Simply Typed Lambda Calculus

From Untyped to Simply Typed Lambda Calculus

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Dream IT
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Untyped Lambda Calculus

Untyped Lambda Calculus - Recapitulation

We can boil down computation to a tiny calculus

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All we need is:

- Function Definition / Abstraction ($\lambda x.e$)
- Function Application ($e\ e$)
- Parameters / Variables (x)

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- Function Definition / Abstraction ($\lambda x.e$)
- Function Application ($e\ e$)
- Parameters / Variables (x)

Then we get:

- Booleans
- Numerals
- Data Structures
- Control Flow
- ...

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- Function Application (e e)
- Parameters / Variables (x)

Then we get:

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- Numerals
- Data Structures
- Control Flow
- ...

Turing Completeness

- If it can be computed, it can be computed in Lambda Calculus!

Example - $(\lambda p.\lambda q.p)\ a\ b$

$$(\lambda p. \qquad \lambda q.p \qquad) \qquad a \qquad b$$

Meaning

$\lambda p.\lambda q.p$ Is a function that returns a function $(\lambda q.p)$

a, b Some variables (defined somewhere else)

p Is a variable that is bound to the parameter with the same name

Example - $(\lambda p.\lambda q.p)\ a\ b$

$$(\lambda p. \quad \lambda q.p \quad) \quad a \quad b \qquad \text{Substitute } p \mapsto a$$

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$(\lambda p.$	$\lambda q.p$	$)$	a	b	Substitute $p \mapsto a$
$($	$\lambda q.a$	$)$		b	

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$($	a	$)$			

Meaning

$\lambda p.\lambda q.p$ Is a function that returns a function $(\lambda q.p)$

a, b Some variables (defined somewhere else)

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Let's build an interpreter

- Deepen our intiution
- Later move on to the *Simply Typed Lambda Calculus*
    - Why do we need types?
    - How does a type checker work?
    - How does it restrict the programs we might write?
- We'll do *Math Driven Development*
    - Look at the concepts in math first, then translate them to Haskell

Structure

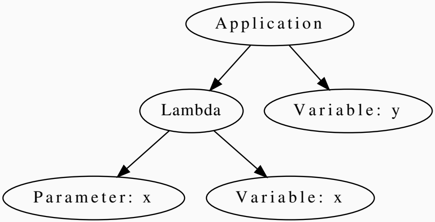
$e ::=$	Expressions:
x	Variable
$\lambda x.e$	Abstraction
$e\ e$	Application

$\lambda x.e$ Function Definition

$e\ e$ Function Application (Function Call)

Abstract Syntax Tree

$(\lambda x.x)\ y$



Meaning:

- Identity function $(\lambda x.x)$ is applied to a variable (y)

Interpreter - Syntax

```haskell
module UntypedSyntax where

type Name = String

data Expr                    -- e ::=        Expressions:
  = Var Name                 --       x        Variable
  | Lambda Name              --       λx.e     Abstraction
           Expr
  | App Expr                 --       e e      Application
        Expr
  deriving (Eq, Show)
```

Interpreter - Syntax - Examples

```haskell
module UntypedSyntaxExamples where

import UntypedSyntax

-- id ≡ λx.x
id :: Expr
id = Lambda "x" $ Var "x"
```

Interpreter - Syntax - Examples

```haskell
module UntypedSyntaxExamples where

import UntypedSyntax

-- id ≡ λx.x
id :: Expr
id = Lambda "x" $ Var "x"
```

```haskell
-- true ≡ λp.λq.p
true :: Expr
true = Lambda "p" (Lambda "q" (Var "p"))

-- false ≡ λp.λq.q
false :: Expr
false = Lambda "p" (Lambda "q" (Var "q"))
```

Interpreter - Syntax - Examples

```haskell
-- and ≡ λp.λq.p q p
and :: Expr
and = Lambda "p" $ Lambda "q" $ App (App (Var "p") (Var "q")) (Var "p")
```

Natural Deduction

Notation

$$\frac{}{\mathit{Axiom}} \quad \text{(A1)}$$

$$\frac{\mathit{Antecedent}}{\mathit{Conclusion}} \quad \text{(A2)}$$

Meaning:

Axiom Rule without Precondition

Antecedent Precondition - if it's fulfilled this rule applies.

Conclusion What follows from this rule.

A1, A2 Names for the rules

Proof: 2 is a Natural Number

$$\frac{}{0 : \texttt{Nat}} \qquad \text{(A1)}$$

$$\frac{n : \texttt{Nat}}{\texttt{succ}(n) : \texttt{Nat}} \qquad \text{(A2)}$$

Meaning:

- **A1** 0 is a natural number (by definition)
- **A2** The successor of a natural number is a natural number

Proof: 2 is a Natural Number

$$\frac{}{0 : \texttt{Nat}} \quad \text{(A1)}$$

$$\frac{n : \texttt{Nat}}{\texttt{succ}(n) : \texttt{Nat}} \quad \text{(A2)}$$

$$\dfrac{\dfrac{\dfrac{}{0 : \mathit{Nat}}\ \text{(A1)}}{\mathit{succ}(0) : \mathit{Nat}}\ \text{(A2)}}{\mathit{succ}(\mathit{succ}(0)) : \mathit{Nat}}\ \text{(A2)}$$

Meaning:

A1 0 is a natural number (by definition)

A2 The successor of a natural number is a natural number

$\rightarrow$ Thus the successor of the successor of 0 (2) must be a natural number

Evaluation Rules

Evaluation Rules - Call by Value - E-App1

$$\frac{e_1 \rightarrow e_1'}{e_1\, e_2 \rightarrow e_1'\, e_2} \qquad \text{E-App1}$$

Meaning:

- Under the condition that e_1 can be reduced further, do it.

