Reagents:
lock-free programming for the masses

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University of Cambridge

OCaml Labs

Multicore OCaml

Concurrency *Parallelism*

Libraries

Language + Stdlib

Compiler

Multicore OCaml

Concurrency | *Parallelism*

Libraries

Language + Stdlib

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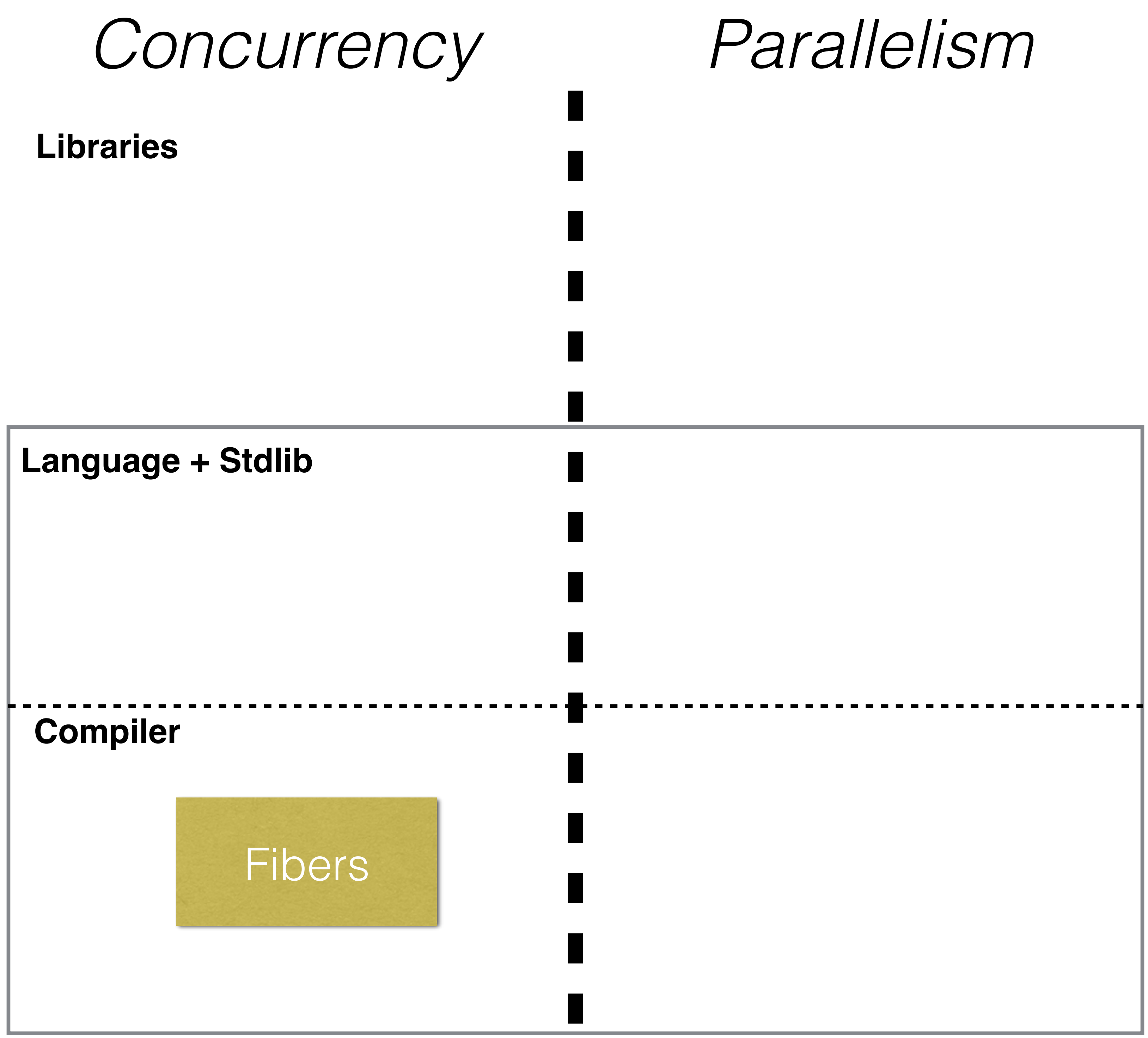
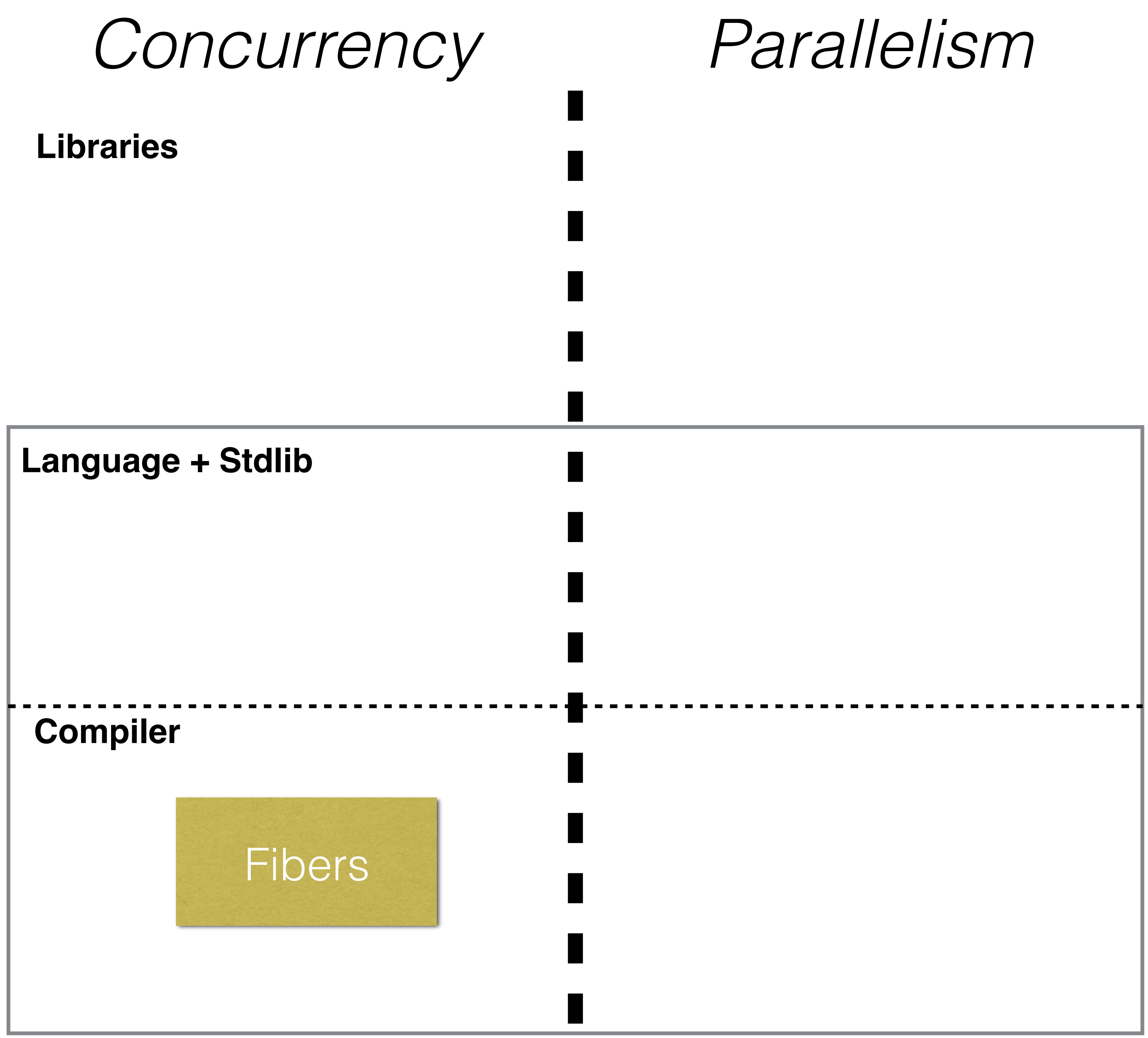
Multicore OCaml

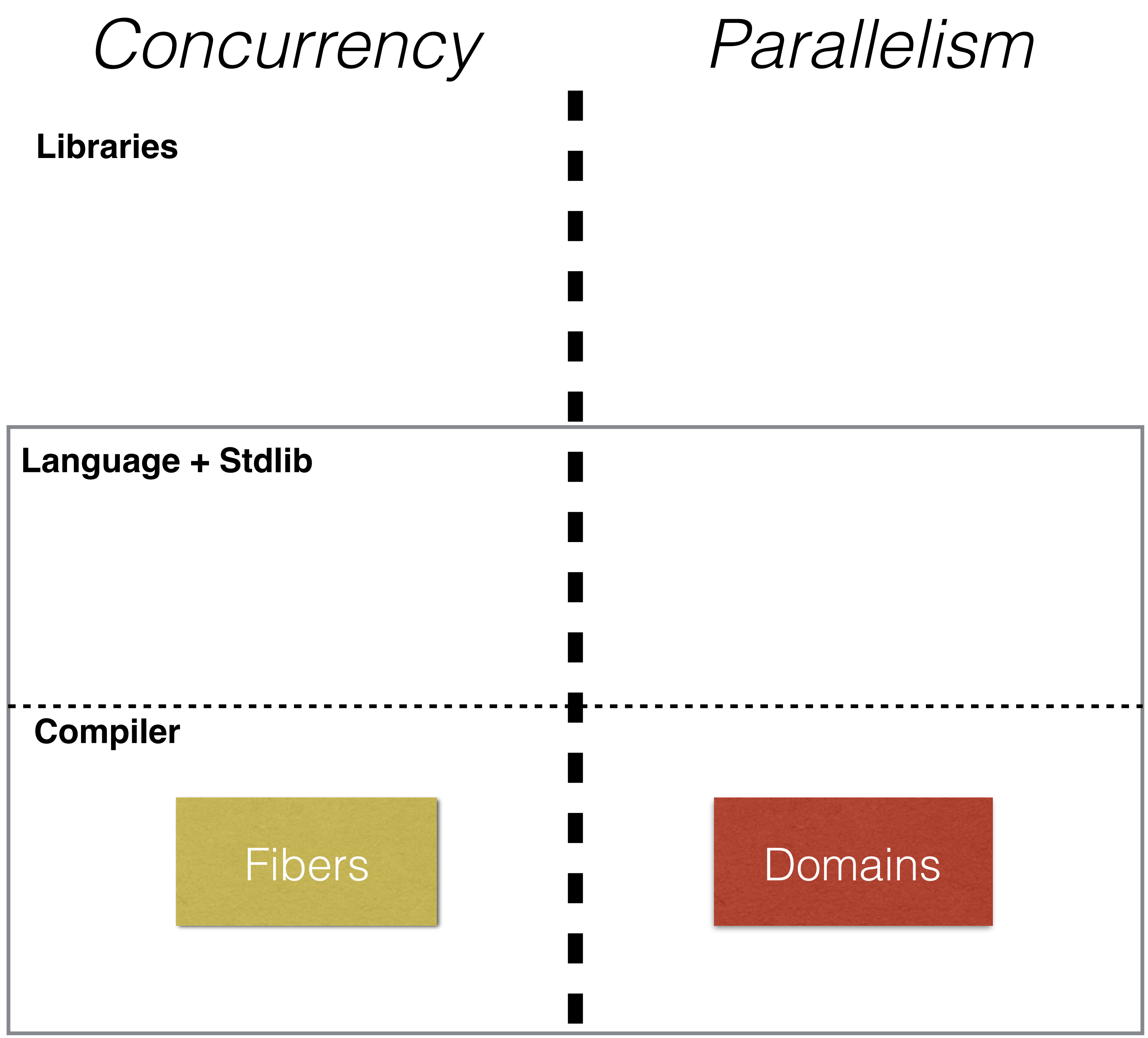


Multicore OCaml



- **12M** fibers/s on 1 core
- **30M** fibers/s on 4 cores

Multicore OCaml



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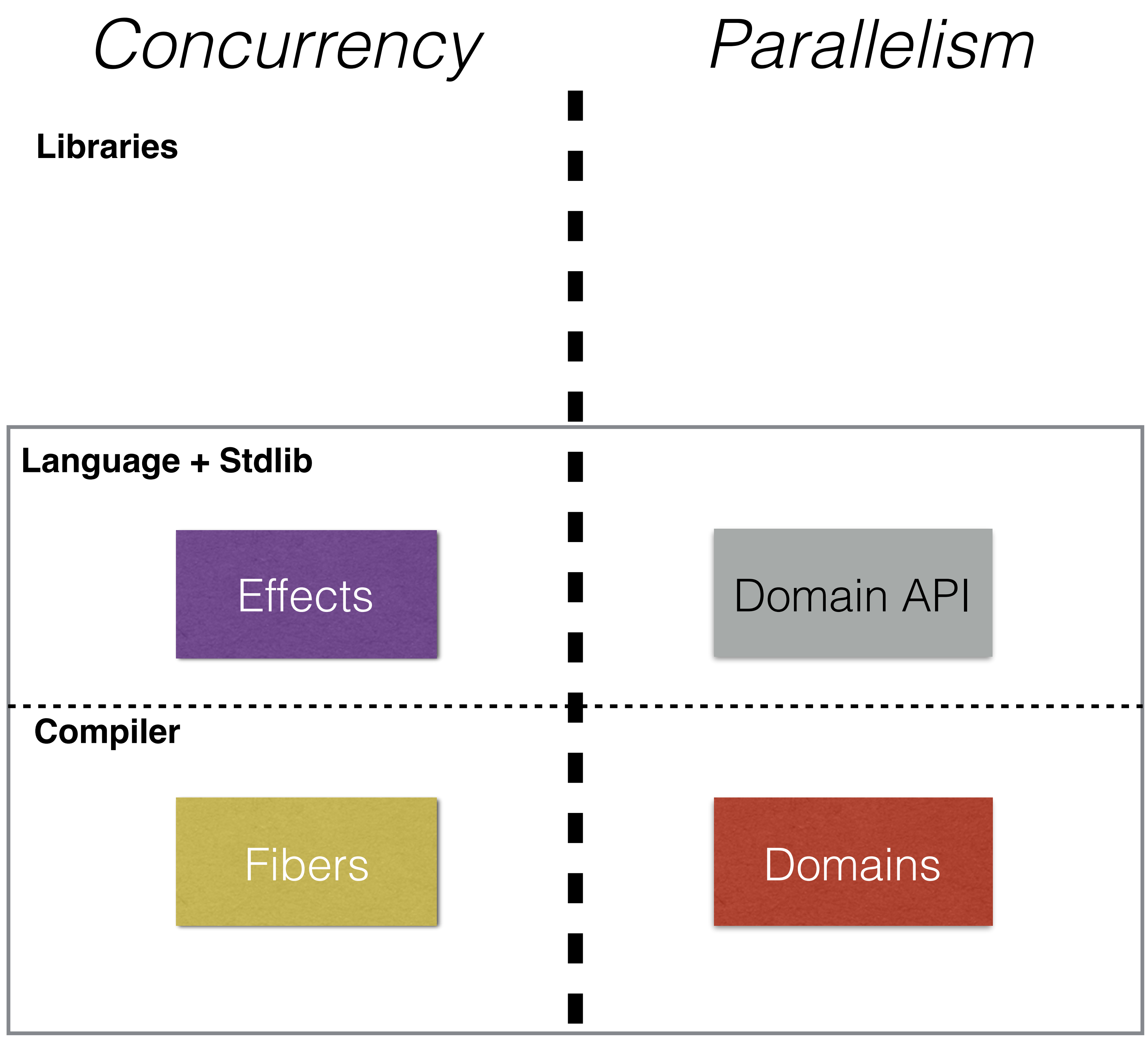

