Effects for Less

Alexis King

ZuriHac 2020

Feb 2016 — Alexis starts writing Haskell.

- → Mostly a CRUD app.
- → Performance not that important.

Dec 2017 — Effect management is getting complicated.

- → Start exploring effect systems.
- → Clean up `freer`, release as `freer-simple`.

Feb 2018 — Break from writing Haskell to write Racket.

Jul 2019 — Back to writing Haskell.

HASURA

“Realtime GraphQL on PostgreSQL”

Secretly: a GraphQL to SQL JIT compiler

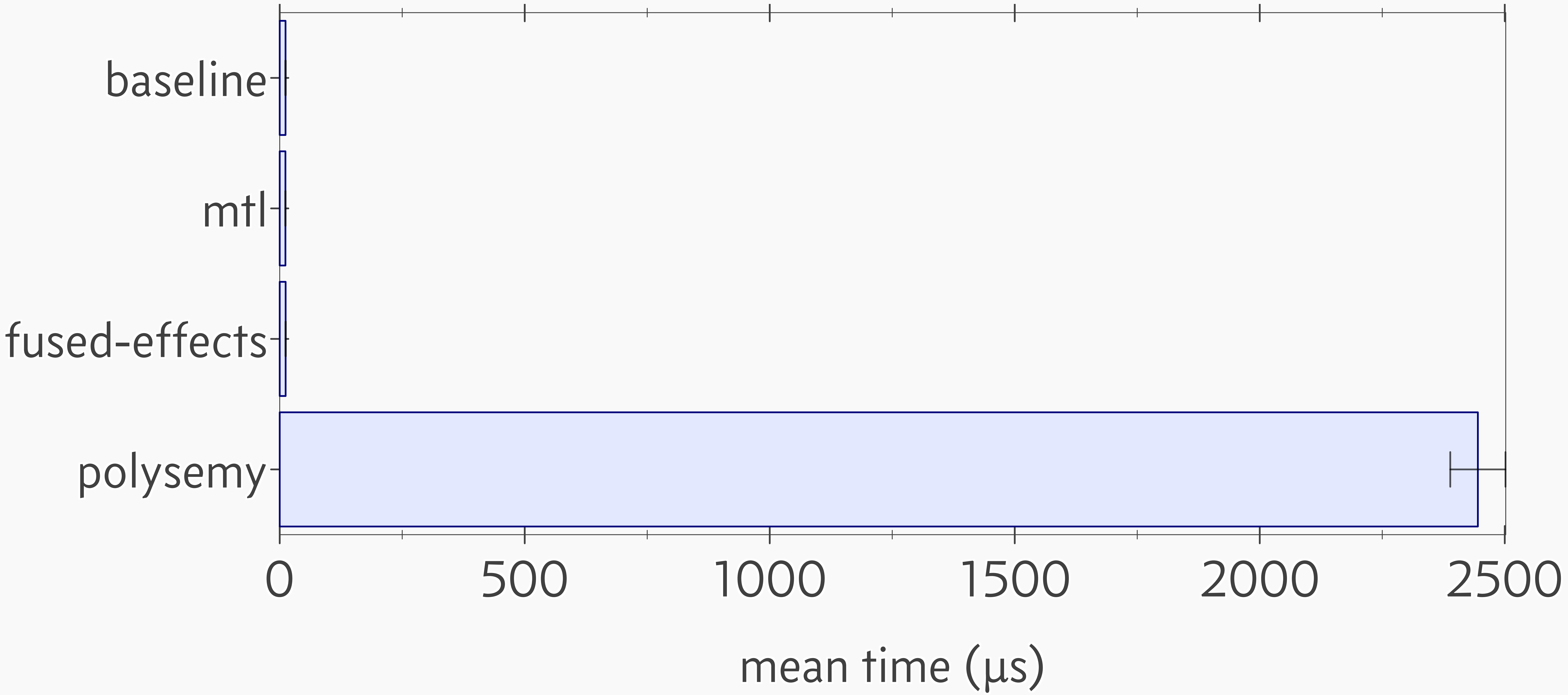
Performance is *really* important!

Can we afford to use an effect system?

BENCHMARKS

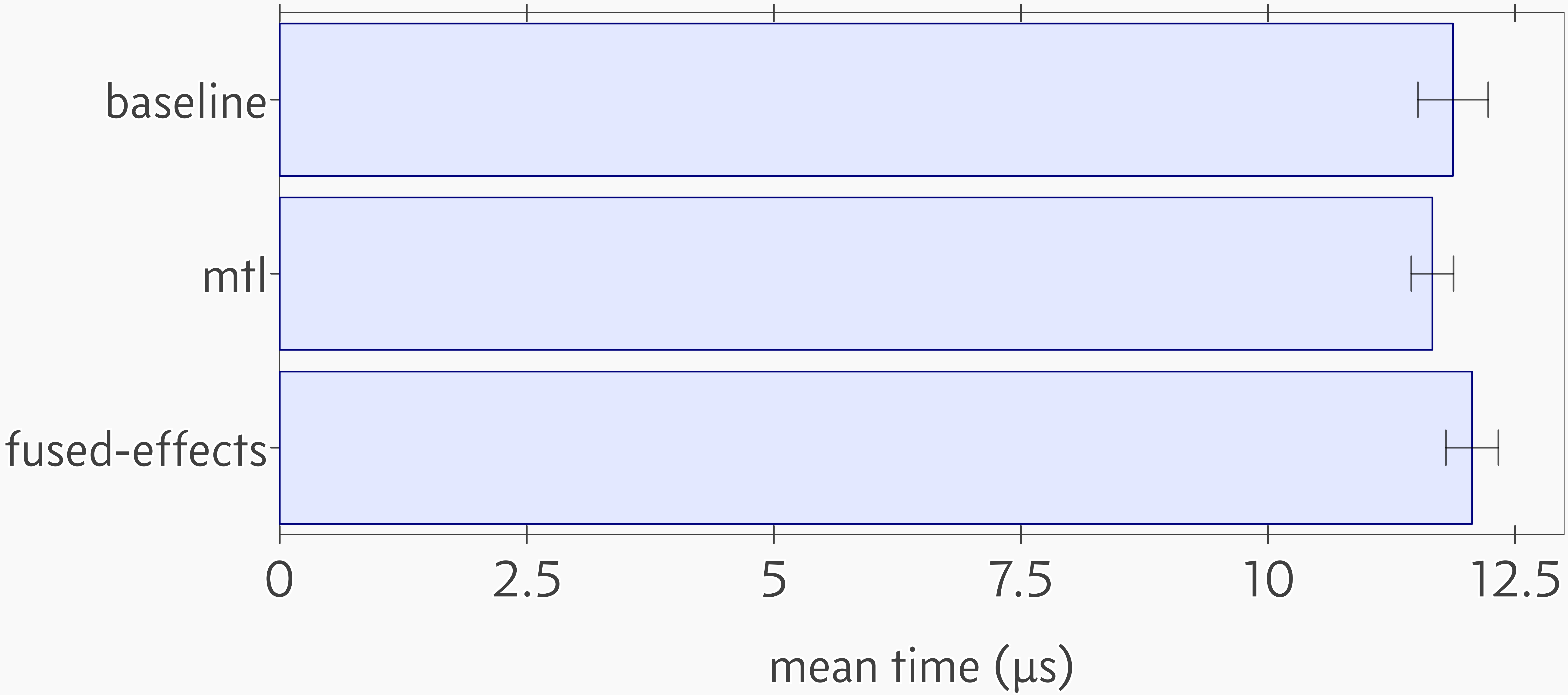
BENCHMARK: COUNTDOWN

(lower is better)



BENCHMARK: COUNTDOWN

(lower is better)



Can we afford to use an effect system?

Answer: yes.

Just don't pick polysemy.

It’s never that simple!

QUESTIONS

1. What *is* the countdown benchmark?
2. What is the "baseline" implementation?
3. Are these differences even meaningful?
4. Why does polysemy do *that* much worse?

