Safe Zero-cost Coercions for Haskell

Joachim Breitner
Karlsruhe Institute of Technology
breitner@kit.edu

Richard Eisenberg
University of Pennsylvania
eir@cis.upenn.edu

Simon Peyton Jones
Microsoft Research
simonpj@microsoft.com

Stephanie Weirich
University of Pennsylvania
sweirich@cis.upenn.edu

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Abstraction can be a drag...

```
newtype HTML = MkH String
  -- MkH is not exported
  -- safety increase over using String
  -- “no runtime overhead”

string :: HTML → String
string (MkH s) = s

stringList :: [HTML] → [String]
stringList hs = map string hs
  -- this no-op takes linear time!
```

Outline, in brief

I. How we make “zero-cost” abstractions cost nothing, retaining type safety

II. Consequences of our design & other practicalities

A new equivalence relation: ≈

```
coerce :: a ≈ b ⇒ a → b
```

We want: (`a ≈ b`) ⇒ (`[a] ≈ [b]`)

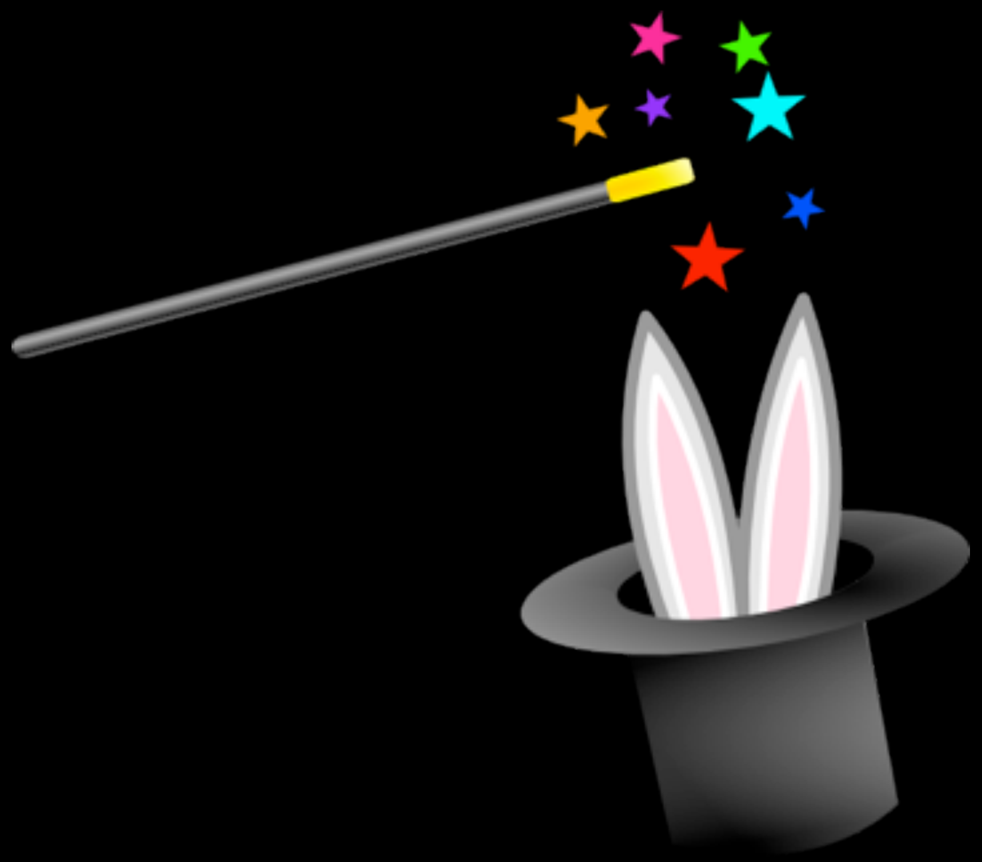
So: Use a type class!

```
class a ≈ b
instance a ≈ b ⇒ [a] ≈ [b]
```

`(≈)` is spelled `Coercible` in GHC 7.8

coerce must be free!

```
coerce :: a ≈ b ⇒ a → b
coerce x =
```



Instances of (≈) must be sound!

Instances of $(\approx)$

Reflexivity:

```
   instance a ≈ a
```

No symmetry or transitivity:
we need syntax-directed solving

Symmetry and transitivity are admissible

Instances of (≈)

From newtype declarations:

“(un)wrapping instance”

```
newtype HTML = MkH String    ⇒
  instance a ≈ String ⇒ a ≈ HTML
  instance String ≈ b ⇒ HTML ≈ b
```

Assume `newtype ValidHTML = MkV HTML`

Can derive (String ≈ ValidHTML):

```
String ≈ String
⇒ String ≈ HTML
⇒ String ≈ ValidHTML
```

Instances of (≈)

From data declarations:

```
data Maybe a = Nothing | Just a
```

“lifting instance” ⇒

```
  instance a ≈ b ⇒ Maybe a ≈ Maybe b
```

Lifting instances also made for newtypes

Can derive (Maybe HTML ≈ Maybe String):

```
String ≈ String
⇒ HTML ≈ String
⇒ Maybe HTML ≈ Maybe String
```

But that’s too permissive!

```
type family F a
type instance F String = Int
type instance F HTML   = Bool → Bool

newtype UhOh a = MkUO (F a)
```

