Parallelism and Concurrency (Part II)

COS 326
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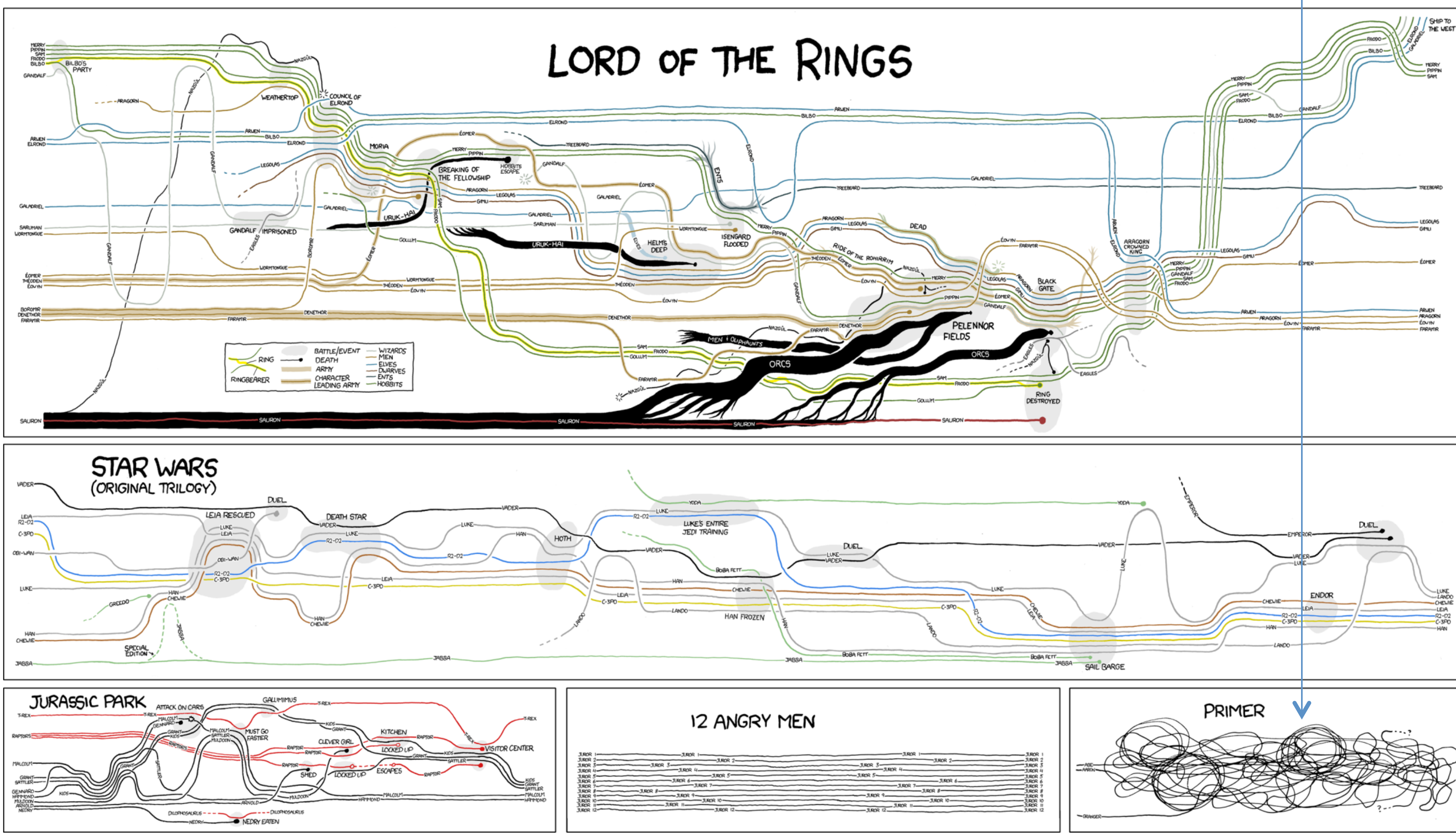
Perils of Parallelism

explain this movie!

THESE CHARTS SHOW MOVIE CHARACTER INTERACTIONS. THE HORIZONTAL AXIS IS TIME. THE VERTICAL GROUPING OF THE LINES INDICATES WHICH CHARACTERS ARE TOGETHER AT A GIVEN TIME.



Pure Functions

A function (or expression) is *pure* if it has no *effects*.

- Valuable expressions should not have effects either

Recall that a function has an *effect* if its behavior cannot be completely explained by a *deterministic* relation between its inputs and its outputs

Expressions have effects when they:

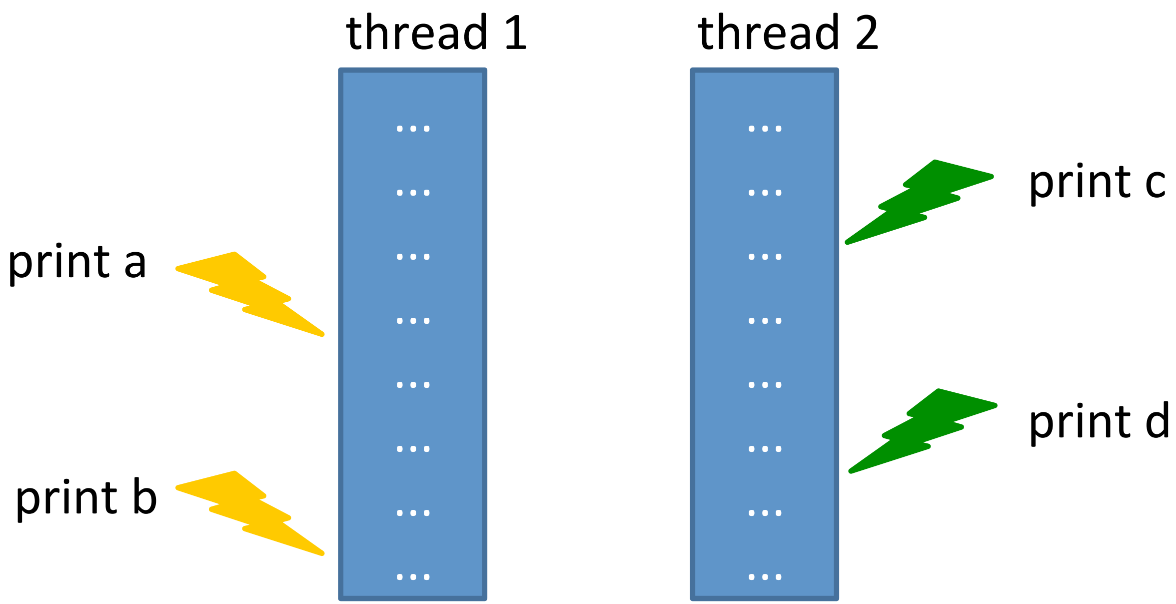
- don't terminate
- raise exceptions
- read from stdin/print to stdout
- read or write to a shared mutable data structure