THE COUNTDOWN MICROBENCHMARK

```haskell
countDown :: Int → (Int, Int)
countDown initial = runState program initial

program :: MonadState Int m ⇒ m Int
program = do n ← get
             if n ≤ 0
               then return n
               else put (n - 1) >> program
```

COUNTDOWN MICROBENCHMARK: BASELINE

```
countDown :: Int → (Int, Int)
countDown = program

program :: Int → (Int, Int)
program n = if n ⩽ 0 then (n, n)
                      else program (n - 1)
```

This is incredibly synthetic!

Is countdown a bad benchmark?

IN DEFENSE OF MICROBENCHMARKS

	REAL-WORLD BENCHMARKS	MICROBENCHMARKS
PROS	→ Probably representative of *something*. → Unlikely to be a fluke/flaw of the benchmarking process.	→ Easy to isolate costs! → Small enough to *completely* understand. → If thoroughly understood, can provide a useful cost model.
CONS	→ Really big! → Difficult to isolate costs. → May be challenging to extrapolate results.	→ Easy to measure the wrong thing! → *Crucial* to understand the scope of results. → Costs are not considered in context.

Effects are *particularly* hard to measure with real-world benchmarks!

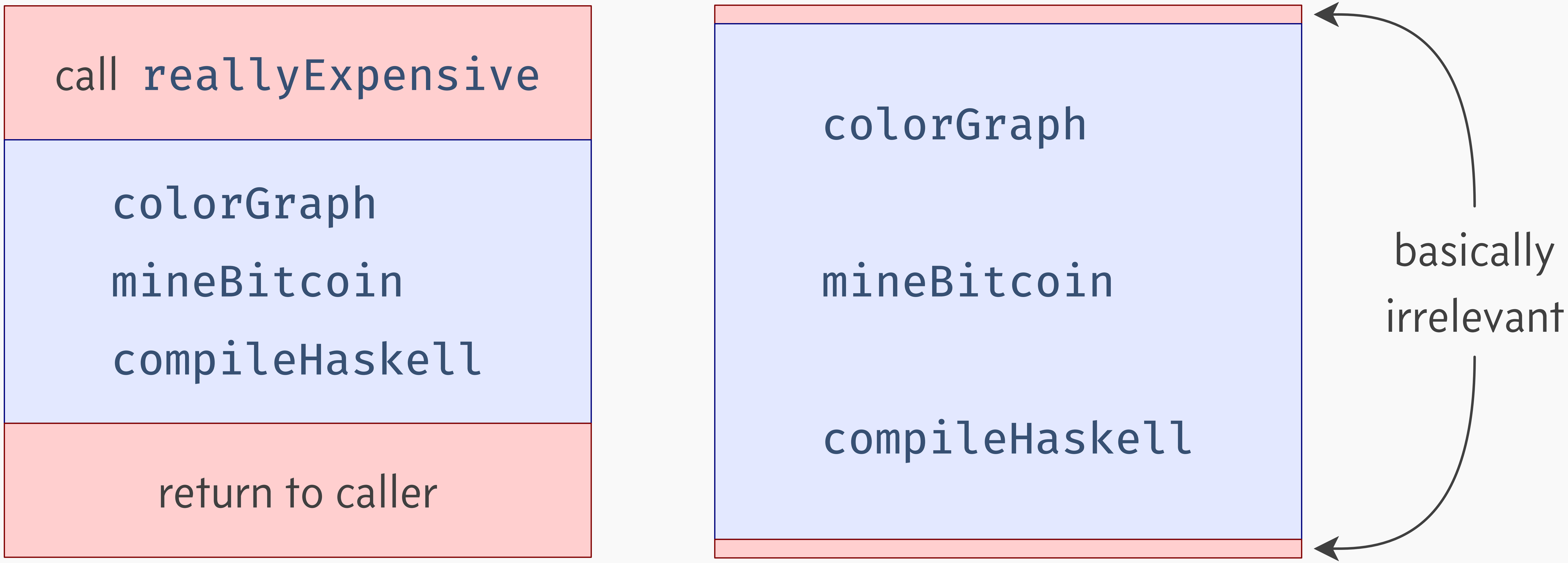
Effects are *particularly* hard to measure with real-world benchmarks!

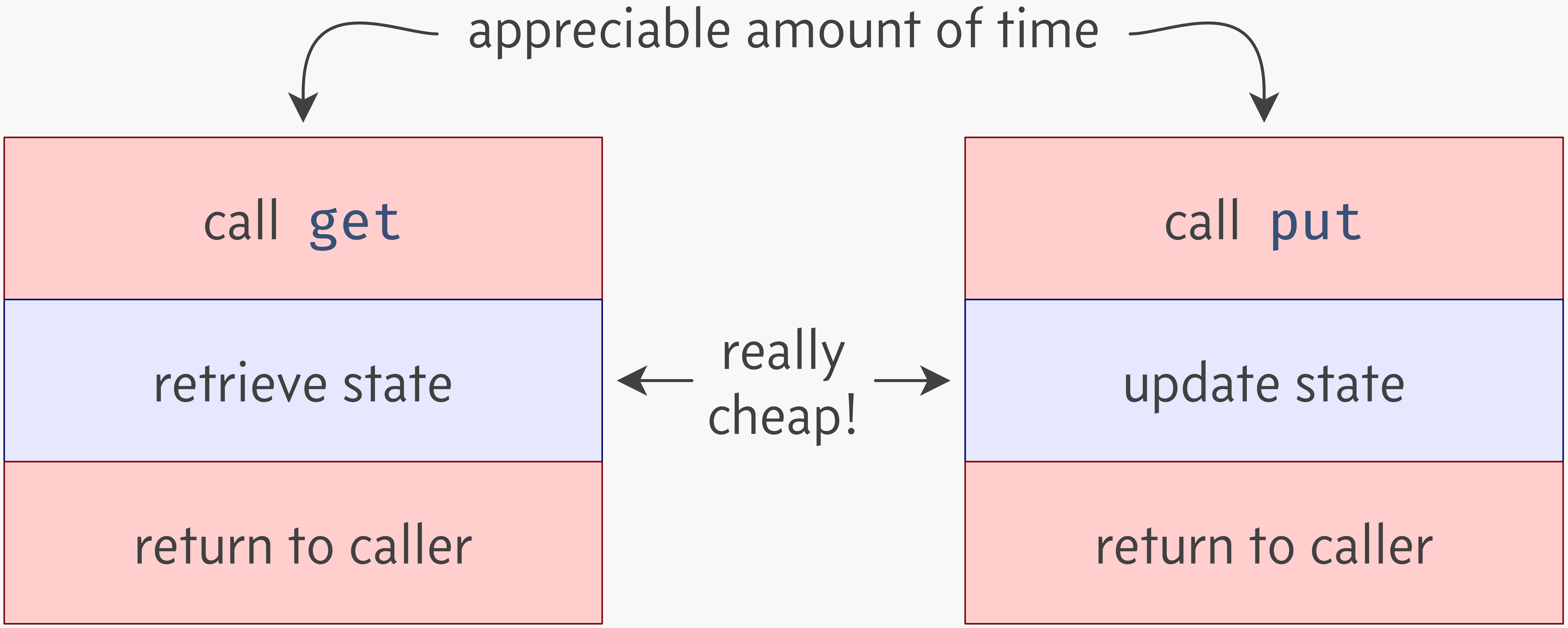
What does countdown measure?

```
countDown :: Int → (Int, Int)
countDown initial = runState program initial

program :: MonadState Int m ⇒ m Int
program = do n ← get
             if n ≤ 0
               then return n
               else put (n - 1) >> program
```

```haskell
reallyExpensive :: MonadExpensive m ⇒ m Blah
reallyExpensive = colorGraph >> mineBitcoin >> compileHaskell
```





Countdown benchmarks *effect dispatch*.

```haskell
countDown :: Int -> (Int, Int)
countDown initial = runState program initial

program :: MonadState Int m => m Int
program = get >>= \n ->
            if n <= 0
              then return n
              else put (n - 1) >> program
```

