SOFTWARE TRANSACTIONAL MEMORY
(WITH A DETOUR THROUGH HASKELL)

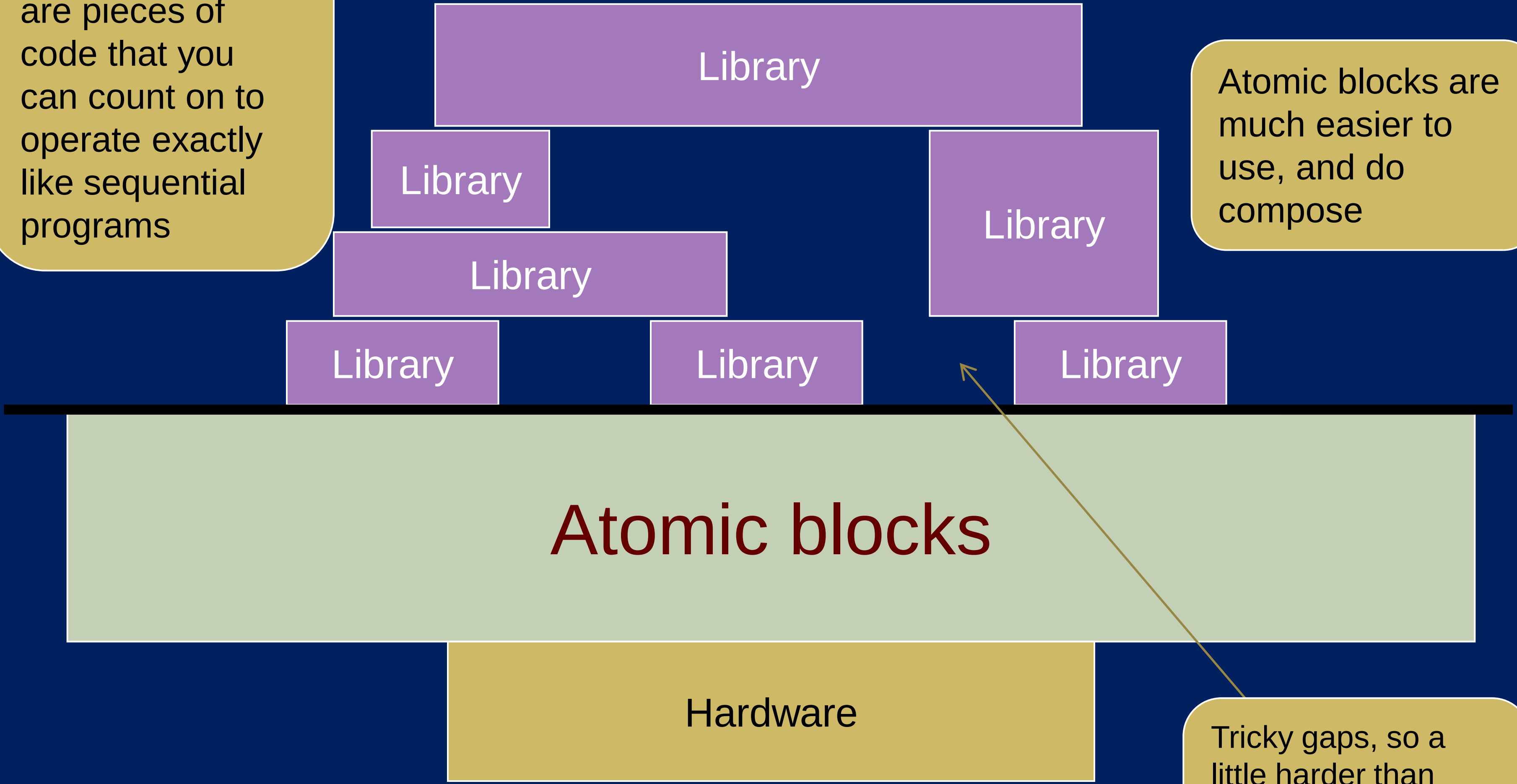
David Walker

Thanks to Kathleen Fisher and recursively to
Simon Peyton Jones for much of the content of these slides.

Optional Reading:
“Beautiful Concurrency”,
“The Transactional Memory / Garbage Collection Analogy”
“A Tutorial on Parallel and Concurrent Programming in Haskell”

Second Idea: Replace locks with atomic blocks

Atomic blocks are pieces of code that you can count on to operate exactly like sequential programs



Atomic blocks are much easier to use, and do compose

Tricky gaps, so a little harder than immutable data but you can do more stuff

The Punchline for STM

Coding style	Difficulty of queue implementation
Sequential code	Undergraduate (COS 226)
Efficient parallel code with locks and condition variables	Publishable result at international conference[1]
Parallel code with STM	*Undergraduate*

[1] Simple, fast, and practical non-blocking and blocking concurrent queue algorithms.

```
in parallel:
   (atomic action1)        (atomic action2)
```

just a function call in Haskell

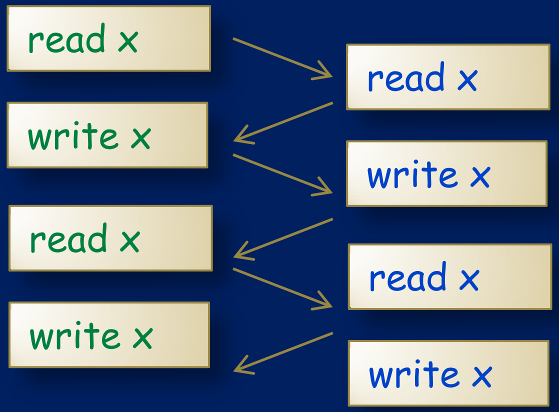
action 1:

```
read x
write x
read x
write x
```

action 2:

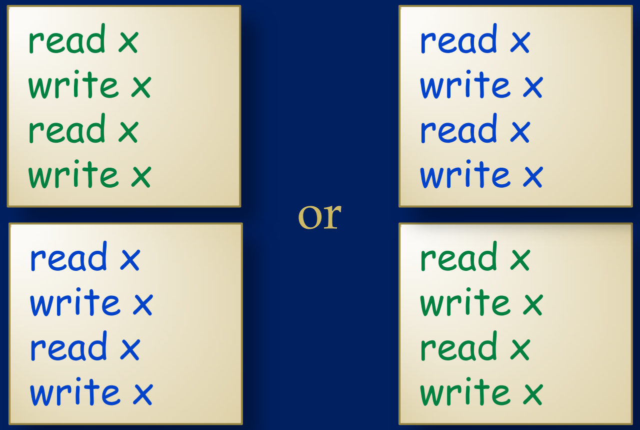
```
read x
write x
read x
write x
```

without transactions:



(some interleaving -- the programmer must worry about which one)

with transactions:



(programmer gets to cut down non-determinism as much as he/she wants)

A Detour:
Haskell and Monads

Back to Basics: What's an interface?

An interface declares some new abstract types and some operations over values with those abstract types. For example:

```
module type CONTAINER = sig

  type 'a t            (* the type of the container *)

  val empty : 'a t

  val insert : 'a -> 'a t -> 'a t

  val remove : 'a t -> 'a option * 'a t

  val fold : ('a -> 'b -> 'b) -> 'b -> 'a t -> 'b

end
```

There are lots of different implementations of such containers: queues, stacks, sets, randomized sets, ...

Interfaces can come with some *equations* one expects every implementation to satisfy. eg:

fold f base empty == base

The equations specify some, but not all of the behavior of the module (eg: stacks and queues remove elements in different orders)

Monads

A *monad* is just a particular *interface*. Two views:

- interface for a very generic container, with operations designed to support *composition* of computations over the contents of containers
- interface for an abstract computation that does some "book keeping" on the side. Book keeping is code for "has an effect". Once again, the support for composition is key.
- since functional programmers know that functions are data, the two views actually coincide

Many different kinds of monads:

- monads for handling/accumulating errors (last week)
- monads for processing collections en masse
- monads for logging strings that should be printed
- monads for coordinating concurrent threads (Jane St. Talk)
- monads for back-tracking search
- monads for *transactional memory*

Because a monad is just a particular interface (with many useful implementations), *you can implement monads in any language*

- But, Haskell is famous for them because it has a special built-in syntax that makes monads particularly easy and elegant to use
- F#, Scala have adopted similar syntactic ideas
- Monads also play a very special role in the overall design of the Haskell language

What is the monad interface?

```
module type MONAD = sig

  type 'a M

  val return : 'a -> 'a M

  val (>>=) : 'a M -> ('a -> 'b M) -> 'b M

end
```

+ some equations specifying how return and bind are required to interact

Consider first the "container interpretation": 'a M is a container for values with type 'a

- return x puts x in the container
- bind c f takes the values in c out of the container and applies f to them, forming a new container holding the results
  - bind c f is often written as: c >>= f