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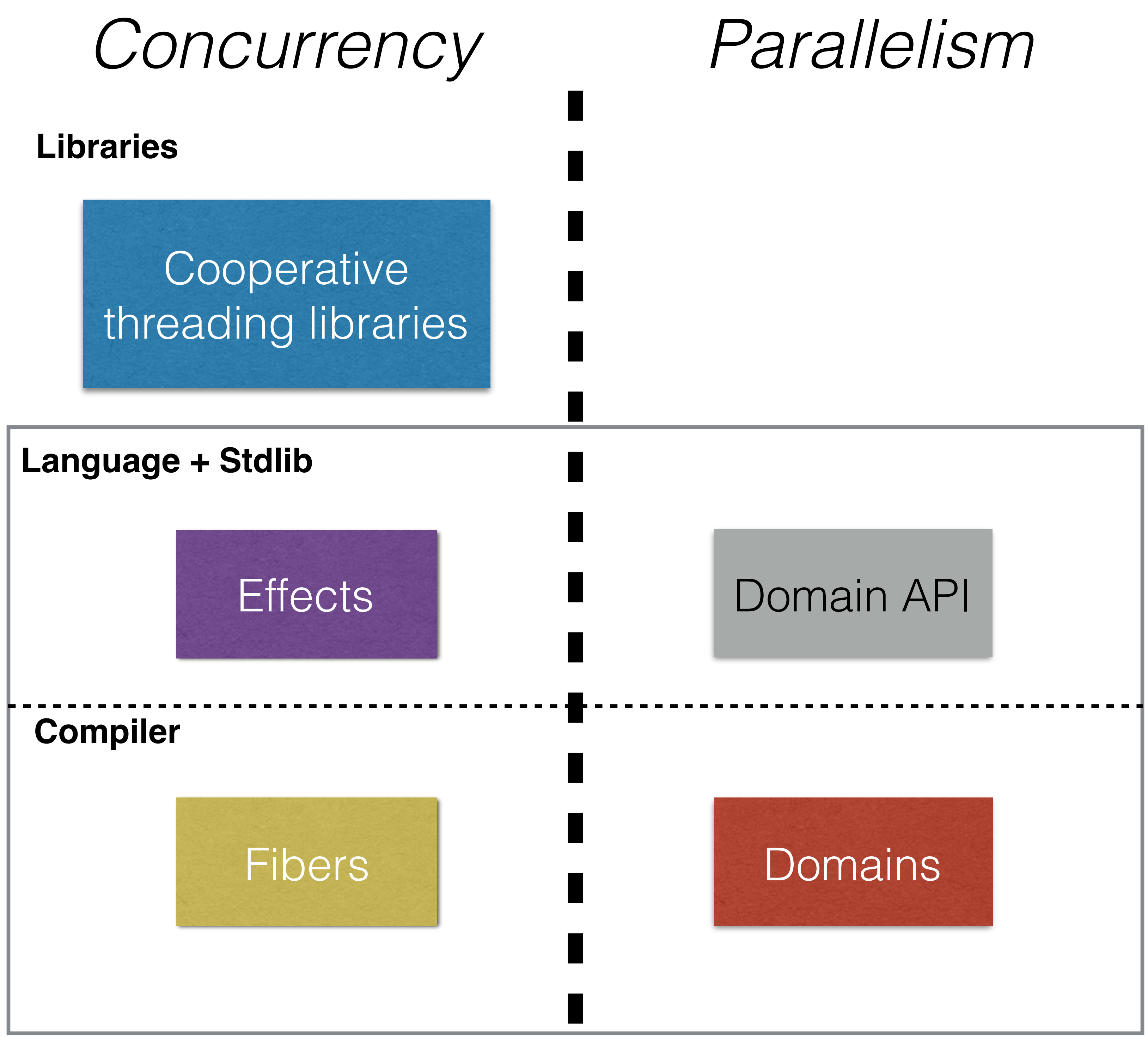

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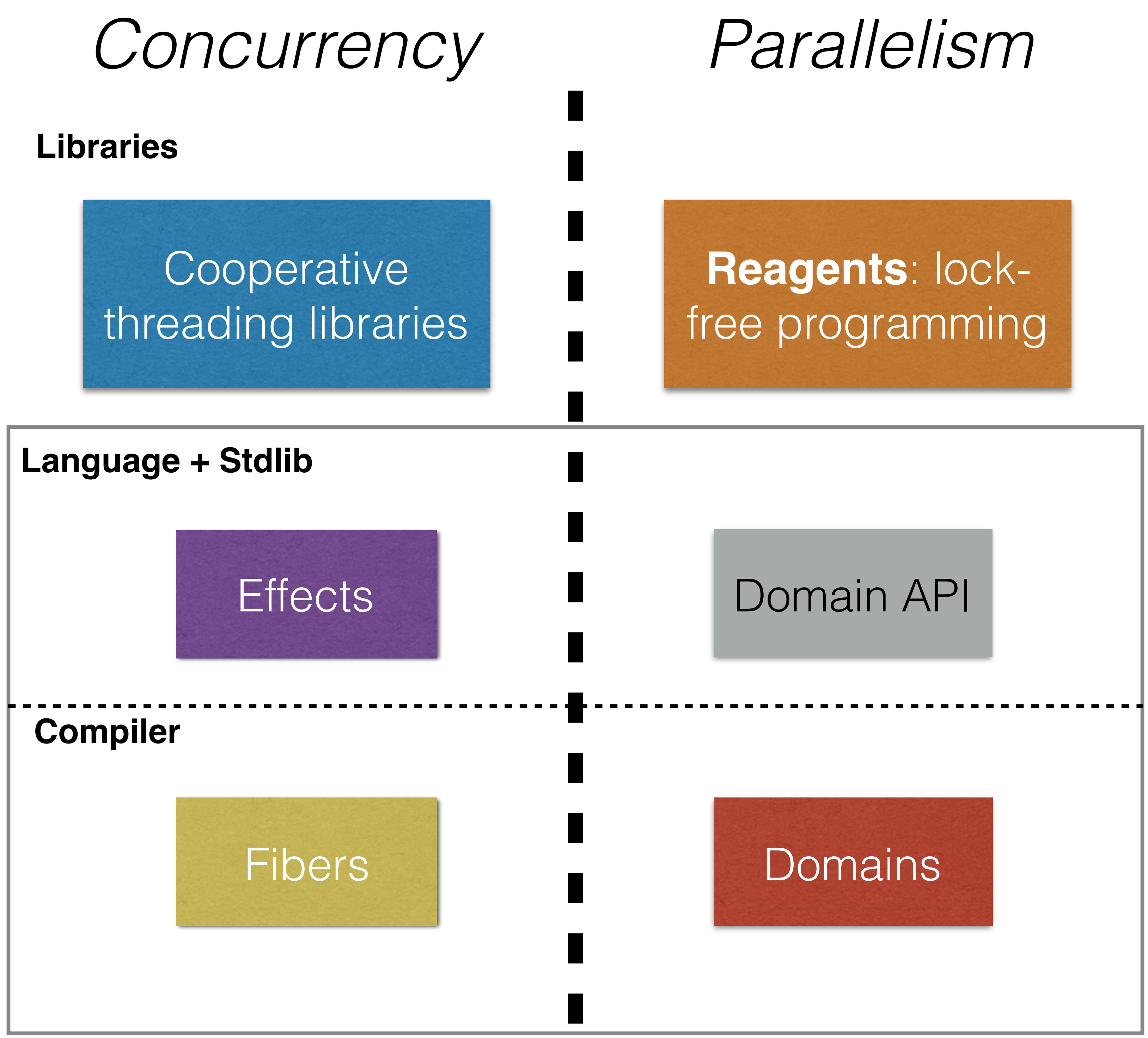

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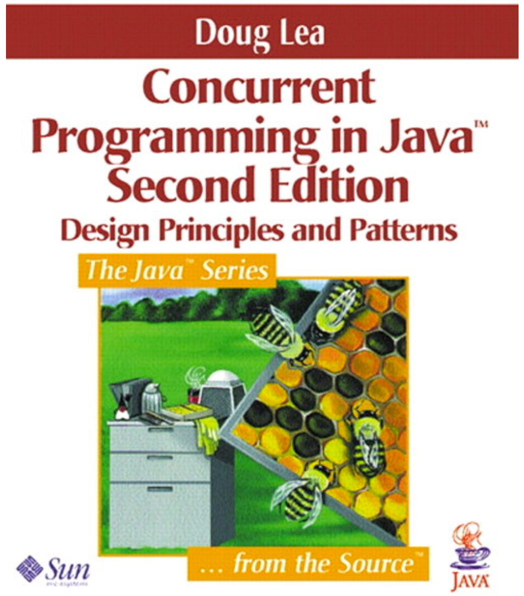
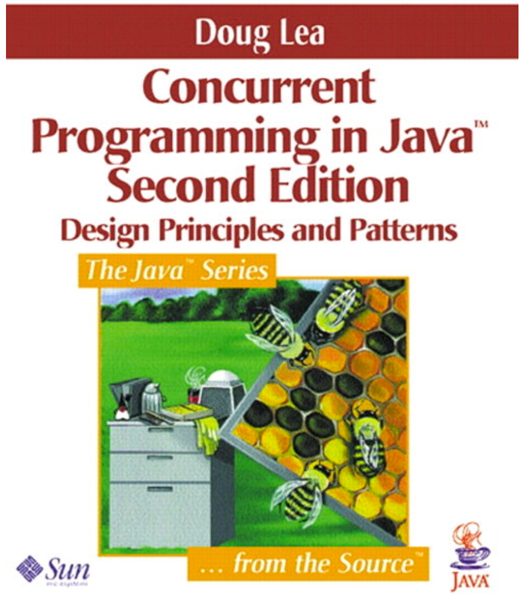


JVM: `java.util.concurrent` **.Net:** `System.Concurrent.Collections`



Microsoft .NET

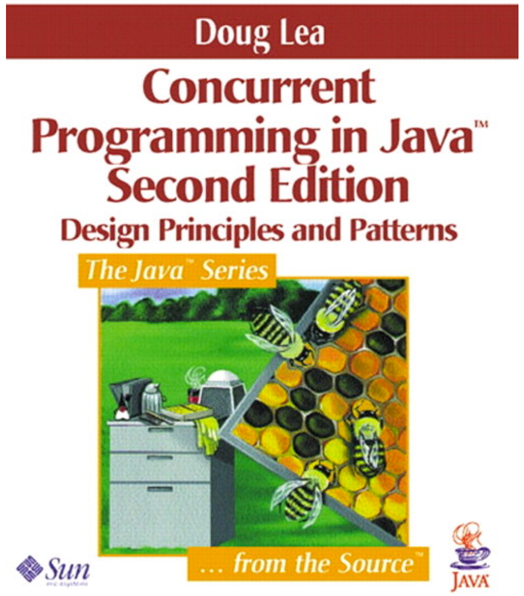
JVM: `java.util.concurrent`   **.Net:** `System.Concurrent.Collections`

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)



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Data st

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Priority, blocking
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Maps (hash & skiplist)

Not Composable

How to build *composable* lock-free programs?

lock-free

lock-free

Under contention, **at least 1** thread makes progress

lock-free	Under contention, **at least 1** thread makes progress
obstruction-free	Single thread **in isolation** makes progress

wait-free	Under contention, **each** thread makes progress
lock-free	Under contention, **at least 1** thread makes progress
obstruction-free	Single thread **in isolation** makes progress

