Parallelism I

COS 326

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Parallelism:

The ability to do many things at the same time instead of one after the other.

UNDERSTANDING TECHNOLOGY TRENDS

Moore's Law

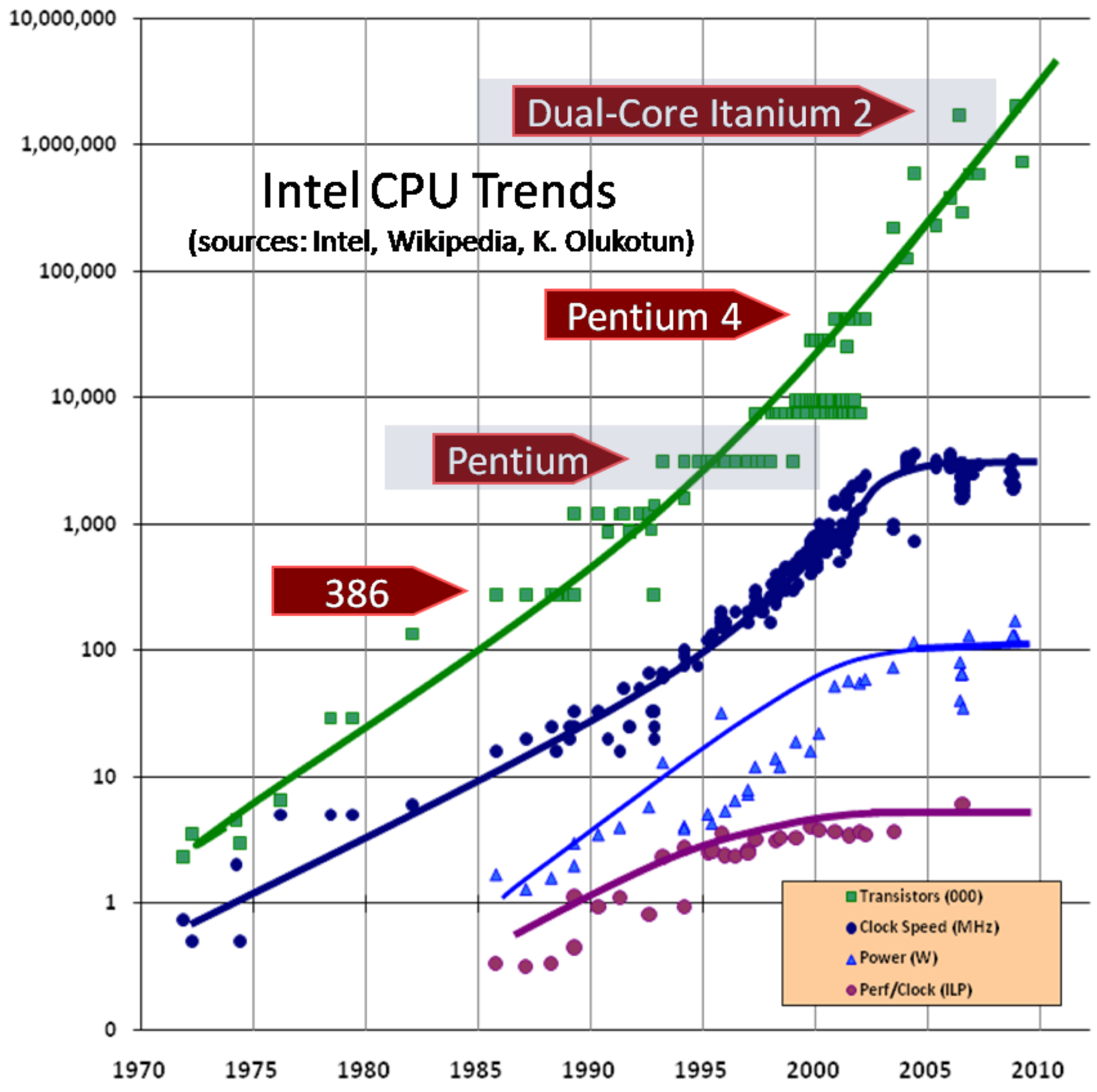
Moore's Law: *The number of transistors you can put on a computer chip doubles (approximately) every couple of years.*

Consequence for most of the history of computing: *All programs double in speed every couple of years.*

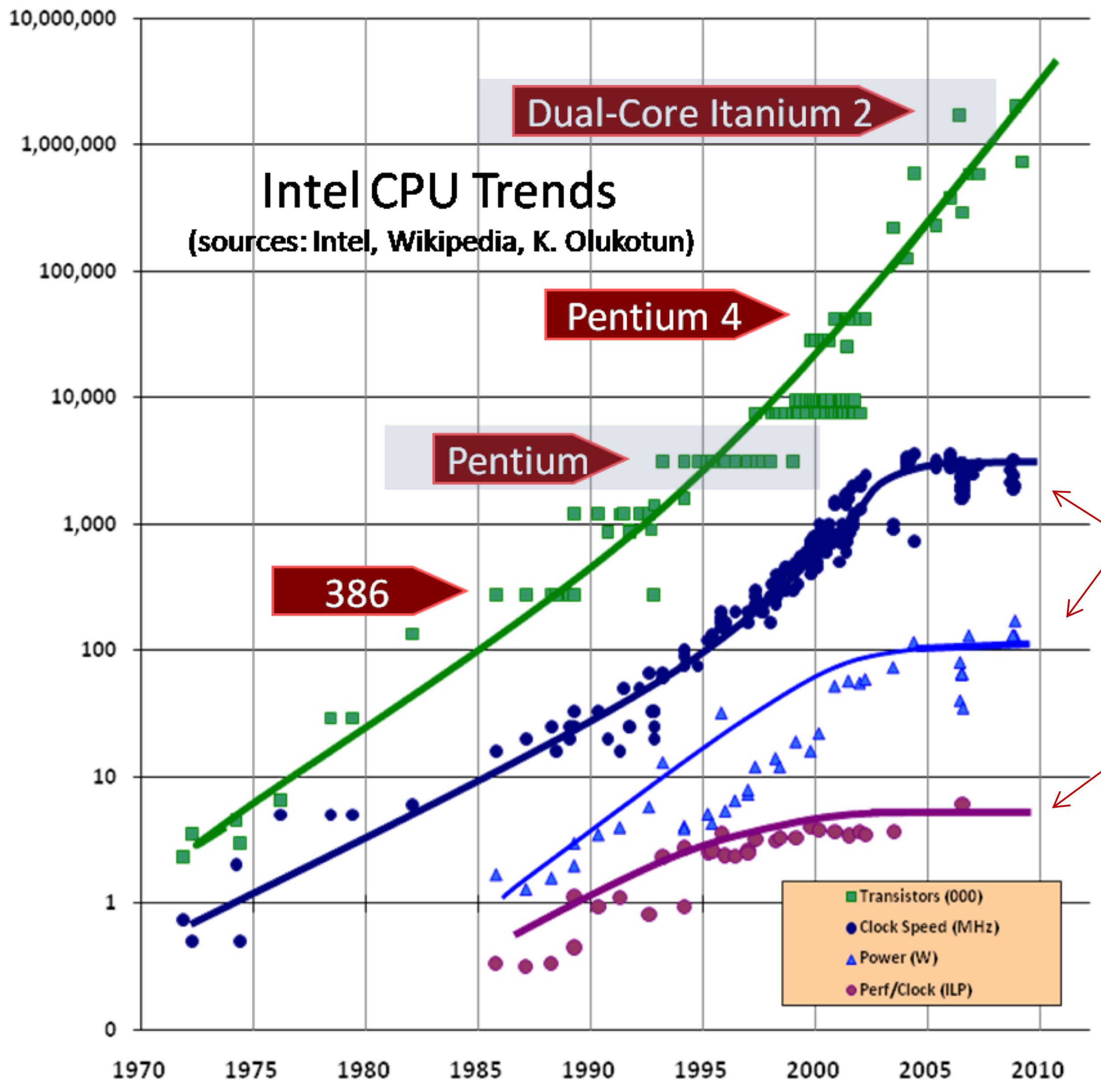
- Why? Hardware designers are wicked smart.
- They have been able to use those extra transistors to (for example) double the number of instructions executed per time unit, thereby processing speed of programs

