# Make It Purple

## An Introduction to Type Level Programming

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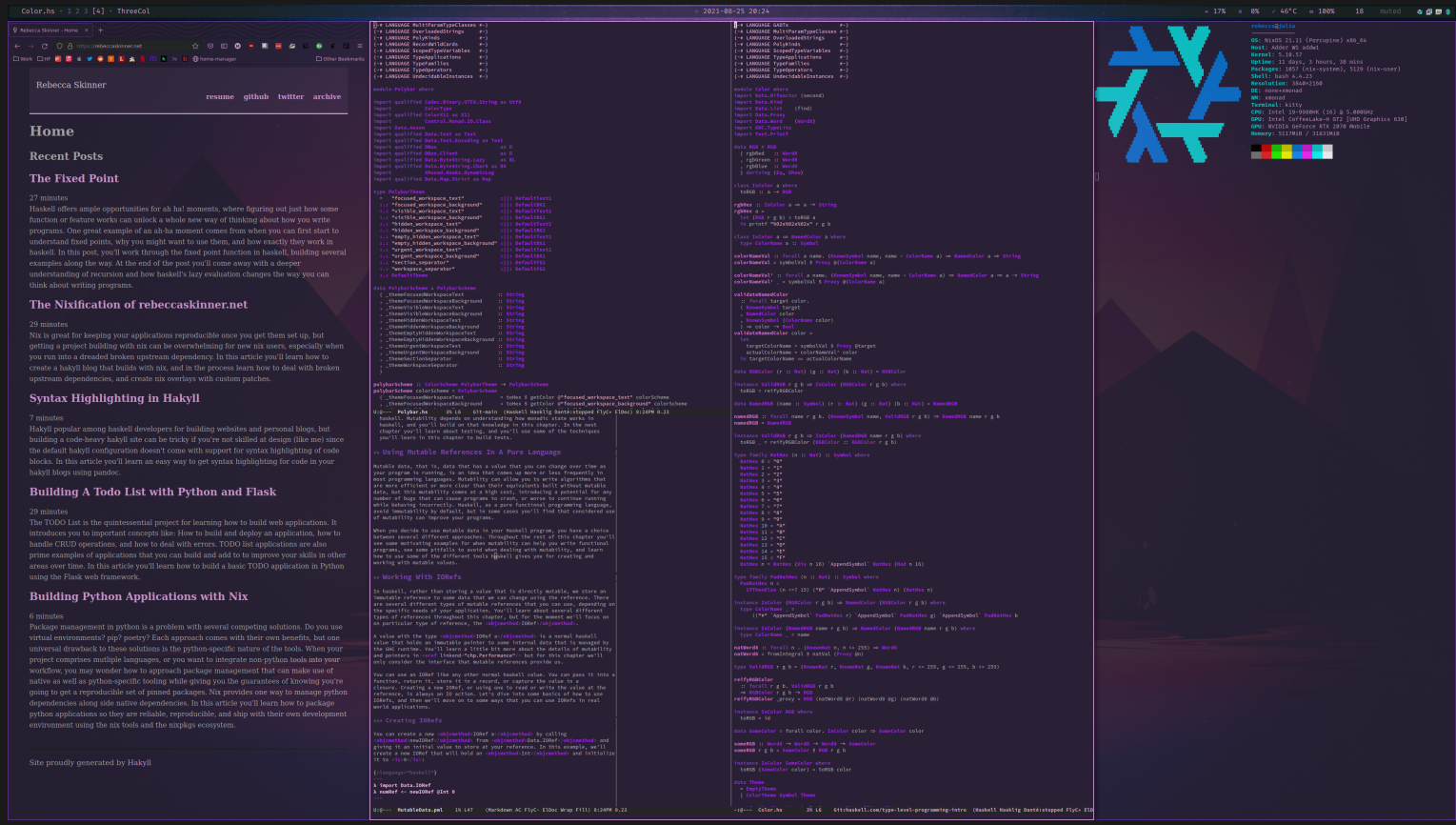
# Prelude

# Hello, World

- Rebecca Skinner: Me
- Mercury: My Employer (We're Hiring)
- The Ideas and Contents of this Talk: My Own
- Effective Haskell: My Book! (Est. late 2021 / early 2022)
- @cercerilla: Twitter
- Slides and Code: https://rebeccaskinner.net

# Building A Theming Engine for XMonad

# XMonad: Purple Edition



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polybarColorScheme = PolybarColorScheme
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  }
```

But now a change to our theme means changing every individual element.

