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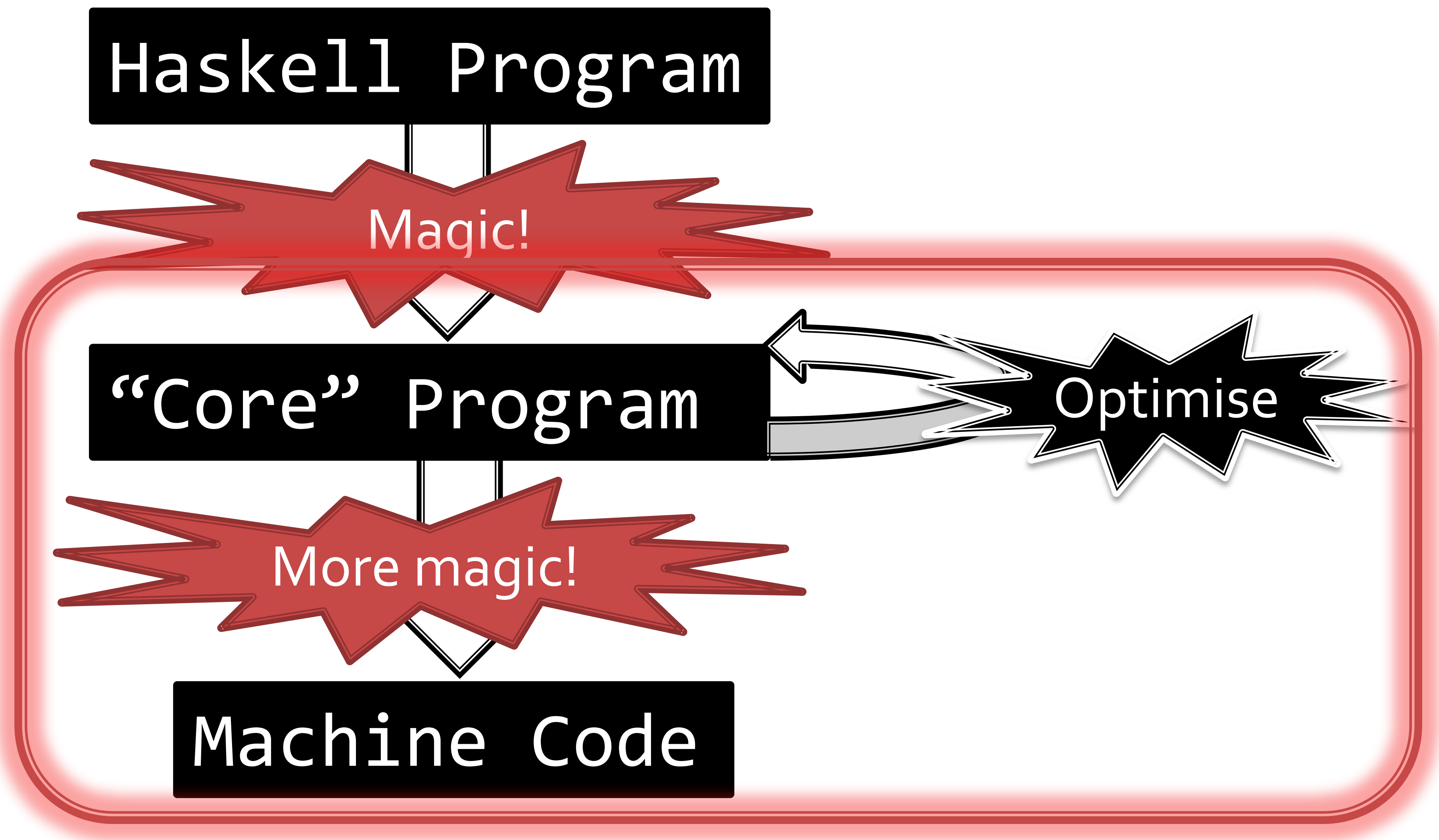
Types Are Calling Conventions

Introduction

- GHC misses some fundamental optimisation opportunities!
  - We have to generate more **dynamic tests** than we would really like to when you use features like *laziness* and *higher order arguments*
- We present a new compiler intermediate language designed to recover those opportunities
- Essential observation: it is insufficient to derive a function’s calling convention from its source language type in a higher-order lazy language
  - So we make sure that **our** intermediate language’s types express all the calling conventions we are interested in