The Options as a Container

```
module type MONAD = sig

  type 'a M

  val return : 'a -> 'a M

  val (>>=) : 'a M -> ('a -> 'b M) -> 'b M

end
```

```
module OptionMonad = struct

  type 'a M = 'a option

  let return x = Some x

  let (>>=) c f =
     match c with
        None -> None
     | Some v -> f v

end
```

put value in
a container

take value v out
of a container c
and then apply f,
producing a new container

The Options as a Container

```
module type MONAD = sig

  type 'a M

  val return : 'a -> 'a M

  val (>>=) : 'a M -> ('a -> 'b M) -> 'b M

end
```

```
module OptionMonad = struct

  type 'a M = 'a option

  let return x = Some x

  let (>>=) c f =
     match c with
        None -> None
     | Some v -> f v

end
```

using the option container:

```
type file_name = string

val read_file : file_name -> string M

let concat f1 f2 =
  readfile f1              >>= (fun contents1 ->
  readfile f2              >>= (fun contents2 ->
  return (contents1 ^ contents2)
;;
```

put value in
a container

take value v out
of a container c
and then apply f,
producing a new container

The Option Monad as Possibly Erroneous Computation

```
module type MONAD = sig

  type 'a M

  val return : 'a -> 'a M

  val (>>=) : 'a M -> ('a -> 'b M) -> 'b M

end
```

```
module ErrorMonad = struct

  type 'a M = 'a option

  let return x = Some x

  let (>>=) c f =
     match c with
        None -> None
     | Some v -> f v

end
```

using the error monad:

```
type file_name = string

val read_file : file_name -> string M

let concat f1 f2 =
  readfile f1            >>= (fun contents1 ->
  readfile f2            >>= (fun contents2 ->
  return (contents1 ^ contents2)
;;
```

check to see if error has occurred, if so return None, else continue

setting up book keeping for error processing

Lists as Containers

```
module type MONAD = sig

  type 'a M

  val return : 'a -> 'a M

  val (>>=) : 'a M -> ('a -> 'b M) -> 'b M

end
```

```
module ListMonad = struct

  type 'a M = 'a list

  let return x = [x]

  let (>>=) c f =
     List.flatten (List.map f c)

end
```

put element in to list container

apply f to all elements of the list c, creating a list of lists and then flatten results in to single list

using the list monad:

```
random_sample : unit -> int M
monte_carlo : int -> int -> int -> result

let experiments : result M =
  random_sample() >>= (fun s1 ->
  random_sample() >>= (fun s2 ->
  random_sample() >>= (fun s3 ->
  return (monte_carlo s1 s2 s3)
;;
```

The List Monad as Nondeterministic Computation

```
module type MONAD = sig

  type 'a M

  val return : 'a -> 'a M

  val (>>=) : 'a M -> ('a -> 'b M) -> 'b M

end
```

```
module ListMonad = struct

  type 'a M = 'a list

  let return x = [x]

  let (>>=) c f =
     List.flatten (List.map f c)

end
```

using the non-determinism monad:

```
random_sample : unit -> int M
monte_carlo : int -> int -> int -> result

let experiments : result M =
  random_sample() >>= (fun s1 ->
  random_sample() >>= (fun s2 ->
  random_sample() >>= (fun s3 ->
  return (monte_carlo s1 s2 s3)
;;
```

one result;
no non-determinism

compose many
possible results (c)
with a non-deterministic
continuation f

A Container with a String on the Side
(aka: A logging/printing monad)

```
module type MONAD = sig

  type 'a M

  val return : 'a -> 'a M

  val (>>=) : 'a M -> ('a -> 'b M) -> 'b M

end
```

```
module LoggingMonad = struct

  type 'a M = 'a * string

  let return x = (x, "")

  let (>>=) c f =
     let (v, s) = c in
     let (v',s') = f v in
     (v', s ^ s')
end
```

concatenate the log of c with the log produced by running f

nothing logged yet

using the logging monad:

```
record : ('a -> 'b) -> 'a -> string -> 'b M

let record f x s = (f x, s)

let do x =
  record read x "read it" >>= (fun v ->
  record write v "wrote it" >>= (fun _ ->
  record write v "wrote it again" >>= (fun _ ->
  return v
;;
```

Monad Laws

Just like one expects any CONTAINER to behave in a particular way, one has expectations of MONADs.

Left identity: “return does nothing observable”

(1) `return v >>= f  == f v`

Right identity: “return still doesn’t do anything observable”

(2) `m >>= return == m`

Associativity: “composing m with f first and then doing g is the same as doing m with the composition of f and g”

(3) `(m >>= f) >>= g  ==  m >>= (fun x -> f x >>= g)`

Breaking the Law

Just like one expects any CONTAINER to behave in a particular way, one has expectations of MONADs.

Left identity: “return does nothing observable”

(1) return v >>= f == f v

```
module LoggingMonad = struct

  type 'a M = 'a * string

  let return x = (x, “start”)

  let (>>=) c f =
     let (v, s) = c in
     let (v',s') = f v in
     (v', s ^ s')
end
```

```
return 3 >>= fun x -> return x
== (3,“start”) >>= fun x -> return x
== (3, “start” ^ “start”)
== (3, “startstart”)
```

```
(fun x -> return x) 3
== return 3
== (3, “start”)
```

Breaking the Law

What are the consequences of breaking the law?

Well, if you told your friend you’ve implemented a monad and they can use it in your code, they will expect that they can rewrite their code using equations like this one:

```
return x >>= f   ==   f x
```

If you tell your friend you’ve implemented the monad interface but none of the monad laws hold your friend will probably say: Ok, tell me what your functions do then and please stop using the word monad because it is confusing. It is like you are claiming to have implemented the QUEUE interface but insert and remove are First-In, First-Out like a stack.

In Haskell or Fsharp or Scala, breaking the monad laws may have more severe consequences, because the compiler actually uses those laws to do some transformations of your code.

Monads in Haskell

Haskell vs. OCaml

```
module type MONAD = sig
  type 'a M
  return : 'a -> 'a M
  (>>=) : 'a M -> ('a -> 'b M) -> 'b M
end
```

OCaml

```
val read_file : file_name -> string M

let concat f1 f2 =
  readfile f1              >>= (fun contents1 ->
  readfile f2              >>= (fun contents2 ->
  return (contents1 ^ contents2)
;;
```

```
do          readfile f1
then do     readfile f2
then do     contents1 ^
             contents2
```

Haskell vs. OCaml

```
module type MONAD = sig
  type 'a M
  return : 'a -> 'a M
  (>>=) : 'a M -> ('a -> 'b M) -> 'b M
end
```

OCaml

```
val read_file : file_name -> string M

let concat f1 f2 =
  readfile f1                 >>= (fun contents1 ->
  readfile f2                 >>= (fun contents2 ->
  return (contents1 ^ contents2)
;;
```

```
do          readfile f1
then do     readfile f2
then do     contents1 ^
             contents2
```

the kind of monad is controlled by the type Maybe == option

Haskell

```
concat :: filename -> filename -> Maybe string

concat y z =
  do
     contents1 <- readfile f1
     contents2 <- readfile f2
     return (contents1 ^ contents2)
     .
```

keyword do begins monadic block of code!

syntax is pretty! Compiler automatically translates in to something very similar to the OCaml

Another Haskell Detail:

Haskell function types are pure -- totally effect-free

```
foo : int -> int
```

Haskell's type system *forces** purity on functions with type `a -> b`

- no printing
- no mutable data
- no reading from files
- no concurrency
- no benign effects (like memoization)

* except for a function called unsafePerformIO

Another Haskell Detail:

```
foo :: int -> int
```

totally pure function

```
<code> :: IO int
```

suspended (lazy) computation that performs effects when executed

Another Haskell Detail:

```
foo :: int -> int
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totally pure function

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<code> :: IO int
```

suspended (lazy) computation that performs effects when executed

```
bar :: int -> IO int
```

totally pure function that returns suspended effectful computation

Another Haskell Detail:

```
foo :: int -> int
```

totally pure function

```
<code> :: IO int
```

suspended (lazy) computation that performs effects when executed

```
bar :: int -> IO int
```

totally pure function that returns suspended effectful computation

use monad operations to compose suspended computations

all effects in Haskell are treated as a kind of book keeping

IO is the catch-all monad

An Example

```
print :: string -> IO ()
```

the "IO monad"
-- contains effectful computations like printing

```
reverse :: string -> string
```

```
reverse "hello" :: string
```

```
print (reverse "hello") :: IO ()
```

the type system always tells you when an effect has happened – effects can't "escape" the I/O monad

Another Example

```
read :: Ref a -> IO a
```

```
(+) :: int -> int -> int
```

```
r :: Ref int
```

```
(read r) + 3  :: int
```

Doesn't type check

Another Example

```
read :: Ref a -> IO a
```

```
(+) :: int -> int -> int
```

```
r :: Ref int
```

```
(read r) >>= \x ->
x + 3  :: IO int
```

Use Bind to keep the computation in the monad!!

Another Example

```
read :: Ref a -> IO a
```

```
(+) :: int -> int -> int
```

```
r :: Ref int
```

```
do
    x <- read r
    return (x + 3)
```

Prettier!!

Mutable State

```
new   :: a -> IO (Ref a)
read  :: Ref a -> IO a
write :: Ref a -> a -> IO ()
```

Haskell uses new, read, and write* functions within the IO Monad to manage mutable state.

```
main = do {r <- new 0;    -- int r := 0
           inc r;         -- r := r+1
           s <- read r;   -- s := r;
           print s }

inc :: Ref Int -> IO ()
inc r = do { v <- read r;               -- temp = r
             write r (v+1) }            -- r = temp+1
```

* actually newRef, readRef, writeRef, …

In a nutshell

Haskell is already using monads to implement state

It’s type system controls where mutation can occur

So now, software transactional memory is just a slightly more sophisticated version of Haskell’s existing IO monad.