```
stylishConfig :: XConfig a -> XConfig a
stylishConfig cfg = cfg
  { normalBorderColor  = "#dda0dd"
  , focusedBorderColor = "#2a2035"
  }
```

# With A Color Palette

One solution to allow us to uniformly change our color scheme would be to use a *color palette*.

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```haskell
data RGB = RGB
  { rgbRed   :: Word8
  , rgbGreen :: Word8
  , rgbBlue  :: Word8
  } deriving (Eq, Show)

type ColorPalette = Map Text RGB

defaultPalette = fromList $
  [ ("foreground", RGB 0x3a 0x20 0x35)
  , ("background", RGB 0xdd 0xa0 0xdd) ]
```

# Theming With A Color Palette

Now we can consistently reference colors by their name.

```
polybarColorScheme :: ColorPalette -> Maybe PolybarColorScheme
polybarColorScheme theme = PolybarColorScheme
  <$> theme !? "foreground"
  <*> theme !? "background"
  <*> theme !? "foreground"
  <*> theme !? "background"
```

# Missing Information

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2. We can't easily tell what parts of a palette are being used, making maintenance harder
3. We can't statically guarantee that our theme will work

Runtime errors can be painful when we're configuring a desktop environment, because it might mean that we have to fix everything from a terminal.

# Using The Type System To Improve Our Theming System

# Needs More Type System

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Let's look at how we can use the type system to help make our theming system easier to use.
Here's what we'd like to do:

- Ensure that the type of any function that uses theme elements tells what elements it uses
- Ensure that we can't pass a theme to a function if it's missing required elements

# But First, A Demo

Our `colorDemo` function lets us get colors from a `theme` by name. Instead of passing the color we want as a string, we're using *visible type applications* to pass in the color as a *type*.

```
{-# LANGUAGE TypeApplications #-}

colorDemo theme =
  let r = lookupColor @"red" theme
      g = lookupColor @"green" theme
      b = lookupColor @"blue" theme
  in show (r,g,b)
```

# But First, A Demo

The type of `colorDemo` can be inferred for us, and tells us exactly which colors must be available in our theme.

```
{-# LANGUAGE TypeApplications #-}

colorDemo
  :: ( HasColor "red" theme
     , HasColor "green" theme
     , HasColor "blue" theme )
  => ThemeInstance theme -> String
colorDemo theme =
  let r = lookupColor @"red" theme
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```

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```
newtype ThemeInstance                    =
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  deriving Show
```

# A Theme Instance With Phantom Types

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We can constrain `theme` by giving it a *Kind Signature*. Here we're saying the kind of `theme` must be `Theme`.

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```

# How Kind of You

When we're programming at the value level, we tend to think in terms of *types* and *values*. A type has *inhabitants* that are plain haskell values. For example, the `Bool` type has two inhabitants: `True` and `False`.

# How Kind of You

When we're programming at the value level, we tend to think in terms of *types* and *values*. A type has *inhabitants* that are plain haskell values. For example, the `Bool` type has two inhabitants: `True` and `False`. A kind is analogous to a type, but where the inhabitants of a type are values, the inhabitants of a kind are types. In other words, *kinds are the types of types*.

# Defining A Theme At The Type Level

# What Is a Theme?

We said that `ThemeInstance` has a phantom type parameter with the kind `Theme`, but what is a `Theme` anyway?

- A collection of colors

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- A collection of colors
- Known at compile time
- Identifiable with a name like *"red"* or *"foreground"*

# Colors At The Type Level

A `Theme` is a collection of type-level colors, so we need to define what a color looks like at the type level.

# Theme Elements By Name

We want to refer to theme elements by name (*"red"*, *"green"*, *"blue"*).
We could define types for all the colors:

```
data Red
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data Blue
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But what a pain! We could try to enumerate every named color, but it would be a nightmare. Instead, let's use *type-level strings*

# Symbolism

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`KnownSymbol` is a typeclass that let's us get a string from a symbol.