The Glasgow Haskell Compiler



How Many Parameters? 1

How many parameters can you supply to a function of this type?

```
f :: Int -> Int -> Int
```

As far as the user is concerned, the answer is obviously two:

```
f 1 2
```

How Many Parameters? 2

However, the compiler actually makes a finer grained distinction:

Two:

```
f2 = \y -> \z -> let x = fib 10 in x + y + z
```

One:

```
f1 = \y -> let x = fib 10 in \z -> x + y + z
```

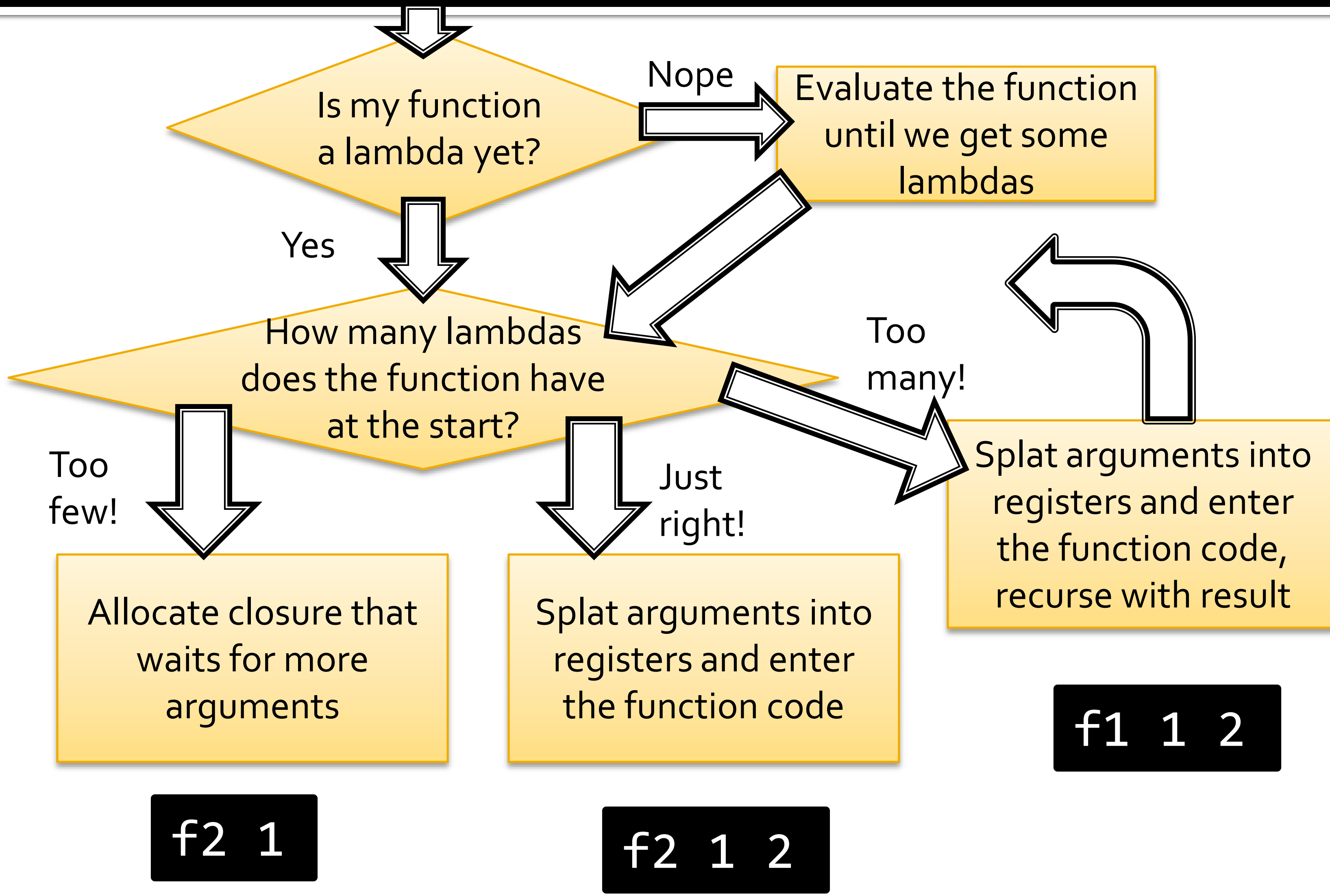
Zero!

```
f0 = let x = fib 10 in \y -> \z -> x + y + z
```

Arity is the number of arguments we can apply before the function does some "real work". The arity changes how we call the function.