PS: Scala Monads

Check out James Iry blog:

- http://james-iry.blogspot.com/2007/09/monads-are-elephants-part-1.html + 3 more parts
- he’s a hacker and he’s using equational reasoning to explain monads!

Main thing to remember:

- bind is called “flatmap” in Scala
- return is called “unit” in Scala
- do notation in Haskell is similar to for notation in Scala

```
for (x <- monad) yield result
== monad >>= (fun x -> return result)
== map (fun x -> result) monad
```

PPS: Check out monads in Python via generators:
http://www.valuedlessons.com/2008/01/monads-in-python-with-nice-syntax.html

Back to STM in Haskell

Concurrent Threads in Haskell

- The fork function spawns a thread.
- It takes an action as its argument.

```
fork :: IO a -> IO ThreadId
```

```
main = do
          id <- fork action1
           action2
           ...
```

action 1 and action 2 in parallel

Atomic Blocks in Haskell

- Idea: add a function atomic that guarantees atomic execution of a suspended (effectful) computation

```
main = do
           id <- fork (atomic action1)
           atomic action2
           ...
```

action 1 and
action 2
atomic
and parallel

```
main = do
            id <- fork (atomic action1)
            atomic action2
            ...
```

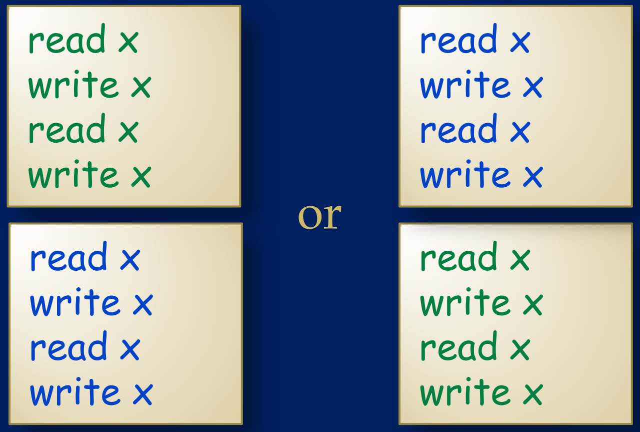
action 1:

```
read x
write x
read x
write x
```

action 2:

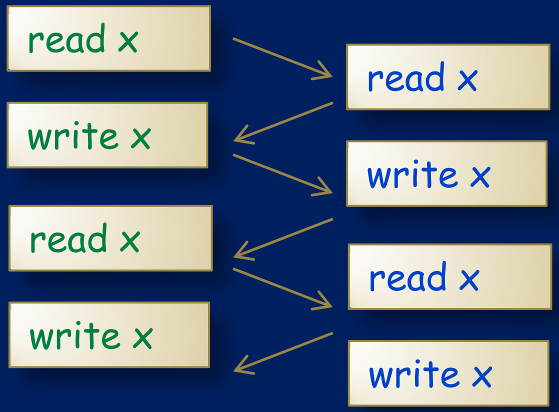
```
read x
write x
read x
write x
```

with transactions:



(programmer gets to cut down non-determinism as much as he/she wants)

without transactions:



(some interleaving -- the programmer must worry about which one)

Atomic Details

- Introduce a type for imperative transaction variables (TVar) and a new Monad (STM) to track transactions.
  - STM a == a computation producing a value with type a that does transactional memory book keeping on the side
  - Haskell type system ensures TVars can only be modified in transactions.

$$\begin{tikzcd}
\text{TVar a} & == & \text{'a ref} \\
\text{Haskell} \arrow[u] & & \text{OCaml} \arrow[u]
\end{tikzcd}$$

```
atomic      :: STM a -> IO a
new         :: a -> STM (TVar a)
read        :: TVar a -> STM a
write       :: TVar a -> a -> STM ()
```

Atomic Example

```
-- inc adds 1 to the mutable reference r
inc :: TVar Int -> STM ()

inc r = do
           v <- read r
           write r (v+1)


main   = do
           r <- atomic (new 0)
           fork (atomic (inc r))
           atomic (inc r);
```

Atomic Example

```
-- inc adds 1 to the mutable reference r
inc :: TVar Int -> STM ()

inc r = do
           v <- read r
           write r (v+1)


main  = do
           r <- atomic (new 0)
           fork (atomic (inc r))
           atomic (inc r);
```

Haskell is lazy so these computations are suspended and executed within the atomic block

STM in Haskell

```
atomic     :: STM a -> IO a
new        :: a -> STM (TVar a)
read       :: TVar a -> STM a
write      :: TVar a -> a -> STM()
```

The STM monad includes a specific set of operations:

- Can’t use TVars outside atomic block
- Can’t do IO inside atomic block:

```
atomic (if x<y then launchMissiles)
```

- atomic is a function, not a syntactic construct
  - called *atomically* in the actual implementation
- ...and, best of all...

STM Computations Compose (unlike locks)

```
inc r = do
           v <- read r
           write r (v+1)

inc2 r = do
           inc r
           inc r

foo = atomic (inc2 r)
```

The type guarantees that an STM computation is always executed atomically.

- Glue many STM computations together inside a “do” block
- Then wrap with atomic to produce an IO action.

Composition is THE way to build big programs that work

Exceptions

- The STM monad supports exceptions:

```
throw  :: Exception -> STM a
catch  :: STM a ->(Exception -> STM a) -> STM a
```

- In the call (atomic s), if s throws an exception, *the transaction is aborted with no effect* and the exception is propagated to the enclosing code.
- *No need to restore invariants, or release locks!*

Three more ideas:
retry, orElse, always

Idea 1: Compositional Blocking

```
withdraw :: TVar Int -> Int -> STM ()
withdraw acc n =

   do bal <- readTVar acc
      if bal < n then retry
      writeTVar acc (bal-n)
```

```
retry :: STM ()
```

- **retry** means "abort the current transaction and re-execute it from the beginning".
- Implementation avoids early retry using reads in the transaction log (i.e. acc) to wait on all read variables.
  - ie: retry only happens when one of the variables read on the path to the retry changes

Compositional Blocking

```
withdraw :: TVar Int -> Int -> STM ()
withdraw acc n =
         do { bal <- readTVar acc;
              if bal < n then retry;
              writeTVar acc (bal-n) }
```

- Retrying thread is woken up automatically when acc is written, so there is no danger of forgotten notifies.
- No danger of forgetting to test conditions again when woken up because the transaction runs from the beginning.
- *Correct-by-construction design!*

What makes Retry Compositional?

- **retry** can appear anywhere inside an atomic block, including nested deep within a call. For example,

```
atomic (do { withdraw a1 3;
             withdraw a2 7 })
```

waits for:

- a1 balance > 3
- *and* a2 balance > 7
- *without any change to withdraw function.*

Idea 2: Choice

- Suppose we want to transfer 3 dollars from either account a1 or a2 into account b.

Try this

...and if it retries, try this

```
atomic (
   do
          (withdraw a1 3) `orElse` (withdraw a2 3)
          deposit b 3
)
```

then afterward, do this

```
orElse :: STM a -> STM a -> STM a
```

Choice is composable, too!

```
transfer ::
    TVar Int ->
    TVar Int ->
    TVar Int ->
    STM ()

transfer a1 a2 b =
  do
    withdraw a1 3 `orElse` withdraw a2 3
    deposit b 3
```

```
atomic (
  transfer a1 a2 b
    `orElse` transfer a3 a4 b
)
```

- The function transfer calls orElse, but calls to transfer can still be composed with orElse.

Equational Reasoning

STM supports nice equations for reasoning:

```
a `orElse` (b `orElse` c) == (a `orElse` b) `orElse` s
retry `orElse` s == s
s `orElse` retry == s
```

(These equations make STM an instance of a structure known as a MonadPlus -- a Monad with some extra operations and properties.)

Idea 3: Invariants

The route to sanity is to *establish invariants* that are *assumed on entry*, and *guaranteed on exit*, by *every atomic block*.

- just like in a module with *representation invariants*
- this gives you *local reasoning about your code*

Invariants: One New Primitive

```
always :: STM Bool -> STM ()
```

```
newAccount :: STM (TVar Int)

newAccount =
  do { r <- new 0;
       always (accountInv r);
       return v }


accountInv r = do { x <- read r;
                    return (x >= 0)};
```

An arbitrary boolean valued STM computation

Any transaction that modifies the account will check the invariant (no forgotten checks). If the check fails, the transaction restarts. A persistent assert!!