Consequence for application writers:

- *watch TV for a while and your programs optimize themselves*!
- new applications thought impossible became possible because of increased computational power



Intel CPU Trends
(sources: Intel, Wikipedia, K. Olukotun)
Dual-Core Itanium 2
Pentium 4
Pentium
386
10,000,000
1,000,000
100,000
10,000
1,000
100
10
1
0
1970
1975
1980
1985
1990
1995
2000
2005
2010
Transistors (000)
Clock Speed (MHz)
Power (W)
Perf/Clock (ILP)



Power to chip peaking

Darn!
Intel engineers no longer optimize my programs while
I watch TV!

Parallelism

Why is it particularly important (today)?

- Roughly every other year, a chip from Intel would:
  - halve the feature size (size of transistors, wires, etc.)
  - double the number of transistors
  - double the clock speed
  - this drove the economic engine of the IT industry (and the US!)
- No longer able to double clock or cut voltage: a processor won't get any faster!
  - (so why should you buy a new laptop, desktop, etc.?)
  - power and heat are limitations on the clock
  - errors, variability (noise) are limitations on the voltage
  - but we can still pack a lot of transistors on a chip… (at least for another 10 to 15 years.)

So…

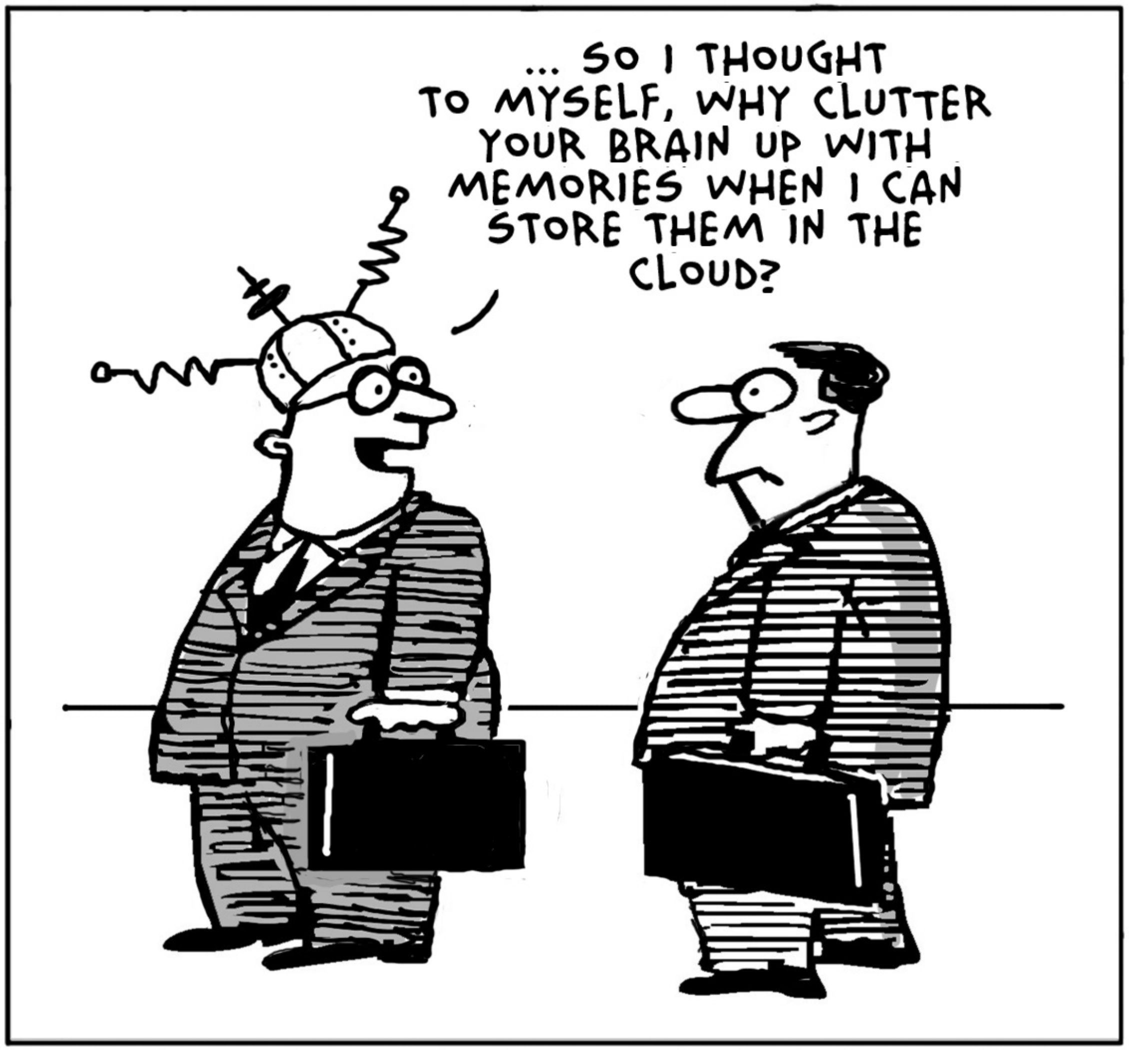
Instead of trying to make your CPU go faster, Intel's just going to pack more CPUs onto a chip.

- a few years ago: dual core (2 CPUs).
- a little more recently: 4, 6, 8 cores.
- Intel is testing 48-core chips with researchers now.
- Within 10 years, you'll have ~1024 Intel CPUs on a chip.