Arity depends on the **implementation** of the function, not its type! In stark contrast to C, where all calling convention information **must** be derivable from the type!

Function Application Today



What Sucks

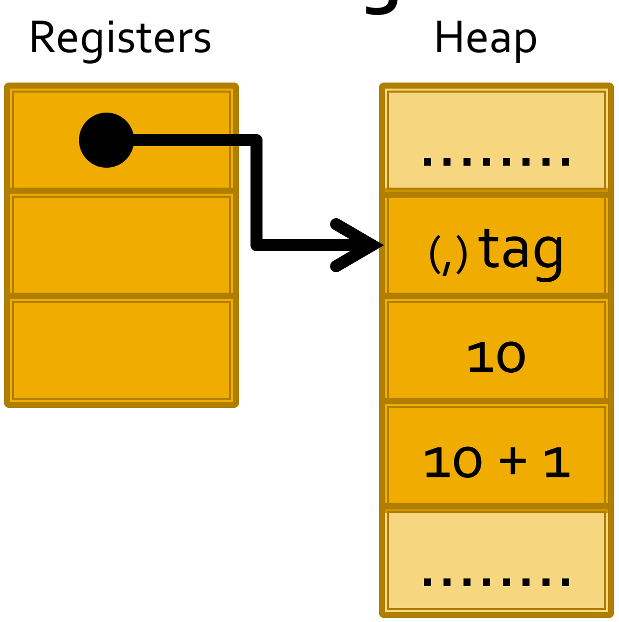
- Mandatory **dynamic** check of the function's runtime *arity* against the number of available arguments
- Mandatory **dynamic** check that the function has actually been evaluated to some lambdas
  - Things are actually worse than this: for example, there is no way to encode the fact that e.g. a `Bool` argument must have been evaluated by the caller!
  - So **unnecessary thunks are being allocated**–bad!
- In effect we decide the precise function calling convention at runtime, on a per-function basis!

Multiple Results

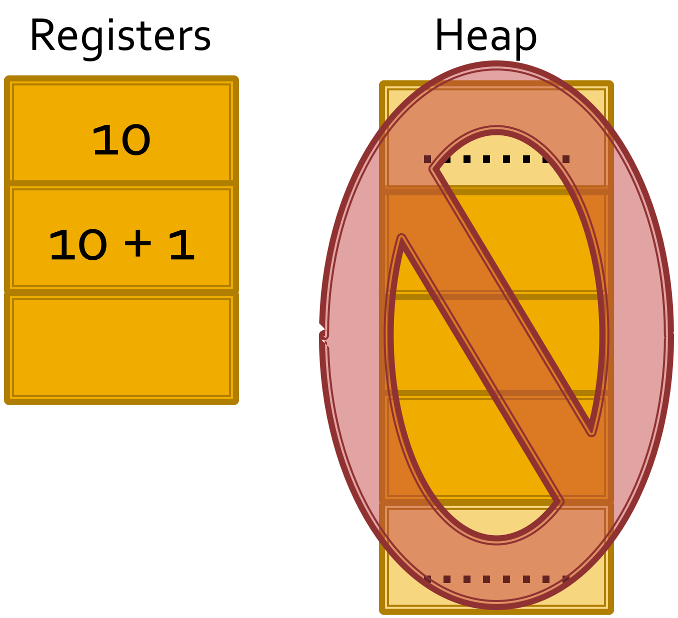
A "symmetric" source of slowness: returning multiple **results**:

```
silly x = (x, x + 1)
result = silly 10
```

What we **get**:



What we **want**:



The Question

A vanilla functional language like GHC's current Core language doesn't let us express optimisations that act to remove these sources of inefficiency.

Is there a language in which we can express the differences in calling convention arising from:

1. Precisely how many arguments the function takes before doing "real work"
2. Whether or not we have decided to return results from a function in several registers

(…and hence express **optimisation** of these two properties!)

- In a way that the compiler can chew on all that information statically?
- That doesn't impose unbearable bureaucratic overhead when building terms and types?
- Which still has a functional flavour?

A Possible Answer: Strict Core

Idea: just put the juicy operational information **in the type system of the compiler intermediate language**

- Invariants enforced via the type system are **stable** – if you break them, your program doesn't typecheck any longer! Easy to **detect compiler bugs**
- Types are a convenient place to encode all statically known information about a value:
  - Types (and their implied invariants) easily available to the code generator
  - Seamless treatment of invariants on **higher order arguments!**

Slogan: (intermediate language) types **are** calling conventions

Strict Core Is Small!