↓ increasingly difficult to deal with

Not an effect: reading from immutable data structures

Effects and Parallelism

The combination of effects and parallelism is difficult to reason about: The run-time system is responsible for scheduling the instructions in each thread. Depending on the schedule, the effects happen in a different order



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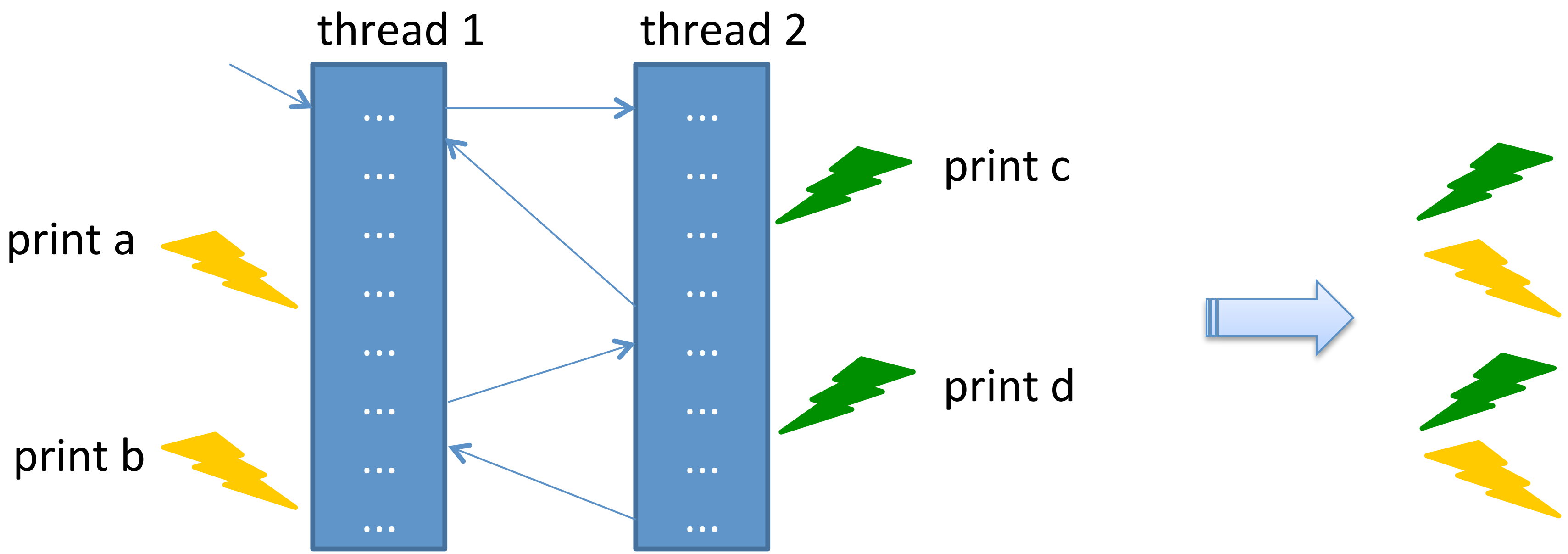

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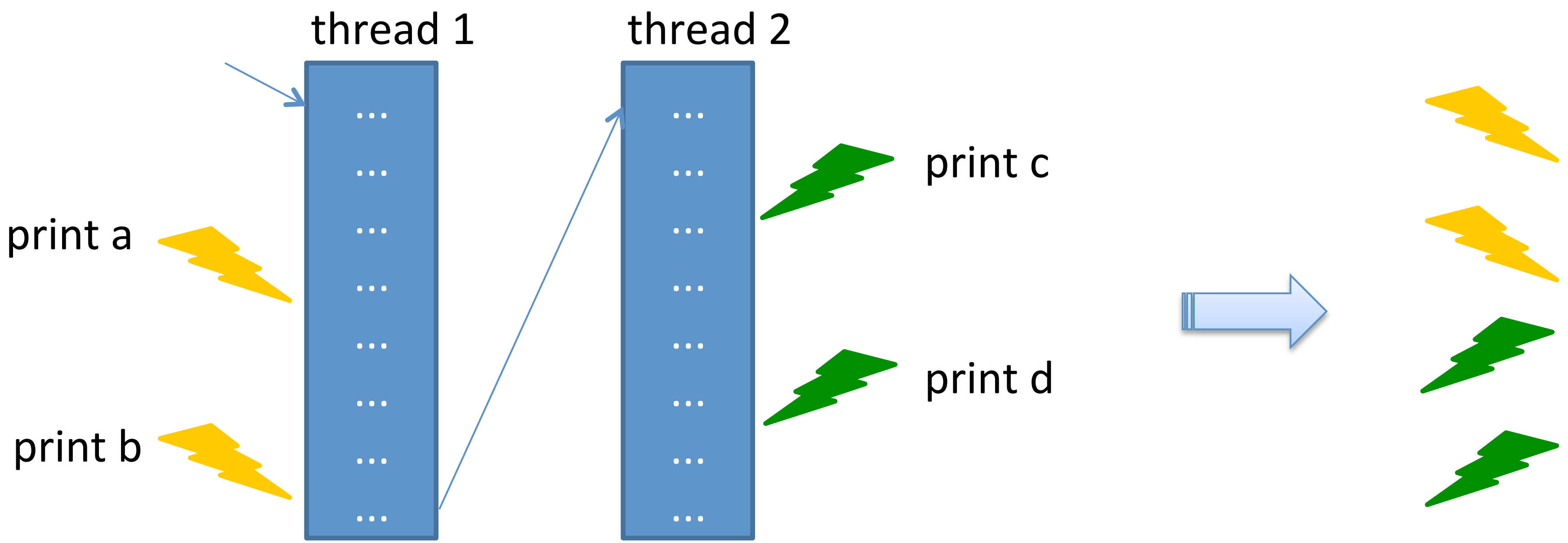

