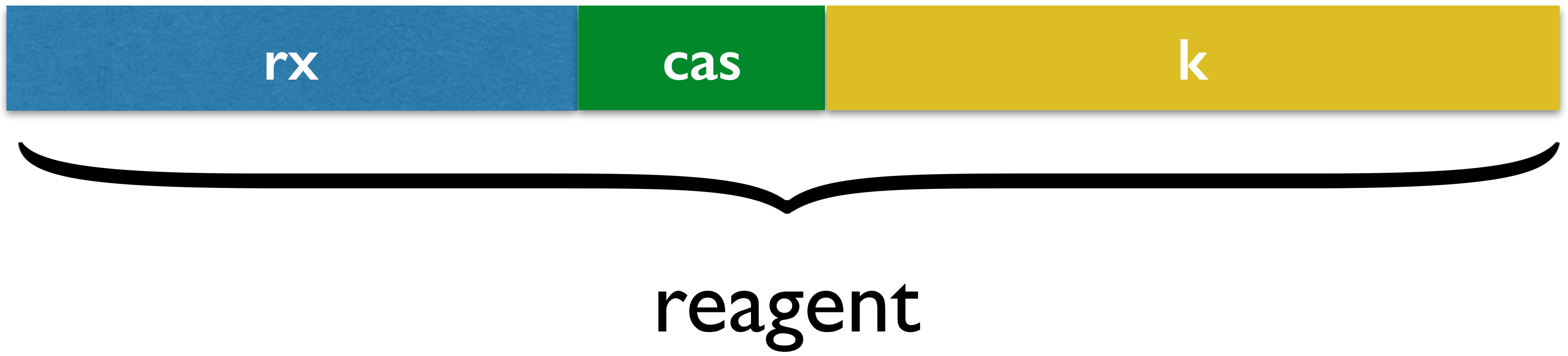

```
let rec <+> : 'a 'b 'r. ('a,'b) t -> ('a,'b) t -> ('a,'b) t =
  fun r1 r2 ->
    { always_commits = r1.always_commits && r1.always_commits;
      may_sync = r1.may_sync || r2.may_sync;
      ...
```

Specialising k-CAS

```
let rec cas r ~expect ~update k =
  let try_react () rx o =
    if Reaction.has_no_cas rx &&
       k.always_commits then
      if CAS.cas r.data expect update then
        ( k.try_react () rx o ) (* Will succeed! *)
      else Retry
    else
      (* slow path with bookkeeping *)
  in
  ...
```



Optimising Transient Failures

```
let rec without_offer pause r v =
  match r.try_react v Reaction.empty None with
  | Done res -> res
  | Retry ->
        ( pause ();
          if r.may_sync
          then with_offer pause r v
          else without_offer pause r v)
  | Block -> with_offer pause r v

let run r v =
  let b = Backoff.create () in
  let pause () = Backoff.once b in
  without_offer pause r v
```