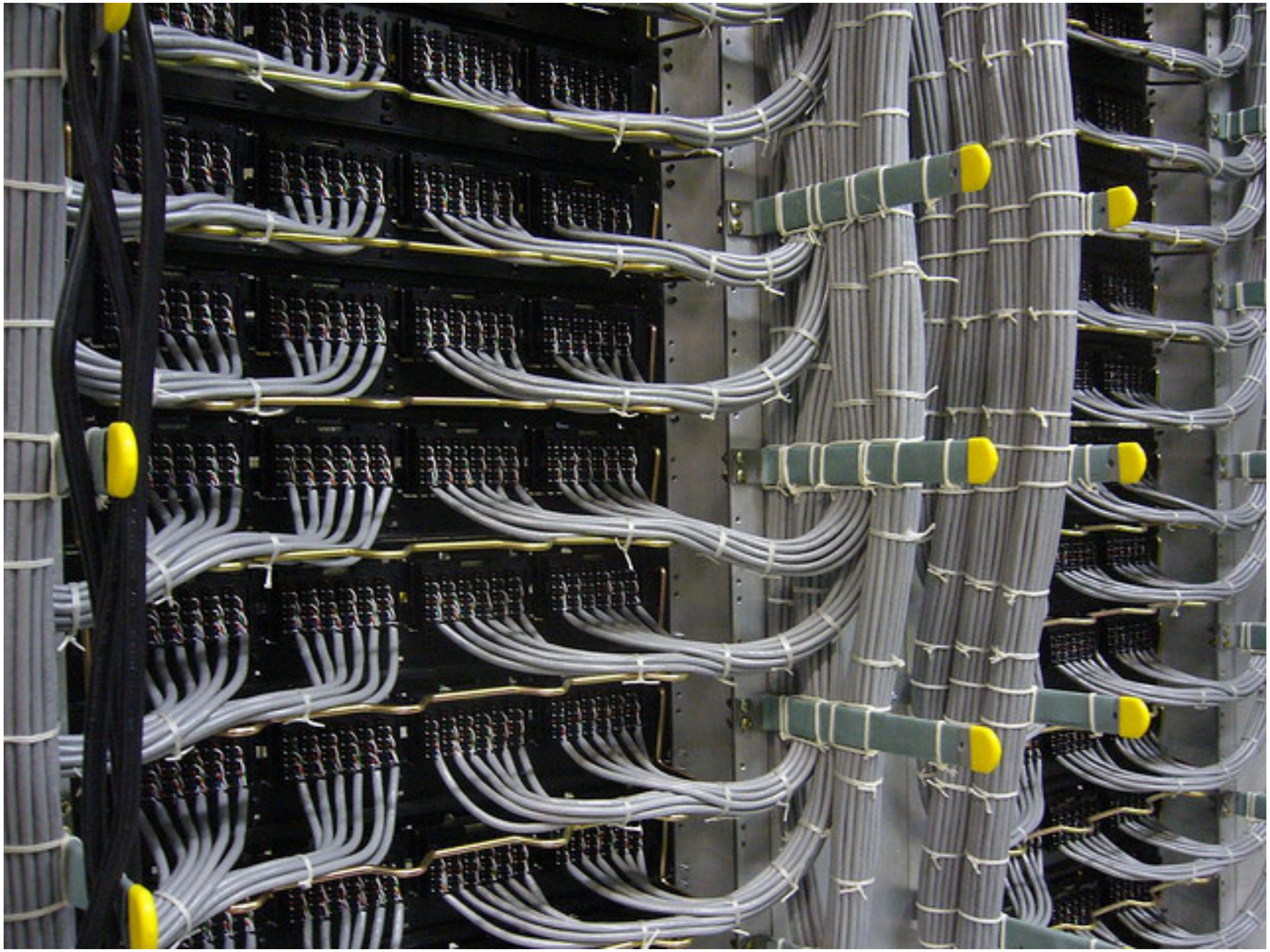
In fact, that's already happening with graphics chips (eg, Nvidia).

- really good at simple data parallelism (many deep pipes)
- but they are *much* dumber than an Intel core.
- and right now, chew up a *lot* of power.
- watch for GPUs to get "smarter" and more power efficient, while CPUs become more like GPUs.

But there's more: Data Centers


... SO I THOUGHT TO MYSELF, WHY CLUTTER YOUR BRAIN UP WITH MEMORIES WHEN I CAN STORE THEM IN THE CLOUD?

Data Centers: *Lots* of Connected Computers!



Data Centers: Lots of Connected Computers

Computer containers for plug-and-play parallelism:

Data Centers

10s or 100s of thousands of computers

All connected together

Motivated by new applications and scalable web services:

- let's catalogue all N billion webpages in the world
- let's all allow anyone in the world to search for the page he or she needs
- let's process that search in less than a second

It's Amazing!

It's Magic!

Sounds Great!

So my old programs will run 2x, 4x, 48x, 256x, 1024x faster?

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No way!

Sounds Great!

So my old programs will run 2x, 4x, 48x, 256x, 1024x faster?

No way!

Single core ==> dual core means new algorithms

- *without work & thought, our programs don't get any faster at all*
- *it takes ingenuity to generate efficient parallel algorithms from sequential ones*

Unfortunately

Most parallel and concurrent programming models are far harder to work with than sequential ones:

- *They introduce nondeterminism*
  - the root of (almost all) evil
  - program parts suddenly have many different outcomes
    - they have different outcomes *on different runs*
    - debugging requires considering *all of the possible outcomes*
    - horrible *heisenbugs* hard to track down
- *They are nonmodular*
  - module A implicitly influences the outcomes of module B
- *They introduce new classes of errors*
  - race conditions, deadlocks
- *They introduce new performance/scalability problems*
  - busy-waiting, sequentialization, contention,

Fortunately

You are taking a class on functional programming ...

Fortunately

You are taking a class on functional programming ...

The correctness of parallel functional programs is pretty easy to reason about because there are efficient parallel functional libraries with the same semantics as their sequential versions!

Parallel functional programs are deterministic

Parallel don’t have race conditions

But it is still trickier to reason about the cost of parallel functional programs than sequence ones

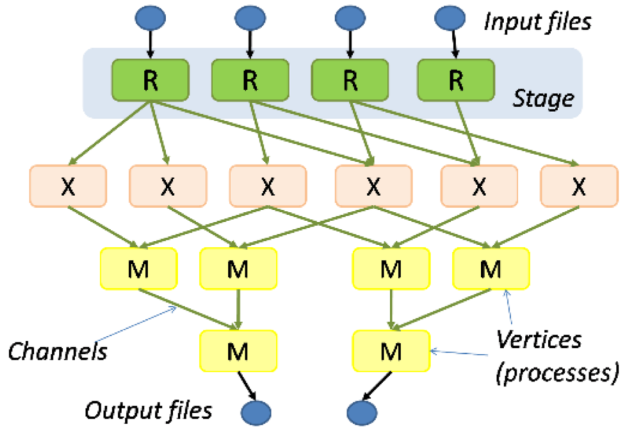
Frameworks for Parallel Functional Programming

Naiad

Pig

hadoop

Dryad



Spark

Lightning-Fast Cluster Computing

INTRODUCING PARALLELISM

Flavors of Parallelism

Data Parallelism

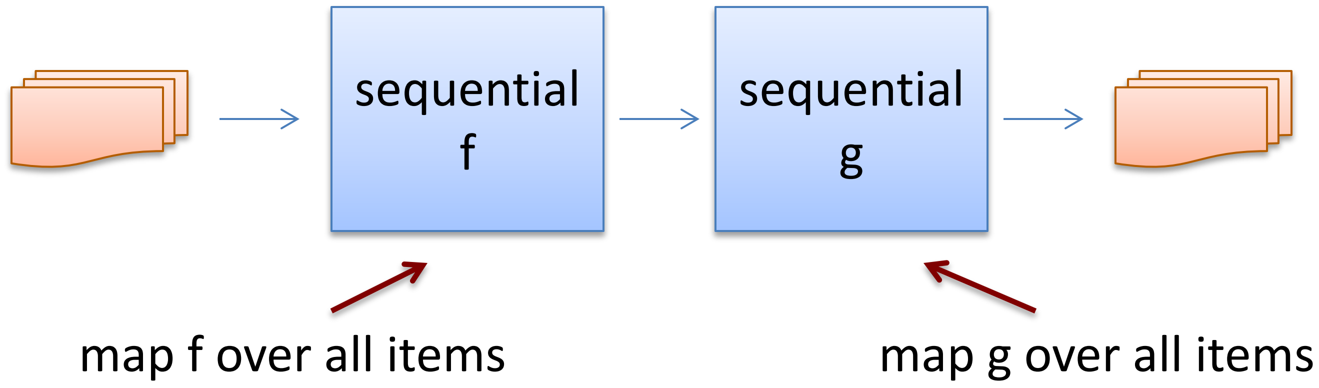
- same computation being performed on a *collection* of independent items
- e.g., adding two vectors of numbers

Task Parallelism

- different computations/programs running at the same time
- e.g., running web server and database

Pipeline Parallelism

- assembly line:



Parallelism vs. Concurrency

Parallelism: performs many tasks *simultaneously*

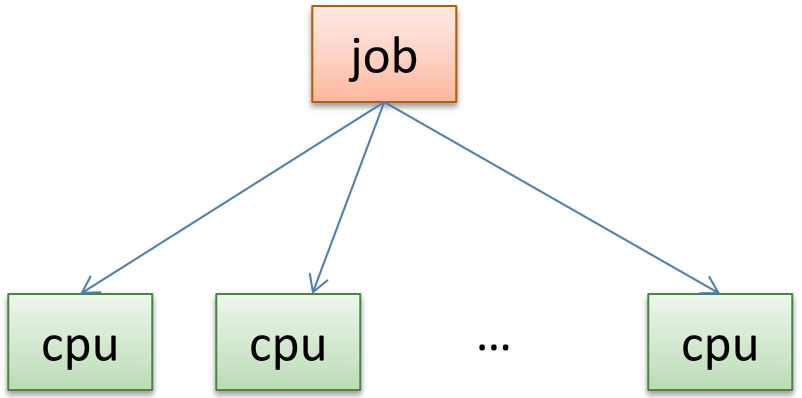
- purpose: improves throughput
- mechanism:
  - many independent computing devices
  - decrease run time of program by utilizing multiple cores or computers
- eg: running your web crawler on a cluster versus one machine.