Binders

b	$::=$	$x:\tau$	Value binding
	$\mid$	$\alpha:\kappa$	Type binding

Types

τ, υ, σ	$::=$	$\mathbf{T}$	Type constructors
	$\mid$	α	Type variable references
	$\mid$	$\overline{b} \to \overline{\tau}$	Function types
	$\mid$	$\tau\ \upsilon$	Type application

Atoms

a	$::=$	x	Term variable references
	$\mid$	ℓ	Literals

Atoms In Arguments

g	$::=$	a	Value arguments
	$\mid$	τ	Type arguments

Multi-value Terms

e	$::=$	$\overline{a}$	Return multiple values
	$\mid$	$\mathbf{let}\ \overline{x:\tau} = e\ \mathbf{in}\ e$	Evaluation
	$\mid$	$\mathbf{valrec}\ \overline{x:\tau = v}\ \mathbf{in}\ e$	Allocation
	$\mid$	$a\ \overline{g}$	Application
	$\mid$	$\mathbf{case}\ a\ \mathbf{of}\ \overline{p \to e}$	Branch on values

Heap Allocated Values

v	$::=$	$\lambda\overline{b}.\, e$	Closures
	$\mid$	$\mathbf{C}\ \overline{\tau}, \overline{a}$	Constructed data

Strict Core Has Simple Types!

The type system should be very familiar, apart from a single changed production:

Types

τ, υ, σ	$::=$	$\mathbf{T}$	Type constructors
	$\mid$	α	Type variable references
	$\mid$	$\boxed{\overline{b} \to \overline{\tau}}$	Function types
	$\mid$	$\tau\ \upsilon$	Type application

```
<Int> -> <Int, Int>
```

```
<Int, Int> -> <Int>
```

```
<a :: *, a> -> <a>
```

If you have ***n*** **types in <brackets>** to the left (right) of a function arrow then *n* arguments (results) are passed into (out of) the function call **in registers**

Strict Core Has Simple Expressions!

A strict functional language which we present in A-normal form:

Multi-value Terms

e	$::=$	$\overline{a}$	Return multiple values
	$\mid$	$\mathbf{let}\ \overline{x:\tau} = e\ \mathbf{in}\ e$	Evaluation
	$\mid$	$\mathbf{valrec}\ \overline{x:\tau = v}\ \mathbf{in}\ e$	Allocation
	$\mid$	$a\ \overline{g}$	Application
	$\mid$	$\mathbf{case}\ a\ \mathbf{of}\ \overline{p \to e}$	Branch on values

```
<1, x, 10>
```

```
let <x, y> = <1, 2>
in <x>
```

```
valrec
  x = Just y
  y = \<x>. ...
in ...
```

```
id <Int, 10>
```

- All allocation is done by **valrec**
- Stack frames are pushed by **let**
- **case** is only responsible for branching, not forcing of the scrutinee

Thunks

- Thunks are **zero-argument functions**
  - Very natural – lambdas somehow induce a **delay** in evaluation
  - Similar to classic lazy lists in ML
- However, we want to **share the result of the function** between several calls
  - Add special cases to the operational semantics that **update** thunks with what they evaluate to

```
{τ,...,τ}  ≜  <> -> <τ,...,τ>
      {e}  ≜  \<>. e
```

From Haskell To Strict Core

Given this Haskell function:

```
twice :: (a -> a) -> a -> a
twice = \f -> \x -> f (f x)
```

We produce this Strict Core one:

```
twice :: <{<{a}> -> <a>}>
      -> <<{a}> -> <a>>
twice = \<f>. <\<x>.
  f <> <{f <> <{x <>}>}>>
```

Reprise

- *Mandatory* dynamic evaluatedness checks:
  - **Gone**! Can see **statically** if something is certainly evaluated
- *Mandatory* dynamic arity checks:
  - **Gone**! Can see **statically** how many arguments a functional value is expecting
- Returning several things in registers:
  - **Expressible**!
- **But** the functions I'm getting directly from Haskell make *little or no use* of these capabilities!