```
> symbolVal $ Proxy @"green"
"green"
> :t symbolVal
symbolVal :: KnownSymbol n => proxy n -> String
```

# A Theme Of Many Colors

Great. But we want a *Theme* not a single color.

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```
type Theme = [Symbol]
```

# Checking The Colors In A Theme

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```
lookupColor
  :: forall colorName theme.
  ( KnownSymbol colorName
  , HasColor colorName theme)
  => ThemeInstance theme
  -> RGB
```

# Implementing HasColor

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We'll call the recursive case if the head of the theme isn't what we want.

```
instance                          (HasColor color colors)
  => HasColor color (currentColor : colors)
```

# Dealing with Overlapping Instances

And now we have a problem.

- `color` and `color` are always the same.

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instance {-# OVERLAPPABLE #-} (HasColor color colors)
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# Dealing with Overlapping Instances

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- `color` and `color` are always the same.
- `color` and `currentColor` might be the same.

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# Getting A Theme Element

`HasColor` Accomplished. Let's get colorful.

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```haskell
lookupColor
  :: forall colorName theme.
  ( KnownSymbol colorName
  , HasColor colorName theme)
  => ThemeInstance theme -> RGB
lookupColor (ThemeInstance colors) =
  let
    targetName = symbolVal $ Proxy @colorName
  in colors Map.! targetName
```

# Demo

```haskell
demoThemeInstance :: ThemeInstance ["red","green","blue"]
demoThemeInstance = ThemeInstance . Map.fromList $
  [("red", RGB 0xff 0x00 0x00)
  ,("green", RGB 0x00 0xff 0x00)
  ,("blue", RGB 0x00 0x00 0xff)]
```

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We succeed when we should.

```
> lookupColor @"red" demoThemeInstance
RGB {rgbRed = 255, rgbGreen = 0, rgbBlue = 0}
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We succeed when we should.

```
> lookupColor @"red" demoThemeInstance
RGB {rgbRed = 255, rgbGreen = 0, rgbBlue = 0}
```

More importantly, we fail when we should.

```
> lookupColor @"yellow" demoThemeInstance

<interactive>:80:1: error:
    • No instance for (HasColor "yellow" '[])
        arising from a use of ‘lookupColor’
    • In the expression: lookupColor @"yellow" demoThemeInstance
      In an equation for ‘it’:
          it = lookupColor @"yellow" demoThemeInstanc
```

# Building A Better Theme Instance

# Mind The Gap

```
> :t demoThemeInstance
demoThemeInstance :: ThemeInstance ["red","green","blue"]

> lookupColor @"blue" demoThemeInstance
  *** Exception: Map.!: given key is not an element in the map
  CallStack (from HasCallStack):
    error, called at
      libraries/containers/containers/src/Data/Map/Internal.hs:627:17
      in containers-0.6.2.1:Data.Map.Internal
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# Mind The Gap

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But we don't always fail when we should

# An Instance of Weakness

What happened?

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demoThemeInstance :: ThemeInstance ["red","green","blue"]
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```

# Fixing The Problem

We need to construct the theme and the value at the same time.

# Colors At The Type Level: Part 2

Our goal: Capture all of the relevant information about a color at compile time.

# X11 Colors At The Type Level

We can build a type-level color pallet with X11 colors.

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data RebeccaPurple = RebeccaPurple
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And we're still limited to a fixed palette of colors.

# Type Level RGB

What if RGB, but at the type level?

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```
data RGBColor (r :: Nat) (g :: Nat) (b :: Nat) = RGBColor
```

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We still need to get a runtime representation of color.

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```haskell
class IsColor a where
  toRGB :: a -> RGB

instance IsColor RGB where
  toRGB = id

instance IsColor RebeccaPurple where
  toRGB = const $ RGB 0x66 0x33 0x99
```

# The RGB Problem

```
toRGB (RGBColor @975 @2148 @8)
```

# Making an `RGBColor` Type Into a Runtime Value

Ok, how about only valid RGB Colors are colors?