Concurrency: mediates multi-party access to shared resources

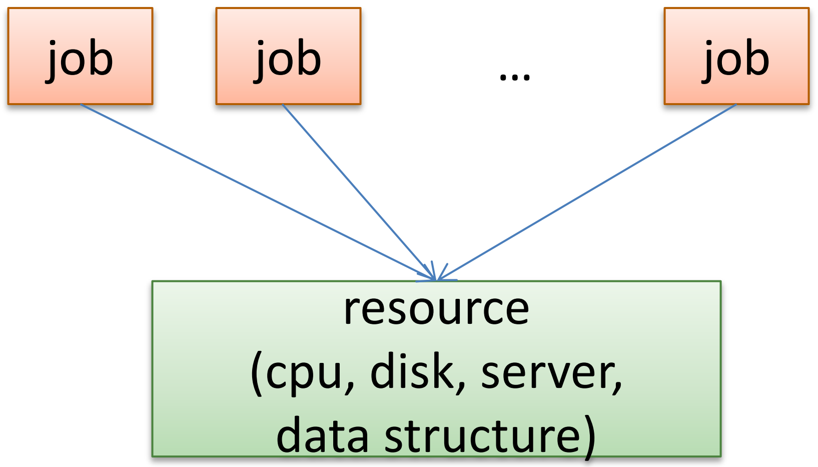
- purpose: decrease response time
- mechanism:
  - switch between different threads of control
  - work on one thread when it can make useful progress; when it can't, suspend it and work on another thread
- eg: running your clock, editor, chat at the same time on a single CPU.
  - OS gives each of these programs a small time-slice (~10msec)
  - often *slows* throughput due to cost of switching contexts
- eg: don't block while waiting for I/O device to respond, but let another thread do useful CPU computation

Parallelism vs. Concurrency

<u>Parallelism:</u>
perform several independent tasks simultaneously



<u>Concurrency:</u>
mediate/multiplex access to shared resource



many efficient programs use some parallelism and some concurrency

THREADS: A CONVENTIONAL PARALLEL PROGRAMMING MODEL

Threads: A Warning

Concurrent Threads with Locks: the classic shoot-yourself-in-the-foot concurrent programming model

- all the classic error modes

Why Threads?

- almost all programming languages will have a threads library
  - OCaml in particular!
- you need to know where the pitfalls are
- the assembly language of concurrent programming paradigms
  - we'll use threads to build several higher-level programming models

Threads

A thread is an abstraction of a processor.

- programmer (or compiler) decides that some work can be done in parallel with some other work, e.g.:

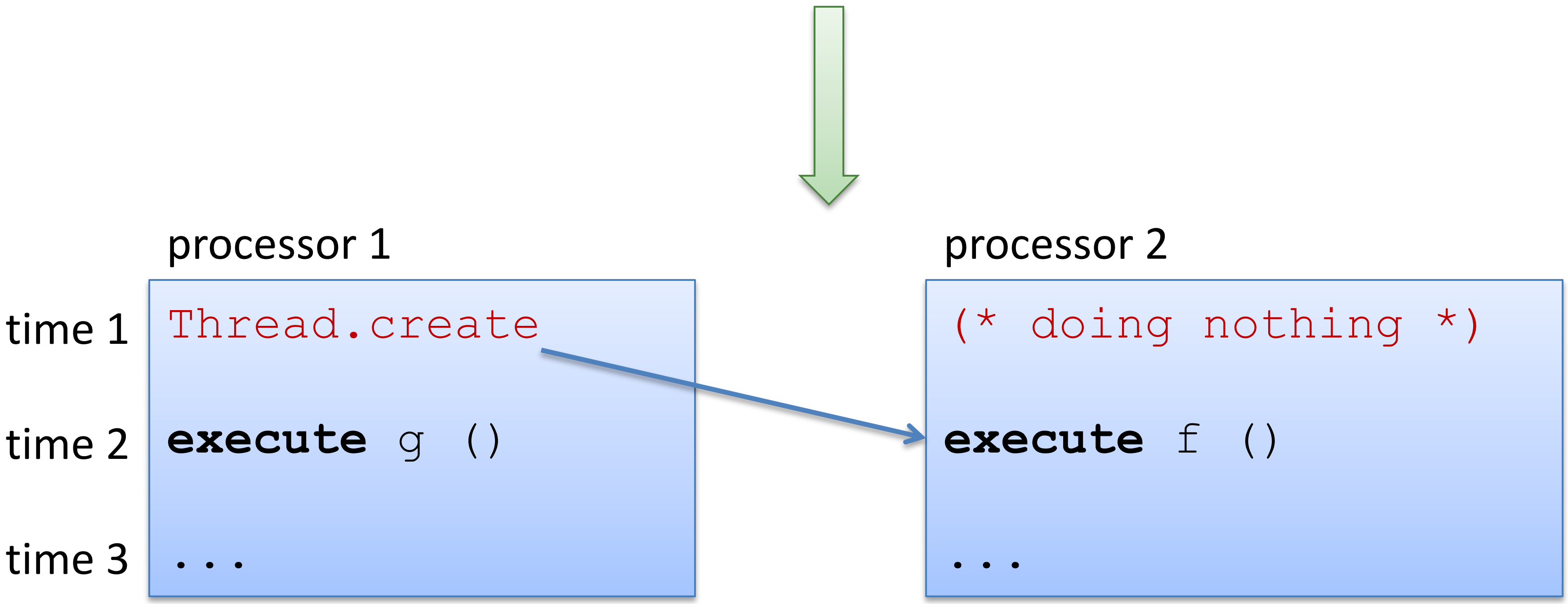
```
let _ = compute_big_thing() in
let y = compute_other_big_thing() in
...
```

- we *fork* a thread to run the computation in parallel, e.g.:

```
let t = Thread.create compute_big_thing () in
let y = compute_other_big_thing () in
 ...
```

Intuition in Pictures

```
let t = Thread.create f () in
let y = g () in
 ...
```



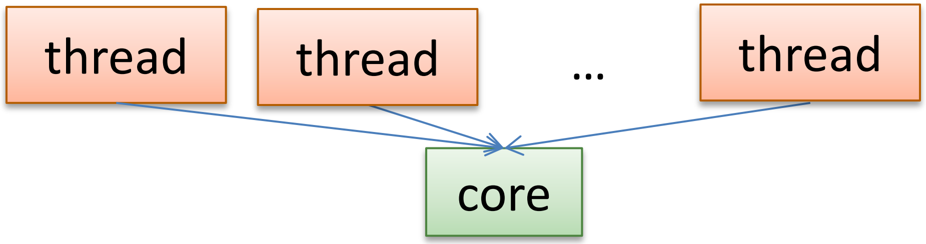
Of Course…

Suppose you have 2 available cores and you fork 4 threads. In a typical multi-threaded system,

- the operating system provides *the illusion* that there are an infinite number of processors.
  - not really: each thread consumes space, so if you fork too many threads the process will die.
- it *time-multiplexes* the threads across the available processors.
  - about every 10 msec, it stops the current thread on a processor, and switches to another thread.
  - so a thread is really a *virtual processor*.