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
```

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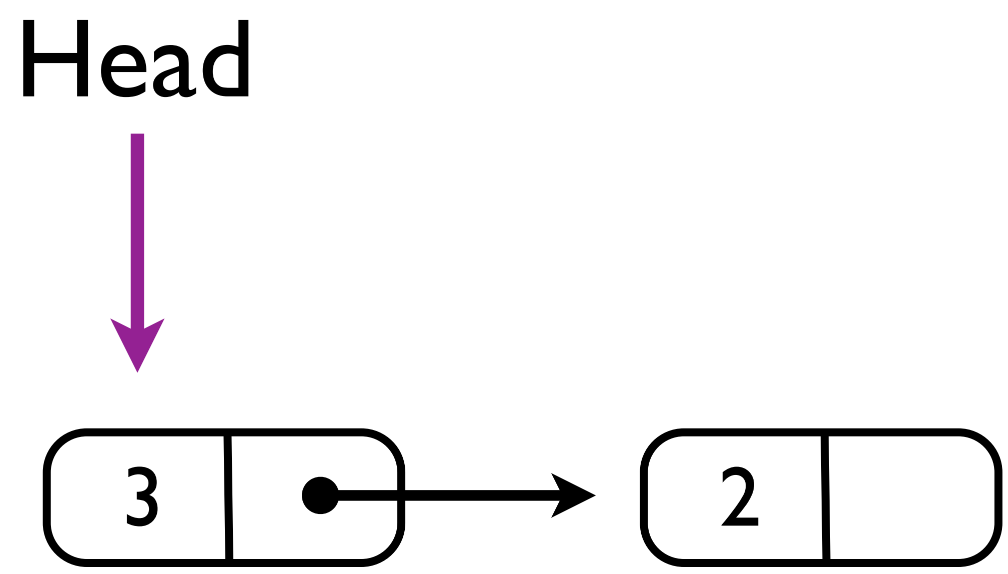
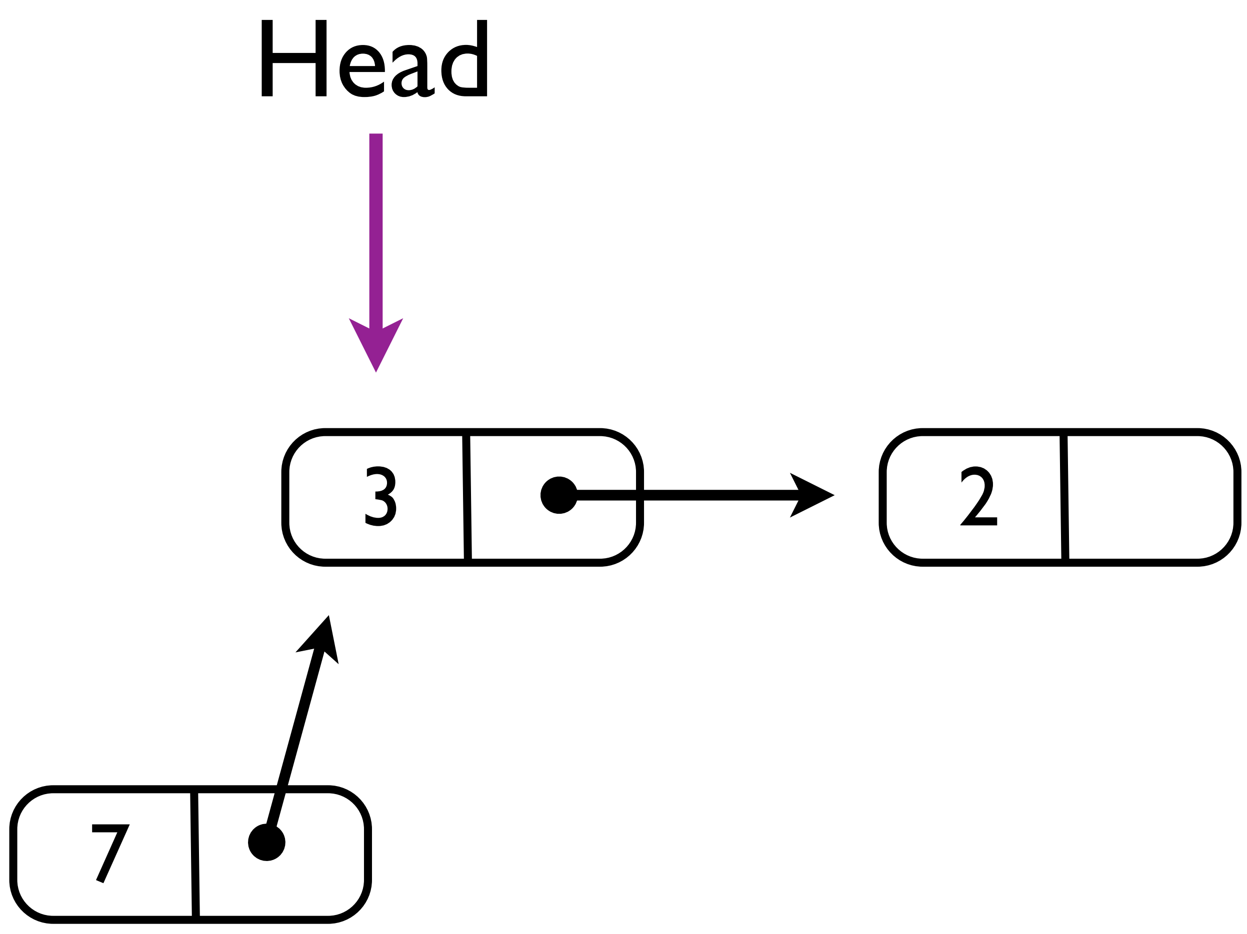
- Implemented *atomically* by processors
  - x86: CMPXCHG and friends
  - arm: LDREX, STREX, etc.
  - ppc: lwarx, stwcx, etc.


Head
3
2


Head
3
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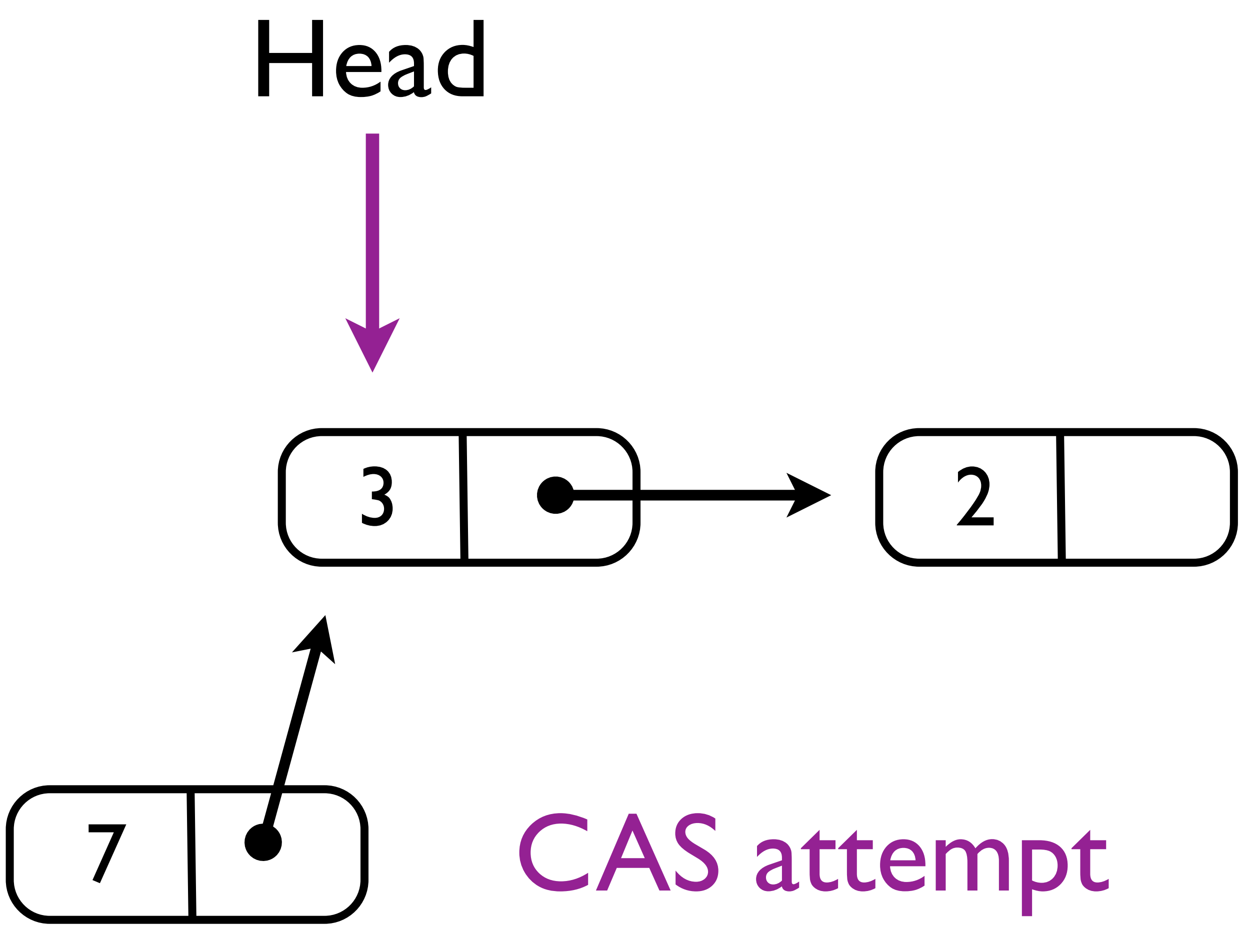
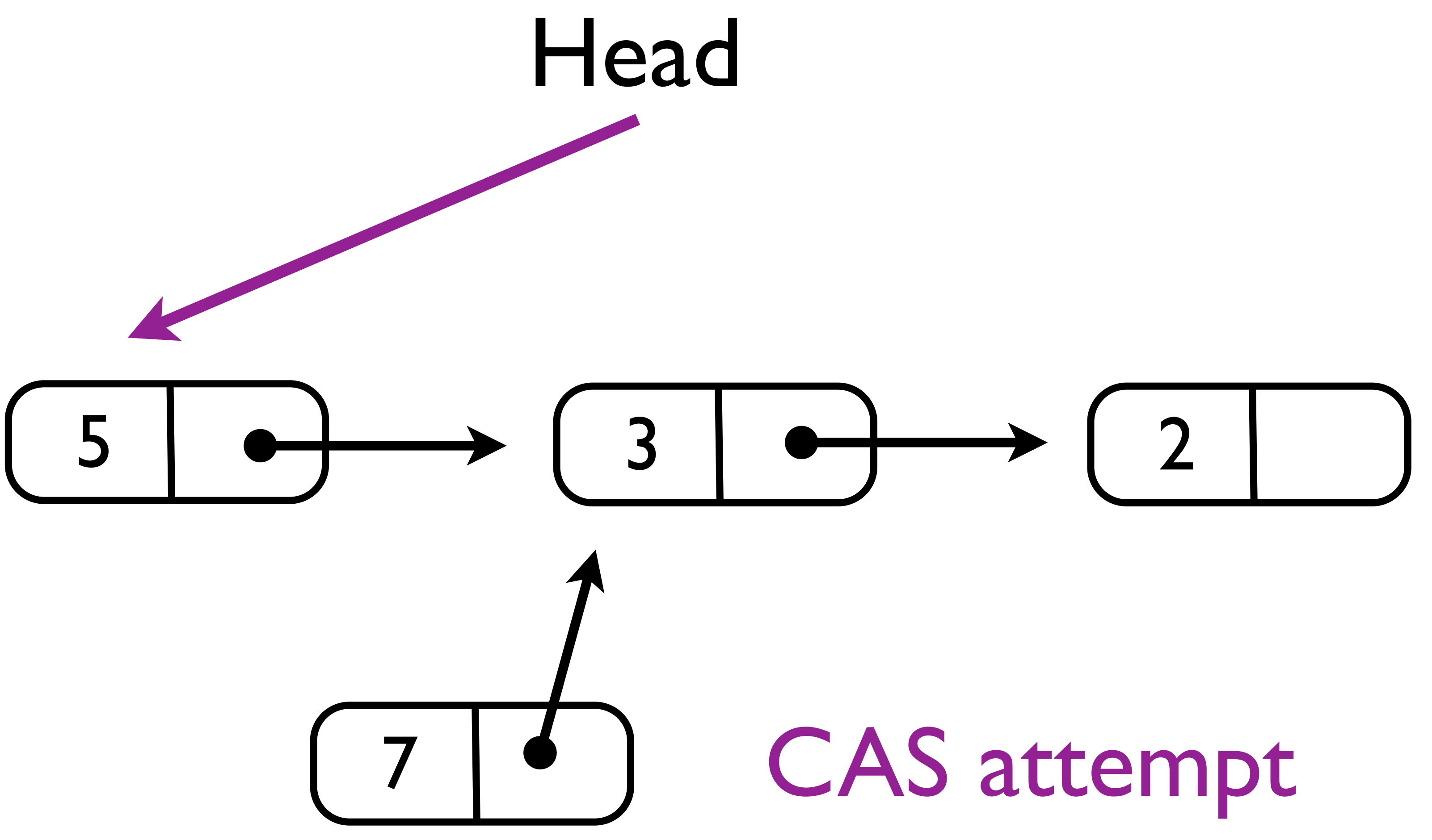
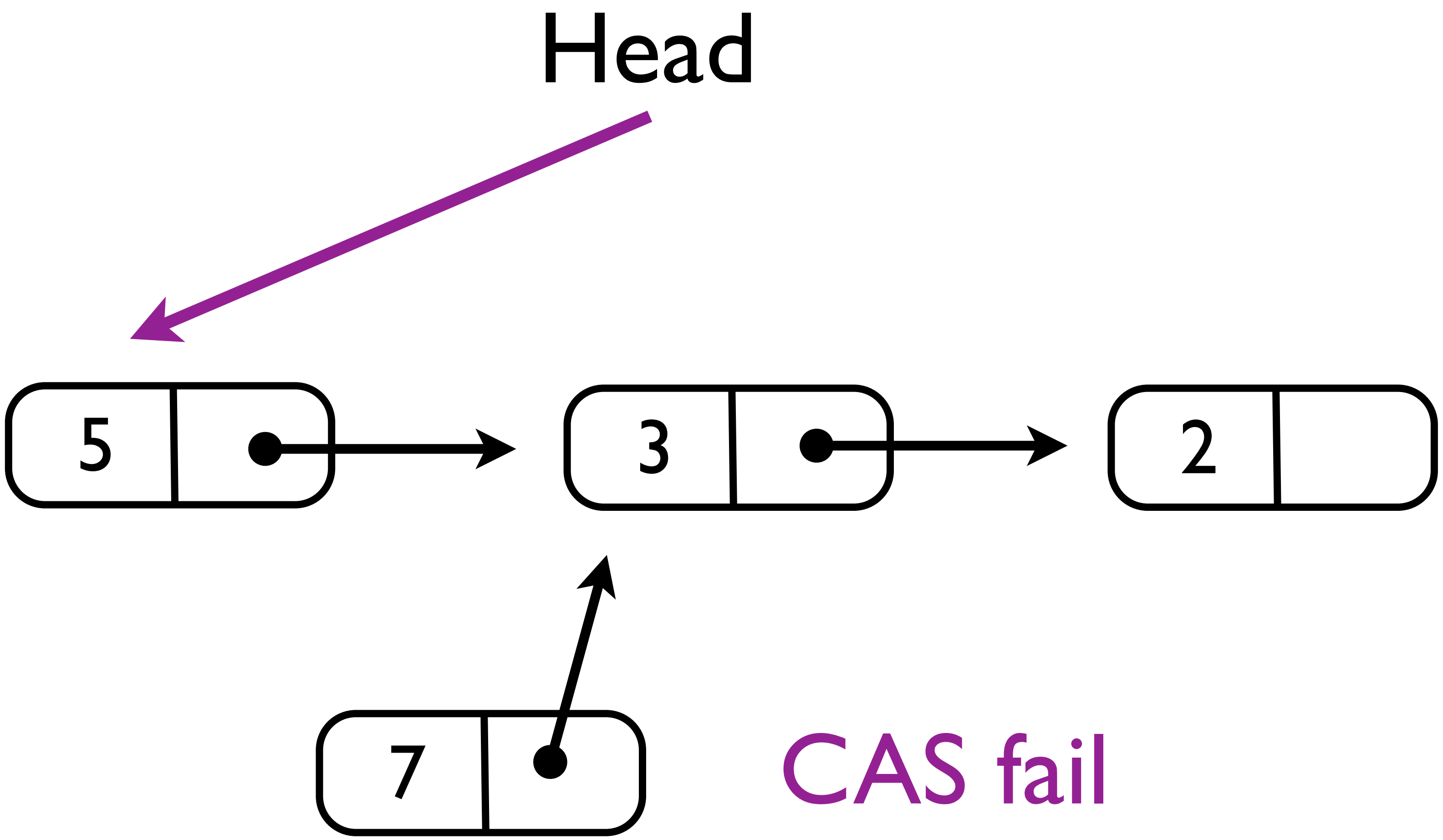

Head
3
2
7
CAS attempt


Head
5
3
2
7
CAS attempt


Head
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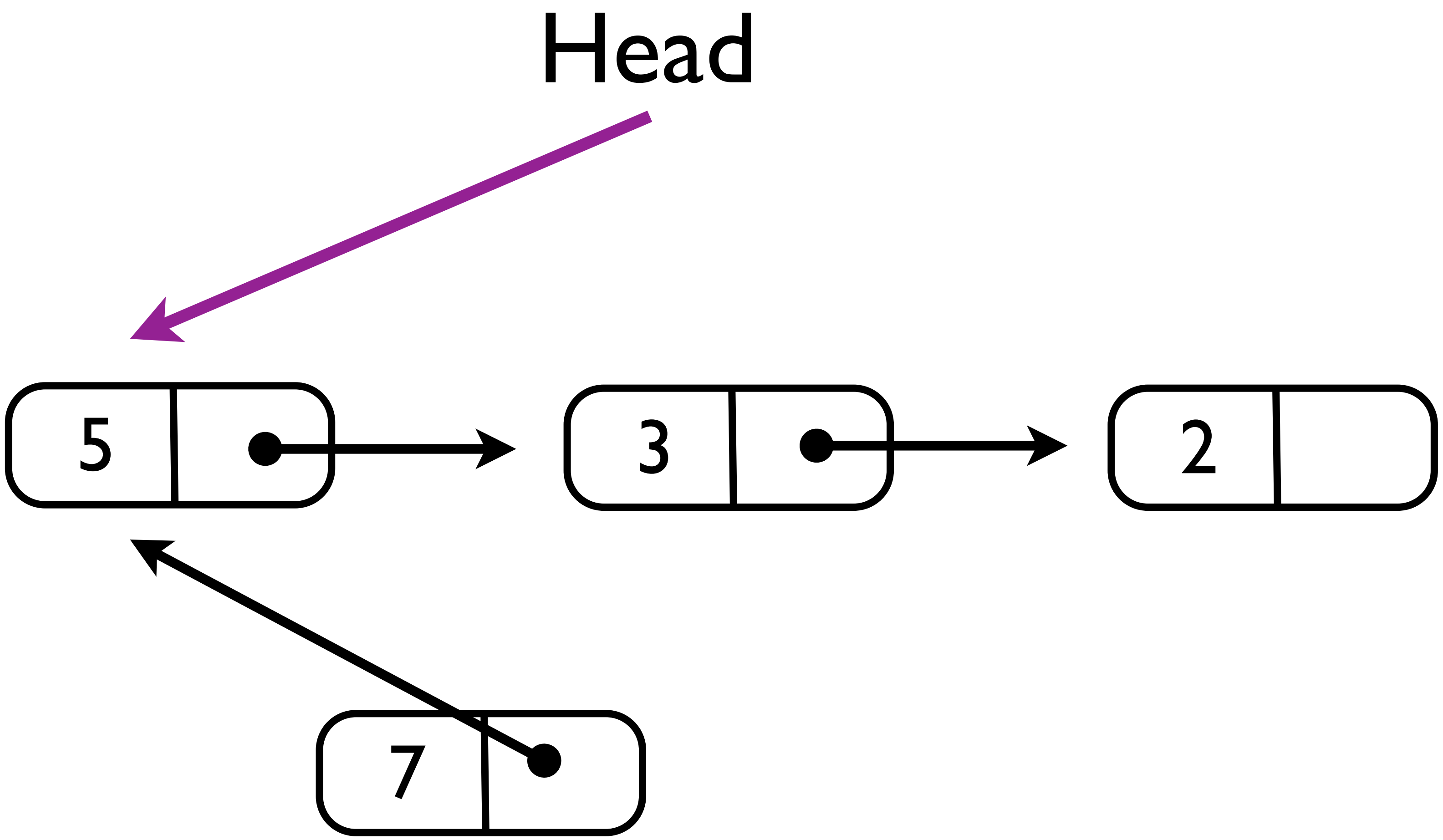
3
2
7
CAS fail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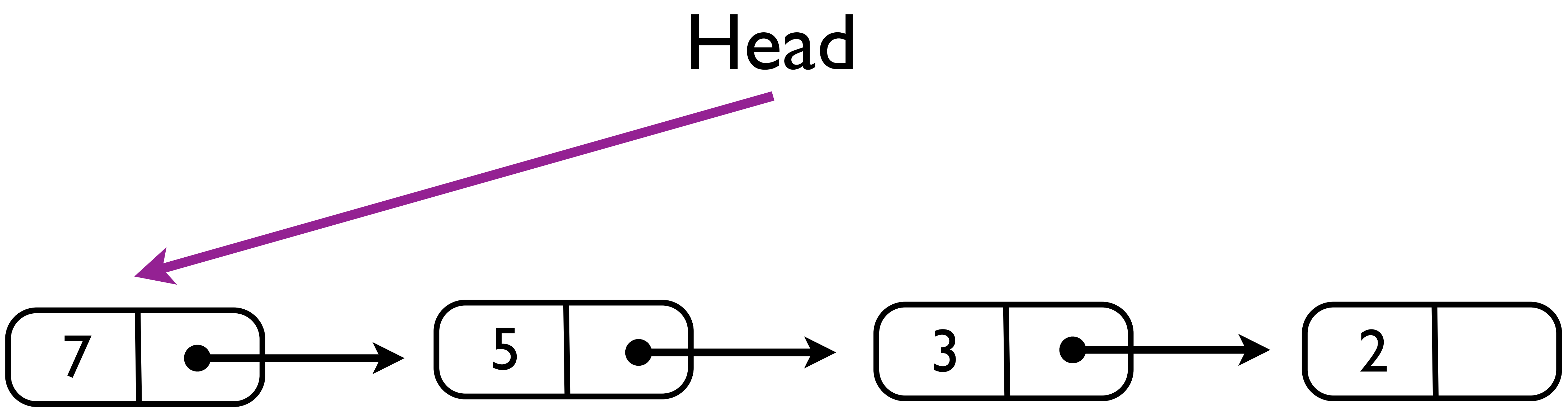
Head
7
5
3
2