# Making an `RGBColor` Type Into a Runtime Value

Ok, how about only valid RGB Colors are colors?
We can use `ConstraintKinds` to create an alias for this set of constraints:

```
type ValidRGB r g b =
  ( KnownNat r, KnownNat g, KnownNat b
  , r <= 255, g <= 255, b <= 255)
```

# Converting an RGBColor Into A Runtime RGB Value

```
instance ValidRGB r g b => IsColor (RGBColor r g b) where
  toRGB _ = RGB (natWord8 @r) (natWord8 @g) (natWord8 @b)
```

# The RGBColor Problem

```
polybarColorScheme = PolybarColorScheme
  { focusedWorkspaceText         = RGBColor :: RGBColor 255 255 255
  , focusedWorkspaceBackground   = RGBColor :: RGBColor 0 0 0
  --- more like this
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Remind you of anything?

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# The Hardest Problem in Computer Science

The next in a series of problems

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# The Hardest Problem in Computer Science

The next in a series of problems

- We've got type level names for colors: `Symbol`
- We've got type level colors: `RGBColor`
- We've got no way to connect them together

# Type Families

We need a function from `RGBColor r g b` to `Symbol`

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We need a function from `RGBColor r g b` to `Symbol` A function

between types is called a Type Family

# Creating A Type Family For Color Names

```
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  type ColorName a :: Symbol
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`ColorName` is an *associated type family*

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```haskell
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```

ColorName is an *associated type family*

```haskell
colorNameVal :: forall a. KnownSymbol (ColorName a) => String
colorNameVal = symbolVal $ Proxy @(ColorName a)
```

# Simple NamedColor Instances

Creating a named color for the colors in our color palet is easy.

```
instance NamedColor RebeccaPurple where
  type ColorName RebeccaPurple = "RebeccaPurple"
```

# When In Doubt, Hardcode It

To name an RGBColor, we just give it a name:

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To name an RGBColor, we just give it a name:

```
data NamedRGB (name :: Symbol) (r :: Nat) (g :: Nat) (b :: Nat) = NamedRGB

instance ValidRGB r g b => IsColor (NamedRGB name r g b) where
  toRGB _ = toRGB $ (RGBColor :: RGBColor r g b)

instance IsColor (NamedRGB name r g b)
  => NamedColor (NamedRGB name r g b) where

  type ColorName _ = name
```

# Renaming Things Is An Even Harder Problem

But we really should support naming `RGBColor` too:

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But we really should support naming `RGBColor` too:

```
 colorNameVal @(RGBColor 0 190 239)
"#00BEEF"
```

# Hexing The Type Families

`NatHex` is a *Closed Type Family* from `Nat` to `Symbol`

# Casting Hexes

```haskell
type family NatHex (n :: Nat) :: Symbol where
  NatHex 0  = "0"
  NatHex 1  = "1"
  NatHex 2  = "2"
  -- And so on
  NatHex 14 = "E"
  NatHex 15 = "F"
  NatHex n = NatHex (Div n 16) `AppendSymbol` NatHex (Mod n 16)
```

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```

```
> :kind! NatHex 11
NatHex 11 :: Symbol
= "B"
> :kind! NatHex 250
NatHex 250 :: Symbol
= "FA"
```

# Padding, Part 1

Let's pad those numbers

```
if the number is less than 15:
  return "0" prepended to the stringified value
else:
  return the stringified value
```

# It's Looking Kind of Iffy

If it were only so easy. . .

# It's Looking Kind of Iffy

If it were only so easy...

```
type family IfThenElse (p :: Bool) (t :: a) (f :: a) where
  IfThenElse True t f = t
  IfThenElse False t f = f
```

# Bringing It All Together

```
type family PadNatHex (n :: Nat) :: Symbol where
  PadNatHex n =
    IfThenElse (n <=? 15) ("0" `AppendSymbol` NatHex n) (NatHex n)
```

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Using `PadNatHex` we can now also write an instance of `NamedColor` for plain `RGBColor` types:

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Using `PadNatHex` we can now also write an instance of `NamedColor` for plain `RGBColor` types:

```
instance IsColor (RGBColor r g b) => NamedColor (RGBColor r g b) where
  type ColorName _ =
    (("#" `AppendSymbol` PadNatHex r)
      `AppendSymbol` PadNatHex g
    ) `AppendSymbol` PadNatHex b
```

# Constructing A Theme Instance With `NamedColor`

# What's Old Is New Again

Let's make a well-typed theme at runtime.