What always does

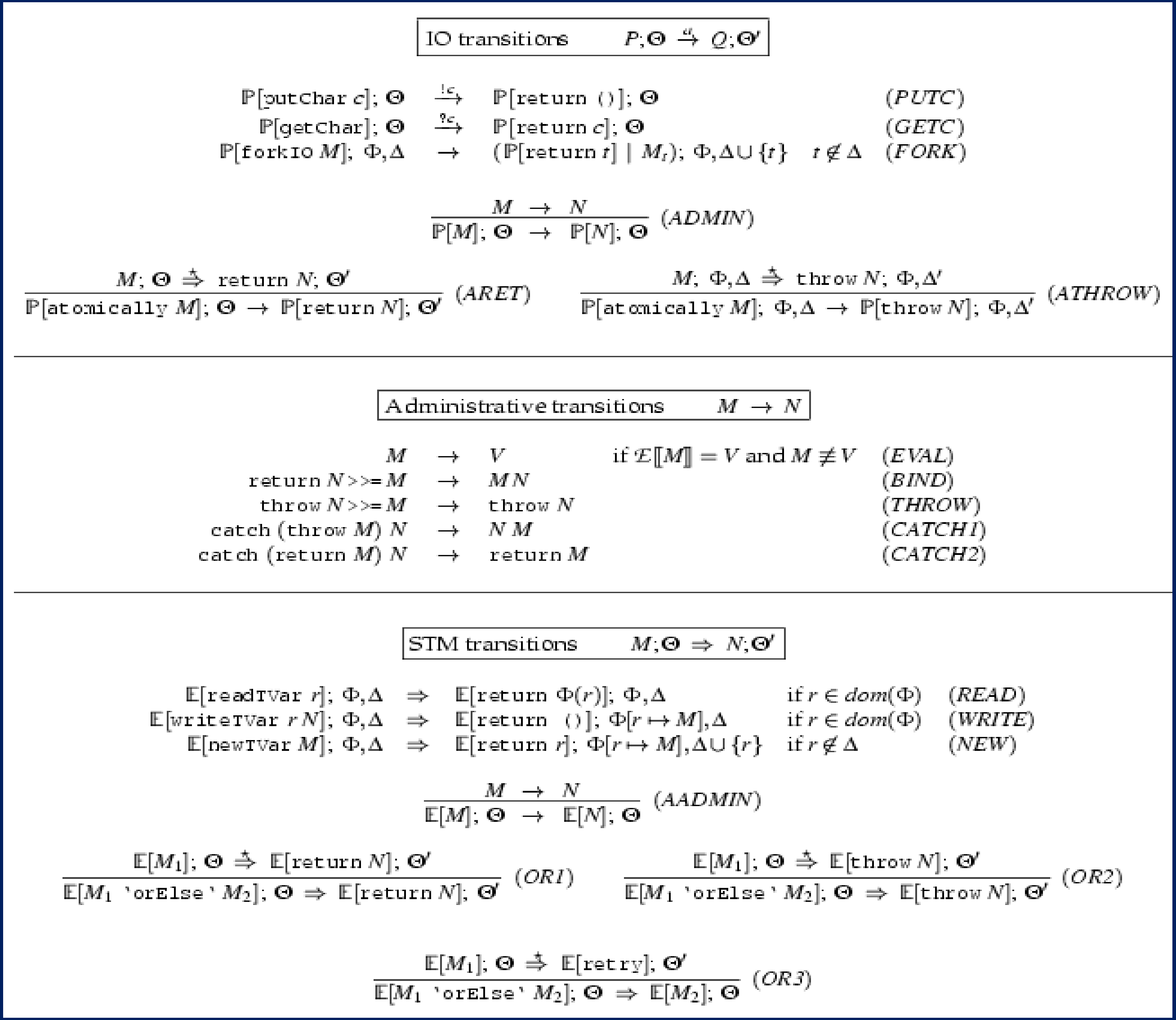
```
always :: STM Bool -> STM ()
```

- The function **always** adds a new invariant to a global pool of invariants.
- Conceptually, every invariant is checked as every transaction commits.
- But the implementation checks only invariants that read TVars that have been written by the transaction
- ...and garbage collects invariants that are checking dead Tvars.

What does it all mean?

- Everything so far is intuitive and arm-wavey.
- But what happens if it’s raining, and you are inside an orElse and you throw an exception that contains a value that mentions...?
- We need a precise specification!

One exists



$$\boxed{\text{IO transitions} \qquad P;\Theta \xrightarrow{a} Q;\Theta'}$$

$$\begin{array}{rcll}
\mathbb{P}[\texttt{putChar}\ c];\ \Theta & \xrightarrow{!c} & \mathbb{P}[\texttt{return}\ ()];\ \Theta & & (PUTC) \\
\mathbb{P}[\texttt{getChar}];\ \Theta & \xrightarrow{?c} & \mathbb{P}[\texttt{return}\ c];\ \Theta & & (GETC) \\
\mathbb{P}[\texttt{forkIO}\ M];\ \Phi,\Delta & \rightarrow & (\mathbb{P}[\texttt{return}\ t] \mid M_t);\ \Phi,\Delta \cup \{t\} & t \notin \Delta & (FORK)
\end{array}$$

$$\frac{M \ \rightarrow\ N}{\mathbb{P}[M];\ \Theta \ \rightarrow\ \mathbb{P}[N];\ \Theta}\ (ADMIN)$$

$$\frac{M;\ \Theta \overset{*}{\Rightarrow} \texttt{return}\ N;\ \Theta'}{\mathbb{P}[\texttt{atomically}\ M];\ \Theta \rightarrow \mathbb{P}[\texttt{return}\ N];\ \Theta'}\ (ARET) \qquad \frac{M;\ \Phi,\Delta \overset{*}{\Rightarrow} \texttt{throw}\ N;\ \Phi,\Delta'}{\mathbb{P}[\texttt{atomically}\ M];\ \Phi,\Delta \rightarrow \mathbb{P}[\texttt{throw}\ N];\ \Phi,\Delta'}\ (ATHROW)$$

$$\boxed{\text{Administrative transitions} \qquad M \rightarrow N}$$

$$\begin{array}{rcll}
M & \rightarrow & V & \text{if } \mathcal{E}[\![M]\!] = V \text{ and } M \not\equiv V \quad (EVAL) \\
\texttt{return}\ N \texttt{>>=} M & \rightarrow & M\ N & (BIND) \\
\texttt{throw}\ N \texttt{>>=} M & \rightarrow & \texttt{throw}\ N & (THROW) \\
\texttt{catch}\ (\texttt{throw}\ M)\ N & \rightarrow & N\ M & (CATCH1) \\
\texttt{catch}\ (\texttt{return}\ M)\ N & \rightarrow & \texttt{return}\ M & (CATCH2)
\end{array}$$

$$\boxed{\text{STM transitions} \qquad M;\Theta \Rightarrow N;\Theta'}$$

$$\begin{array}{rclll}
\mathbb{E}[\texttt{readTVar}\ r];\ \Phi,\Delta & \Rightarrow & \mathbb{E}[\texttt{return}\ \Phi(r)];\ \Phi,\Delta & \text{if } r \in dom(\Phi) & (READ) \\
\mathbb{E}[\texttt{writeTVar}\ r\ N];\ \Phi,\Delta & \Rightarrow & \mathbb{E}[\texttt{return}\ ()];\ \Phi[r \mapsto M],\Delta & \text{if } r \in dom(\Phi) & (WRITE) \\
\mathbb{E}[\texttt{newTVar}\ M];\ \Phi,\Delta & \Rightarrow & \mathbb{E}[\texttt{return}\ r];\ \Phi[r \mapsto M],\Delta \cup \{r\} & \text{if } r \notin \Delta & (NEW)
\end{array}$$

$$\frac{M \ \rightarrow\ N}{\mathbb{E}[M];\ \Theta \ \rightarrow\ \mathbb{E}[N];\ \Theta}\ (AADMIN)$$

$$\frac{\mathbb{E}[M_1];\ \Theta \overset{*}{\Rightarrow} \mathbb{E}[\texttt{return}\ N];\ \Theta'}{\mathbb{E}[M_1\ \texttt{`orElse`}\ M_2];\ \Theta \Rightarrow \mathbb{E}[\texttt{return}\ N];\ \Theta'}\ (OR1) \qquad \frac{\mathbb{E}[M_1];\ \Theta \overset{*}{\Rightarrow} \mathbb{E}[\texttt{throw}\ N];\ \Theta'}{\mathbb{E}[M_1\ \texttt{`orElse`}\ M_2];\ \Theta \Rightarrow \mathbb{E}[\texttt{throw}\ N];\ \Theta'}\ (OR2)$$

$$\frac{\mathbb{E}[M_1];\ \Theta \overset{*}{\Rightarrow} \mathbb{E}[\texttt{retry}];\ \Theta'}{\mathbb{E}[M_1\ \texttt{`orElse`}\ M_2];\ \Theta \Rightarrow \mathbb{E}[M_2];\ \Theta}\ (OR3)$$

See "**Composable Memory Transactions**" for details.

STM in Mainstream Languages

- There are similar proposals for adding STM to Java and other mainstream languages.

```
class Account {
  float balance;
  void deposit(float amt) {
    atomic { balance += amt; }
  }
  void withdraw(float amt) {
    atomic {
      if(balance < amt) throw new OutOfMoneyError();
      balance -= amt;  }
  }
  void transfer(Acct other, float amt) {
    atomic {  // Can compose withdraw and deposit.
      other.withdraw(amt);
      this.deposit(amt); }
  }
}
```

Weak vs Strong Atomicity

- Unlike Haskell, type systems in mainstream languages don’t control where effects occur.
- What happens if code outside a transaction conflicts with code inside a transaction?
  - Weak Atomicity: Non-transactional code can see inconsistent memory states. Programmer should avoid such situations by placing all accesses to shared state in transaction.
  - Strong Atomicity: Non-transactional code is guaranteed to see a consistent view of shared state. This guarantee may cause a performance hit.