```ocaml
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
```

```
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
```

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

is not ***atomic***

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***

Reagents

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

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

is ***atomic***

PLDI 2012

Reagents: Expressing and Composing Fine-grained Concurrency

Aaron Turon

Northeastern University

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Abstract

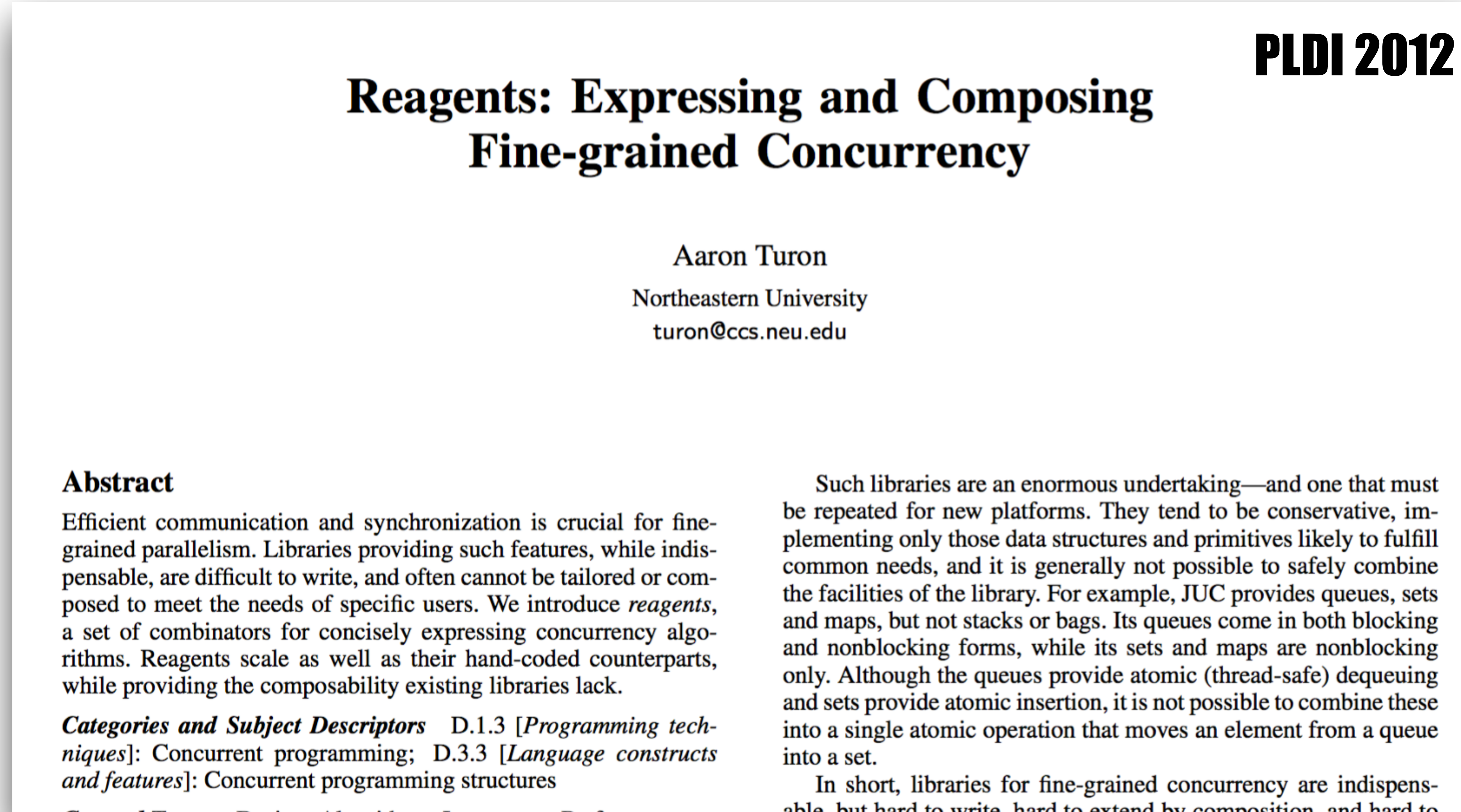
Efficient communication and synchronization is crucial for fine-grained parallelism. Libraries providing such features, while indispensable, are difficult to write, and often cannot be tailored or composed to meet the needs of specific users. We introduce *reagents*, a set of combinators for concisely expressing concurrency algorithms. Reagents scale as well as their hand-coded counterparts, while providing the composability existing libraries lack.

Categories and Subject Descriptors D.1.3 [*Programming techniques*]: Concurrent programming; D.3.3 [*Language constructs and features*]: Concurrent programming structures

General Terms Design, Algorithms, Languages, Performance

Such libraries are an enormous undertaking—and one that must be repeated for new platforms. They tend to be conservative, implementing only those data structures and primitives likely to fulfill common needs, and it is generally not possible to safely combine the facilities of the library. For example, JUC provides queues, sets and maps, but not stacks or bags. Its queues come in both blocking and nonblocking forms, while its sets and maps are nonblocking only. Although the queues provide atomic (thread-safe) dequeuing and sets provide atomic insertion, it is not possible to combine these into a single atomic operation that moves an element from a queue into a set.

In short, libraries for fine-grained concurrency are indispensable, but hard to write, hard to extend by composition, and hard to



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Sequential >>> — Software transactional memory

Parallel <*> — Join Calculus

Selective <+> — Concurrent ML

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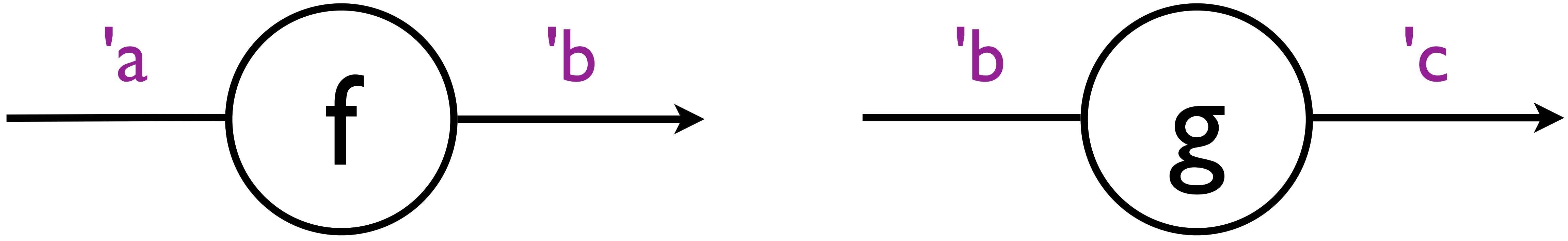
still lock-free!

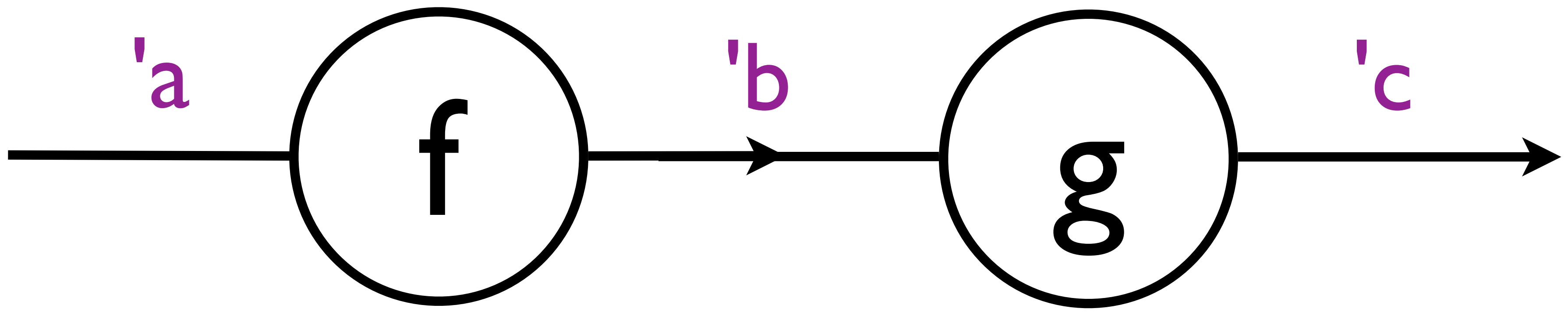
Design

Lambda: the ultimate abstraction



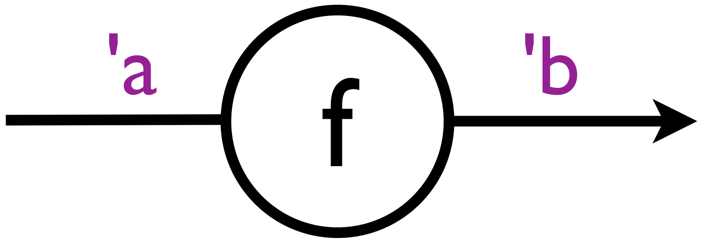

```
val f : 'a -> 'b        val g : 'b -> 'c
```

Lambda: the ultimate abstraction




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

Lambda abstraction:



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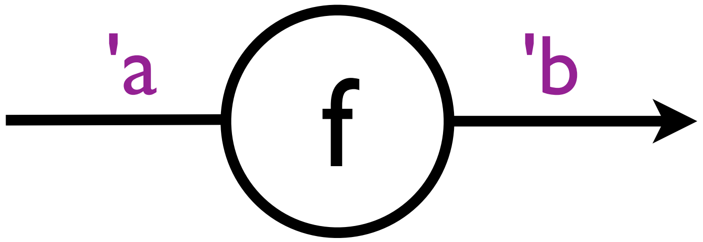

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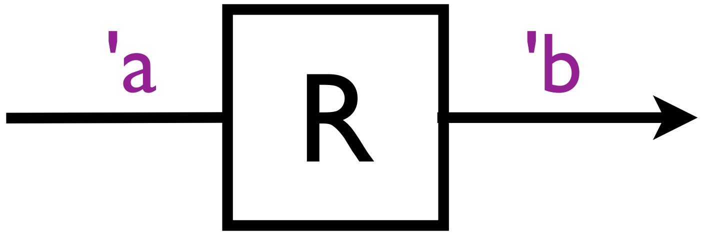
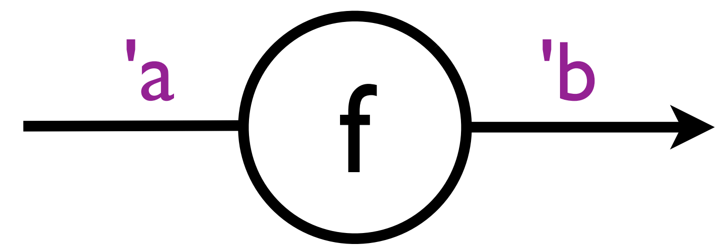
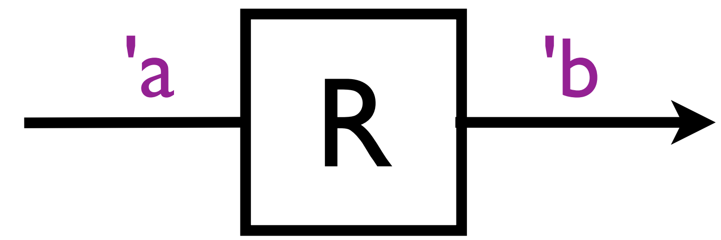



```
('a,'b) Reagent.t
```

Lambda abstraction:



Reagent abstraction:




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

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

Thread Interaction

```
module type Reagents = sig
  type ('a,'b) t

  (* shared memory *)
  module Ref : Ref.S with type ('a,'b) reagent = ('a,'b) t
  (* communication channels *)
  module Channel : Channel.S with type ('a,'b) reagent = ('a,'b) t
  ...
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
```

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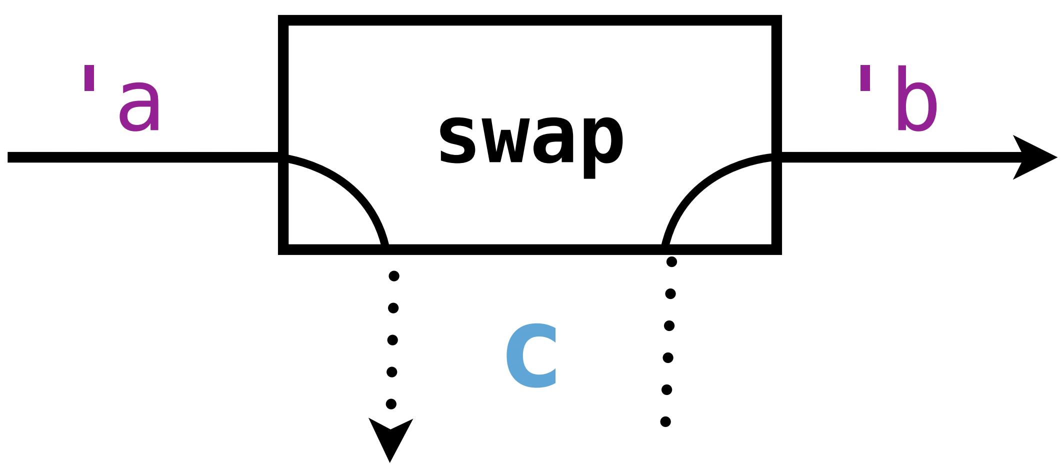
```

c: ('a,'b) endpoint



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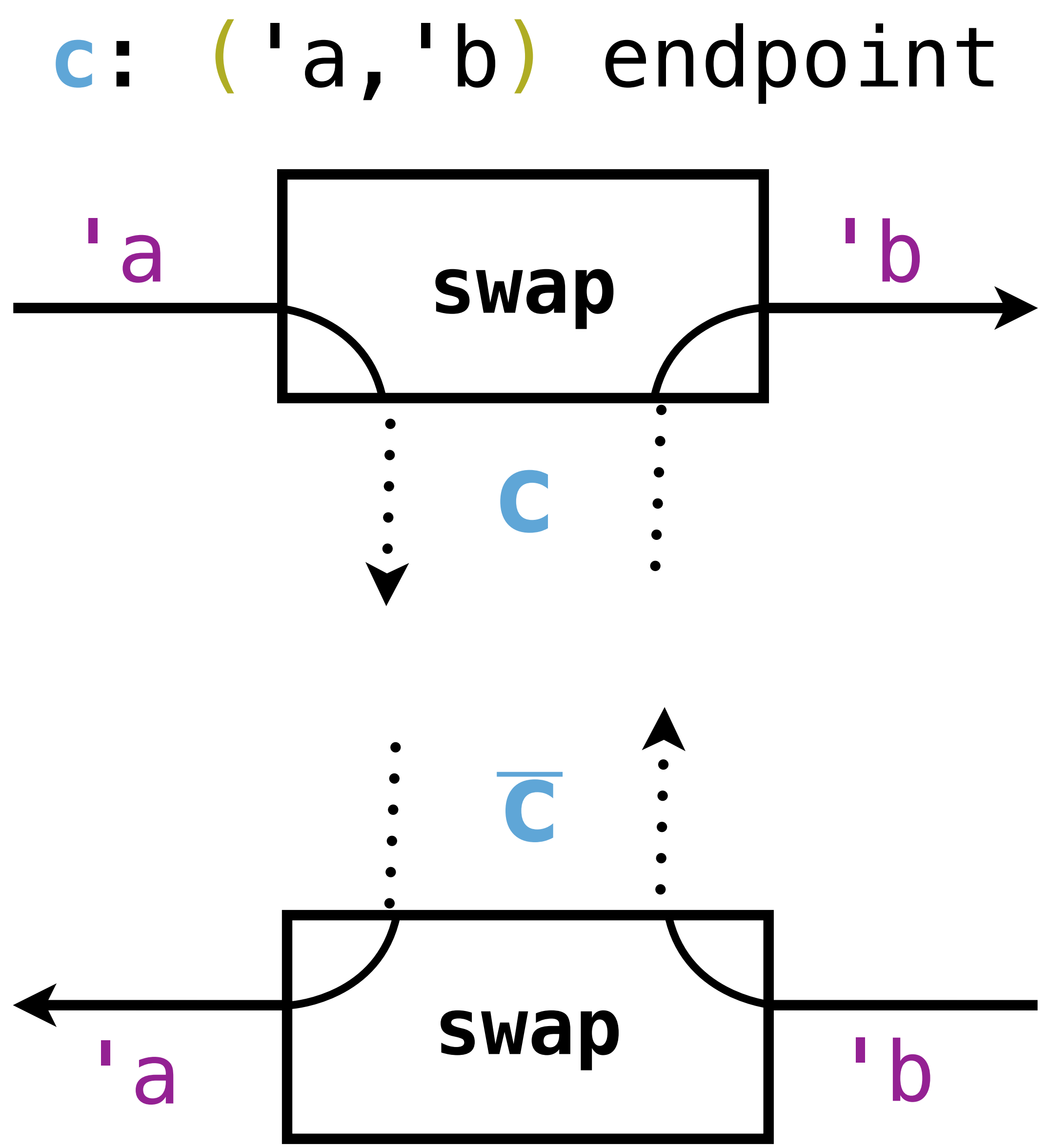
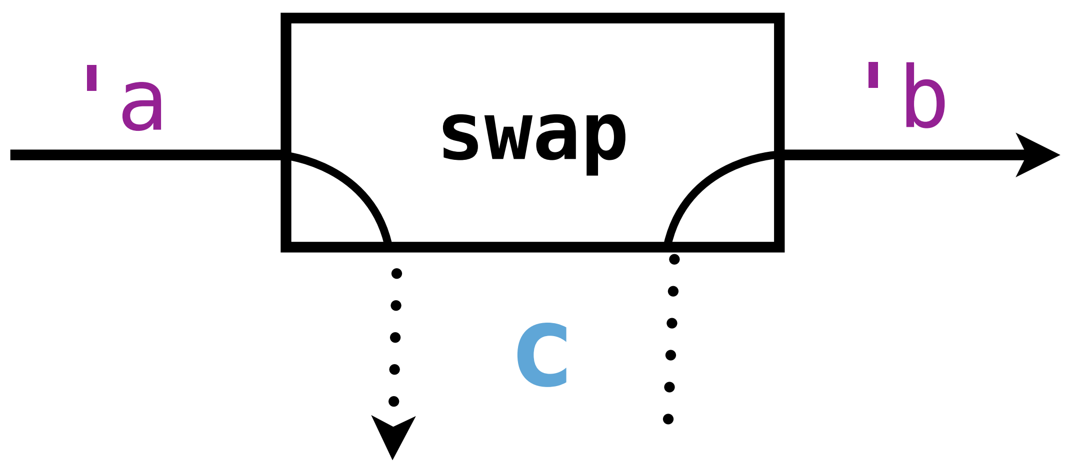
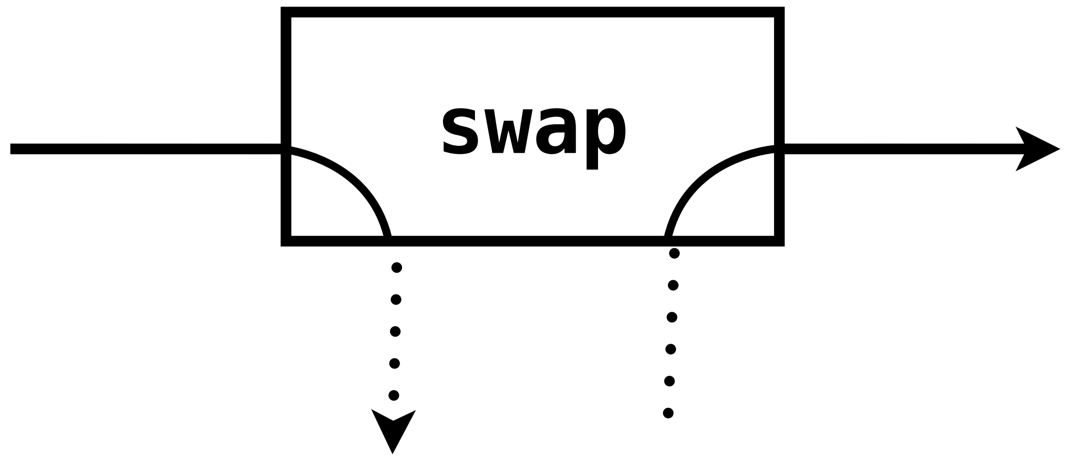