`>>=` is an exceptionally common operation.

```haskell
do a ← f x
   b ← g y
   h a b
```

```haskell
Foo <$> getX
    <*> getY
    <*> getZ
```

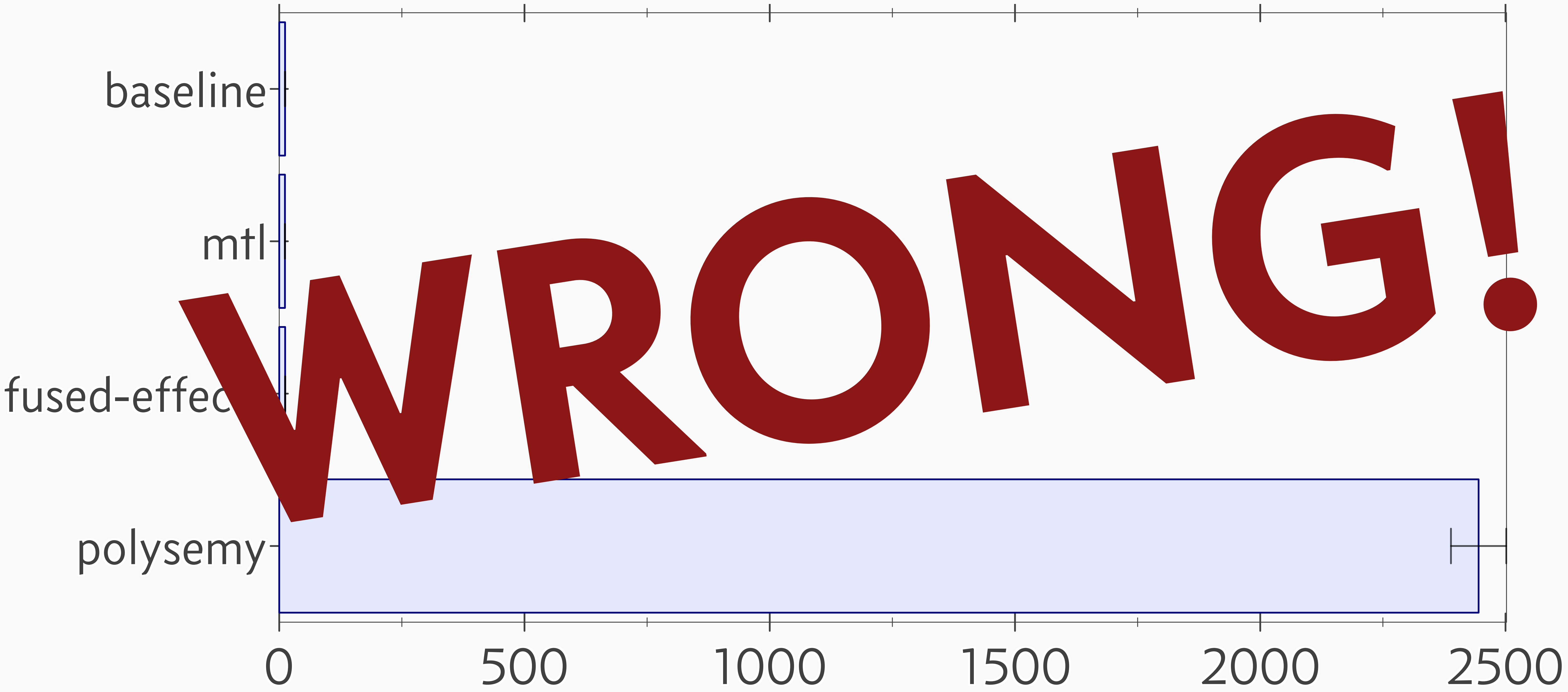
```haskell
mapM
traverse
sequence
```

```haskell
when
unless
replicateM
```

RECAP

1. Countdown is a microbenchmark.
2. Theoretically, it’s a valuable benchmark.
3. It measures two things:
   → …the cost of effect dispatch.
   → …the cost of `>>=`.

Why am I belaboring this point?