Can derive (Int ≈ Bool → Bool): (!!!)

```
  … ⇒ UhOh String ≈ UhOh HTML       lifting
⇒ … ⇒    F String ≈ F HTML       unwrapping
    =         Int ≈ Bool → Bool
```

image: Jim Urquhart/Reuters

A tale of two equalities

`(~)`		`(≈)`
nominal		representational
compile time		run time
equal in Haskell code		equal to code generator
automatic conversion		manual conversion
finer		coarser
`(x ~ y)`	⇒	`(x ≈ y)`
`(x ~ y)`	⇍	`(x ≈ y)`

A tale of two equalities

Type families, GADTs, class instances, etc. can distinguish a newtype and its representation.

```
type instance F String = Int
type instance F HTML   = Bool → Bool
```

Does not respect (≈)

Roles

We must differentiate between

```
data Maybe a
  = Nothing
  | Just a
```

```
newtype UhOh a
  = MkUO (F a)
```

Answer: assign *roles* to type parameters

Adaptation of ideas in previous work [1]:

- Simpler -- doesn't require a new kind system
- Less expressive -- some higher-order types excluded
- More flexible -- roles aren't in kinds

[1]: Weirich, Vytiniotis, Peyton Jones, Zdancewic. *Generative type abstraction and type-level computation.* POPL '11

Roles

Three roles:	examples:
• Nominal (n)	UhOh
• Representational (r)	Maybe, [], Either
• Phantom (p)	data Proxy a = P

instance (UhOh n) ≈ (UhOh n) -- redundant

instance $r_1 \approx r_2 \Rightarrow (\text{Maybe } r_1) \approx (\text{Maybe } r_2)$

instance Proxy $p_1 \approx$ Proxy p_2

- n parameter is unchanged
- r_1 and r_2 must be representationally equal
- no relationship between p_1 and p_2

Role Inference

Goal: Determine the most permissive yet safe role for type parameters

$$P > R > N$$

$(>) \equiv$ "more permissive than"

Algorithm: Find fixed point of propagating role restrictions

Nominal roots: type families, $(\sim)$, GADTs, ...

Representational roots: $(\to)$, ...

Type Safety

Proved progress and preservation using GHC’s typed intermediate language, System FC.

Discussion

Application

```
instance Num Int where ...
newtype Age = MkAge Int
  deriving Num
```

`Num Age` instance built from coerced methods of `Num Int` instance.

`GeneralizedNewtypeDeriving` (GND) is a long-standing feature of GHC, now safely reimplemented in terms of `coerce`.

Abstraction

Q: If `HTML ≈ String`, what happens to safety?

A: Allow newtype (un)wrapping instances only when constructor is in scope

Abstraction

- A `Map k v` maps keys `k` to values `v`
- Keys are ordered by `k`'s `Ord` instance
- `Map` is abstract -- its constructor is not in scope

Q: Should `Map Int String ≈ Map Int HTML`?

A: Yes!

Q: Should `Map String Int ≈ Map HTML Int`?

A: No -- What if `String`'s `Ord` is not `HTML`'s `Ord`?

Abstraction

```
data Map k v = MkMap [(k,v)]
```

The programmer should specify the roles:

```
type role Map nominal representational
```

The Default Debate

Preserve abstraction! Make roles default to nominal!

Be backward compatible! Allow GeneralizedNewtypeDeriving!

GHC 7.8 infers the most permissive roles.

Roles in the Wild

- Roles were included in the GHC dev build on Aug. 2, 2013.
- On Sept. 30, Bryan O'Sullivan did a study, trying to compile all of Hackage[1]
- 3,234 packages compiled with GHC 7.6.3
- Only 4 failed due to compile due to role restrictions around GND
- 3 of these 4 were legitimate bugs
- 1 was due to conservativity of roles

[1] See http://www.haskell.org/pipermail/ghc-devs/2013-September/002693.html

Trouble on the Horizon?

Proposed new `Monad` class:

```
class (...) ⇒ Monad m where
  ...
  join :: forall a. m (m a) → m a
```

Imagine

```
newtype Restr m a = MkR (m a)
  deriving Monad
```

Given: `Restr m a ≈ m a`

Wanted: `Restr m (Restr m a) ≈ m (m a)`

Trouble on the Horizon?

Given: `Restr m a ≈ m a`

Wanted: `Restr m (Restr m a) ≈ m (m a)`

⇑

`m (Restr m a) ≈ m (m a)`

⇑

???????

`m`’s parameter’s role might
be nominal, so we’re stuck!

Trouble on the Horizon?

Proposed solution: Track variable-parameter roles via typeclasses.

See https://ghc.haskell.org/trac/ghc/wiki/Roles2

Added Flexibility

Roles do not appear in a variable’s kind.

```
class Functor (f :: ★ → ★) where ...
instance Functor Maybe where ...
instance Functor UhOh where ...
```

This would not work with the
previous formulation of roles.

Conclusion

- Allowed for an efficient, safe way to make zero-cost abstractions truly free.
- Straightforward interface: `(≈)`/`Coercible`
- Implemented and released in GHC 7.8
- Explored interaction between type abstraction and other type features; these issues exist in other languages too (e.g. OCaml's variance annotations)

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breitner@kit.edu

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eir@cis.upenn.edu

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simonpj@microsoft.com

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