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be called with *values*

# What's Old Is New Again

Let's make a well-typed theme at runtime. A runtime function needs to be called with *values* So we need A Function from Values to Types.

# MkTheme

A GADT is a function from a value to a type

```
data MkTheme theme where
  NewTheme :: MkTheme '[]
  AddColor :: (KnownSymbol (ColorName color), NamedColor color)
           => color
           -> MkTheme theme
           -> MkTheme (ColorName color : theme)
```

# MkTheme-ing A ThemeInstance

What we build up, we must tear down.

```
instantiateTheme :: MkTheme theme -> ThemeInstance theme
```

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What we build up, we must tear down.

```
instantiateTheme :: MkTheme theme -> ThemeInstance theme
instantiateTheme NewTheme = ThemeInstance Map.empty
instantiateTheme (AddColor color mkTheme') =
  let
    (ThemeInstance t) = instantiateTheme mkTheme'
    colorName = colorNameVal' color
    colorVal = SomeColor $ toRGB color
  in ThemeInstance $ Map.insert colorName colorVal t
```

# A MkTheme Demo

Let's try it out:

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```
sampleColorSet =
  instantiateTheme $
  AddColor (namedRGB @"red"   @255 @0   @0)   $
  AddColor (namedRGB @"green" @0   @255 @0)   $
  AddColor (namedRGB @"blue"  @0   @0   @255) $
  NewTheme

sampleThemer theme = show
  ( lookupColor @"red" theme
  , lookupColor @"green" theme
  , lookupColor @"blue" theme)
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```

```
> sampleThemer sampleColorSet
(RGB {rgbRed = 255, rgbGreen = 0,   rgbBlue = 0}
,RGB {rgbRed = 0,   rgbGreen = 255, rgbBlue = 0},
,RGB {rgbRed = 0,   rgbGreen = 0,   rgbBlue = 255})
```

# Generating A Runtime Theme Configuration

# Runtime Configuration

Users don't like to compile things. Let's make it work at runtime too.

# Runtime Configuration

Users don't like to compile things. Let's make it work at runtime too.

At the cost of some safety.

# theme.json

At least it's not YAML...

```
{
    "red": {"rgb": "#ff0000"},
    "green": {"rgb": "#00ff00"},
    "blue": {"x11": "AliceBlue"},
    "text": {"same-as": "blue"},
    "border": {"same-as": "text"}
}
```

# Defining The Theme Config Format

Another dictionary will solve things

```
newtype ThemeConfig = ThemeConfig
  {getThemeConfig :: Map.Map String ColorValue}
```

# Creating A Runtime Color Value

Sometimes things are easy

```
data ColorValue
  = RGBValue RGB
  | X11Value SomeColor
```

# Creating A Runtime Color Value

Sometimes things are easy

```
data ColorValue
  = RGBValue RGB
  | X11Value SomeColor
```

And sometimes they are hard: What about references?

# Reader References

Let's use monad transformers for some reason.

```
newtype ColorReference r a =
  ColorReference {unColorReference :: ExceptT String (Reader r) a}
  deriving newtype (Functor, Applicative, Monad, MonadReader r)

  data ColorValue
    = RGBValue RGB
    | X11Value SomeColor
    | OtherColor (ColorReference ThemeConfig ColorValue)
```

# The Reader Problem

This kind of sucks.

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This kind of sucks.

- Using reader might fail
- And it might not fail immediately
- And it's not very ergonomic

# Strictly Evaluating A Color Value

Is this *Strict Haskell* ?

```haskell
data StrictColorValue
  = StrictRGBValue RGB
  | StrictX11Value SomeColor
  | StrictOtherColor StrictColorValue

strictlyEvaluateColorValue :: ColorValue -> Either String StrictColorValue
```

# Custom Reader References

Let's try it agian without gratuitious duplication.