For more information: “Enforcing Isolation and Ordering in STM”

Even in Haskell: Easier, But Not Easy.

The essence of shared-memory concurrency is *deciding where critical sections should begin and end*. This is still a hard problem.

- Too small: application-specific data races (Eg, may see deposit but not withdraw if transfer is not atomic).
- Too large: delay progress because deny other threads access to needed resources.

In Haskell, we can compose STM subprograms but at some point, we must decide to wrap an STM in "atomic"

- When and where to do it can be a hard decision

Conclusions

- Atomic blocks (atomic, retry, orElse) dramatically raise the level of abstraction for concurrent programming.
  - Gives programmer back some control over when and where they have to worry about interleavings
- It is like using a high-level language instead of assembly code. Whole classes of low-level errors are eliminated.
  - Correct-by-construction design
- Not a silver bullet:
  - you can still write buggy programs;
  - concurrent programs are still harder than sequential ones
  - aimed only at shared memory concurrency, not message passing
- There is a performance hit, but it is usually acceptable in Haskell (and things can only get better as the research community focuses on the question.)

Course Conclusions

STM and monads bring together multiple threads of interest in this course:

- functional programming
- high-level, higher-order abstractions
- modularity, local reasoning and composition
- correct-by-construction design
- equational reasoning & proofs about programs
- controlling non-determinism in parallel programs

The development of STM is also an example of modern PL research

- Just like with polymorphism, garbage collection, monads and functional parallelism, the ideas may take a while to catch on in the mainstream. In the meantime, you can be ahead of the curve

- if you want to see more math like the kind underpinning the semantics of STM, check out COS 510

This is just an intro. There's way more to learn. Have fun with FP.

- Take the next step: http://lambda-the-ultimate.org/

End

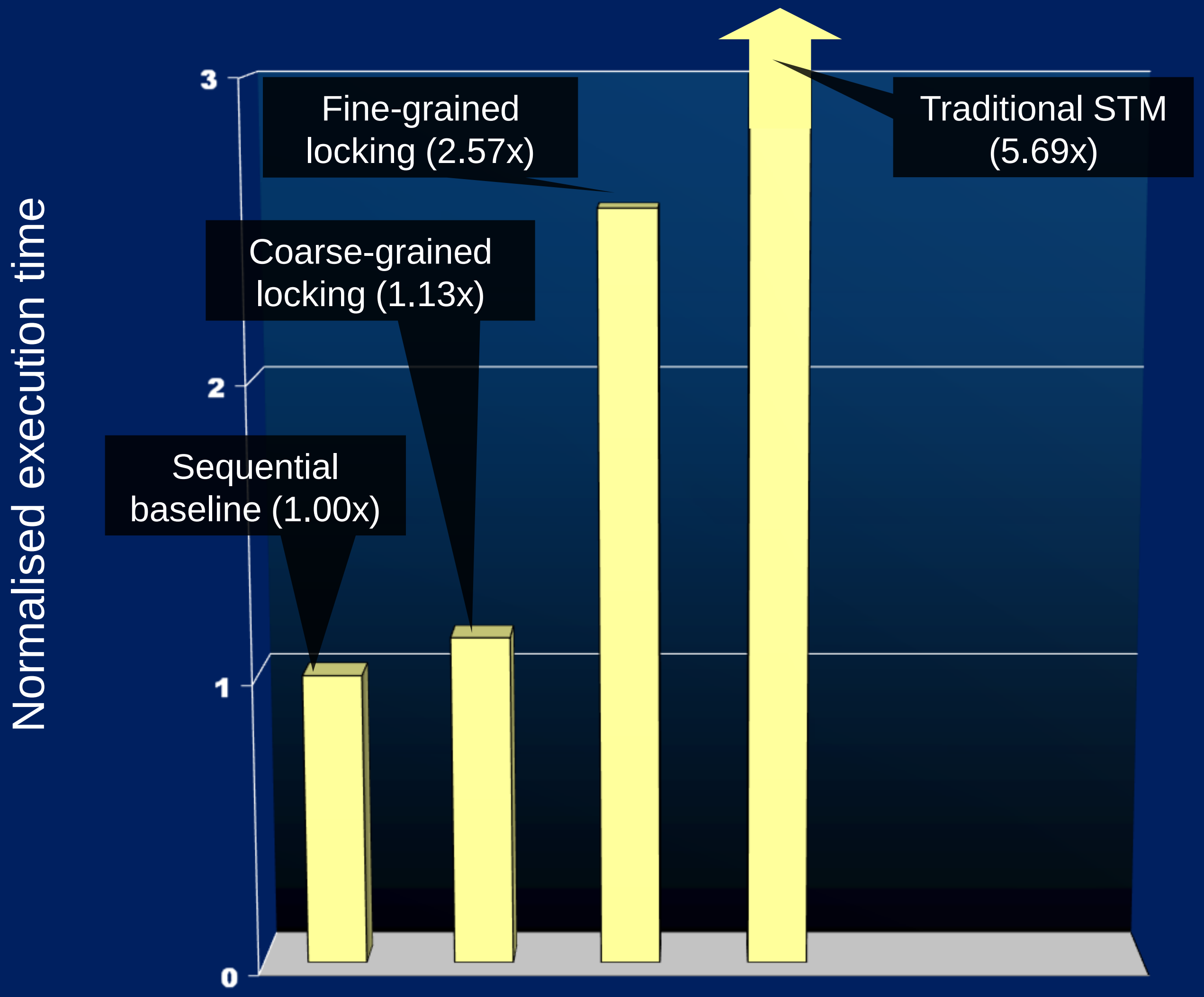
Haskell Implementation

- A complete, multiprocessor implementation of STM exists as of GHC 6.
- Experience to date: even for the most mutation-intensive program, the Haskell STM implementation is as fast as the previous MVar implementation.
  - The MVar version paid heavy costs for (usually unused) exception handlers.
- Need more experience using STM in practice, though!
- You can play with it. See the course website.

Performance

- At first, atomic blocks look insanely expensive. A naive implementation (c.f. databases):
  - Every load and store instruction logs information into a thread-local log.
  - A store instruction writes the log only.
  - A load instruction consults the log first.
  - Validate the log at the end of the block.
    - If succeeds, atomically commit to shared memory.
    - If fails, restart the transaction.

State of the Art Circa 2003



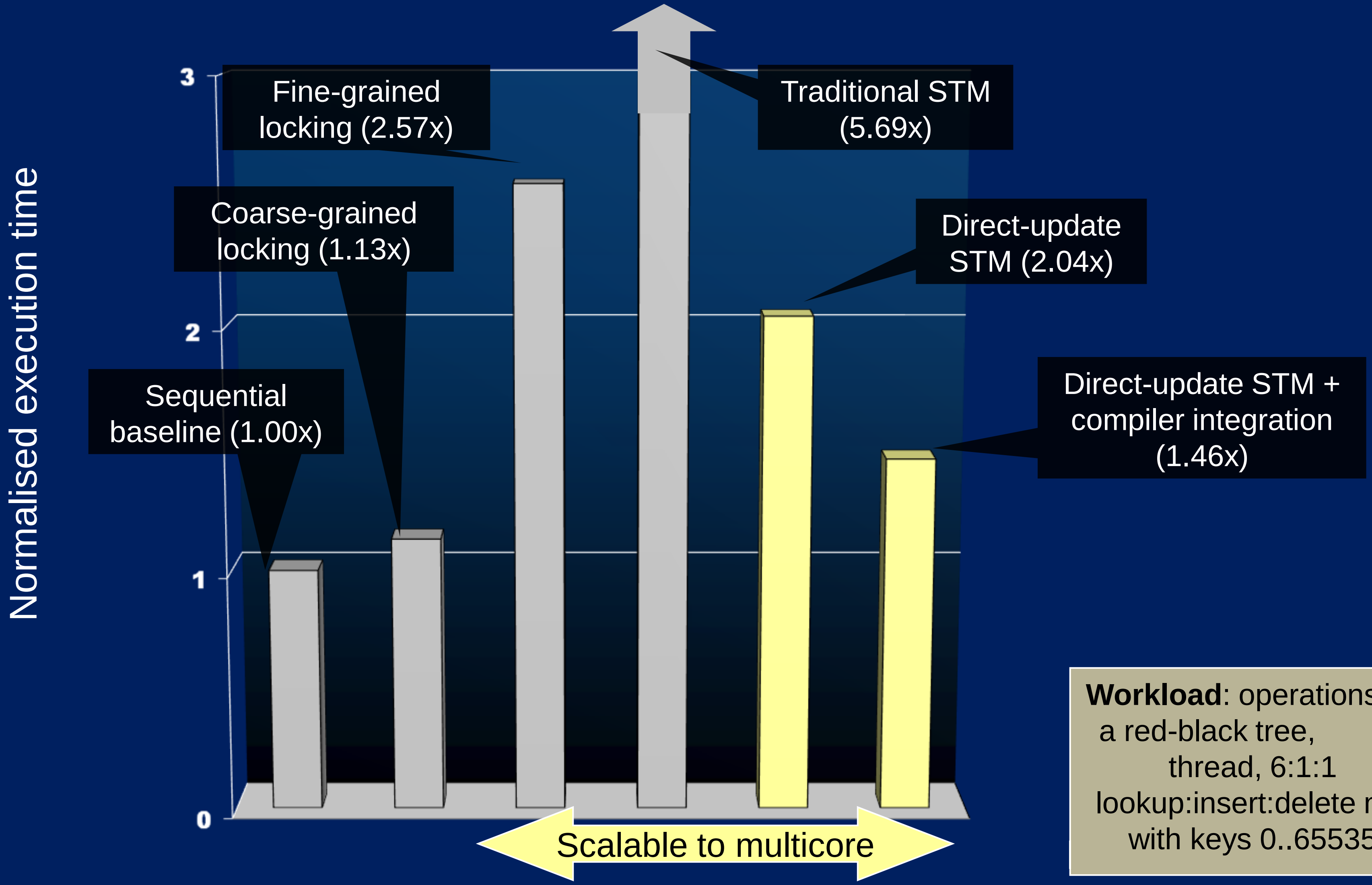
Workload: operations on a red-black tree, 1 thread, 6:1:1 lookup:insert:delete mix with keys 0..65535