`c: ('a,'b) endpoint`

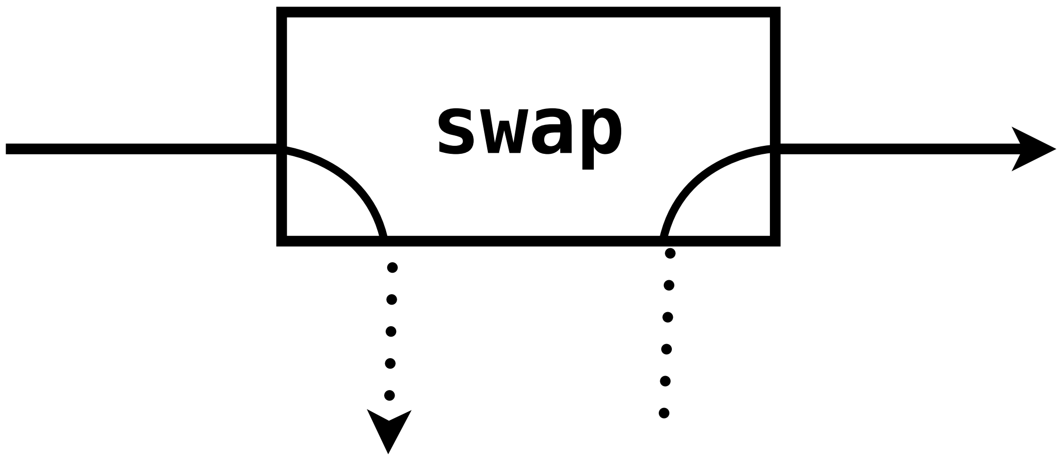


Message passing




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

Message passing

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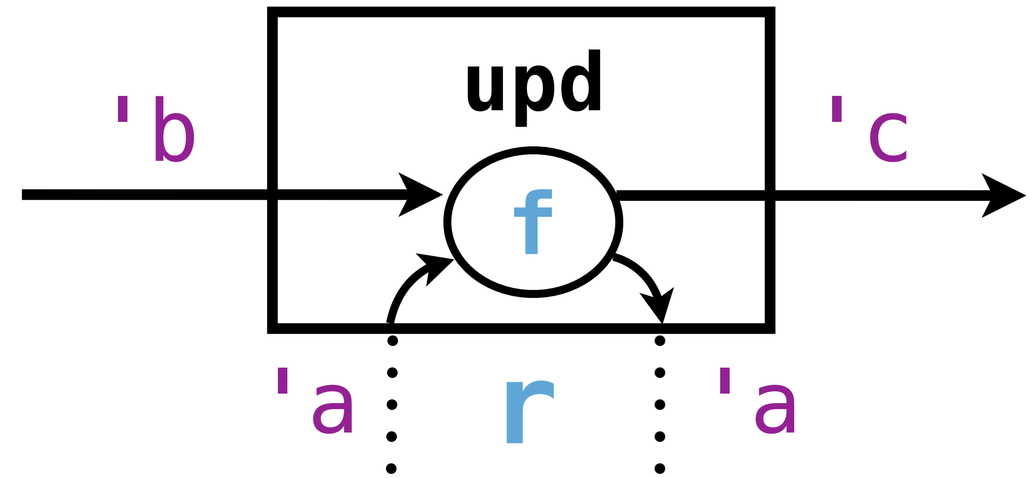
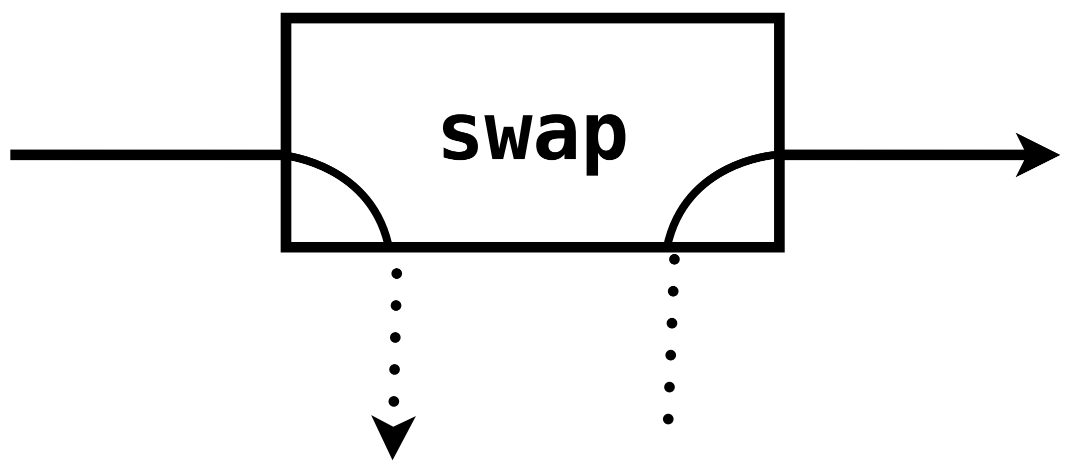
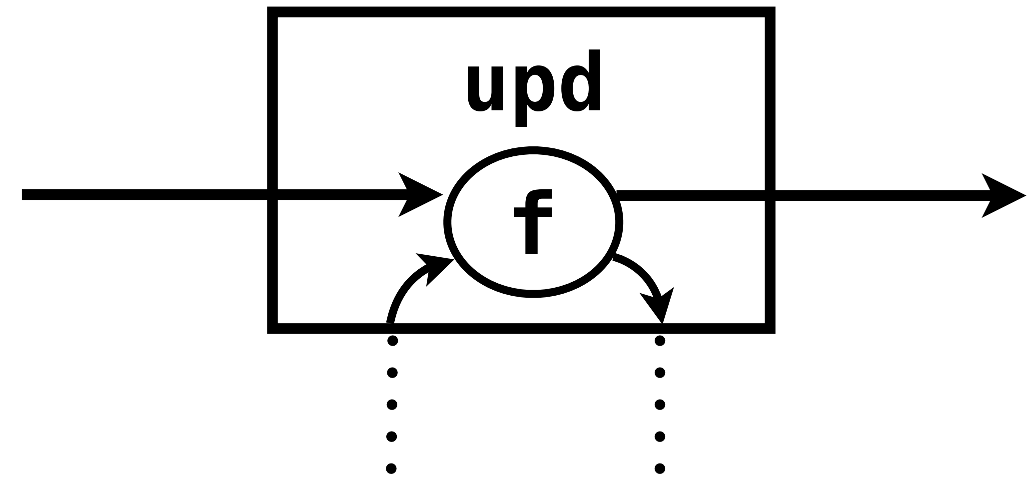


Message passing



Shared state



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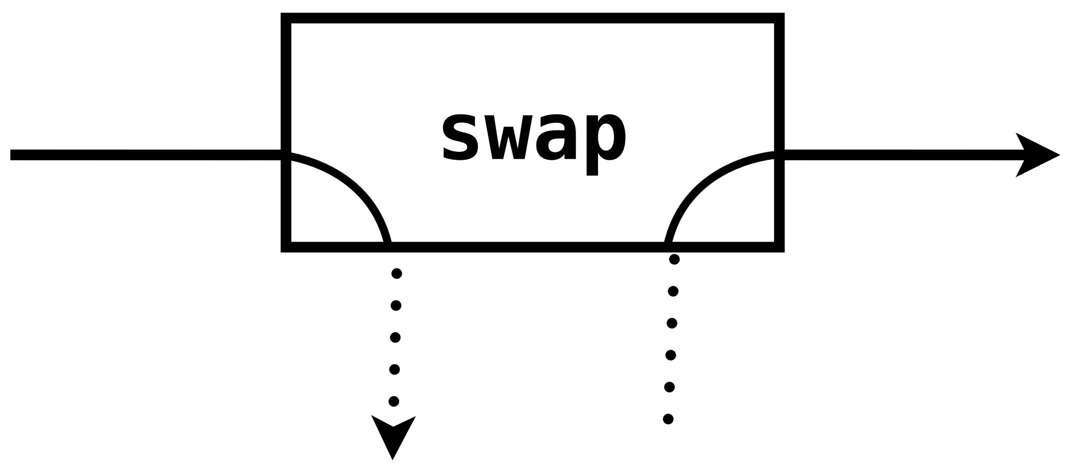

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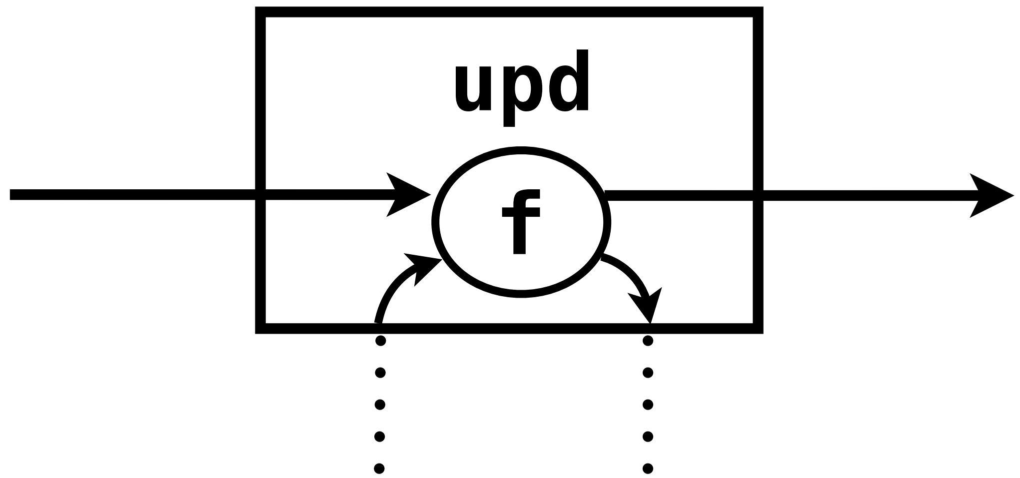

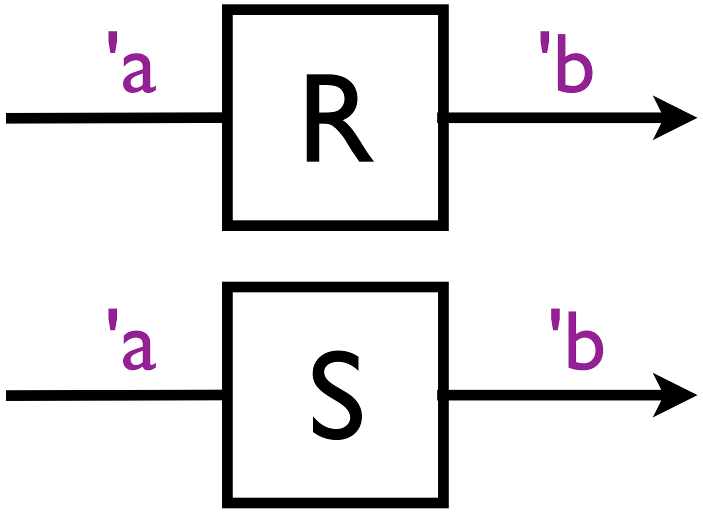

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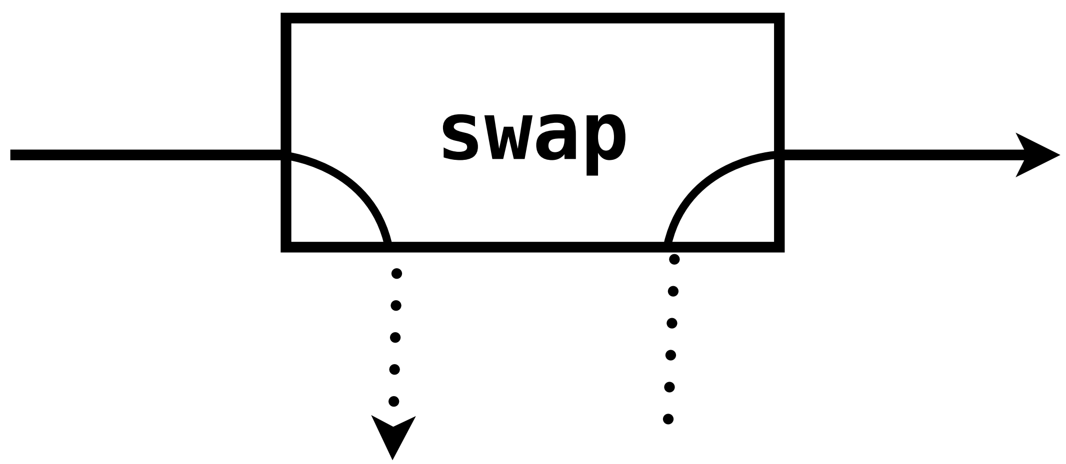

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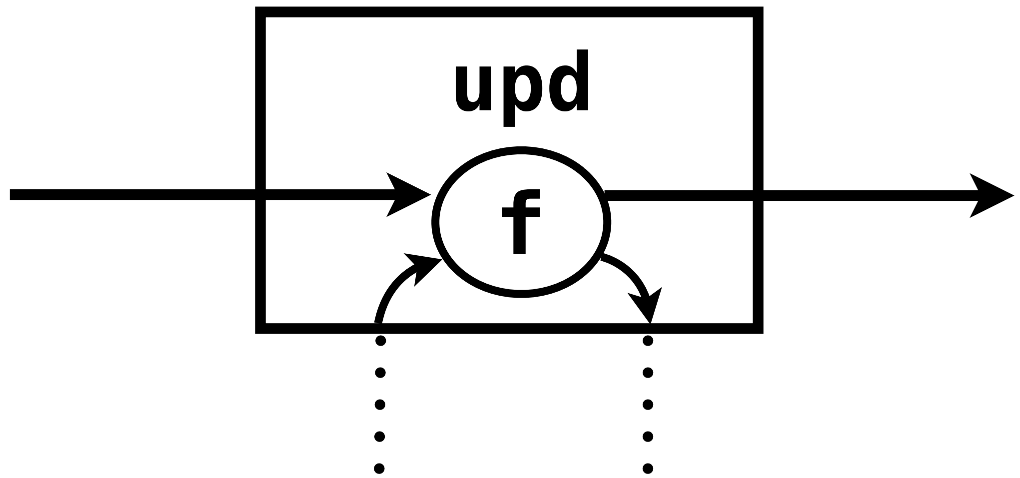