Simple Equational Optimisations

Remember this?

```
twice = \<f>. <\<x>.
  f <> <{f <> <{x <>}>}>>
```

Apply **eta-contraction** to remove redundant thunk allocation:

`{x <>}` ≜ `\<>. x <>` = `x`

Arity Definition Site Analysis 1

```
twice = \<f>. <\<x>. ...>
```

Hang on - we take an argument and then **immediately return a function**? That's stupid! **Let's optimize:**

```
twice'
  :: <{<{a}> -> <a>}, {a}> -> <a>
twice' = \<f, x>. ...

twice =
  \<f>. <\<x>. twice' <f, x>>
```

Worker/Wrapper In Action

```
twice <succ> <0>
```

```
(\<f>. <\<x>. twice’ <f, x>>) <succ> <0>
```

```
twice’ <succ, 0>
```

Arity Definition Site Analysis 2

Q: Can we **always** improve the function arity like that?

```
h :: <Int> -> <<Int> -> <Int>>
h = \<x>. let <z> = fib <x>
          in \<y>. y + z

let h’ = h <10000> in h’ <2> + h’ <1>
```

A: **No!** If we change the type of h to `<Int, Int> -> <Int>` then we won’t be able to **share the partial application** any longer. Result: `fib <10000>` would be **run twice**!

Arity Use Site Analysis

Q: Can we improve the arity of **higher-order arguments**?

```
h :: <<Int> -> <<Int> -> <Int>>>
  -> <Int>
h = \<f>. f <1> <2> + f <3> <4>
```

A: **Yes!** The function h only ever applies f to two arguments at once – and **no partial application is shared**! **Let's optimize:**

```
h’ :: <<Int, Int> -> <Int>>
   -> <Int>
h’ = \<f’>. f’ <1, 2> + f’ <3, 4>
h = \<f>. h’ <\<x,y>. f <x> <y>>
```

Constructed Product Result

```
silly :: <{Int}> -> <({Int}, {Int})>
silly = \<x>. <(x, {x <> + 1})>
```

We take an argument and then **immediately return a product type**? We could cancel that with a use site! **Let’s optimize:**

```
silly’ :: <{Int}> -> <{Int}, {Int}>
silly’ = \<x>. <x, {x <> + 1}>

silly = \<x>. let <y, z> = silly’ <x>
                  in <(y, z)>
```

Strictness

```
i :: <{Bool}> -> <Int>
i = \<b>. case b <> of True -> <...>
                       False -> <...>
```

We have a `{thunked}` argument that we **immediately evaluate**? That’s stupid! **Let’s optimize:**

```
i’ :: <Bool> -> <Int>
i’ = \<b’>. case b’ of True -> <...>
                       False -> <...>


i = \<b>. i’ <b <>>
```

Deep Unboxing

```
i :: <{({Int}, {Int})}> -> <Int>
i = \<p>. case ... of
    True -> <1>
    False -> case p <> of
                (x, y) -> <x <> + y <>>
```

This is more subtle! If `i` ever evaluates p then it certainly evaluates both components of the pair. **Let’s optimize:**

```
i’ :: <{Int, Int}> -> <Int>
i’ = ...
i = ...
```