# The Higher-Kinded Data Pattern

```haskell
type family HKD (wrapper :: Type -> Type) (value :: Type) :: Type where
  HKD Identity value = value
  HKD wrapper value = wrapper value
```

# Using Higher-Kinded Data Improve `ColorValue`

Using HKD is easy, if a little odd looking.

```
data ColorValue w
  = RGBValue RGB
  | X11Value SomeColor
  | OtherColor (HKD w (ColorValue w))
```

# Updating ThemeConfig

Better parameterize `ThemeConfig` too or we've just moved the problem around.

```
newtype ThemeConfig w = ThemeConfig
  {getThemeConfig :: Map.Map String (ColorValue w)}
```

# Infinite Failure

```
newtype ThemeConfig w = ThemeConfig
  {getThemeConfig :: Map.Map String (ColorValue w)}
```

If a `ColorValue` References a theme config, the type of `w` must be:

# Infinite Failure

```
newtype ThemeConfig w = ThemeConfig
  {getThemeConfig :: Map.Map String (ColorValue w)}
```

If a `ColorValue` References a theme config, the type of `w` must be:

```
ColorValue (ColoreReference (ThemeConfig (ColorReference (ThemeConfig ...
```

# Wrapping Up The Theme Config

This is a problem we *can* solve by just not looking at it.

```
newtype ThemeConfig' w = ThemeConfig'
  {getThemeConfig :: Map.Map String (ColorValue w)}

type ThemeConfig = ThemeConfig' Identity

newtype RawThemeConfig = RawThemeConfig
  { getRawThemeConfig :: ThemeConfig' (ColorReference RawThemeConfig) }
```

# Evaluating The ThemeConfig

Strictly evaluating our references is looking a lot better now

```
evalConfig :: RawThemeConfig -> Either String ThemeConfig
evalConfig = undefined
```

# ThemeConfig Demo

```
> loadThemeConfig "../theme.json"
ThemeConfig'
  {getThemeConfig = fromList
    [ ("blue",X11Value RGB {rgbRed = 240, rgbGreen = 248, rgbBlue = 255})
    , ("border",OtherColor (OtherColor (X11Value RGB {rgbRed = 240, rgbGreen =
    , ("green",RGBValue (RGB {rgbRed = 0, rgbGreen = 255, rgbBlue = 0}))
    , ("red",RGBValue (RGB {rgbRed = 255, rgbGreen = 0, rgbBlue = 0}))
    , ("text",OtherColor (X11Value RGB {rgbRed = 240, rgbGreen = 248, rgbBlue =
```

# Integrating The Runtime and Type Level Theming Systems

# Bringing It All Together

- We have typesafe theme configuration.
- And a way to load a theme at runtime.
- Again, let's make these work together.

# Theme Validation

Validation is a function from a type-level `Theme` to a value-level `ThemeInstance`

Functions from types to values are *type classes* so let's start there.

# Theme Validation

Validation is a function from a type-level `Theme` to a value-level `ThemeInstance`

Functions from types to values are *type classes* so let's start there.

```
class ValidateThemeInstance (theme :: Theme) (a :: Theme -> Type) where
  validateThemeInstance :: Map String SomeColor -> Either String (a theme)

instance ValidateThemeInstance '[] ThemeInstance where
  validateThemeInstance theme = Right (ThemeInstance theme)
```

# Stepping Through Theme Validation

```haskell
instance ( KnownSymbol currentColor
         , ValidateThemeInstance rest ThemeInstance
         ) => ValidateThemeInstance (currentColor:rest) ThemeInstance where
  validateThemeInstance theme =
    let targetColor = symbolVal $ Proxy @currentColor
    in case Map.lookup targetColor theme of
      Nothing ->
        let colorName = symbolVal $ Proxy @currentColor
        in Left $ "missing color: " <> colorName
      Just _ -> do
        (ThemeInstance m) <- validateThemeInstance @rest theme
        pure $ ThemeInstance m
```

# Runtime Theme Config Demo

Let's look at how we can use this in a real program

```
type RuntimeTheme = ["blue", "green", "red"]
validateThemeConfig
  :: forall (theme :: Theme).
     ValidateThemeInstance theme ThemeInstance
  => ThemeConfig
  -> Either String (ThemeInstance theme)
validateThemeConfig =
  validateThemeInstance . Map.map SomeColor . getThemeConfig

testQuery :: FilePath -> IO ()
testQuery p = do
  cfg <- loadThemeConfig p
  let
    sampleQuery t = (lookupColor @"red" t, lookupColor @"blue" t)
    r = sampleQuery <$> validateThemeConfig @RuntimeTheme cfg
  print r
```

# Questions