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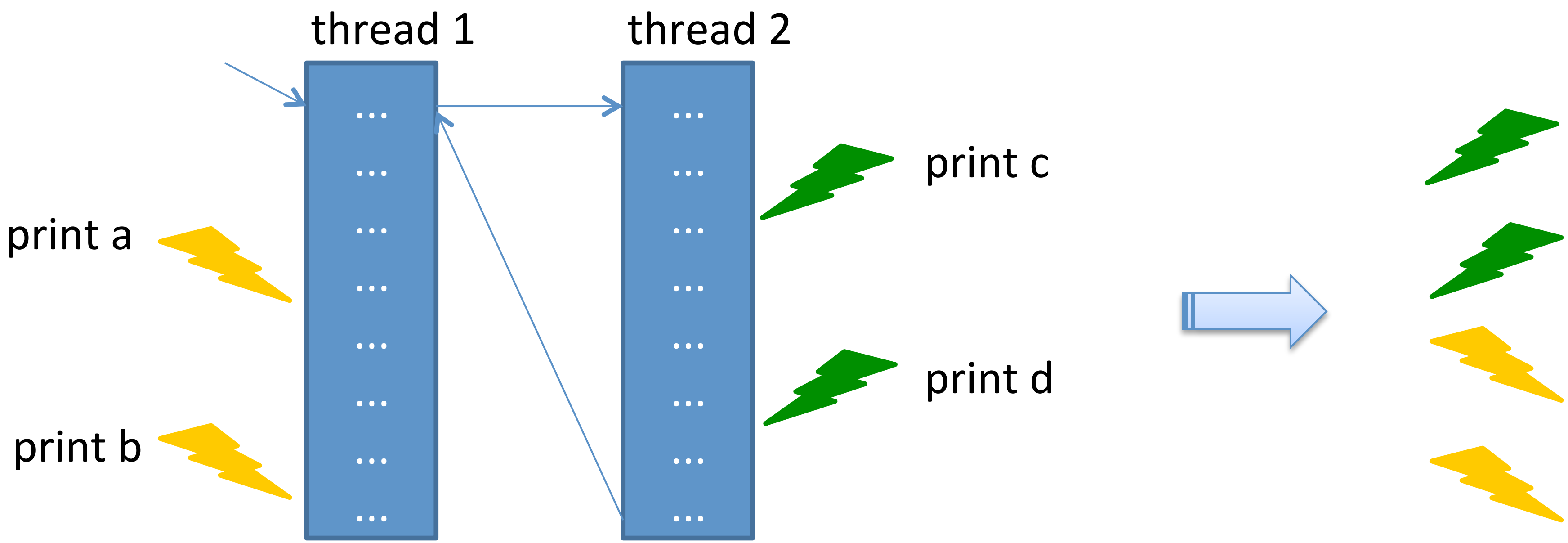

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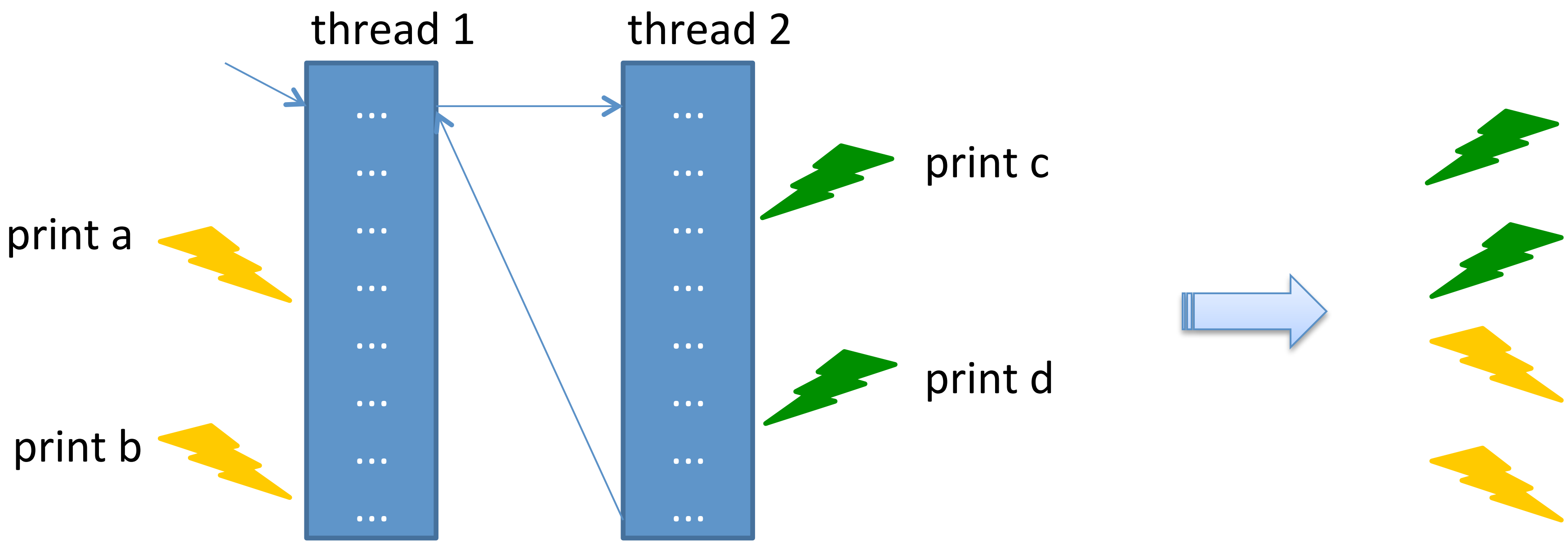
The combination of effects and parallelism is difficult to reason about: The run-time system is responsible for scheduling the instructions in each thread. Depending on the schedule, the effects happen in a different order