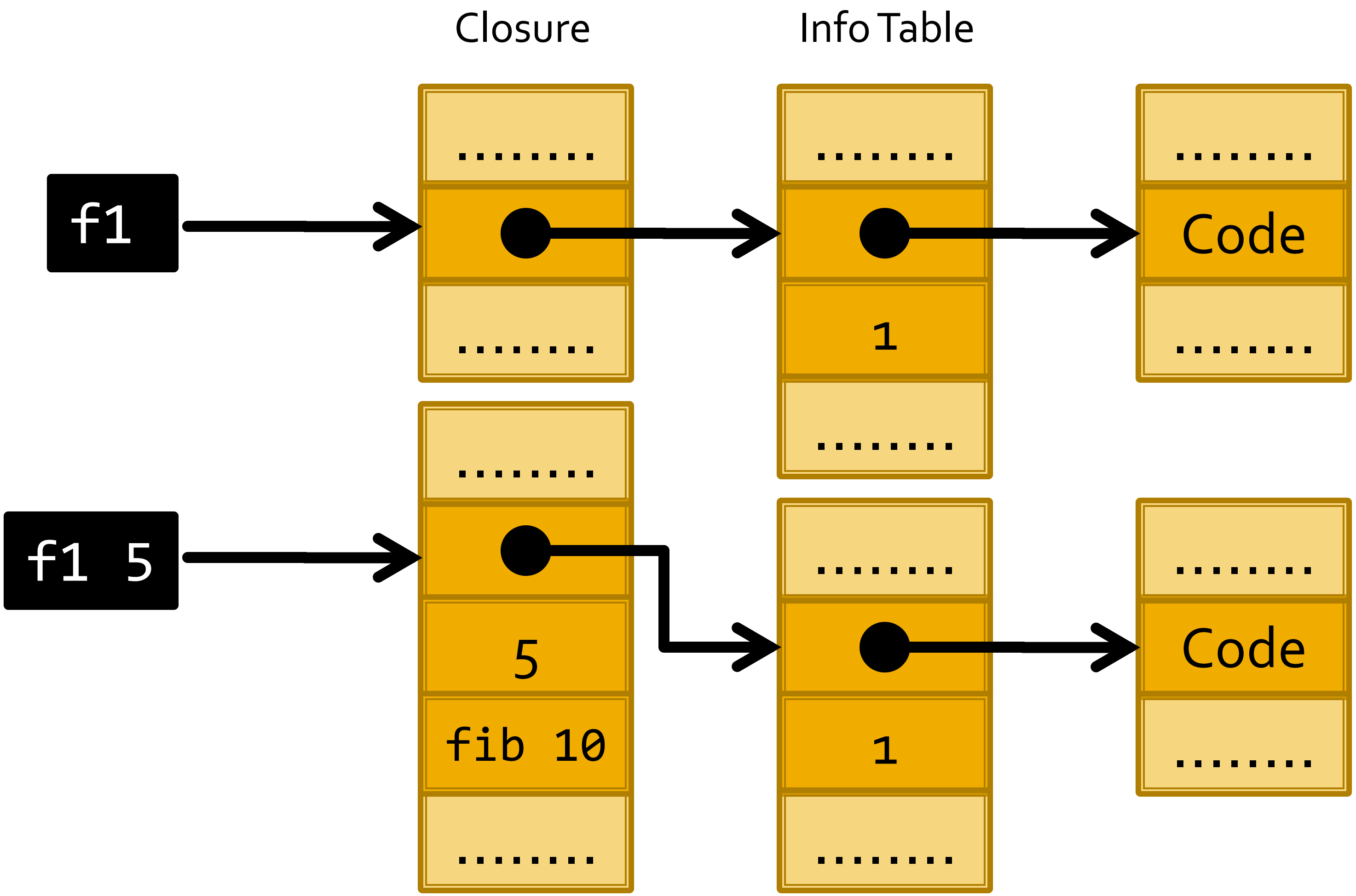
Conclusions

- Identifying **types** with **calling conventions** *looks* like a win, optimization-wise
  - Entirely new optimisation opportunities (arity use-site analysis, deep unboxing)
  - Existing *ad hoc* optimizations put on a sound footing
- A **nice point in the design space**: we couldn't seem to get much more optimisation opportunity without adding a lot of additional complexity
- Surprising (to us): the best choice for the intermediate language of a compiler for a lazy language is **not** *itself* a lazy language
- Exciting direction for future work: push the ability to write strict programs into Haskell!

Extra Material

Representing Functions

```
f1 = \y -> let x = fib 10 in \z -> x + y + z
```



Examples

Expressing the number of **results** we expect:

```
duplicate :: <Int> -> <Int, Int>
duplicate = \<x> -> <x, x>
```

Expressing the number of **arguments** we expect:

```
add2 :: <Int, Int> -> <Int>
add2 = \<x, y> -> <x + y>
```

Polymorphism:

```
id :: <a :: *, a> -> <a>
```

Example Translation 2

```
twice :: <{<{a}> -> <a>}>
      -> <<{a}> -> <a>>
twice = \<f> -> <\<x> ->
  f <> <{f <> <{x <>}>}>>
```

Removing the (notational) line noise:

```
twice :: {{a} -> a}
      -> {a} -> a
twice = \<f> -> <\<x> ->
  f <> {f <> {x <>}}>
```

Let's Optimize!

- I've shown you some of the calling conventions we would **like** to have for our Haskell source functions
- The straightforward translation from Haskell will **not** give you these optimized calling conventions directly
  - Instead, we need to have some optimisations that improve calling conventions through program transformation

Worker/Wrapper In Action

```
case silly <{10}> of
  (x, y) -> <x + y>
```

```
case let <a, b> = silly’ <{10}>
     in <(a, b)> of
  (x, y) -> <x + y>
```

```
let <a, b> = silly’ <{10}>
in <a + b>
```