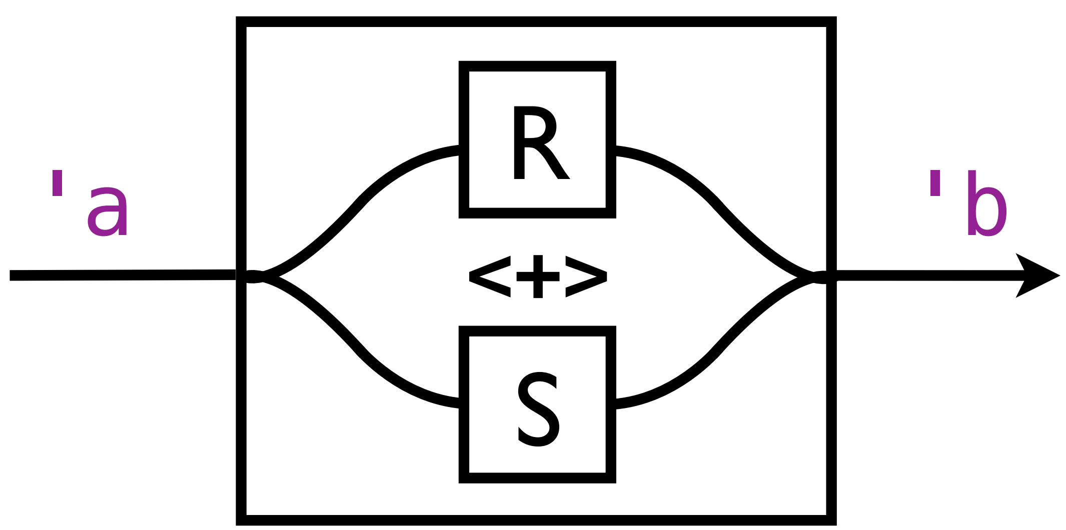

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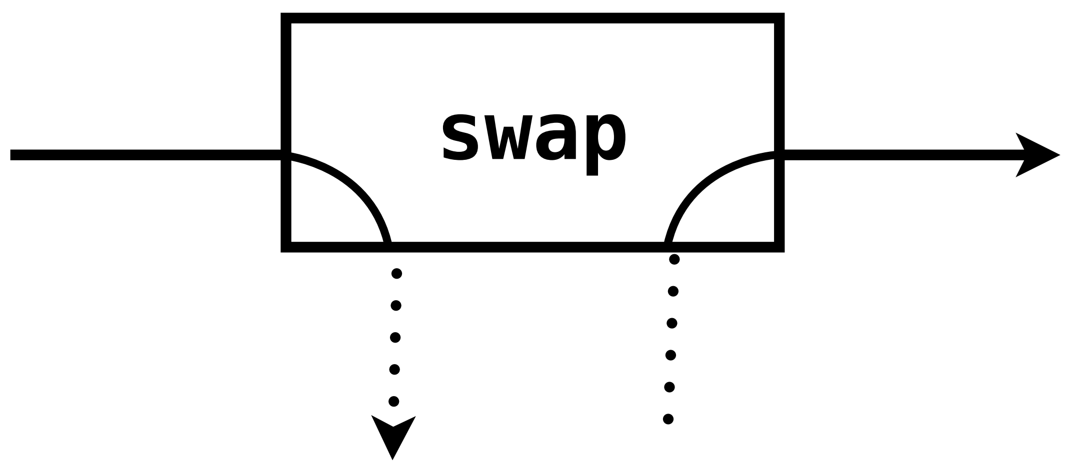

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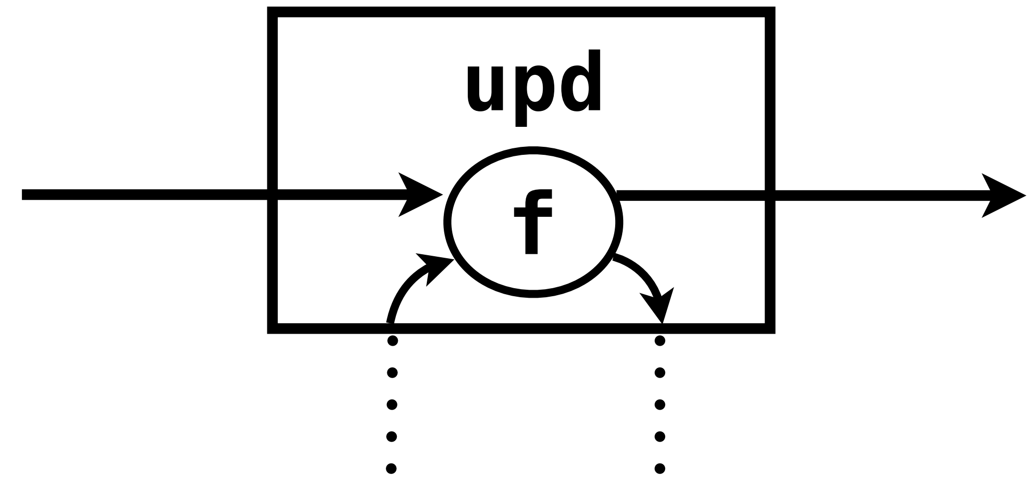
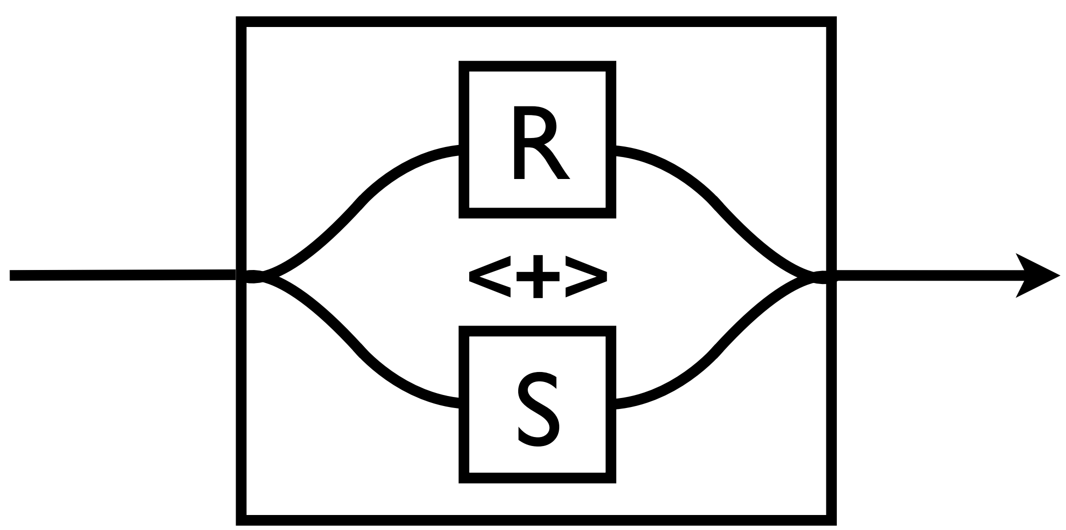


Disjunction



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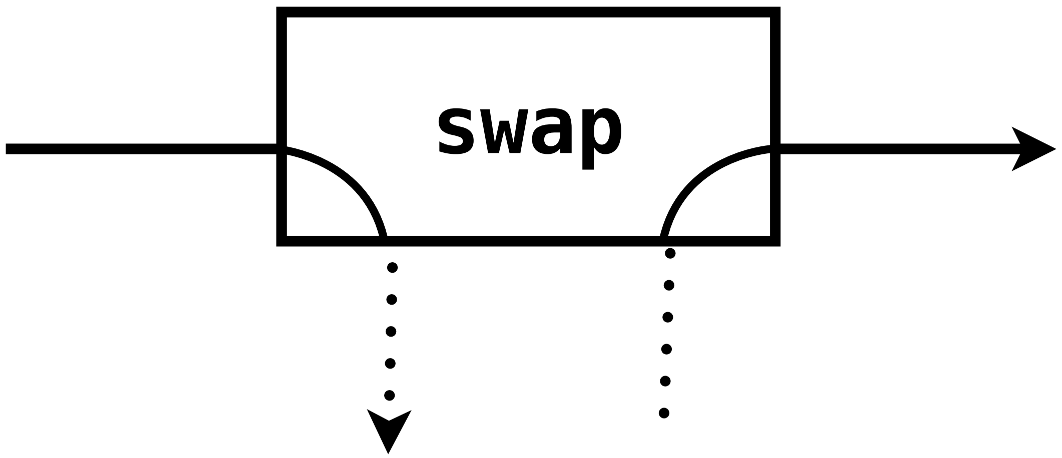

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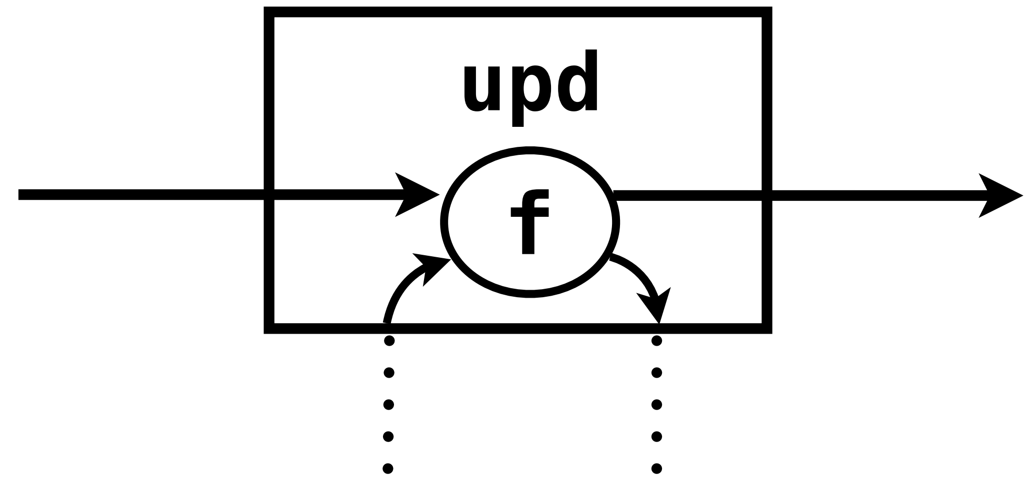

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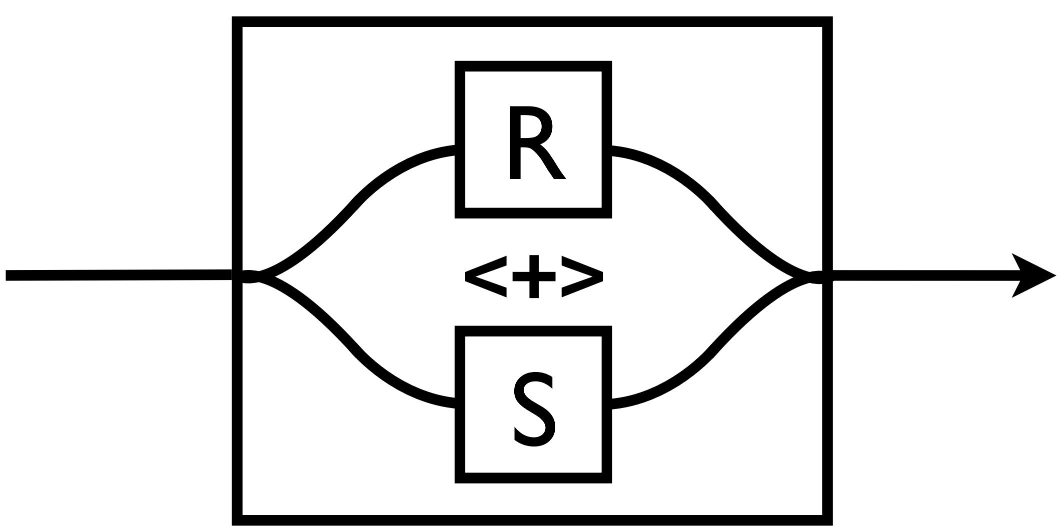

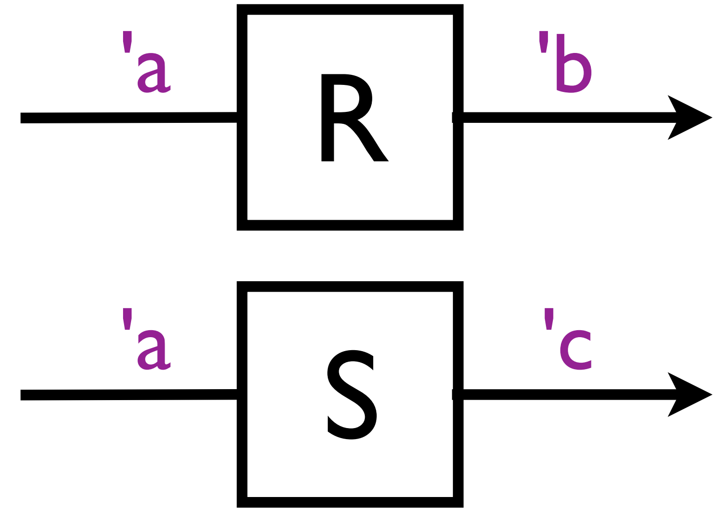

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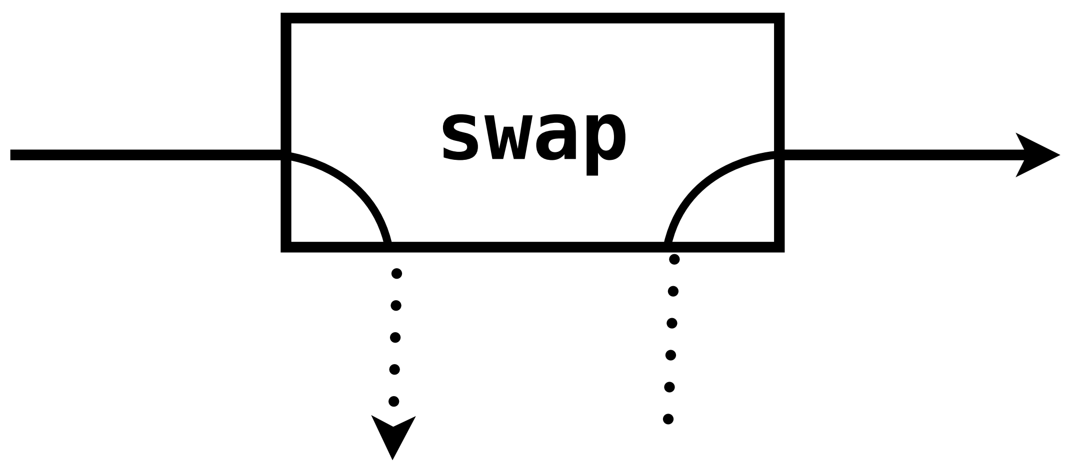