See "Optimizing Memory Transactions" for more information.

New Implementation Techniques

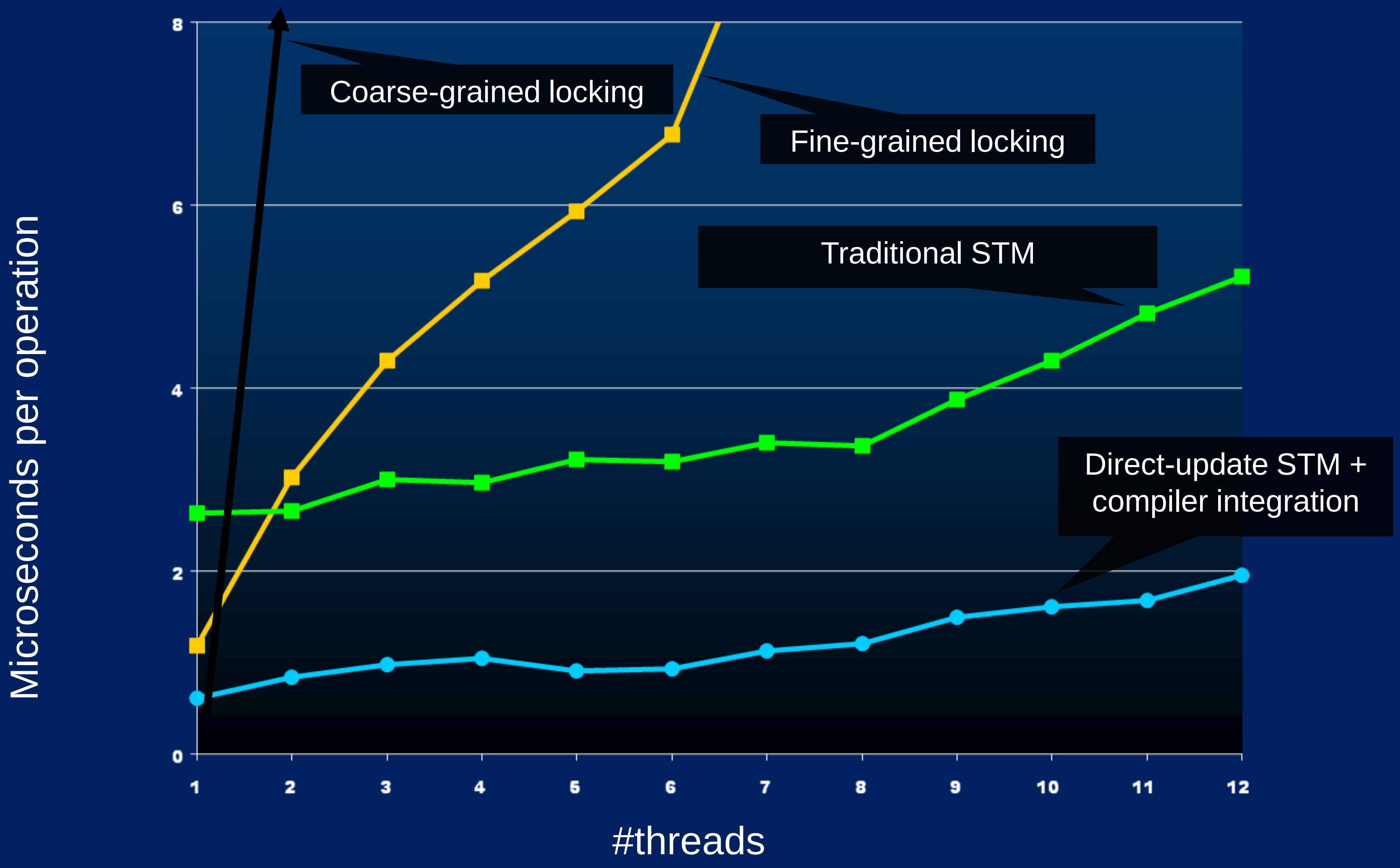
- Direct-update STM
  - Allows transactions to make updates in place in the heap
  - Avoids reads needing to search the log to see earlier writes that the transaction has made
  - Makes successful commit operations faster at the cost of extra work on contention or when a transaction aborts
- Compiler integration
  - Decompose transactional memory operations into primitives
  - Expose these primitives to compiler optimization (e.g. to hoist concurrency control operations out of a loop)
- Runtime system integration
  - Integrates transactions with the garbage collector to scale to atomic blocks containing 100M memory accesses

Results: Concurrency Control Overhead



Workload: operations on a red-black tree, 1 thread, 6:1:1 lookup:insert:delete mix with keys 0..65535

Results: Scalability



Performance, Summary

- Naïve STM implementation is hopelessly inefficient.
- There is a lot of research going on in the compiler and architecture communities to optimize STM.
- This work typically assumes transactions are smallish and have low contention. If these assumptions are wrong, performance can degrade drastically.
- We need more experience with “real” workloads and various optimizations before we will be able to say for sure that we can implement STM sufficiently efficiently to be useful.

Still Not Easy, Example

- Consider the following program:

```
Initially, x = y = 0
```

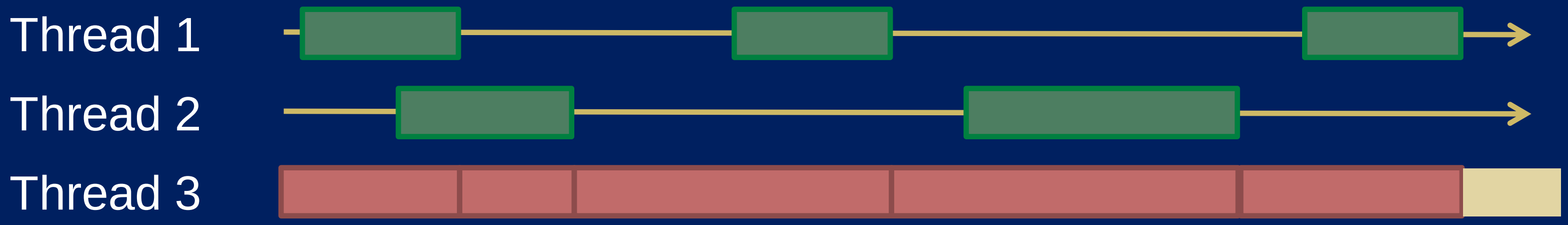
```
Thread 1
// atomic {                                //A0
     atomic { x = 1; }                     //A1
     atomic { if (y==0) abort; }  //A2
//}
```

```
Thread 2
atomic {          //A3
  if (x==0) abort;
  y = 1;
}
```

- Successful completion requires A3 to run after A1 but before A2.
- So adding a critical section (by uncommenting A0) changes the behavior of the program (from terminating to non-terminating).