Understanding the output requires consideration of *all interleavings* of instructions. So many combinations! So much *non-determinism*!

Benign Effects & Futures

Not all uses of effects create non-determinism. Eg: Futures

```
sig
  type 'a future
  val future : (unit -> 'a) -> 'a future
  val force : 'a future -> 'a
end
```

```
struct
  type ‘a future = {tid : Thread.t ; value : 'a option ref}

  let future (f:'a->'b) (x:'a) : 'b future =
    let r = ref None in
    let t = Thread.create (fun () -> r := Some(f x)) () in
    {tid=t ; value=r}

  let force (f:'a future) : 'a =
    Thread.join f.tid ;
    match !(f.value) with
    | Some v -> v
    | None -> failwith “impossible!”
end
```

Benign Effects & Futures

Provided your code contains no other effects, futures do not introduce non-determinism!

Consequence: when it comes to reasoning about the correctness of your programs, *pure functional code + parallel futures is no harder than pure functional sequential code*!

Equational reasoning laws:

```
if e1 is valuable then:
```

```
let x = e1 in        ==      let x = future (fun _ -> e1) in
e2                           e2[force x/x]
```

Moreover

Benign Effects & Futures

if e1 is valuable then:

```
let x = e1 in        ==        let x = future (fun _ -> e1) in
e2                             e2[force x/x]
```

```
type 'a tree = Leaf | Node of 'a * 'a tree * 'a tree

let rec fold (f:'a -> 'b -> 'b -> 'b) (u:'b) (t:'a tree) : 'b =
  match t with
   | Leaf -> u
   | Node (n,left,right) ->
     let left' = fold f u left in
     let right' = fold f u right in
     f n left' right'
```

Benign Effects & Futures

if e1 is valuable then:

```
let x = e1 in        ==     let x = future (fun _ -> e1) in
e2                          e2[force x/x]
```

```
type 'a tree = Leaf | Node of 'a * 'a tree * 'a tree

let rec fold (f:'a -> 'b -> 'b -> 'b) (u:'b) (t:'a tree) : 'b =
  match t with
   | Leaf -> u
   | Node (n,left,right) ->
      let left' = future (fun _ -> fold f u left) in
      let right' = fold f u right in
      f n (force left') right'
```

Benign Effects & Futures

```
if e1 is valuable then:
```

```
let x = e1 in          ==        let x = future (fun _ -> e1) in
e2                               e2[force x/x]
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type 'a tree = Leaf | Node of 'a * 'a tree * 'a tree

let rec fold (f:'a -> 'b -> 'b -> 'b) (u:'b) (t:'a tree) : 'b =
  match t with
   | Leaf -> u
   | Node (n,left,right) ->
      let left' = future (fun _ -> fold f u left) in
      let right' = fold f u right in
      f n (force left') right'
```
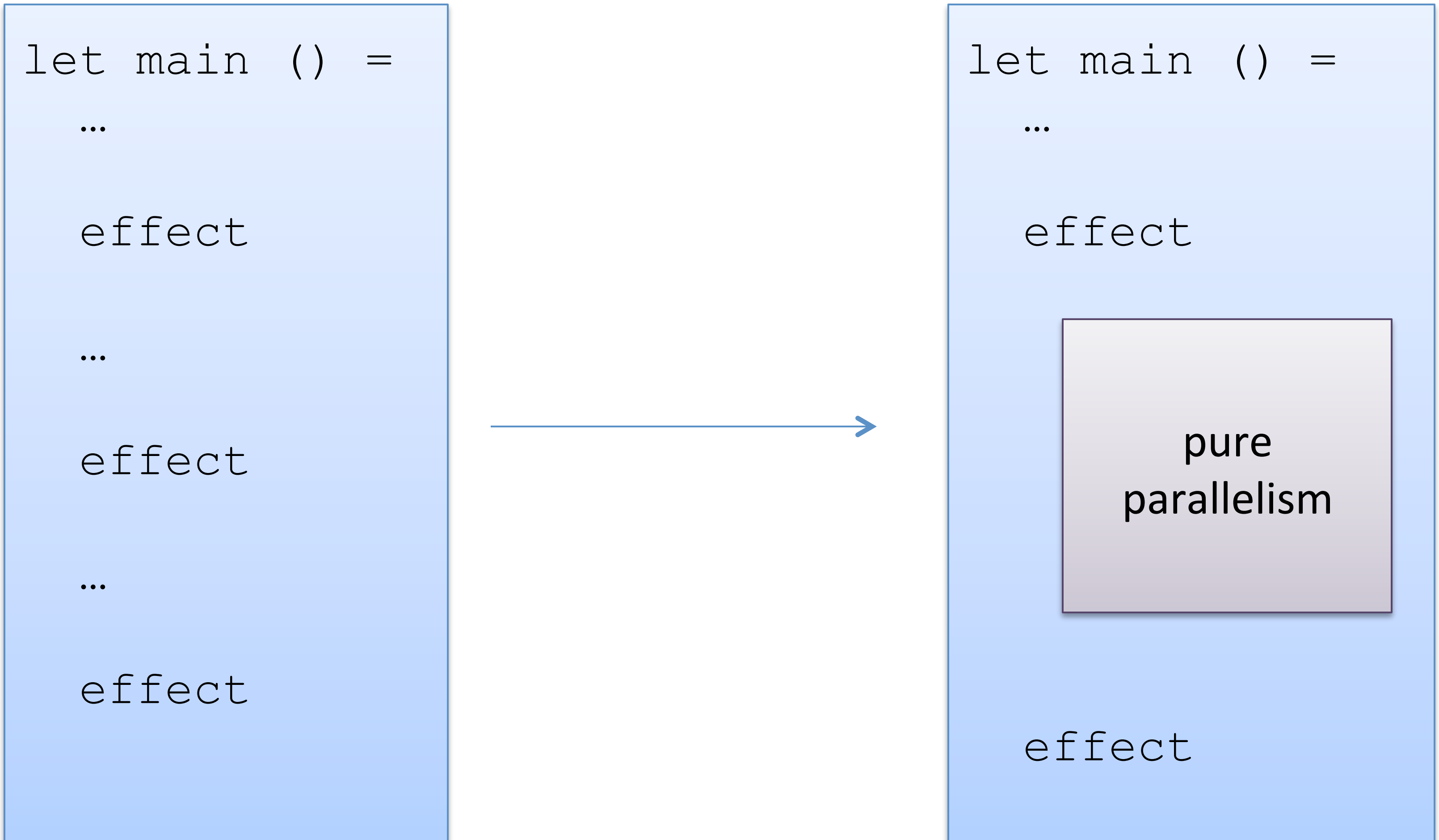