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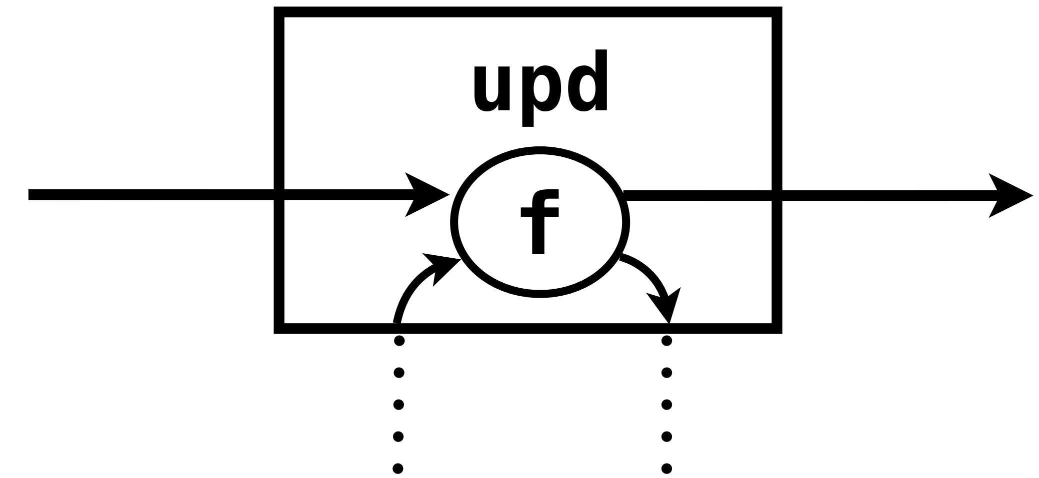
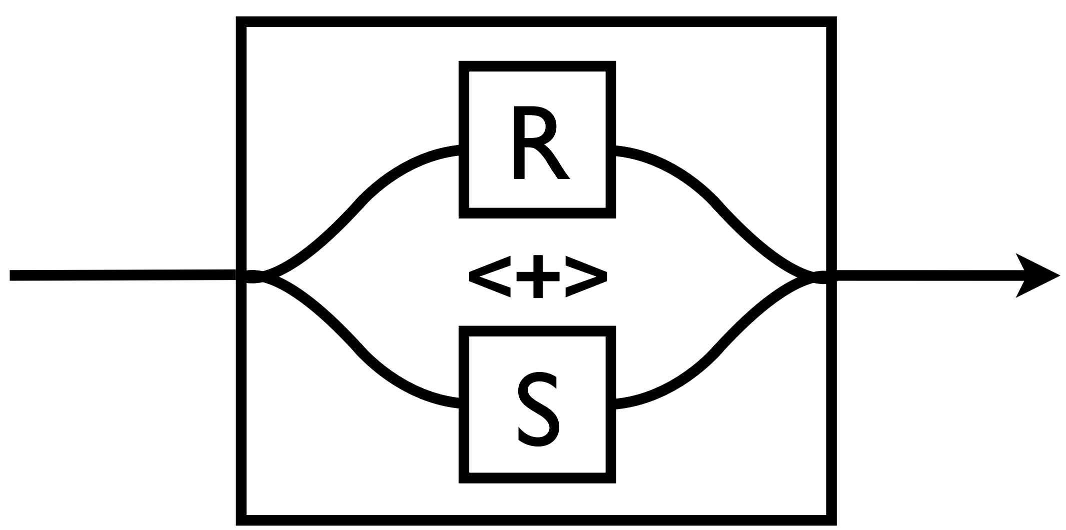
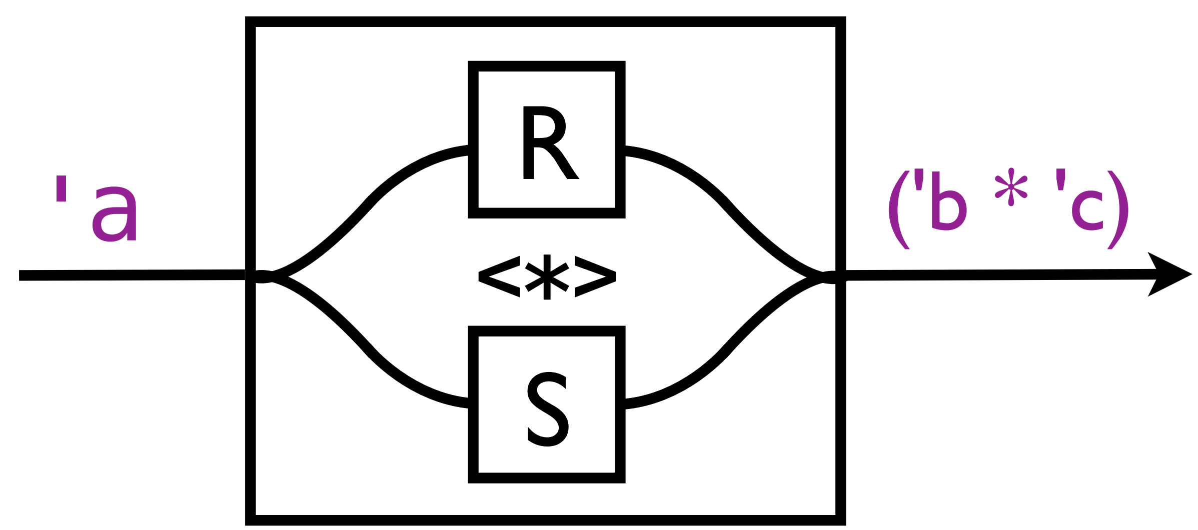
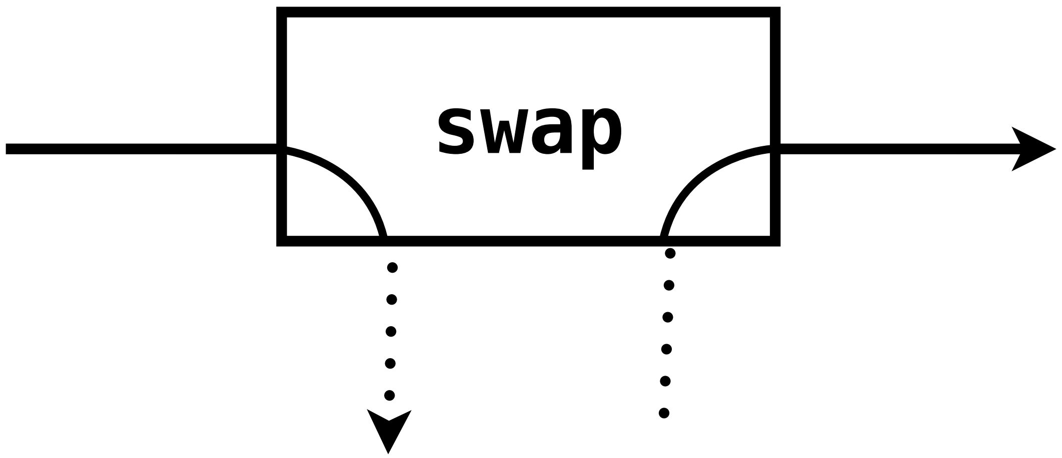


Disjunction

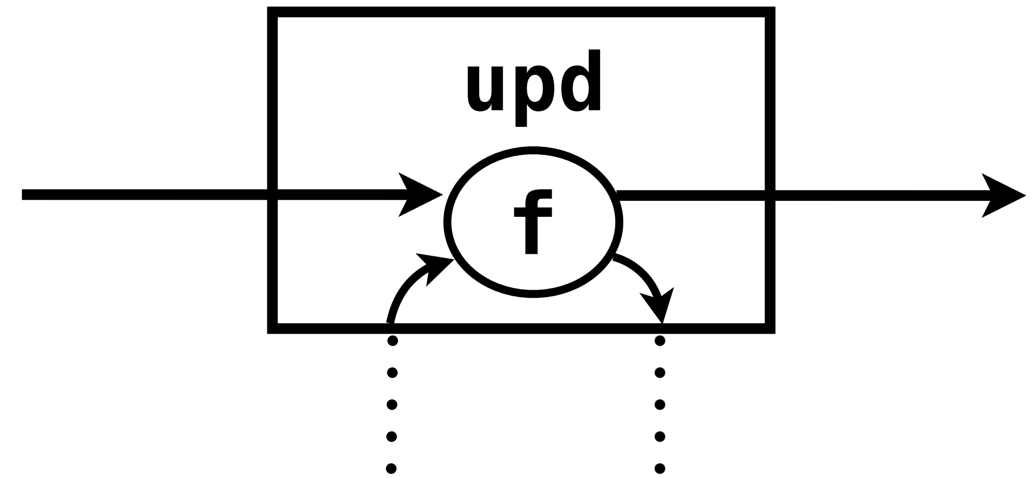




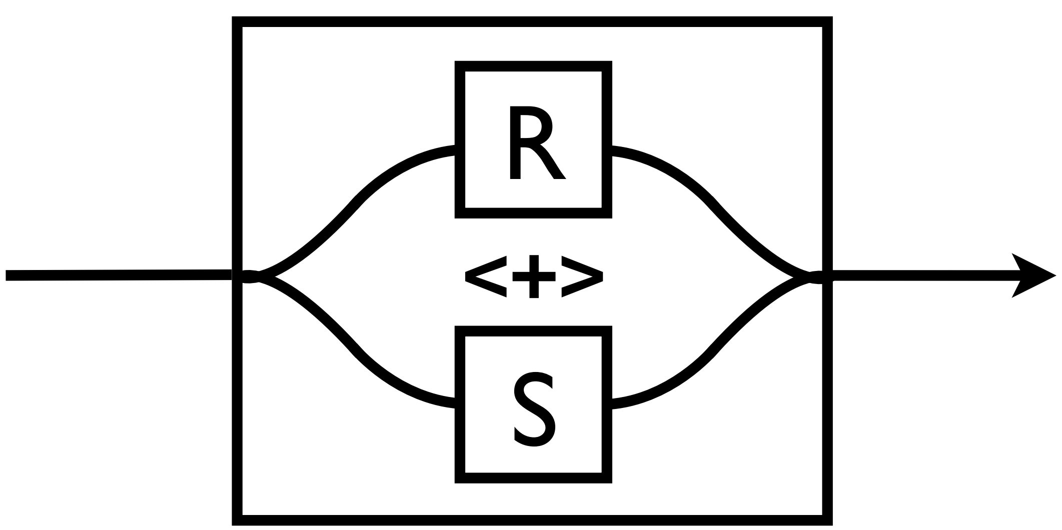
Message passing



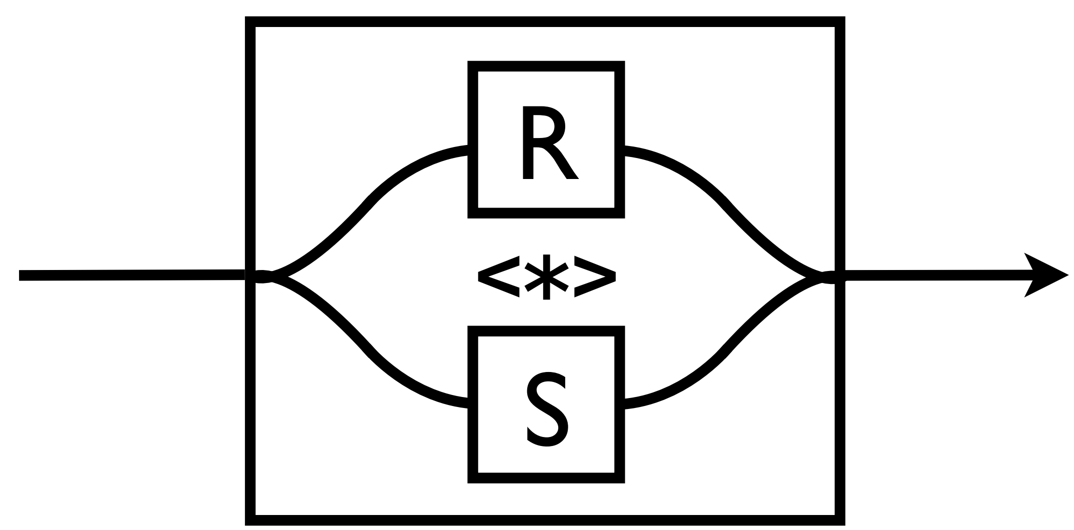
Shared state



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
  ...
end

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

  let create () = Ref.ref []

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

  let pop r = Ref.upd r (fun l () ->
    match l with
    | [] -> None (* block *)
    | 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
```

Composability

Transform arbitrary **blocking** reagent to a **non-blocking** reagent

Composability

Transform arbitrary **blocking** reagent to a **non-blocking** reagent

```
val lift     : ('a -> 'b option) -> ('a,'b) t
val constant : 'a -> ('b,'a) t
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Composability

Transform arbitrary **blocking** reagent to a **non-blocking** reagent

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val lift     : ('a -> 'b option) -> ('a,'b) t
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```
let attempt (r : ('a,'b) t) : ('a,'b option) t =
 (r >>> lift (fun x -> Some (Some x)))
 <+> (constant None)
```

Composability

Transform arbitrary **blocking** reagent to a **non-blocking** reagent

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val lift     : ('a -> 'b option) -> ('a,'b) t
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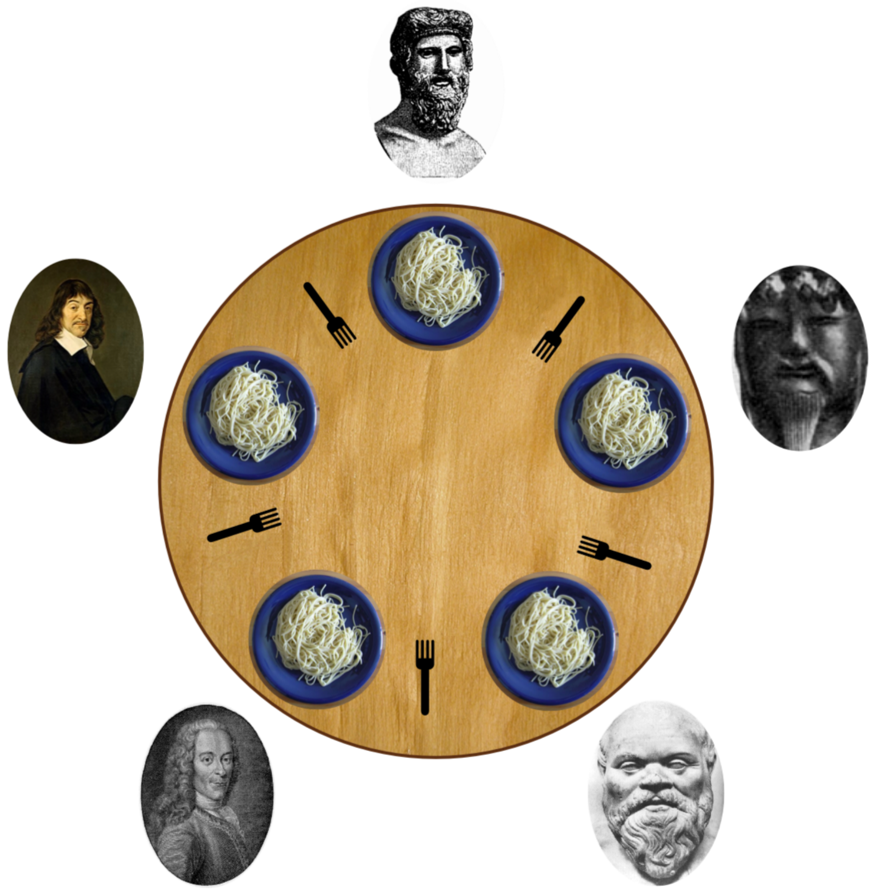
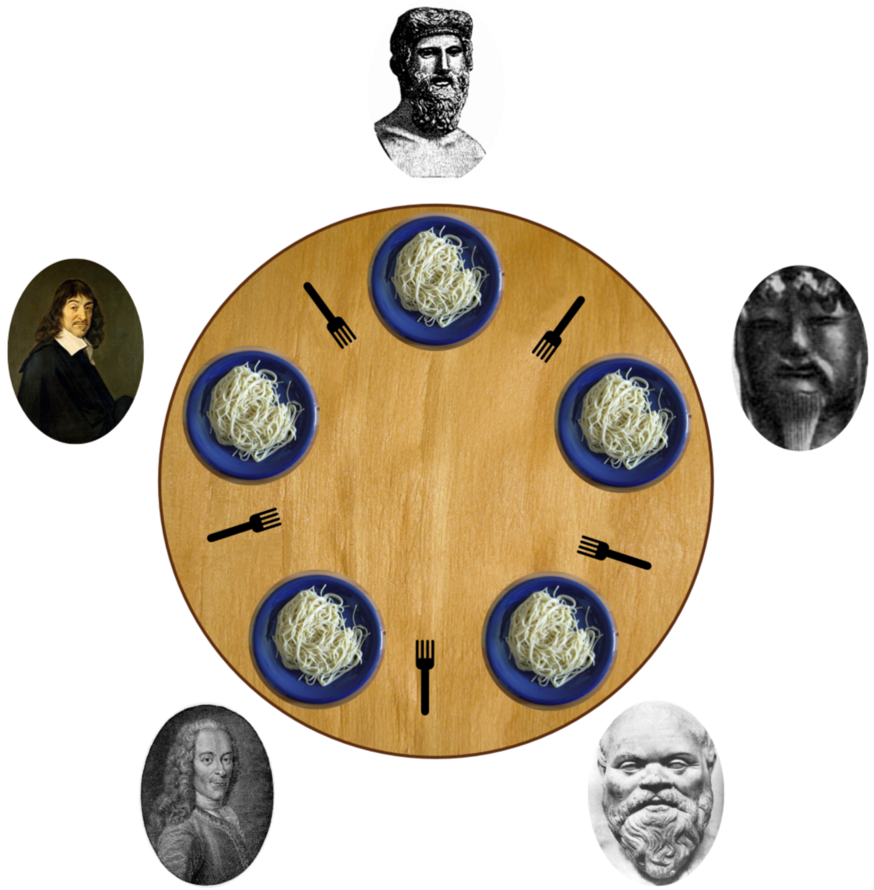
```
let attempt (r : ('a,'b) t) : ('a,'b option) t =
 (r >>> lift (fun x -> Some (Some x)))
 <+> (constant None)

let try_pop stack = attempt (pop stack)
```



- Philosopher’s alternate between thinking and eating
- Philosopher can only eat after obtaining both forks
- No philosopher starves

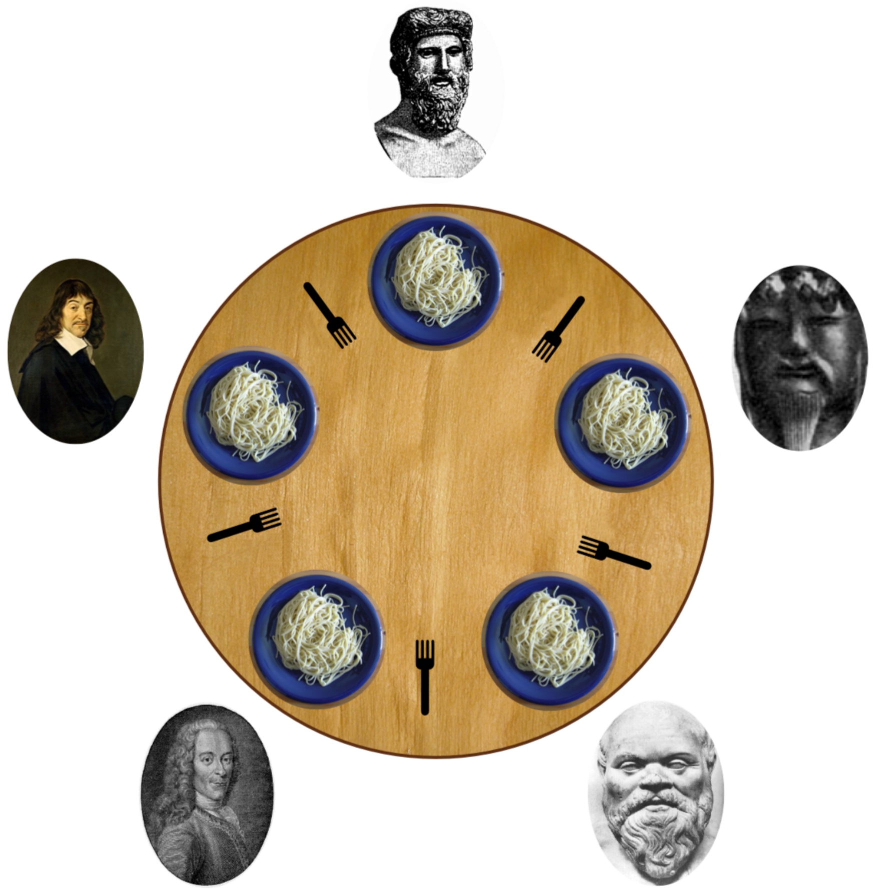


- Philosopher's alternate between thinking and eating
- Philosopher can only eat after obtaining both forks
- No philosopher starves