Starvation

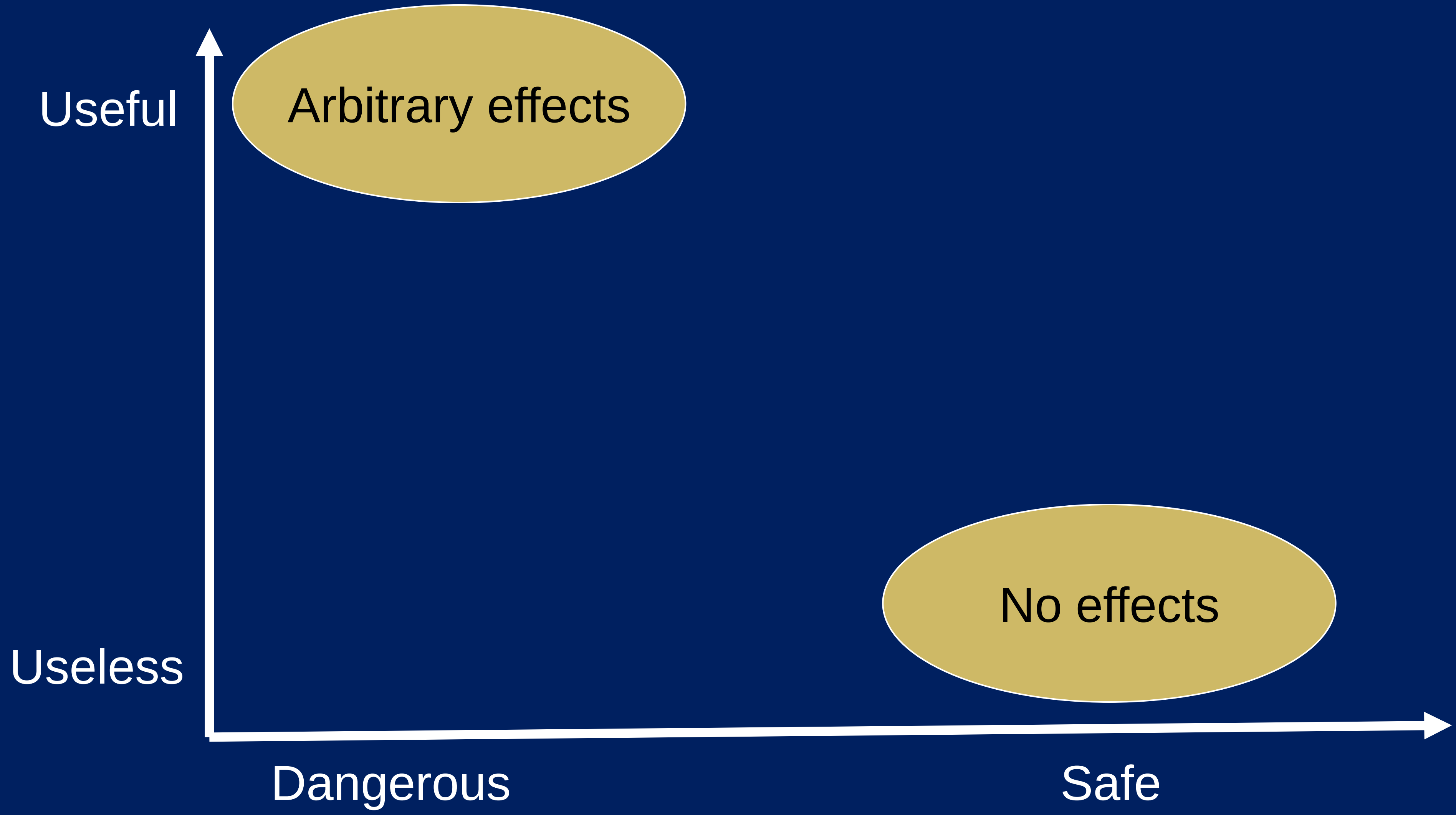
- Worry: Could the system "thrash" by continually colliding and re-executing?
- No: A transaction can be forced to re-execute only if another succeeds in committing. That gives a strong *progress guarantee*.
- But: A particular thread could starve:



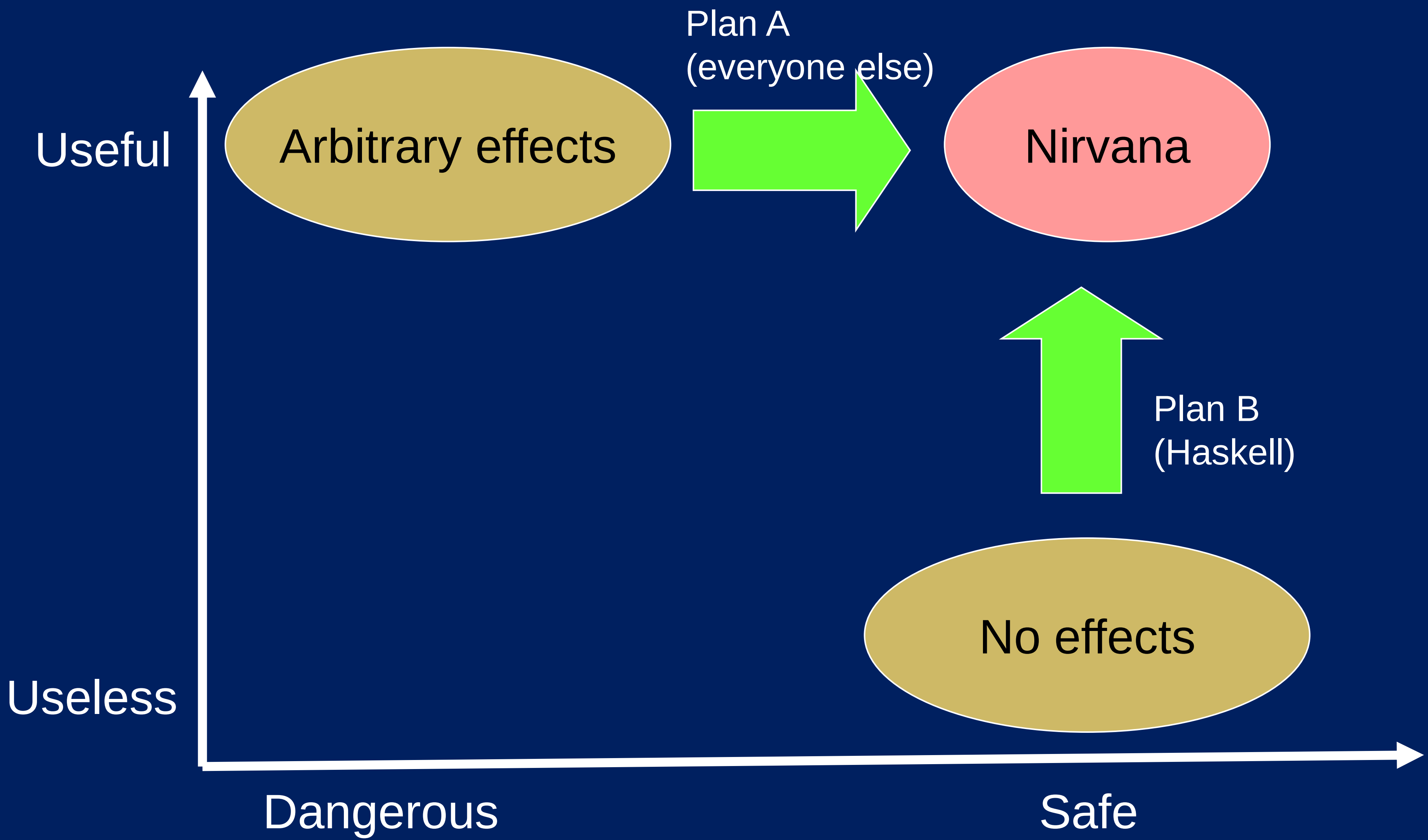
A Monadic Skin

- In languages like ML or Java, the fact that the language is in the IO monad is baked in to the language. There is no need to mark anything in the type system because IO is everywhere.
- In Haskell, the programmer can choose when to live in the IO monad and when to live in the realm of pure functional programming.
- Interesting perspective: It is not Haskell that lacks imperative features, but rather the other languages that lack the ability to have a statically distinguishable pure subset.
- This separation facilitates concurrent programming.