Moral: It is *vastly easier* to introduce parallelism in to *a pure functional program* using futures than using naked references, locks, join

Benign Effects & Futures

What if your program has effects? (Most useful programs do!)

- Try to push the effects to the *edges* of your program and put parallelism in the middle. *Especially* limit mutable data.



MANAGING MUTABLE DATA

Consider a Bank Acount ADT

```
type account = { name : string; mutable bal : int }

let create (n:string) (b:int) : account =
  { name = n; bal = b }

let deposit (a:account) (amount:int) : unit =
  if a.bal + amount < max_balance then
    a.bal <- a.bal + amount

let withdraw (a:account) (amount:int) : int =
  if a.bal >= amount then (
    a.bal <- a.bal - amount;
    amount
  ) else 0
```

What happens here?

```
val bank : account array

let rec atm (loc:string) =
  let id = getAccountNumber() in
  let w = getWithdrawAmount() in
  let d = withdraw (bank.(id)) w in
  dispenseDollars d ;
  atm loc

let world () =
  Thread.create atm "Princeton, Nassau" ;
  Thread.create atm "NYC, Penn Station" ;
  Thread.create atm "Boston, Lexington Square"
```

The ATM problem

- Suppose two ATMs, running in separate threads, try to perform a withdrawal from the same bank account around the same time.
- For example, suppose bank.(0) is an account that starts with $100 in its balance.
- And suppose we have two threads, each executing the service loop, trying to withdraw $50 and $75 respectively.

Simplifying the situation…

```
b = 100
```

```
let w = 50 in
if b > w then
   (b <- b - w ;
    w)
else
   0
```

```
let w = 75 in
if b > w then
   (b <- b - w ;
    w)
else
   0
```

Simplifying the situation…

```
b = 100
```

```
let w = 50 in
if b > w then
   (b <- b - w ;
    w)
else
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let w = 75 in
if b > w then
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```