```
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
```



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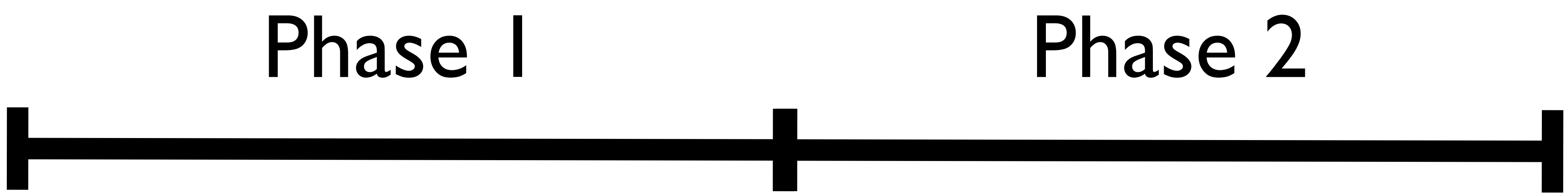
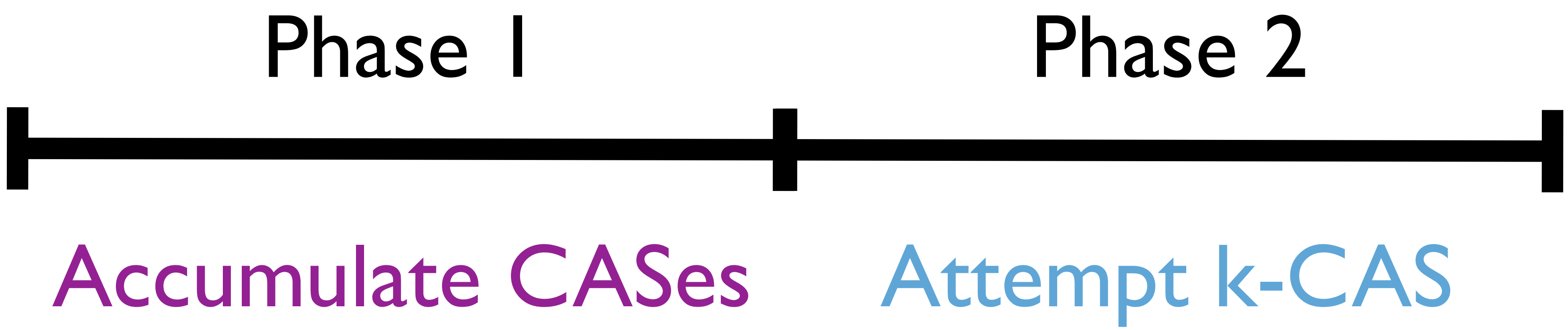
let drop f = swap f.drop
let take f = swap f.take
```

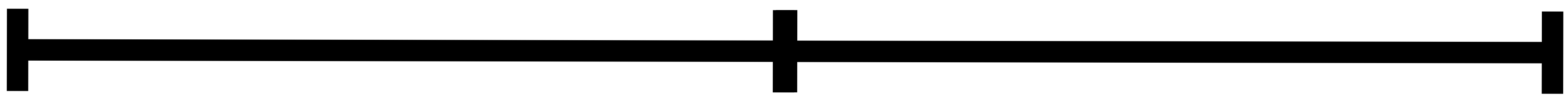
```
let eat l_fork r_fork =
  run (take l_fork <*>
       take r_fork) ();
  (* ...
   * eat
   * ... *)
  spawn @@ run (drop l_fork);
  spawn @@ run (drop r_fork)
```

Implementation

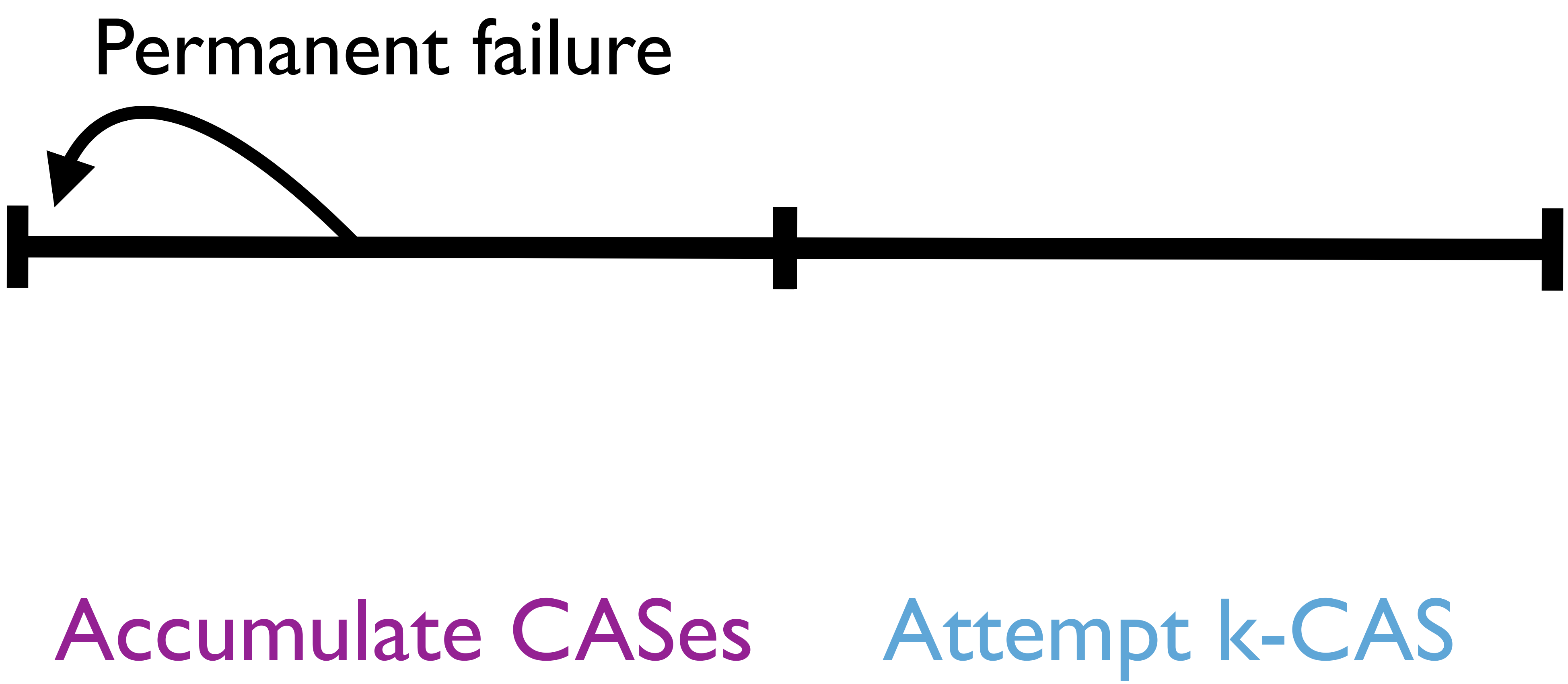

Phase 1
Phase 2

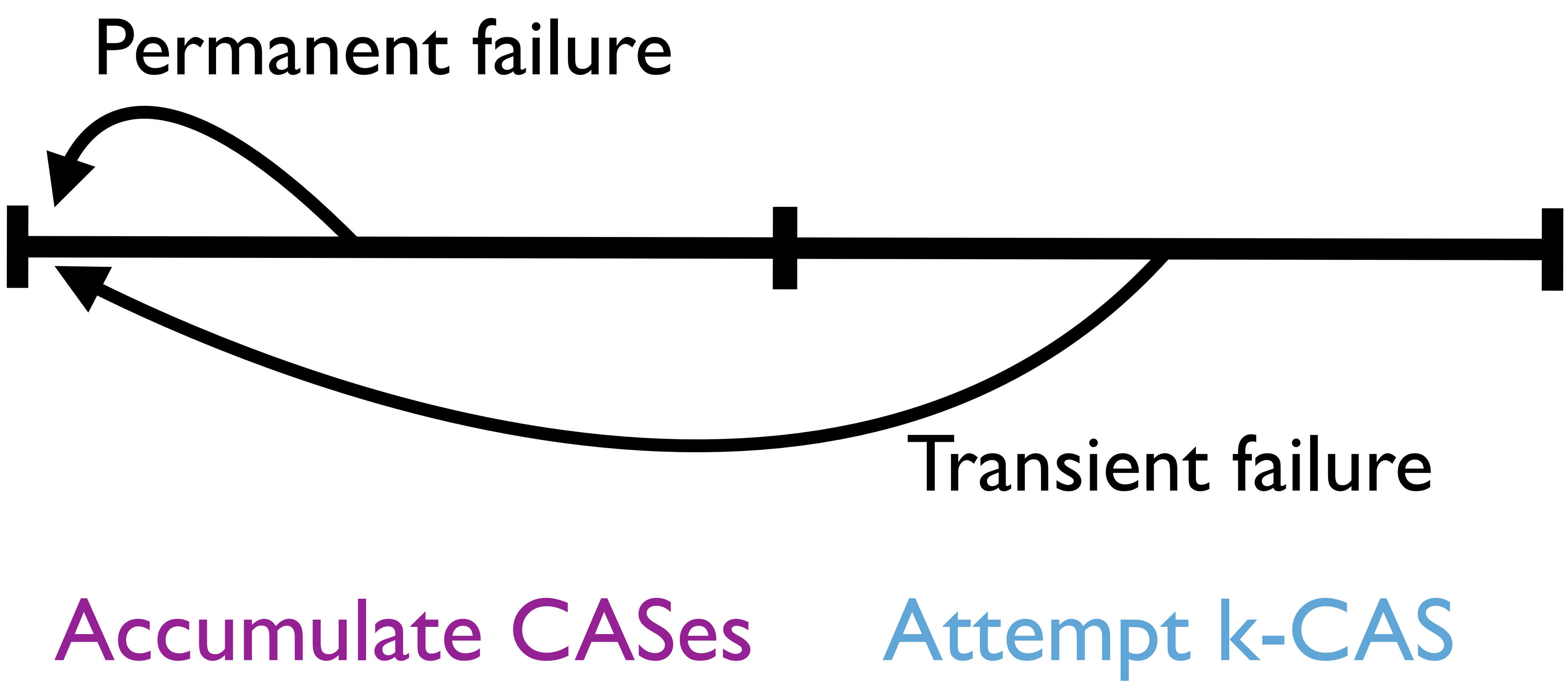

Phase 1
Phase 2
Accumulate CASes

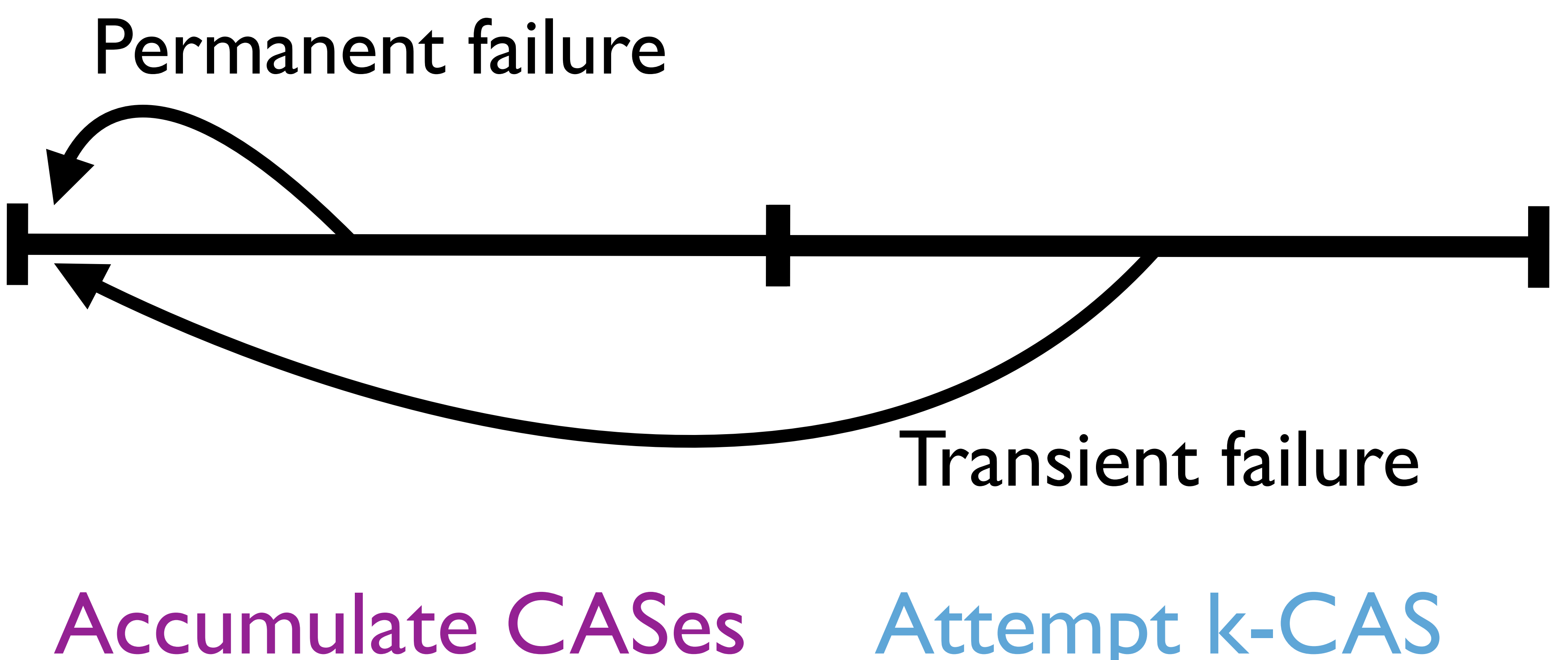

Phase 1
Phase 2
Accumulate CASes
Attempt k-CAS



Accumulate CASes   Attempt k-CAS


Permanent failure
Accumulate CASes
Attempt k-CAS


Permanent failure
Transient failure
Accumulate CASes
Attempt k-CAS


Permanent failure
Transient failure
Accumulate CASes
Attempt k-CAS


HTM Ready

Status

Synchronization

- Locks
- 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
- Stacks
  - Treiber
  - Elimination backoff
- Counters
- Deques
- Sets
- Maps (hash & skiplist)

https://github.com/ocamllabs/reagents

STM vs Reagents

- STM is more ambitious — atomic { … }. Reagents are conservative.
- Reagents don't allow multiple writes to the same memory location.
- Reagents are lock-free. STMs are typically obstruction-free.