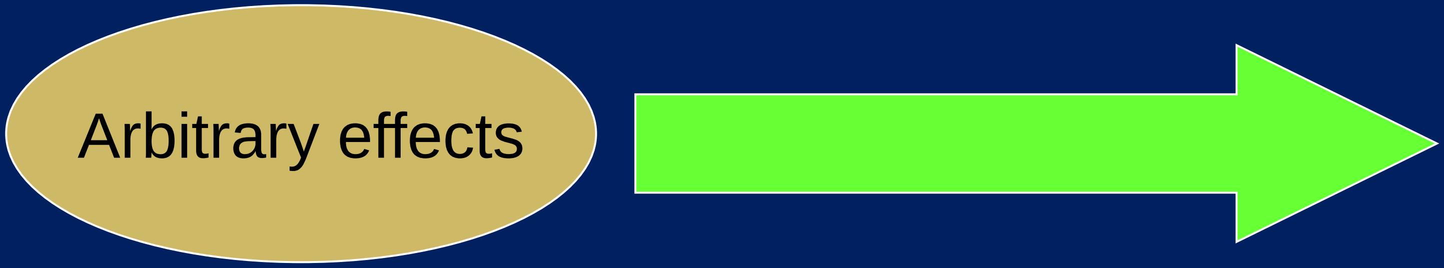
The Central Challenge



The Challenge of Effects



Two Basic Approaches: Plan A



Default = Any effect
Plan = Add restrictions

Examples

- Regions
- Ownership types
- Vault, Spec#, Cyclone

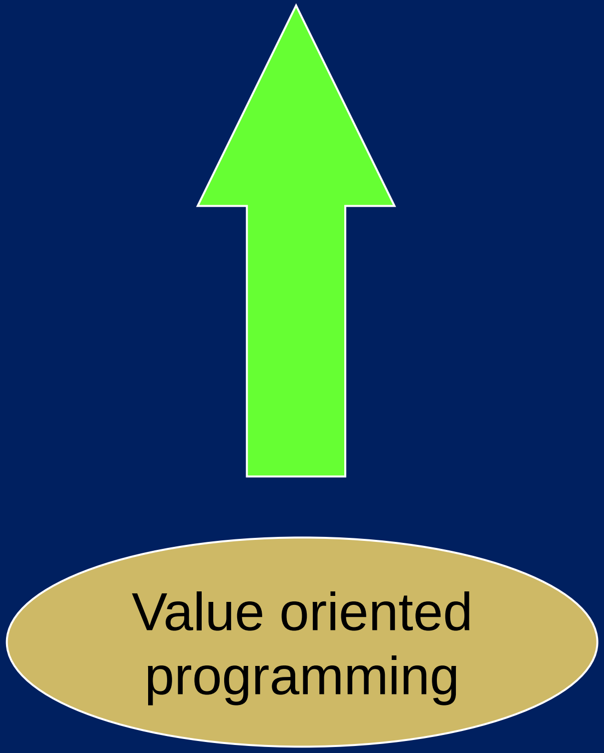
Two Basic Approaches: Plan B

Default = No effects
Plan = Selectively permit effects

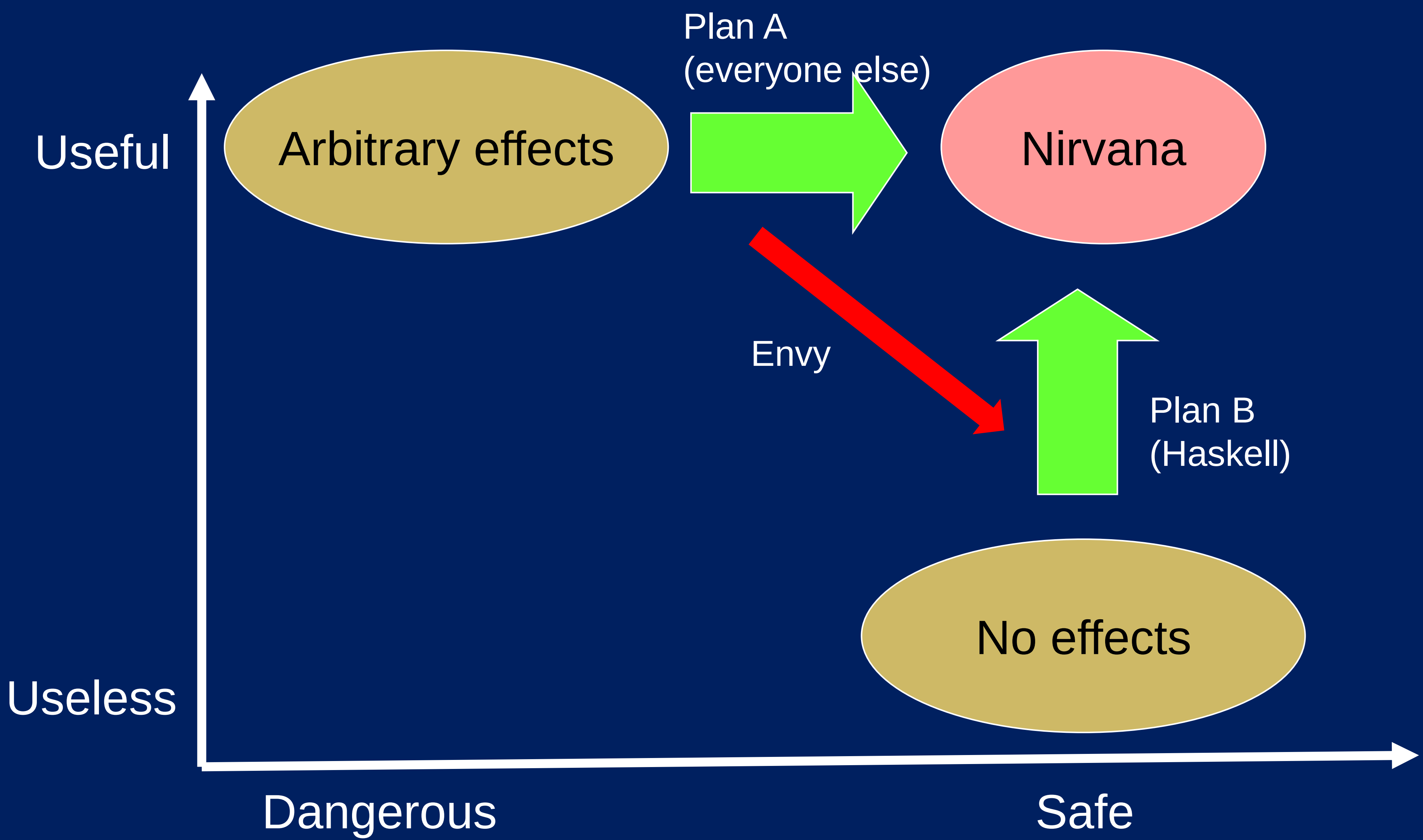
Types play a major role

Two main approaches:

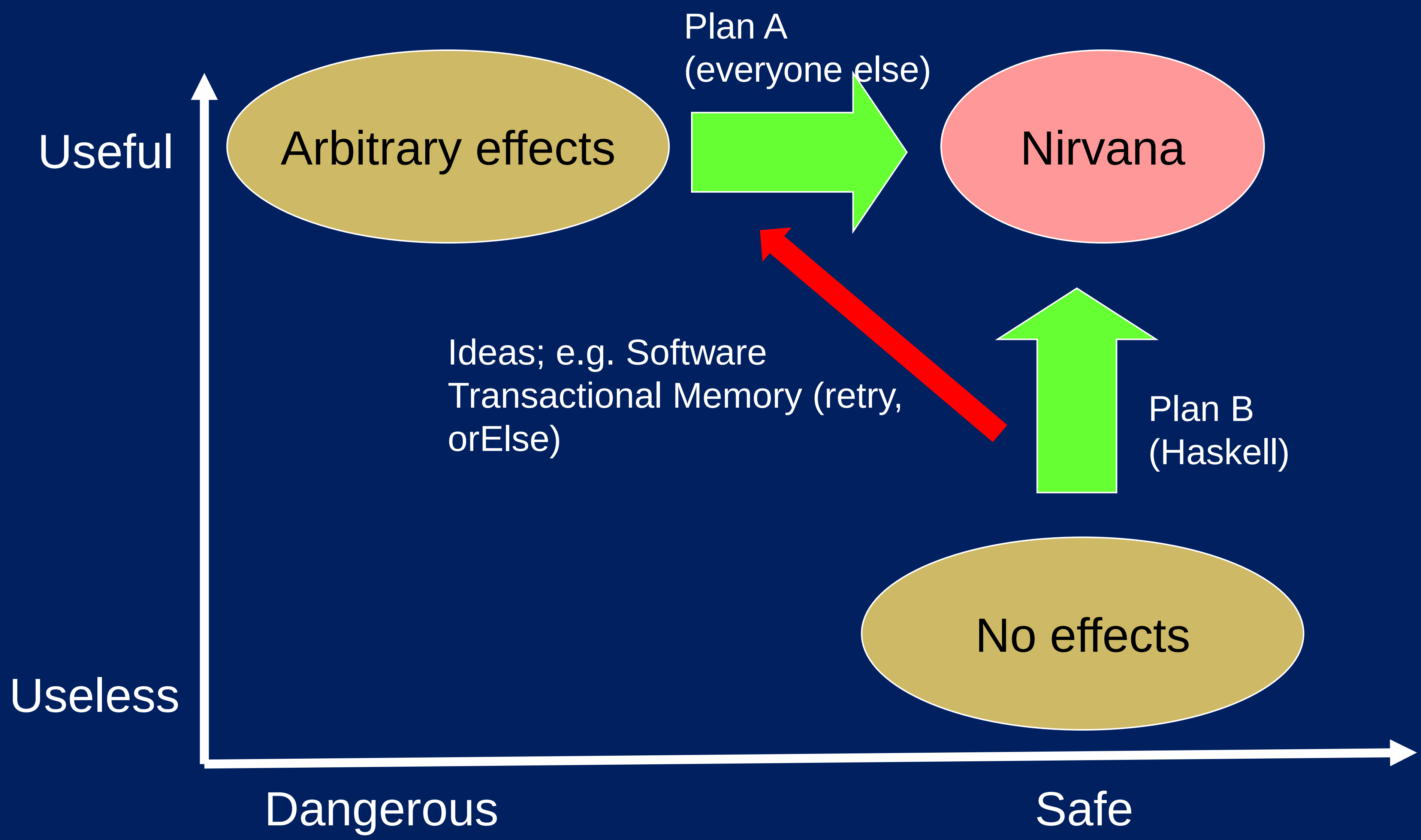
- Domain specific languages (SQL, Xquery, Google map/reduce)
- Wide-spectrum functional languages + controlled effects (e.g. Haskell)



Lots of Cross Over



Lots of Cross Over



An Assessment and a Prediction

One of Haskell’s most significant contributions is to take purity seriously, and relentlessly pursue Plan B.

Imperative languages will embody growing (and checkable) pure subsets.

-- Simon Peyton Jones