```
b = 50
```

Simplifying the situation…

```
b = 100
```

```
let w = 50 in
if b > w then
  (b <- b - w ;
   w)
else
  0
```

```
let w = 75 in
if b > w then
  (b <- b - w ;
   w)
else
  0
```

```
b = 25
```

Another schedule ...

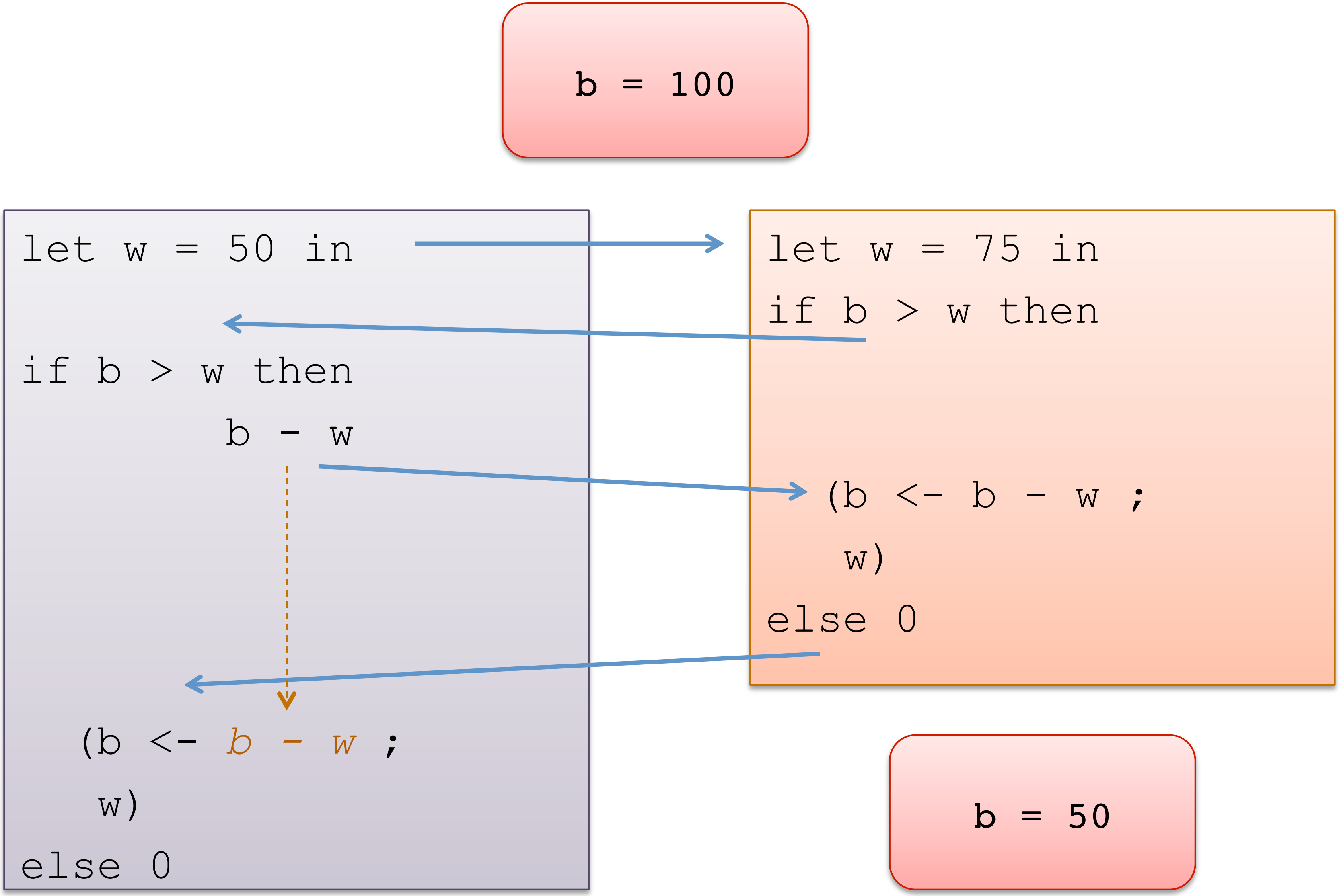
```
b = 100
```

```
let w = 50 in
if b > w then



   (b <- b - w ;
    w)
else
  0
```

```
let w = 75 in
if b > w then
   (b <- b - w ;
    w)
else 0
```

```
b = -25
```

Good for you … (less so for the bank)



Good for you … (less so for the bank)

```
b = 100
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let w = 50 in

if b > w then
        b - w

  (b <- b - w ;
   w)
else 0
```

```
let w = 75 in
if b > w then

  (b <- b - w ;
   w)
else 0
```

Yet we paid out $125!!!

```
b = 50
```

More Synchronization: Locks

This is not a problem we can fix with fork/join/futures

- The ATMs shouldn't ever terminate!
- Yet join only allows us to wait until one thread terminates.

Instead, we're going to us a *mutex lock* to synchronize threads.

- mutex is short for "mutual exclusion"
- locks will give us a way to introduce some controlled access to resources – in this case, the bank accounts.
- controlled access to a shared resource is a *concurrency problem*, not a *parallelization problem*

Mutex Locks in OCaml

```
module type Mutex :
  sig
    type t  (* type of mutex locks *)

    val create : unit -> t (* create a fresh lock *)

    (* try to acquire the lock – makes
       the thread go to sleep until the lock
       is free.  So at most one thread "owns" the lock. *)
    val lock : t -> unit

    (* releases the lock so other threads can
       wake up and try to acquire the lock. *)
    val unlock : t -> unit

    (* similar to lock, but never blocks.  Instead, if
       the lock is already locked, it returns "false". *)
    val try_lock : t -> bool
  end
```

Adding a Lock

```
type account = { name : string; mutable bal : int; lock : Mutex.t }

let create (n:string) (b:int) : account =
  { name = n; bal = b; lock = Mutex.create() }

let deposit (a:account) (amount:int) : unit =
  Mutex.lock a.lock;
    if a.bal + amount < max_balance then
      a.bal <- a.bal + amount;
  Mutex.unlock a.lock

let withdraw (a:account) (amount:int) : int =
  Mutex.lock a.lock;
    let result =
      if a.bal >= amount then (
        a.bal <- a.bal - amount;
        amount ) else 0
    in
  Mutex.unlock a.lock;
  result
```

Better

```
type account = { name : string; mutable bal : int; lock : Mutex.t }

let create (n:string) (b:int) : account =
  { name = n; bal = b; lock = Mutex.create() }

let deposit (a:account) (amount:int) : unit =
  with_lock a.lock (fun () ->
    if a.bal + amount < max_balance then
      a.bal <- a.bal + amount))

let withdraw (a:account) (amount:int) : int =
  with_lock a.lock (fun () ->
      if a.bal >= amount then (
        a.bal <- a.bal - amount;
        amount ) else 0
  )
```

```
let with_lock (l:Mutex.t)
              (f:unit->'b) : 'b =
  Mutex.lock l;
  let res = f () in
  Mutex.unlock l;
  res
```

General Design Pattern

Associate any shared, mutable thing with a lock.

- Java takes care of this for you (but only for one simple case.)
- In Ocaml, C, C++, etc. it's up to you to create & manage locks.

In every thread, before reading or writing the object, acquire the lock.

- This prevents other threads from interleaving their operations on the object with yours.
- *Easy error: forget to acquire or release the lock.*

When done operating on the mutable value, release the lock.

- It's important to minimize the time spent holding the lock.
- That's because you are blocking all the other threads.
- *Easy error: raise an exception and forget to release a lock…*
- *Hard error: lock at the wrong granularity (too much or too little)*

Better Still

```
type account = { name : string; mutable bal : int; lock : Mutex.t }

let create (n:string) (b:int) : account =
  { name = n; bal = b; lock = Mutex.create() }

let deposit (a:account) (amount:int) : unit =
  with_lock a.lock (fun () ->
    if a.bal + amount < max_balance then
      a.bal <- a.bal + amount))

let withdraw (a:account) (amount:i
  with_lock a.lock (fun () ->
      if a.bal >= amount then (
        a.bal <- a.bal - amount;
        amount ) else 0
  )
```