OCaml, Concurrency and Parallelism

Unfortunately, even if your computer has 2, 4, 6, 8 cores, OCaml cannot exploit them. It multiplexes all threads over a single core



Hence, OCaml provides concurrency, but not parallelism. *Why?* Because OCaml (like Python) has no parallel "runtime system" or garbage collector. Other functional languages (Haskell, F#, ...) do.

Fortunately, when thinking about *program correctness*, it doesn't matter that OCaml is not parallel -- I will often pretend that it is.

You can hide I/O latency, do multiprocess programming or distribute tasks amongst multiple computers in OCaml.

Coordination

```
Thread.create : ('a -> 'b) -> 'a -> Thread.t

let t = Thread.create f () in
let y = g () in
 ...
```

How do we get back the result that `t` is computing?

First Attempt

```
let r = ref None
let t = Thread.create (fun _ -> r := Some(f ())) in
let y = g() in
  match !r with
    | Some v -> (* compute with v and y *)
    | None -> failwith "impossible"
```

What’s wrong with this?

Second Attempt

```
let r = ref None
let t = Thread.create (fun _ -> r := Some(f ())) in
let y = g() in
let rec wait() =
  match !r with
    | Some v -> v
    | None -> wait()
in
let v = wait() in
  (* compute with v and y *)
```

Two Problems

```
let r = ref None
let t = Thread.create (fun _ -> r := Some(f ())) in
let y = g() in
let rec wait() =
  match !r with
    | Some v -> v
    | None -> wait()
in
let v = wait() in
  (* compute with v and y *)
```

First, we are *busy-waiting*.

- consuming CPU without doing something useful.
- CPU could either be running a useful thread/program or power down.

Two Problems

```
let r = ref None
let t = Thread.create (fun _ -> r := Some(f ())) in
let y = g() in
let rec wait() =
  match !r with
    | Some v -> v
    | None -> wait()
in
let v = wait() in
  (* compute with v and y *)
```

Second, an operation like r := Some v may not be *atomic.*

- r := Some v requires us to copy the bytes of Some v into the ref r
- we might see part of the bytes (corresponding to Some) before we've written in the other parts (e.g., v).
- So the waiter might see the wrong value.

Atomicity

Consider the following:

```
let inc(r:int ref) = r := !r + 1
```

and suppose two threads are incrementing the same ref r:

Thread 1	Thread 2
`inc(r);`	`inc(r);`
`!r`	`!r`

If r initially holds 0, then what will Thread 1 see when it reads r?

Atomicity

The problem is that we can’t see exactly what instructions the compiler might produce to execute the code.

It might look like this:

```
Thread 1                  Thread 2
EAX := load(r);           EAX := load(r);
EAX := EAX + 1;           EAX := EAX + 1;
store EAX into r          store EAX into r
EAX := load(r)            EAX := load(r)
```

Atomicity

But a clever compiler might optimize this to:

<u>Thread 1</u>

```
EAX := load(r);
EAX := EAX + 1;
store EAX into r
```
~~EAX := load(r)~~

<u>Thread 2</u>

```
EAX := load(r);
EAX := EAX + 1;
store EAX into r
```
~~EAX := load(r)~~

Atomicity

Furthermore, we don’t know the order in which instructions in thread 1 and thread 2 are executed.

On a single processor, they may be interleaved.

<u>Thread 1</u>

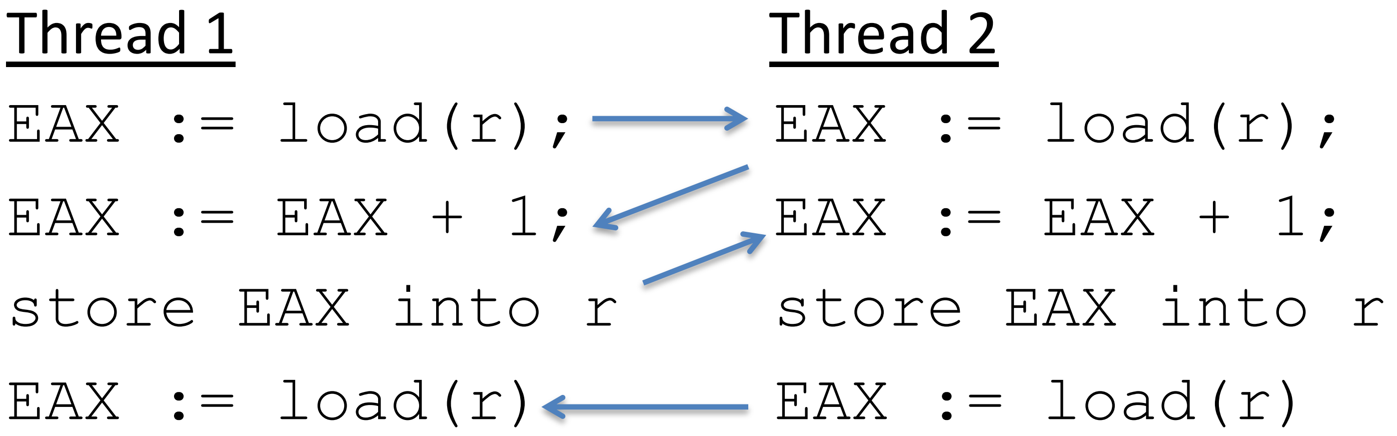
```
EAX := load(r);
EAX := EAX + 1;
store EAX into r
EAX := load(r)
```

<u>Thread 2</u>

```
EAX := load(r);
EAX := EAX + 1;
store EAX into r
EAX := load(r)
```

Atomicity

One possible interleaving of the instructions:



```
Thread 1                          Thread 2
EAX := load(r);                   EAX := load(r);
EAX := EAX + 1;                   EAX := EAX + 1;
store EAX into r                  store EAX into r
EAX := load(r)                    EAX := load(r)
```

What answer do we get if r points to 0 to start?

Atomicity

Another possible interleaving:

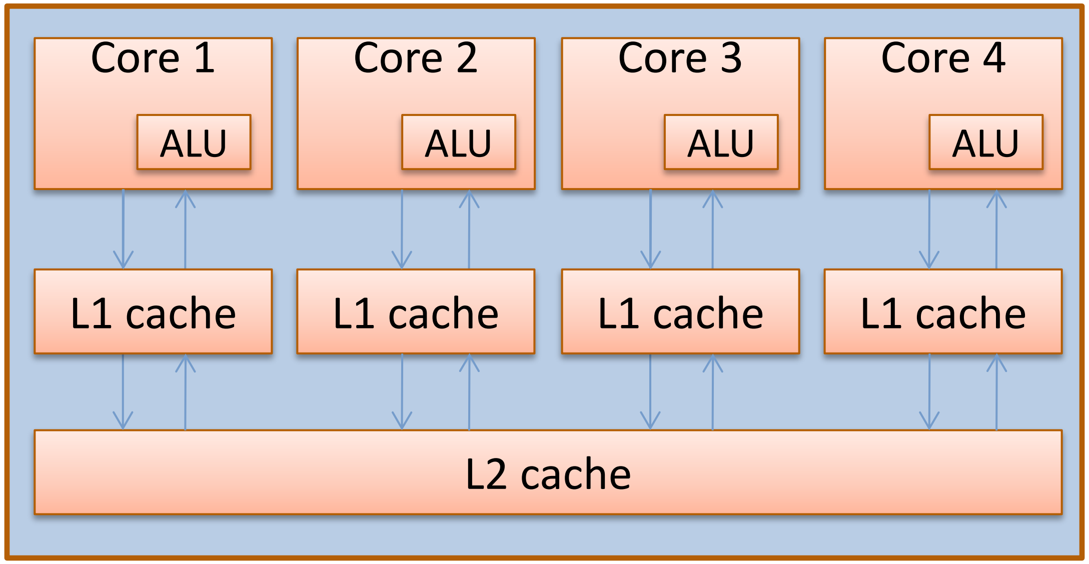
```
Thread 1                 Thread 2
EAX := load(r);          EAX := load(r);
EAX := EAX + 1;          EAX := EAX + 1;
store EAX into r         store EAX into r
EAX := load(r)           EAX := load(r)
```

What answer do we get this time?