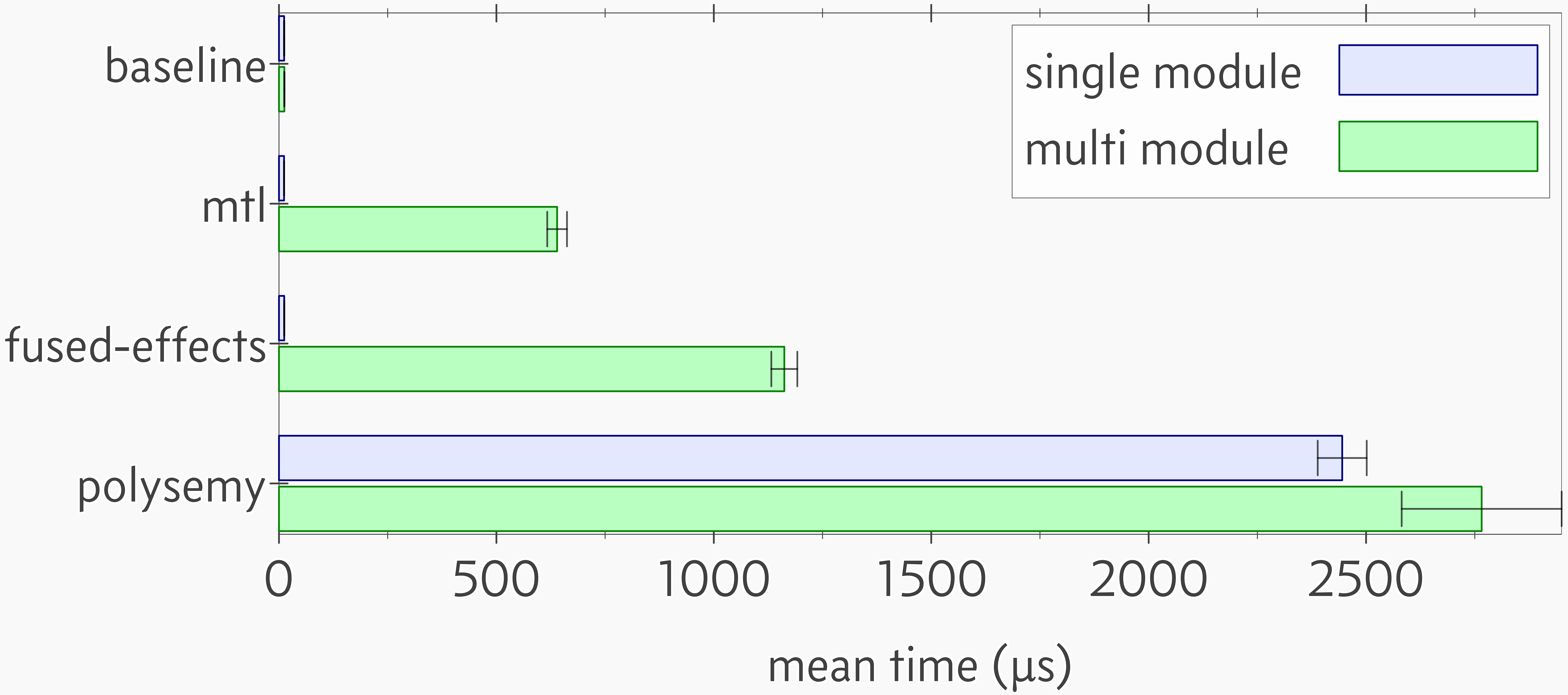


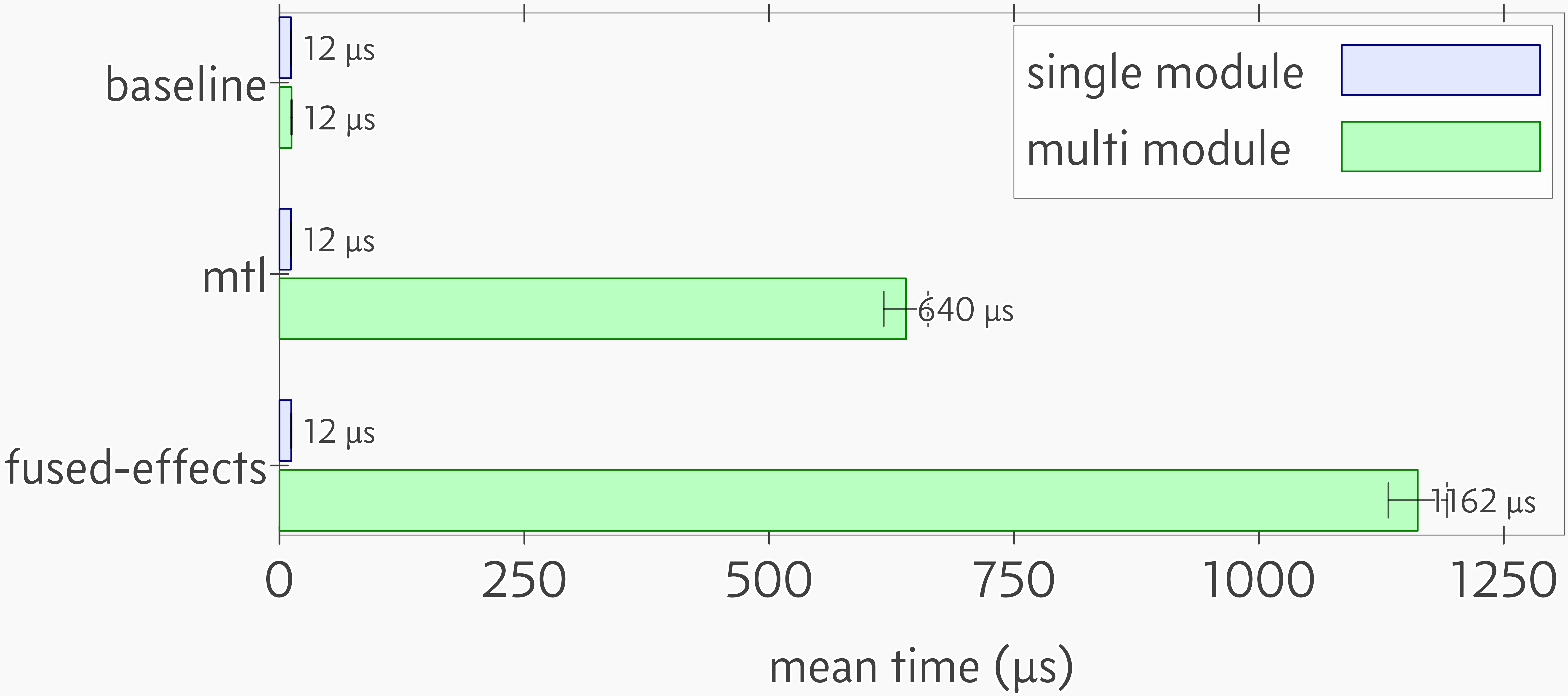
...or at least highly misleading.

```haskell
module CountDown where
  import Program
  countDown :: Int → (Int, Int)
  countDown initial = runState program initial

module Program where
  program :: MonadState Int m ⇒ m Int
  program = do n ← get
               if n ≤ 0
                 then return n
                 else put (n - 1) >> program
```

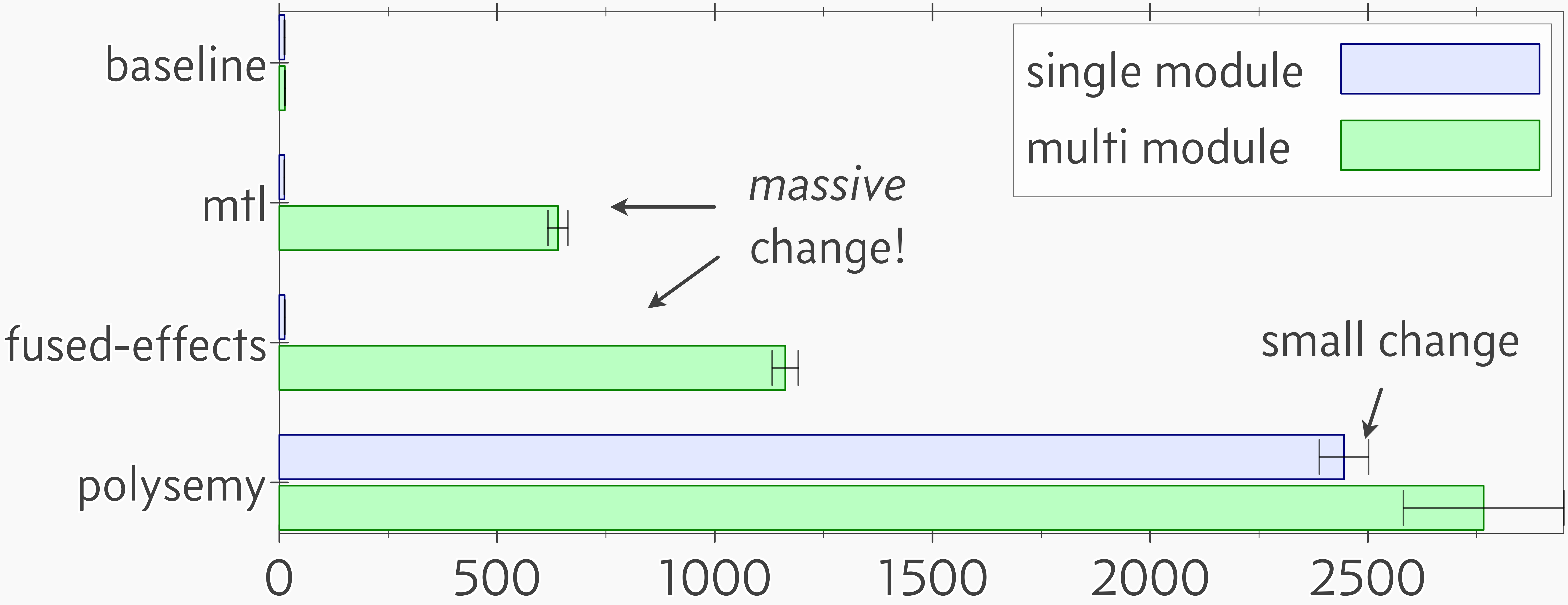
Surely this shouldn't change anything?


baseline
mtl
fused-effects
polysemy
single module
multi module
0
500
1000
1500
2000
2500
mean time (µs)



baseline
mtl
fused-effects
12 µs
12 µs
12 µs
640 µs
12 µs
1162 µs
single module
multi module
0
250
500
750
1000
1250
mean time (µs)

What happened?



mtl and fused-effects are victims of the optimizer.

KEY TAKEAWAYS

1. mtl and fused-effects *are* faster than polysemy…
2. …but are more reliant on compiler optimizations for best-case perf.
3. Tiny program changes can have huge perf diffs!

① Monad transformers + typeclasses.

- → Tried and true; believed to be performant.
- → Can require complex boilerplate.

Examples: `mtl`, `fused-effects`

② Free-like monads.

- → Highly flexible, can be simpler to use.
- → Performance is a known limitation.

Examples: `freer-simple`, `polysemy`

```haskell
program = get >>= \n ->
            if n <= 0
              then return n
              else put (n - 1) >> program
```

▼

```haskell
program :: Eff (State Int) Int
program = Get `Then` \n ->
           if n <= 0
             then Return n
             else Put (n - 1) `Then` \_ -> program
```

```haskell
data Eff f a where
  Return :: a → Eff f a
  Then   :: f a → (a → Eff f b) → Eff f b

data State s a where
  Get    :: State s s
  Put    :: s → State s ()

runState :: s → Eff (State s) a → (s, a)
runState s (Return x)           = (s, x)
runState s (Get    `Then` k) = runState s (k s)
runState _ (Put s `Then` k) = runState s (k ())
```

PROS

- → Beautifully simple.
- → Extremely flexible.