```
let with_lock (l:Mutex.t)
              (f:unit->’b) : ‘a =
  Mutex.lock l;
  let res =
    try f ()
    with exn -> (Mutex.unlock l;
                 raise exn)
  in
  Mutex.unlock l;
  res
```

Another Example

```
type 'a stack = { mutable contents : 'a list;
                  lock : Mutex.t
                };;

let empty () = {contents=[]; lock=Mutex.create()};;

let push (s:'a stack) (x:'a) : unit =
    with_lock s.lock (fun _ ->
      s.contents <- x::s.contents)
;;

let pop (s:'a stack) : 'a option =
    with_lock s.lock (fun _ ->
      match s.contents with
      | [] -> None
      | h::t -> (s.contents <- t ; Some h)
;;
```

Unfortunately…

This design pattern of associating a lock with each object, and using with_lock on each method works well when we need to make the method seem atomic.

- In fact, Java has a *synchronize* construct to cover this.

But it does *not* work when we need to do some set of actions on *multiple* objects.

MANAGING MULTIPLE MUTABLE DATA STRUCTURES

Another Example

```
type 'a stack = { mutable contents : 'a list;
                  lock : Mutex.t }

val empty : () -> 'a stack
val push  : 'a stack -> a -> unit
val pop   : 'a stack -> 'a option

let transfer_one (s1:'a stack) (s2: 'a stack) =
  with_lock s1.lock (fun _ ->
    match pop s1 with
   | None => ()
   | Some x => push s2 x)
```

Another Example

```
type 'a stack = { mutable contents : 'a list;
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val empty : () -> 'a stack
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Unfortunately, we already hold `s1.lock` when we invoke `pop s1` which tries to acquire the lock.

Another Example

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    match pop s1 with
    | None => ()
    | Some x => push s2 x)
```

Unfortunately, we already hold `s1.lock` when we invoke `pop s1` which tries to acquire the lock.

So we end up *dead-locked*.

Another Example

```
type 'a stack = { mutable contents : 'a list;
                  lock : Mutex.t }

val empty : () -> 'a stack
val push  : 'a stack -> a -> unit
val pop   : 'a stack -> 'a option

let transfer_one (s1:'a stack) (s2: 'a stack) =
  with_lock s1.lock (fun _ ->
    match pop s1 with
    | None => ()
    | Some x => push s2 x)
```

Avoid deadlock by deleting the line that aquires s1.lock initially

A trickier problem

```
type 'a stack = { mutable contents : 'a list;
                  lock : Mutex.t }

val empty : () -> 'a stack
val push  : 'a stack -> a -> u
val pop   : 'a stack ->

let pop_two (s1:'a stack)
            (s2:'a stack) : ('a * 'a) option =
  match pop s1, pop s2 with
    | Some x, Some y -> Some (x,y)
    | Some x, None -> push s1 x ; None
    | None, Some y -> push s2 y ; None
```

Either:

(1) pop one from each if both non-empty, or

(2) have no effect at all

A trickier problem

```
type ‘a stack = { mutable contents : ‘a list;
                  lock : Mutex.t }

val empty : () -> ‘a stack
val push  : ‘a stack -> a -> unit
val pop   : ‘a stack -> ‘a option

let pop_two (s1:‘a stack)
            (s2:‘a stack) : (‘      ‘a) option =
  match pop s1, pop s2 with
     | Some x, Some y -> Some (x,y)
     | Some x, None -> push s1 x ; None
     | None, Some y -> push s2 y ; None
```

But some other thread could sneak in here and try to perform an operation on our contents before we’ve managed to push the value back on.

Yet another broken solution

```
let no_lock_pop (s1:'a stack) : 'a option =
  match s1.contents with
  | [] -> None
  | h::t -> (s1.contents <- t ; Some h)

let no_lock_push (s1:'a stack) (x :'a) : unit =
  contents <- x::contents

let pop_two (s1:'a stack)
            (s2:'a stack) : ('a * 'a) option =
  with_lock s1.lock (fun _ ->
  with_lock s2.lock (fun _ ->
  match no_lock_pop s1, no_lock_pop s2 with
     | Some x, Some y -> Some (x,y)
     | Some x, None -> no_lock_push s1 x ; None
     | None, Some y -> no_lock_push s2 y ; None))
```

Yet another broken solution

```
let no_lock_pop (s1:‘a stack) : ‘a option =
  match s1.contents with
   | [] -> None
   | h::t -> (s1.contents <- t ; Some h

let no_lock_push (s1:‘a stack)
  contents <- x::contents

let pop_two (s1:‘a stack)
            (s2:‘a stack) : (‘a * ‘a) option =
  with_lock s1.lock (fun _ ->
  with_lock s2.lock (fun _ ->
  match no_lock_pop s1, no_lock_pop s2 with
     | Some x, Some y -> Some (x,y)
     | Some x, None -> no_lock_push s1 x ; None
     | None, Some y -> no_lock_push s2 y ; None))
```

Problems?

Yet another broken solution

```
let no_lock_pop (s1:‘a stack) : ‘a option =
  match s1.contents with
  | [] -> None
  | h::t -> (s1.contents <- t ; Some

let no_lock_push (s1:‘a stack)
  contents <- x::contents

let pop_two (s1:‘a stack)
            (s2:‘a stack) : (‘a * ‘a) option =
  with_lock s1.lock (fun _ ->
  with_lock s2.lock (fun _ ->
  match no_lock_pop s1, no_lock_pop s2 with
     | Some x, Some y -> Some (x,y)
     | Some x, None -> no_lock_push s1 x ; None
     | None, Some y -> no_lock_push s2 y ; None))
```

What happens if we call
pop_two x x?

Yet another broken solution

In particular, consider:

```
Thread.create (fun _ -> pop_two x y)
Thread.create (fun _ -> pop_two y x)
```

What happens if two threads are trying to call pop_two at the same time?