Real Machines

Today's multicore processors don't even have *sequentially consistent* memory models.

That means that we can't even assume that what we will see corresponds to *some* interleaving of the threads' instructions!



Beyond the scope of this course.

Summary

```
let inc(r:int ref) = r := !r + 1
```

thread 1

```
inc r;
!r
```

thread 2

```
inc r;
!r
```

If you mix threads and ordinary imperative code, it is extraordinarily difficult to figure out what your code may do, even for experts.

Solution: Synchronization Primitives

All systems for parallel programming have synchronization primitives.

Examples:

- locks
- semaphores
- compare-and-swap
- synchronized methods

Today:

- fork-join parallelism
  - join is the synchronization primitive

Recall our Problem

```
Thread.create : ('a -> 'b) -> 'a -> Thread.t

let t = Thread.create f () in
let y = g () in
 ...
```

How do we get back the result that `t` is computing?

One Solution (using join)

```
let r = ref None
let t = Thread.create (fun _ -> r := Some(f ())) in
 let y = g() in
   Thread.join t ;
   match !r with
   | Some v -> (* compute with v and y *)
   | None -> failwith "impossible"
```

One Solution (using join)

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    Thread.join t ;
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    | Some v -> (* compute with v and y *)
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```

`Thread.join t` causes the current thread to *wait* until the thread `t` terminates.

One Solution (using join)

```
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 let y = g() in
    Thread.join t ;
    match !r with
    | Some v -> (* compute with v and y *)
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```

Synchronization

So after the join, we know that any of the operations of t have *completed*.

The happens-before relation

Rule 1: Given two expressions (or instructions) in sequence, e1; e2, in a single thread, we know that e1 happens before e2.

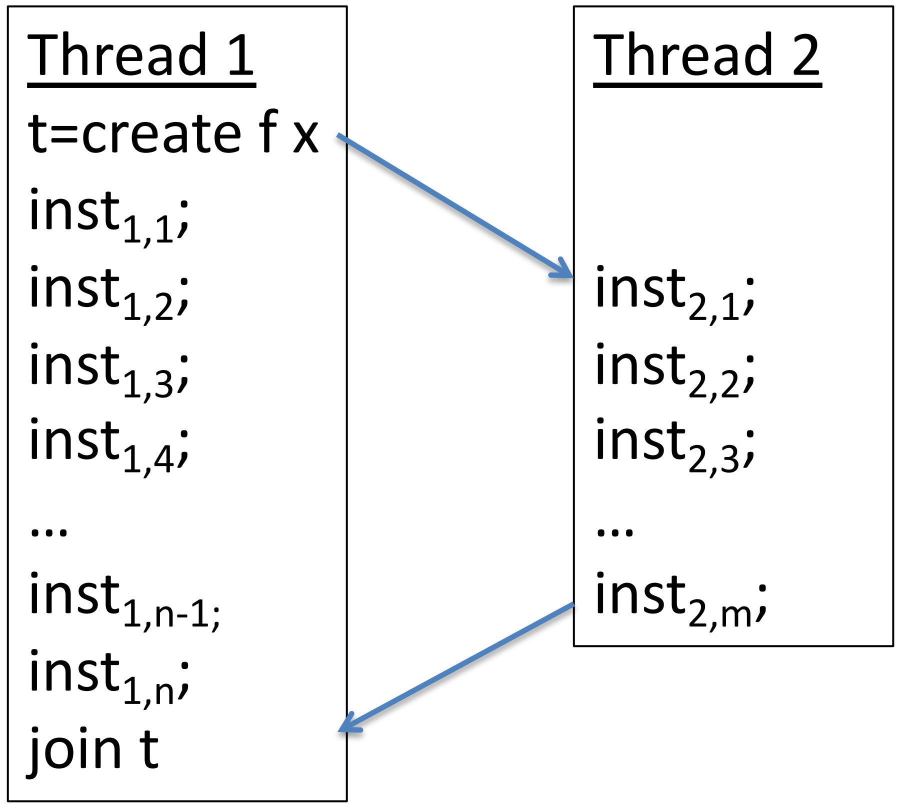
Rule 2: Given a program:

```
let t = Thread.create f x in
....
Thread.join t;
e
```

we know that (f x) happens before e.

Rule 3: Transitivity

In Pictures



Thread 1

t=create f x

$\text{inst}_{1,1}$;

$\text{inst}_{1,2}$;

$\text{inst}_{1,3}$;

$\text{inst}_{1,4}$;

…

$\text{inst}_{1,n-1;}$

$\text{inst}_{1,n}$;

join t

Thread 2

$\text{inst}_{2,1}$;

$\text{inst}_{2,2}$;

$\text{inst}_{2,3}$;

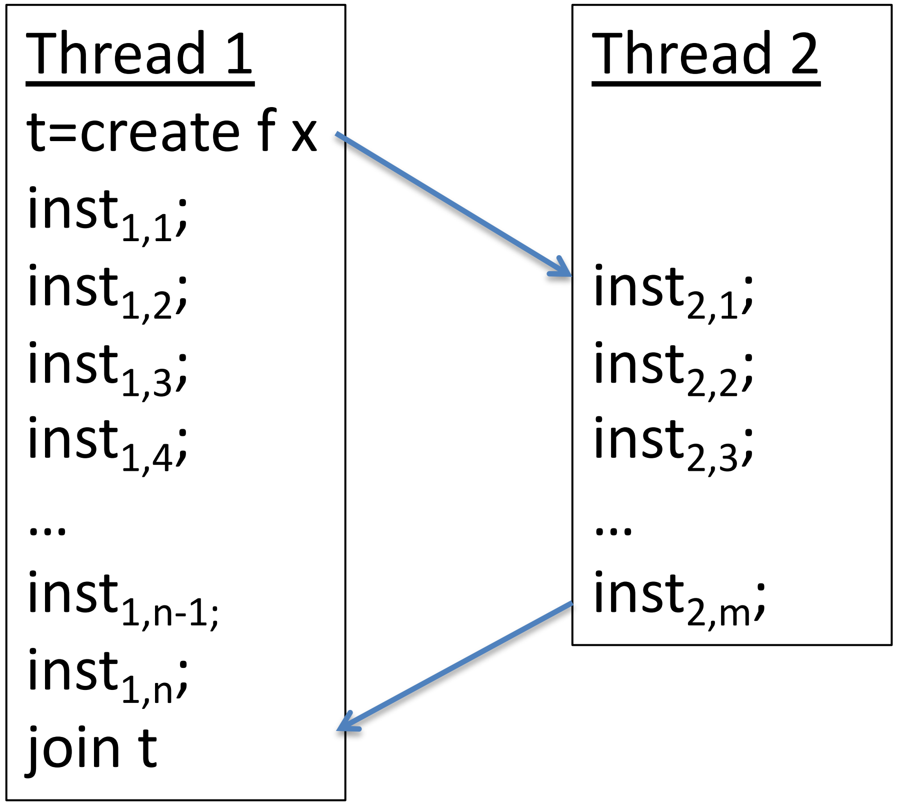
…

$\text{inst}_{2,m}$;

We know that for each thread the previous instructions must happen before the later instructions.

So for instance, $\text{inst}_{1,1}$ must happen before $\text{inst}_{1,2}$.

In Pictures



Thread 1

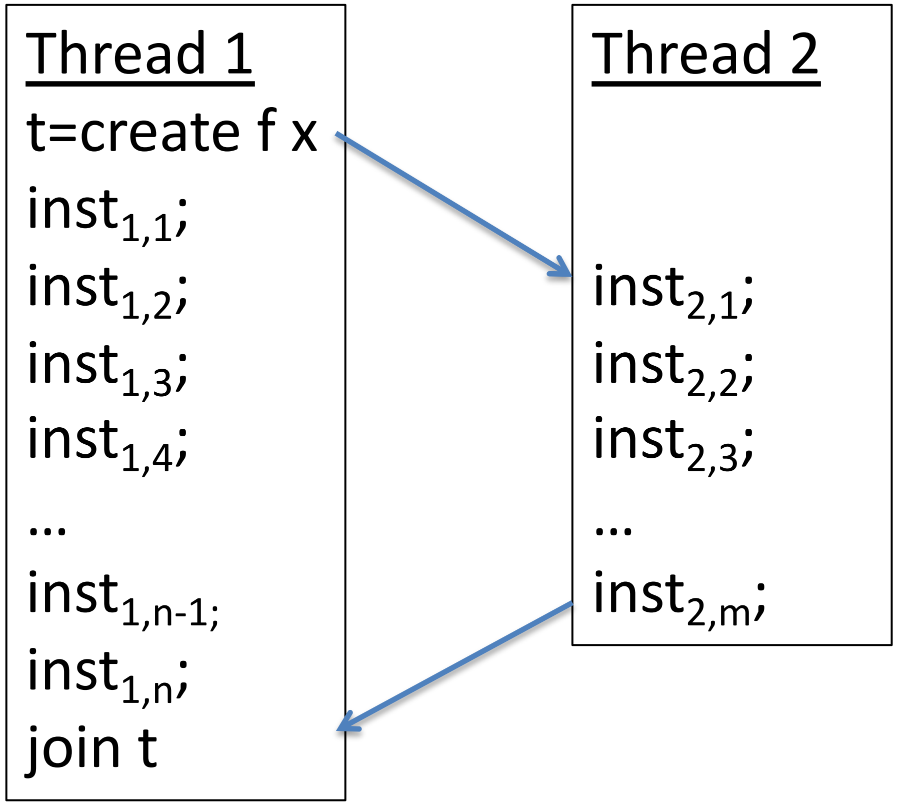
```
t=create f x
inst_{1,1};
inst_{1,2};
inst_{1,3};
inst_{1,4};
…
inst_{1,n-1};
inst_{1,n};
join t
```

Thread 2

```
inst_{2,1};
inst_{2,2};
inst_{2,3};
…
inst_{2,m};
```

We also know that the fork must happen before the first instruction of the second thread.

In Pictures



Thread 1

t=create f x

$\text{inst}_{1,1}$;

$\text{inst}_{1,2}$;

$\text{inst}_{1,3}$;

$\text{inst}_{1,4}$;

…

$\text{inst}_{1,n-1;}$

$\text{inst}_{1,n}$;

join t

Thread 2

$\text{inst}_{2,1}$;

$\text{inst}_{2,2}$;

$\text{inst}_{2,3}$;

…

$\text{inst}_{2,m}$;

We also know that the fork must happen before the first instruction of the second thread.

And thanks to the join, we know that all of the instructions of the second thread must be completed before the join finishes.

Fork-Join

Fork-Join parallelism cuts down on the number of interleavings

Reduces non-determinism

A very useful pair of primitives

But we still do have to think about all those interleavings and how they interact with mutable references. It's very, very hard to write and debug programs in this model.

Can we avoid doing such reasoning altogether?

FUTURES: A PARALLEL PROGRAMMING ABSTRACTION

Futures

```
module type FUTURE =
sig
  type 'a future

  (* future f x forks a thread to run f(x)
     and stores the result in a future when complete *)
  val future : ('a->'b) -> 'a -> 'b future

  (* force f causes us to wait until the
     thread computing the future value is done
     and then returns its value. *)
  val force : 'a future -> 'a
end
```

Does that interface looks familiar .... ?

Future Implementation

```
module Future : FUTURE =
struct
  type ‘a future = {tid   : Thread.t      ;
                   value : ’a option ref }
end
```

Future Implementation

```
module Future : FUTURE =
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}





end
```

Future Implementation

```
module Future : FUTURE =
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
```

Now using Futures

```
let x = future f () in
let y = g () in
let v = force x in
(* compute with v and y *)
```

Back to the Futures

```
module type FUTURE =
sig
  type 'a future

  val future : ('a->'b) -> 'a -> 'b future
  val force :'a future -> 'a
end
```

```
val f : unit -> int
val g : unit -> int
```

with futures library:

```
let x = future f () in
let y = g () in
let v = force x in
y + v
```

without futures library:

```
let r = ref None
let t = Thread.create
           (fun _ -> r := Some(f ()))
           ()
in
let y = g() in
Thread.join t ;
match !r with
    Some v -> y + v
  | None -> failwith "impossible"
```

Back to the Futures

```
module type FUTURE =
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  type 'a future

  val future : ('a->'b) -> 'a -> 'b future
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let r = ref None
let t = Thread.create
            (fun _ -> r := Some(f ()))
            ()
in
let y = g() in
Thread.join t ;
match !r with
    Some v -> y + v
  | None -> failwith "impossible"
```

what happens if we delete these lines?

Back to the Futures

```
module type FUTURE =
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  type 'a future

  val future : ('a->'b) -> 'a -> 'b future
  val force :'a future -> 'a
end
```

```
val f : unit -> int
val g : unit -> int
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with futures library:

```
let x = future f () in
let y = g () in
let v = force x in
y + x
```

without futures library:

```
let r = ref None
let t = Thread.create
           (fun _ -> r := Some(f ()))
           ()
in
let y = g() in
Thread.join t ;
match !r with
    Some v -> y + v
  | None -> failwith "impossible"
```

what happens if we use x and forget to force?

Back to the Futures

```
module type FUTURE =
sig
  type 'a future

  val future : ('a->'b) -> 'a -> 'b future
  val force :'a future -> 'a
end
```

```
val f : unit -> int
val g : unit -> int
```

with futures library:

```
let x = future f () in
let y = g () in
let v = force x in
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without futures library:

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let r = ref None
let t = Thread.create
           (fun _ -> r := Some(f ()))
           ()
in
let y = g() in
Thread.join t ;
match !r with
    Some v -> y + v
  | None -> failwith "impossible"
```

Moral: Futures + typing ensure entire categories of errors can't happen -- you protect yourself from your own stupidity

Back to the Futures

```
module type FUTURE =
sig
  type 'a future

  val future : ('a->'b) -> 'a -> 'b future
  val force :'a future -> 'a
end
```

```
val f : unit -> int
val g : unit -> int
```

with futures library:

```
let x = future f () in
let v = force x in
let y = g () in
y + x
```

without futures library:

```
let r = ref None
let t = Thread.create
          (fun _ -> r := Some(f ()))
          ()
in
Thread.join t ;
let y = g() in
match !r with
    Some v -> y + v
  | None -> failwith "impossible"
```

what happens if you relocate force, join?