CONS

- → Reifies the entire program as a tree.
- → Obscures structure to the optimizer.

```haskell
program :: Eff (State Int) Int
program = Get `Then` \n →
            if n ≤ 0
              then Return n
              else Put (n - 1) `Then` \_ → program
```

```haskell
newtype State s a = State { runState :: s → (s, a) }

instance Monad (State s) where
  return x = State $ \s → (s, x)
  m ≫= f = State $ \s → case runState m s of
    (s', a) → runState (f a) s'

get :: State s s
get = State $ \s → (s, s)

put :: s → State s ()
put s = State $ \_ → (s, ())
```

```haskell
program :: State Int Int
program = get >>= \n ->
            if n <= 0
              then return n
              else put (n - 1) >> program
```

```haskell
program :: State Int Int
program = State $ \s1 → runState get s1 of
  (s2, n) → if n ≤ 0
              then runState (return n) s2
              else case runState (put (n - 1)) s2 of
                (s3, _) → runState program s3
```

```haskell
program :: Int → (Int, Int)
program s1 = case get s1 of
  (s2, n) → if n ⩽ 0
              then (s2, n)
              else case put (n - 1) s2 of
                     (s3, _) → program s3
```

```haskell
program :: Int → (Int, Int)
program s1 = case get s1 of
  (s2, n) → if n ⩽ 0
              then (s2, n)
              else case (n - 1, ()) of
                     (s3, _) → program s3
```

```
program :: Int → (Int, Int)
program s1 = case get s1 of
  (s2, n) → if n ≤ 0
              then (s2, n)
              else program (n - 1)
```

```haskell
program :: Int → (Int, Int)
program s1 = case (s1, s1) of
  (s2, n) → if n ≤ 0
              then (s2, n)
              else program (n - 1)
```

```haskell
program :: Int → (Int, Int)
program s1 = if s1 ≤ 0
               then (s1, s1)
               else program (s1 - 1)
```

```haskell
program :: Int → (Int, Int)
program s1 = if s1 ⩽ 0
               then (s1, s1)
               else program (s1 - 1)

program :: Int → (Int, Int)
program n = if n ⩽ 0
              then (n, n)
              else program (n - 1)
```

This is great! But it’s not an effect system.

```
program :: State Int Int
program = get >>= \n ->
            if n <= 0
              then return n
              else put (n - 1) >> program
```

coupled to implementation

Can we get the flexibility of free monads
with the performance of monad transformers?

Similar to the list fusion problem.

```
foldr (+) 0 [1..5]
```

consumer producer

Similar to the list fusion problem.

```
foldr (+) 0 [1..5]
```

```
foldr (+) 0 (1:2:3:4:5:[])
```

```
1 + 2 + 3 + 4 + 5 + []
```

Similar to the list fusion problem.

```
foldr (+) 0 [1..5]
```

$\Downarrow$

```
foldr (+) 0 (1:2:3:4:5:[])
```

```
1 + 2 + 3 + 4 + 5 + 0
```

Similar to the list fusion problem.

```
foldr (+) 0 [1..5]
```

▼

```
foldr (+) 0 (1:2:3:4:5:[])
```

```
1 + 2 + 3 + 4 + 5 + 0
```

```haskell
program :: Eff (State Int) Int
program = Get `Then` \n →
            if n ≤ 0
              then Return n
              else Put (n - 1) `Then` \_ → program
```

producer

consumer

```haskell
runState :: s → Eff (State s) a → (s, a)
runState s (Return x)          = (s, x)
runState s (Get     `Then` k) = runState s (k s)
runState _ (Put s `Then` k)   = runState s (k ())
```

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Can we get GHC to do this?

Might `mtl` do better?

```haskell
program :: MonadState Int m ⇒ m Int
program = get ≫= \n →
            if n ⩽ 0
              then return n
              else put (n - 1) >> program
```

How is this compiled?

How are typeclasses compiled?

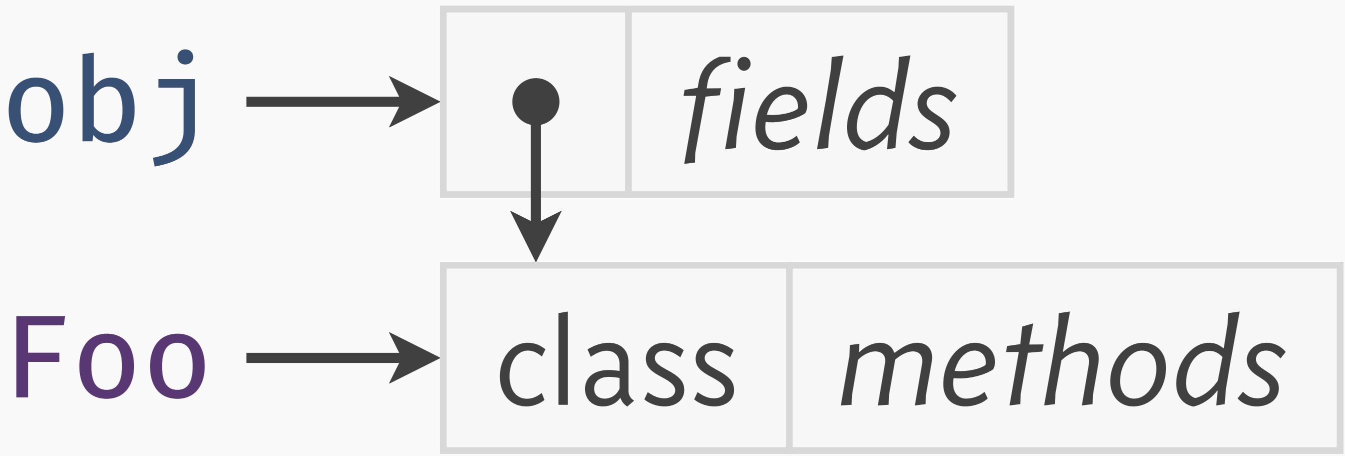
Non-Solution 1: Type Dispatch

```
show x = case typeOf x of
  Bool   → show_Bool x
  Char   → show_Char x
  String → show_String x
  …
```

Immediate problem: requires whole-program compilation.

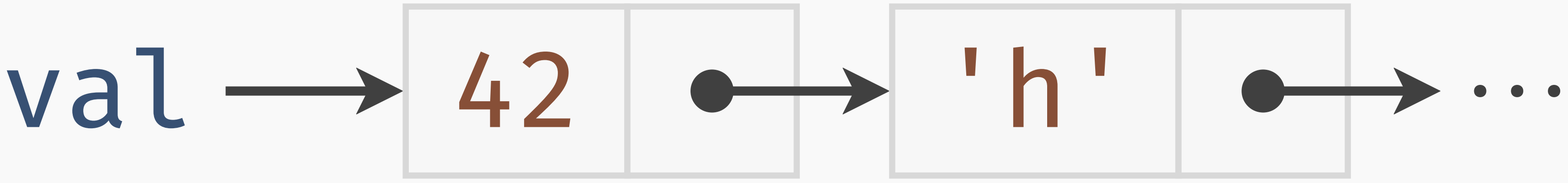
Deeper problem: full type erasure.