```
let no_lock_pop (s1:
  match s1.contents w
  | [] -> None
  | h::t -> (s1.contents <- t ;

let no_lock_push (s1:'a stack)
  contents <- x::contents

let pop_two (s1:'a stack)
            (s2:'a stack) : ('a * 'a) option =
  with_lock s1.lock (fun _ ->
  with_lock s2.lock (fun _ ->
  match no_lock_pop s1, no_lock_pop s2 with
     | Some x, Some y -> Some (x,y)
     | Some x, None -> no_lock_push s1 x ; None
     | None, Some y -> no_lock_push s2 y ; None))
```

Yet another broken solution

```
let no_lock_pop (s1:
  match s1.contents w
  | [] -> None
  | h::t -> (s1.contents <- t ; So   h)

let no_lock_push (s1:'a stack)
  contents <- x::contents

let pop_two (s1:'a stack)
            (s2:'a stack) : (
  with_lock
  with_lock
  match no_l                         ith
     | Some x, Some y -> Some (x,y)
     | Some x, None -> no_lock_push s1 x ; None
     | None, Some y -> no_lock_push s2 y ; None))
```

In particular, consider:

```
Thread.create (fun _ -> pop_two x y)
Thread.create (fun _ -> pop_two y x)
```

One possible interleaving:
T1 acquires x's lock.
T2 acquires y's lock.
T1 tries to acquire y's lock and blocks.
T2 tries to acquire x's lock and blocks.

DEADLOCK

A fix

```
type 'a stack = { mutable contents : 'a list; lock : Mutex.t; id : int }

let new_id : unit -> int =
  let c = ref 0 in (fun _ -> c := (!c) + 1 ; !c)

let empty () = {contents=[]; lock=Mutex.create(); id=new_id()};;

let no_lock_pop_two (s1:'a stack) (s2:'a stack) : ('a * 'a) option =
      match no_lock_pop s1, no_lock_pop s2 with
       | Some x, Some y -> Some (x,y)
       | Some x, None -> no_lock_push s1 x; None
       | None, Some y -> no_lock_push s2 y; None

let pop_two (s1:'a stack) (s2:'a stack) : ('a * 'a) option =
  if s1.id < s2.id then
    with_lock s1.lock (fun _ ->
    with_lock s2.lock (fun _ ->
      no_lock_pop_two s1 s2))
  else if s1.id > s2.id then
    with_lock s2.lock (fun _ ->
    with_lock s1.lock (fun _ ->
      no_lock_pop_two s1 s2))
  else with_lock s1.lock (fun _ -> no_lock_pop_two s1 s2)
```

sigh …

```
type 'a stack = { mutable contents : 'a list; lock : Mutex.t; id : int }

let new_id : unit -> int =
  let c = ref 0 in let l = Mutex.create() in
 (fun _ -> with_lock l (fun _ -> (c := (!c) + 1 ; !c)))

let empty () = {contents=[]; lock=Mutex.create(); id=new_id()};;

let no_lock_pop_two (s1:'a stack) (s2:'a stack) : ('a * 'a) option =
      match no_lock_pop s1, no_lock_pop s2 with
       | Some x, Some y -> Some (x,y)
       | Some x, None -> no_lock_push s1 x; None
       | None, Some y -> no_lock_push s2 y; None

let pop_two (s1:'a stack) (s2:'a stack) : ('a * 'a) option =
  …
;;
```

Refined Design Pattern

- *Associate a lock with each shared, mutable object.*
- *Choose some ordering on shared mutable objects.*
  - doesn't matter what the order is, as long as it is total.
  - in C/C++, often use the address of the object as a unique number.
  - Our solution: *add a unique ID number to each object*
- *To perform actions on a set of objects S atomically:*
  - acquire the locks for the objects in S *in order*.
  - perform the actions.
  - release the locks.

BUT: IN A BIG PROGRAM, IT IS REALLY HARD TO GET THIS RIGHT

A HUGE COMPONENT OF PL RESEARCH INVOLVES TRYING TO FIND THE MISTAKES PEOPLE MAKE WHEN DOING THIS. AVOID WHENEVER POSSIBLE. USE FUNCTIONAL ABSTRACTIONS.

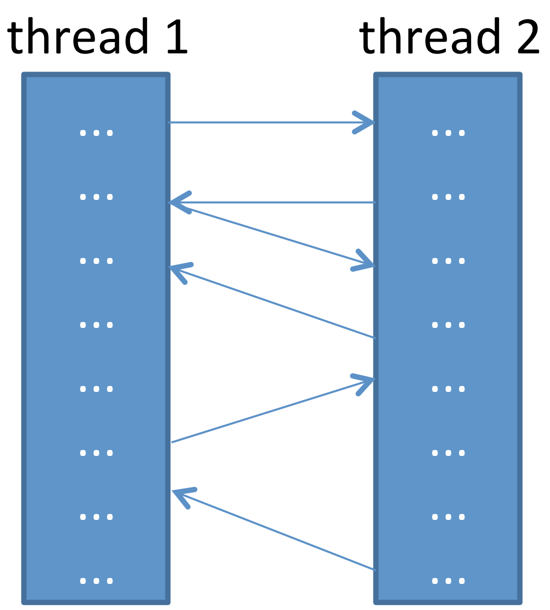
SUMMARY

Programming with mutation, threads and locks

Reasoning about pure parallel programs that include futures is easy -- no harder than ordinary, sequential programs

Reasoning about concurrent programs with effects requires considering *all interleavings of instructions of concurrently executing threads.*

- often too many interleavings for normal humans to keep track of
- non-modular: you often have to look at the details of each thread to figure out what is going on
- locks cut down interleavings
- but knowing you have done it right still requires deep analysis



END