Back to the Futures

```
module type FUTURE =
sig
  type ‘a future

  val future : (’a->’b) -> ’a -> ‘b future
  val force :’a future -> ‘a
end
```

```
val f : unit -> int
val g : unit -> int
```

with futures library:

```
let x = future f () in
let v = force x in
let y = g () in
y + x
```

without futures library:

```
let r = ref None
let t = Thread.create
           (fun _ -> r := Some(f ()))
           ()
in
Thread.join t ;
let y = g() in
match !r with
    Some v -> y + v
  | None -> failwith “impossible”
```

Moral: Futures are not a universal savior

An Example: Mergesort on Arrays

```
let mergesort (cmp:'a->'a->int)
              (arr : 'a array) : 'a array =
  let rec msort (start:int) (len:int) : 'a array =
    match len with
      | 0 -> Array.of_list []
      | 1 -> Array.make 1 arr.(start)
      | _ -> let half = len / 2 in
             let a1 = msort start half in
             let a2 = msort (start + half)
                            (len - half) in
               merge a1 a2

  and merge (a1:'a array) (a2:'a array) : 'a array =
      ...
```

An Example: Mergesort on Arrays

```
let mergesort (cmp:'a->'a->int)
              (arr : 'a array) : 'a array =
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    match len with
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             let a1 = msort start half in
             let a2 = msort (start + half)
                            (len - half) in
               merge a1 a2

  and merge (a1:'a array) (a2:'a array) : 'a array =
      ...
```

Opportunity for parallelization

Making Mergesort Parallel

```
let mergesort (cmp:'a->'a->int)
              (arr : 'a array) : 'a array =
  let rec msort (start:int) (len:int) : 'a array =
    match len with
      | 0 -> Array.of_list []
      | 1 -> Array.make 1 arr.(start)
      | _ -> let half = len / 2 in
             let a1_f =
               Future.future (msort start) half in
             let a2 =
               msort (start + half)(len - half) in
             merge (Future.force a1_f) a2

  and merge (a1:'a array) (a2:'a array) : 'a array =
```

Divide-and-Conquer

This is an instance of a basic *divide-and-conquer* pattern in parallel programming

- take the problem to be solved and divide it in half
- fork a thread to solve the first half
- simultaneously solve the second half
- synchronize with the thread we forked to get its results
- combine the two solution halves into a solution for the whole problem.

Warning: the fact that we only had to rewrite 2 lines of code for mergesort made the parallelization transformation look deceptively easy

- we also had to verify that any two threads did not touch overlapping portions of the array -- if they did we would have to again worry about scheduling nondeterminism

Caveats

There is some overhead for creating a thread.

- On uniprocessor, parallel code *slower* than sequential code.

Even on a multiprocessor, we do *not always* want to fork.

- when the subarray is small, faster to sort it sequentially than to fork
  - similar to using insertion sort when arrays are small vs. quicksort
- this is known as a *granularity problem*
  - more parallelism than we can effectively take advantage of.

Caveats

Optimizing requires benchmarking and experience

Typically, use parallel divide-and-conquer until:

- we have generated *at least* as many threads as there are processors
  - often *more threads* than processors because different jobs take different amounts of time to complete and we would like to keep all processors busy
- the sub-arrays have gotten small enough that it's not worth forking.

We're not going to worry about these performance-tuning details but rather focus on the distinctions between *parallel* and *sequential algorithms*.

Another Example

```
type 'a tree = Leaf | Node of 'a node
and 'a node = {left  : 'a tree ;
               value : 'a      ;
               right : 'a tree }

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

let sum (t:int tree) = fold (+) 0 t
```

Another Example

```
type 'a tree = Leaf | Node of 'a node
and 'a node = {left  : 'a tree ;
               value : 'a      ;
               right : 'a tree }

let rec pfold (f:'a -> 'b -> 'b -> 'b) (u:'b)
              (t:'a tree) : 'b =
  match t with
  | Leaf -> u
  | Node n ->
     let l_f = Future.future (pfold f u) n.left in
     let r = pfold f u n.right in
     f n.value (Future.force l_f) r

let sum (t:int tree) = pfold (+) 0 t
```

Note

If the tree is unbalanced, then we’re not going to get the same speedup as if it’s balanced.

Consider the degenerate case of a list.

- The forked child will terminate without doing any useful work.
- So the parent is going to have to do all that work.
- Pure overhead… ☹

In general, lists are a horrible data structure for parallelism.

- *we can’t cut the list in half in constant time*
- for arrays and trees, we can do that (assuming the tree is balanced.)

Side Effects?

```
type 'a tree = Leaf | Node of 'a node
and 'a node = { left  : 'a tree ;
                value : 'a      ;
                right : 'a tree }

let rec pfold (f:'a -> 'b -> 'b -> 'b) (u:'b)
              (t:'a tree) : 'b =
  match t with
  | Leaf -> u
  | Node n ->
     let l_f = Future.future (pfold f u) n.left in
     let r = pfold f u n.right in
     f n.value (Future.force l_f) r

let print (t:int tree) =
  pfold (fun n _ _ -> Printf.print “%d\n” n) ()
```

Huge Point

If code is purely functional, then it never matters in what order it is run.

If f () and g () are pure then all of the following are equivalent:

```
let x = f() in
let y = g() in
e
```

```
let x_f = future f () in
let y   = g ()        in
let x   = force x_f   in
e
```

```
let y = g () in
let x = f () in
e
```

```
let y_g = future g () in
let x   = f ()        in
let y   = force y_g   in
e
```

As soon as we introduce *side-effects*, the order starts to matter.

- This is why, IMHO, *imperative* languages where even the simplest of program phrases involves a side effect, are doomed.
- Of course, we've been saying this for 30 years!
- See J. Backus's Turing Award lecture, "*Can Programming be Liberated from the von Neumann Style? A Functional Style and Its Algebra of Programs*."

  http://www.cs.cmu.edu/~crary/819-f09/Backus78.pdf

SUMMARY

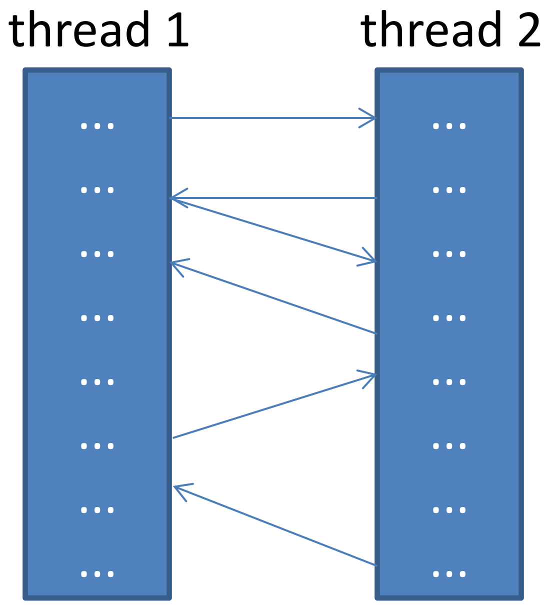
Programming with mutation, threads and locks

Reasoning about the correctness of pure parallel programs that include futures is easy -- no harder than ordinary, sequential programs. (Reasoning about their performance may be harder.)

Reasoning about shared variables is *hard* in general, but *futures* some structure for getting it right.

Much of programming-language design is the art of finding structure that encourages good programs and discourages bad ones.

Also true of abstract data type design: engineer interfaces that make it harder for the user to make mistakes.


thread 1
thread 2