Java: `if (obj instanceof Foo) { … }`



Haskell: `data Foo = MkFoo Int String`

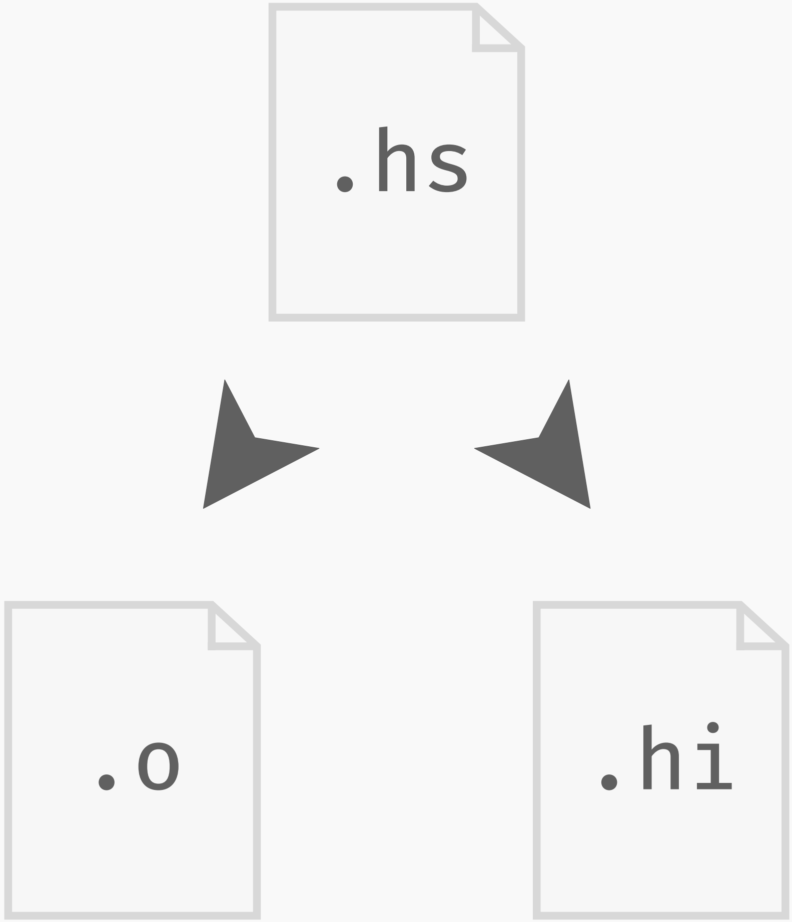
`let val = MkFoo 42 "hello"`



Non-Solution 2: Monomorphization

```
exclaim :: Show a ⇒ a → String
exclaim x = show x ++ "!"
```

1. Generate *no code* for `exclaim`.
2. Record `exclaim`'s definition in the interface file.



`.hi` — "Haskell interface"

- → type/class/instance declarations
- → types of exported bindings
- → source code of small bindings
- → for monomorphization: source code of *all* overloaded bindings

```
exclaim True
```

```
exclaim :: Show a ⇒ a → String
exclaim x = show x ++ "!"
```

```
exclaim_Bool :: Bool → String
exclaim_Bool x = show_Bool x ++ "!"
```

```
exclaim True ➤ exclaim_Bool True
```

Overloading has no runtime cost!

...but it can create a lot of bloat.

```
exclaim True    exclaim 42    exclaim "hello"
```

▼

```
exclaim_Bool :: Bool → String
exclaim_Bool x = show_Bool x ++ "!"

exclaim_Int :: Int → String
exclaim_Int x = show_Int x ++ "!"

exclaim_String :: String → String
exclaim_String x = show_String x ++ "!"
```

```
reallyBig :: (Foo a, Bar b, Baz c) ⇒ …
reallyBig = 
```
$<$ *really big RHS* $>$

```
reallyBig @Bool   @Bool   @Bool     reallyBig @Bool   @Bool   @Int      reallyBig @Bool   @Bool   @String
reallyBig @Bool   @Int    @Bool     reallyBig @Bool   @Int    @Int      reallyBig @Bool   @Int    @String
reallyBig @Bool   @String @Bool     reallyBig @Bool   @String @Int      reallyBig @Bool   @String @String
reallyBig @Int    @Bool   @Bool     reallyBig @Int    @Bool   @Int      reallyBig @Int    @Bool   @String
reallyBig @Int    @Int    @Bool     reallyBig @Int    @Int    @Int      reallyBig @Int    @Int    @String
reallyBig @Int    @String @Bool     reallyBig @Int    @String @Int      reallyBig @Int    @String @String
reallyBig @String @Bool   @Bool     reallyBig @String @Bool   @Int      reallyBig @String @Bool   @String
reallyBig @String @Int    @Bool     reallyBig @String @Int    @Int      reallyBig @String @Int    @String
reallyBig @String @String @Bool     reallyBig @String @String @Int      reallyBig @String @String @String
```

Monomorphization

- → Can be good for runtime performance.
- → Can be very bad for code size & compile times.
- → C++/Rust programmers have to worry about this!
- → Haskell programmers generally do not.

```
exclaim :: Show a ⇒ a → String
exclaim x = show x ++ "!"
```

▼

```
exclaim :: (a → String) → a → String
exclaim show_a x = show_a x ++ "!"
```

```
exclaim True ➤ exclaim show_Bool True

exclaim 42 ➤ exclaim show_Int 42
```

```haskell
class Show a where
  show      :: a → String
  showsPrec :: Int → a → ShowS
  showList  :: [a] → ShowS

data Show a = ShowDict
  { show      :: a → String
  , showsPrec :: Int → a → ShowS
  , showList  :: [a] → ShowS }

exclaim :: Show a → a → String
exclaim dict x = show dict x ++ "!"
```

This is *dictionary passing*.

- → Elegantly simple.
- → Cheap to compile.
- → Does it have a runtime cost?

```haskell
program :: MonadState Int m ⇒ m Int
program = get ≫= \n →
            if n ⩽ 0
              then return n
              else put (n - 1) >> program
```

```haskell
program :: MonadState Int m → m Int
program stateDict@(MonadStateDict monadDict _ _) =
  (≫=) monadDict
       (get stateDict)
       (\n → if n ⩽ 0
          then return monadDict n
          else (>>) monadDict
                    (put stateDict (n - 1))
                    (program stateDict)
```

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Is this performant?

Nope: we can't inline anything.

```
program :: MonadState Int m → m Int
program stateDict@(MonadStateDict monadDict _ _) =
  (≫=) monadDict
       (get stateDict)
       (\n → if n ≤ 0
          then return monadDict n
          else (>>) monadDict
                    (put stateDict (n - 1))
                    (program stateDict)
```

Most calls are *known* calls.

```
fst ("hello", "world")
```

```
fst :: (a, b) → a
fst (x, _) = x
```

Most calls are *known* calls.

```
fst ("hello", "world")
```

▼

```
(\(x, _) → x) ("hello", "world")
```

▼

```
"hello"
```

Higher-order functions make *unknown* calls.

```
foldr :: (a → b → b) → b → [a] → b
foldr _ v []     = v
foldr f v (x:xs) = f x (foldr f v xs)
```

???

Unknown calls are *hard stops* for the optimizer.

KNOWN CALL

- → Compiled to direct jump.
- → Exposes strictness info.
- → Args can be unboxed.
- → Can have rewrite RULES.
- → Inlined if small.

UNKNOWN CALL

- → Compiled to indirect jump.
- → Assumed lazy in all args.
- → Args must have declared types.
- → Opaque to RULES.
- → Never inlined.

This is the cost of AOT compilation!

Typeclass overloading creates unknown calls.

Overloading is **not** free!

Unknown calls are not a death sentence.

```
sumIndicies :: Eq a ⇒ a → [a] → [Int]
sumIndicies v xs = zip [1..] xs
                 & filter ((== v) . snd)
                 & map fst
                 & sum
```

List fusion can still happen!

Unknown calls to >>= are a problem.

```
foo :: k → Map k Int → Either String Int
foo key vals = do
  nums ← case Map.lookup key vals of
           Nothing  → Left "not found"
           Just val → Right [1..val]
  Right $ sum nums
```

Unknown calls to >>= are a problem.

```haskell
foo :: MonadError String m ⇒ k → Map k Int → m Int
foo key vals = do
  nums ← case Map.lookup key vals of
           Nothing  → throwError "not found"
           Just val → return [1..val]
  return $ sum nums
```

>>= is *glue*.

Conclusion: not surprising at all that `mtl` has a cost!

But why is it *sometimes* fast?

SPECIALIZATION

GHC monomorphizes in limited circumstances.

1. GHC looks for calls to overloaded functions at known, concrete types.
2. The function must satisfy *at least one* of the following:
   → It is defined in the current module.
   → It was declared with an `INLINABLE` pragma.
   → It is a class method *and* its unfolding (source code) is in the interface file.

GHC monomorphizes in limited circumstances.

1. GHC looks for calls to overloaded functions at known, concrete types.
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    - → It is defined in the current module.
    - → It was declared with an `INLINABLE` pragma.
    - → It is a class method *and* its unfolding (source code) is in the interface file.

```haskell
program :: MonadState Int m ⇒ m Int
program = do n ← get
             if n ⩽ 0
               then return n
               else put (n - 1) >> program
```

```haskell
program :: State Int Int
program = get ≫= \n →
            if n ⩽ 0
              then return n
              else put (n - 1) >> program
```

```haskell
program :: MonadState Int m ⇒ m Int
program = do n ← get
             if n ≤ 0
               then return n
               else put (n - 1) >> program
```

▼

```haskell
program :: MonadState Int m → m Int
program stateDict@(MonadStateDict monadDict _ _) =
  (>>=) monadDict
        (get stateDict)
        (\n → if n ≤ 0
           then return monadDict n
           else (>>) monadDict
                     (put stateDict (n - 1))
                     (program stateDict)
```

Why bother explaining all of this?

Because we're not done.

Can we avoid the performance regression?

→ It is defined in the current module.

→ It was declared with an `INLINABLE` pragma.

→ It is a class method *and* its unfolding (source code) is in the interface file.

This approach has many problems.

1. It would be annoying.
2. It requires *whole-program* specialization!
    → Probably recompiles everything in `Main.hs`.
    → Compilation may not terminate.
    → This cost is incurred for *each* specialization.
    → Can be defeated by existential quantification.

Let’s take a step back.

Why is specialization necessary here?

Proposition 1: effect systems are *fundamentally* about dynamic dispatch.

```
program = get >>= \n ->
            if n ⩽ 0
              then return n
              else put (n - 1) >> program
```

interpretation not yet decided!

Proposition 2: effect dispatch can be made perfectly affordable. The real problem is $\gg=$.

```
program = get >>= \n →
            if n ≤ 0
              then return n
              else put (n - 1) >> program
```

Passing $\gg=$ via dictionary creates problems!

1. $\gg=$ gets called a *lot*.
2. $\gg=$ is glue; it needs to be inlined to expose further optimizations.
3. Unknown calls to $\gg=$ balloon closure allocation.

captured in closure

used under a lambda

```haskell
f x y = foo x >>= \z -> bar (+ y z)
```

stored on stack

```haskell
f x y = case foo x of
  Left e  -> Left e
  Right z -> bar (+ y z)
```

used in a case RHS

If `>>=` is an unknown call, the caller must allocate a closure for the continuation.

When `>>=` is passed via dictionary, the program is *reified as a tree of lambdas!*

```haskell
program :: Eff (State Int) Int
program = Get `Then` \n →
            if n ⩽ 0
              then Return n
              else Put (n - 1) `Then` \_ → program
```

Without specialization, these *aren't that different!*

```haskell
program :: MonadState Int m ⇒ m Int
program = get ⤜ \n →
            if n ⩽ 0
              then return n
              else put (n - 1) >> program
```

How do we escape?

ESCAPE PLAN

① We need a monad with an inlinable $\gg=$.

② $\gg=$ itself must not allocate.

③ It must be able to handle all algebraic effects.

④ Effect dispatch can be dynamic (but must be fast).

This is not a small order.

Requirements ② and ③ are especially hard.

Monad transformers are out of the question.

(Effect behavior lives in `>>=`.)

Free-like monads are also disqualified.

(`>>=` must allocate to construct the tree.)

What's left?

DELIMITED CONTINUATIONS

There is a deep, well-known connection between delimited continuations and algebraic effects.

(Well outside the scope of this talk!)

Big idea: equip a monad with a pair of super powerful control operators, `prompt` and `control`.

All effect handlers can be defined in terms of these operators.

`>>=` does not need to know anything about effect behavior.

New problem: the only way to implement delimited continuations in Haskell is CPS.

In CPS, continuation is passed via closure:

```
m >>= f = \k -> m (\x -> f x k)
```

All calls to non-inlined monadic functions must allocate. (This isn't much better than free monads.)

Cost is okay for continuation-happy code, but effects that don't need them (very common!) still must pay for them.

But this is frustrating!

There are well-known, efficient implementation techniques for delimited continuations!

I give up. Let’s just patch GHC.

ghc-proposals / ghc-proposals

Watch 143

Code | Issues 15 | Pull requests 61 | Actions | Security 0 | Insights

Delimited continuation primops #313

Open lexi-lambda wants to merge 4 commits into `ghc-proposals:master` from `lexi-lambda:delimited-continuation-`

Conversation 39 | Commits 4 | Checks 0 | Files changed 2

lexi-lambda commented on Feb 22 • edited

This is a proposal for adding primops for capturing slices of the RTS stack to improve the performance of algebraic effect systems, which require delimited continuations.

Rendered

👍 75 🎉 17 ❤️ 10 🚀 10

EFF

hasura / eff

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🚧 a work in progress effect system for Haskell 🚧

Edit

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lexi-lambda Rename `shift` to `control` … Latest commit 17cc75d on Mar 3

eff	Rename `shift` to `control`	3 months ago
.gitignore	initial commit	8 months ago
.travis.yml	Update to support continuation primop changes	4 months ago
LICENSE	initial commit	8 months ago
README.md	Rename `swizzle` to `lift`, remove old version of `lift`	3 months ago
cabal.project	Completely rewrite implementation to use delimited continuations	4 months ago
cabal.project.travis	Completely rewrite implementation to use delimited continuations	4 months ago

README.md

`eff` — screaming fast extensible effects for less

build passing | docs 0.0.0.0

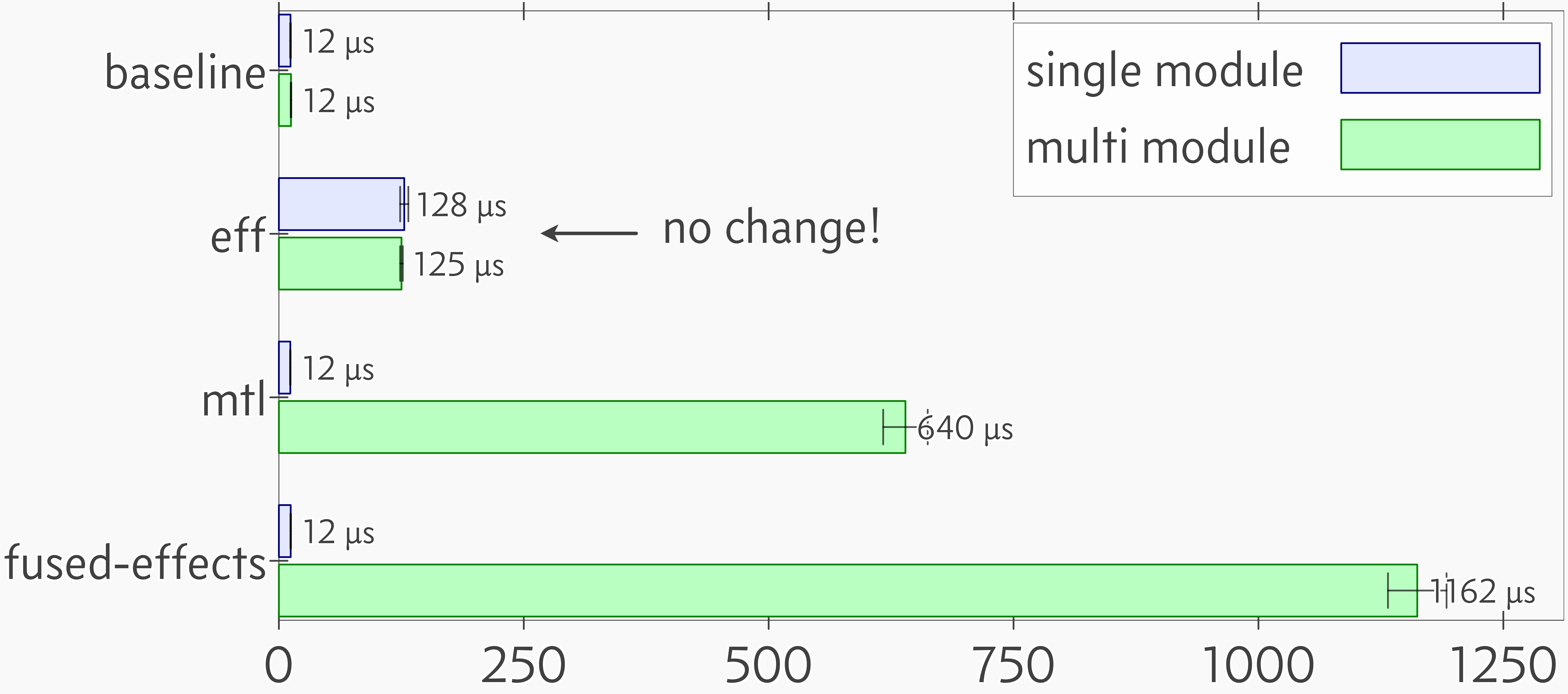
🚧 This library is currently under construction. 🚧

`eff` is a work-in-progress implementation of an *extensible effect system* for Haskell, a general-purpose solution for tracking effects at the type level and handling them in flexible ways. Compared to other effect systems currently available, `eff` differentiates itself in the following respects:

EFF: KEY FEATURES

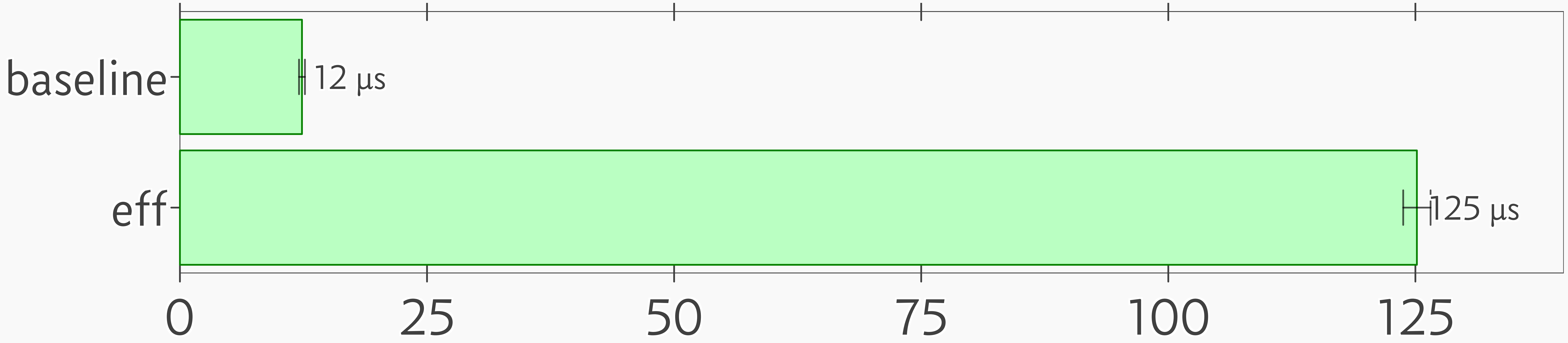
- → API is similar to free-like approaches (actually simpler!).
- → Provides a single monad, named `Eff`.
- → Basically `ReaderT` over `ST` under the hood.
  - → Reader context holds current handlers.
  - → Wraps the unsafe primops in a safe API.
- → Effect dispatch takes constant time (not amortized).
- → Faster for most use cases than unspecialized `mtl`.

EFF: THE NUMBERS



`eff`'s performance does *not* depend on compiler optimizations!

EFF: THE NUMBERS



Should we be worried?

COUNTDOWN: THE REST OF THE STORY

```
program :: Int → (Int, Int)
program n = if n ≤ 0 then (n, n)
            else program (n - 1)
```

Why *so* much faster?

```haskell
program :: Int → (Int, Int)
program n = if n ⩽ 0 then (n, n)
                     else program (n - 1)
```

▼

```haskell
$wprogram :: Int# → (# Int#, Int# #)
$wprogram n = if n ⩽# 0# then (# n, n #)
                         else $wprogram (n -# 1#)
```

```haskell
$wprogram :: Int# → (# Int#, Int# #)
$wprogram n = if n ⩽# 0# then (# n, n #)
                         else $wprogram (n -# 1#)
```

```asm
_c4ap: addq $16,%r12
       cmpq 856(%r13),%r12
       ja _c4aB
_c4aA: testq %r14,%r14
       jle _c4aw
_c4av: addq $-16,%r12
       decq %r14
       jmp _c4ap
```

8 instructions!

```haskell
program :: Int → (Int, Int)
program n = if n ⩽ 0 then (n, n)
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```

```haskell
program :: Integer → (Integer, Integer)
program n = if n ⩽ 0 then (n, n)
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```
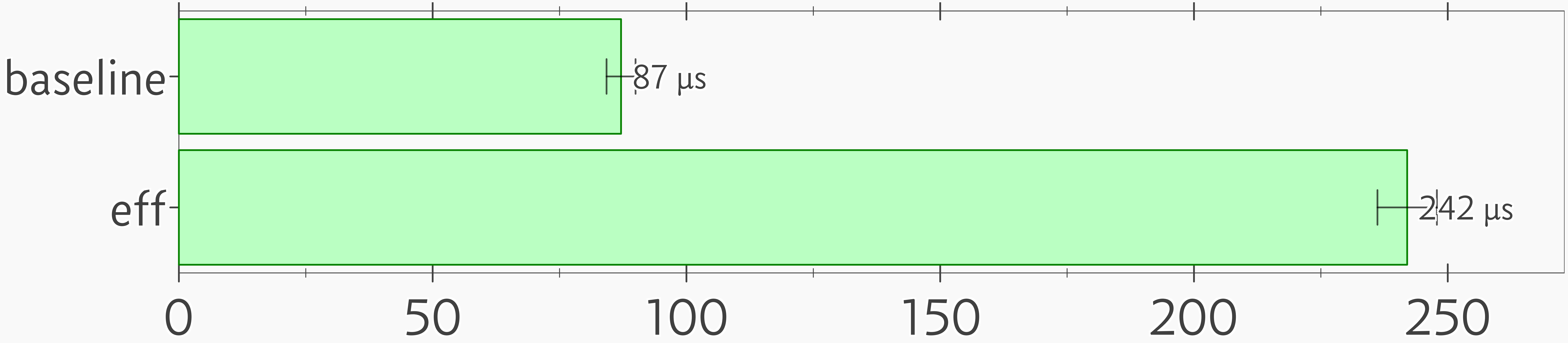

COUNTDOWN: NO UNBOXING



Not quite so bad, after all!

Phew.

RECAP

- → Countdown benchmarks `>>=` and effect dispatch.
- → `mtl` and `fused-effects` rely on compiler optimizations.
- → Those optimizations are very often not viable.
- → `eff` closes the gap by being inherently fast:
  - → It exposes more local transformations to the optimizer.
  - → Delimited continuation primops avoid CPSing.
  - → Result: `eff` handily wins the benchmark shootout.
- → Numbers are not enough. It is our responsibility to ask why.

CLOSING THOUGHTS

- The `eff` story is not over.
  - Need to plumb in support for `IO` exceptions.
  - The GHC proposal needs to be accepted.
- The design of `eff` itself could be its own talk!
- `mtl`'s performance is misunderstood and overhyped!
- Effect systems are too foundational to ignore perf.
- We really do need good real-world benchmarks.
- Someday: effect specialization?

THE END

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- Effect systems are too foundational to ignore perf.
- We really do need good real-world benchmarks.
- Someday: effect specialization?

`eff`: https://github.com/hasura/eff
benchmarks: https://github.com/ocharles/effect-zoo
proposal: https://github.com/ghc-proposals/ghc-proposals/pull/313
Hasura: https://hasura.io
me: https://lexi-lambda.github.io