Evaluation Rules - E-App1 - Example

$$\frac{e_1 \to e_1'}{e_1\, e_2 \to e_1'\, e_2}$$

Example

$$\overbrace{((\lambda x.x)\ (\lambda y.y))}^{e_1}\ e_2$$

Evaluation Rules - E-App1 - Example

$$\frac{e_1 \to e_1'}{e_1\, e_2 \to e_1'\, e_2}$$

Example

$$\overbrace{((\lambda x.x)\ (\lambda y.y))}^{e_1}\ e_2$$

Evaluation Rules - E-App1 - Example

$$\frac{e_1 \to e_1'}{e_1\, e_2 \to e_1'\, e_2}$$

Example

$$\overbrace{((\lambda x.x)\ (\lambda y.y))}^{e_1}\ e_2$$

$$\to (\lambda y.y)\ z$$

Evaluation Rules - Call by Value - E-App2

$$\frac{e_2 \to e_2'}{v_1\, e_2 \to v_1\, e_2'} \qquad \text{E-App2}$$

Meaning:

- Under the condition that e_2 can be reduced further and v_1 is a value, do it.
- "Bare" Untyped Lambda Calculus:
  - Only Lambdas (functions) are values.
  - But you can add Ints, Booleans, etc. ("Enriched Untyped Lambda Calculus")

Evaluation Rules - E-App2 - Example

$$\frac{e_2 \rightarrow e_2'}{v_1\, e_2 \rightarrow v_1\, e_2'} \qquad \text{E-App2}$$

Example

$$\overbrace{(\lambda x.x)}^{v_1}\ \overbrace{((\lambda y.y)\ 42)}^{e_2}$$

Evaluation Rules - E-App2 - Example

$$\frac{e_2 \rightarrow e_2'}{v_1\, e_2 \rightarrow v_1\, e_2'} \qquad \text{E-App2}$$

Example

$$\overbrace{(\lambda x.x)}^{v_1}\ \overbrace{((\lambda y.y)\ 42)}^{e_2}$$

Evaluation Rules - E-App2 - Example

$$\frac{e_2 \to e_2'}{v_1\, e_2 \to v_1\, e_2'} \qquad \text{E-App2}$$

Example

$$\overbrace{(\lambda x.x)}^{v_1}\ \overbrace{((\lambda y.y)\ 42)}^{e_2}$$

$$\to (\lambda x.x)\ 42$$

Evaluation Rules - Call by Value - E-AppLam

$$(\lambda x.e)v \rightarrow [x/v]e \qquad \text{E-AppLam}$$

Meaning:

- If a lambda (function) is applied to a value, substitute that value for it's parameter.
- "substitute" : replace it for every occurence in the lambda's body

Evaluation Rules - E-AppLam -Example

$$(\lambda x.e)v \to [x/v]e \qquad \text{E-AppLam}$$

Example

$$(\lambda x.\lambda y.x)\ z$$

Evaluation Rules - E-AppLam -Example

$$(\lambda x.e)v \rightarrow [x/v]e \qquad \text{E-AppLam}$$

Example

$$(\lambda x.\lambda y.x)\ z$$

Evaluation Rules - E-AppLam -Example

$$(\lambda x.e)v \to [x/v]e \qquad \text{E-AppLam}$$

Example

$$(\lambda x.\lambda y.x)\ z$$
$$\to \lambda y.z$$

Interpreter - Evaluation

```haskell
module UntypedEval where

import UntypedSyntax

eval :: Expr -> Expr
-- No rule for variables
eval variable@(Var _) = variable
-- No rule for lambdas
eval lambda@(Lambda _ _) = lambda
```

Interpreter - Evaluation

```haskell
eval (App e1 e2)
--
-- $\frac{e_1 \rightarrow e_1'}{e_1\, e_2 \rightarrow e_1'\, e_2} \quad (E-App1)$
--
 =
  let e1' = eval e1
--
-- $\frac{e_2 \rightarrow e_2'}{v_1\, e_2 \rightarrow v_1\, e_2'} \quad (E-App2)$
--
   in let e2' = eval e2
       in case e1'
               of
--
-- $(\lambda x.e) v \rightarrow [x/v] e \quad (E-AppLam)$
--
            (Lambda name e1'_body) -> eval $ substitute name e2' e1'_body
            e1' -> App e1' e2'
```

Interpreter - Substitution

```haskell
substitute :: Name -> Expr -> Expr -> Expr
--
-- If the Name matches: Substitute this Var by it's substitution
-- Otherwise: Leave it as is
--
substitute name substitution var@(Var varName)
  | name  == varName = substitution
  | otherwise = var
--
-- Recursively substitute in both parts of Applications
--
substitute name substitution (App term1 term2) =
  App (substitute name substitution term1) (substitute name substitution term2)
```

Interpreter - Substitution

```haskell
--
-- Only substitute in Lambda's body, if the parameter doesn't
-- redefine the Name in it's scope
--
substitute name substitution (Lambda varName term) =
  if name == varName
    then Lambda varName term
    else Lambda varName (substitute name substitution term)
```

Tests

```
module UntypedEvalExamplesSpec where

import NaiveUntypedEval
import Prelude hiding (and)
import Test.Hspec
import UntypedSyntax
import UntypedSyntaxExamples

main :: IO ()
main = hspec spec

spec :: Spec
spec =
  describe "eval" $
    it "should evaluate these terms"  $ do
--
-- a → a
--
      eval (Var "a") `shouldBe` Var "a"
```

Tests

```
--
-- true ≡ λp.λq.p
--
-- true a b → a
--
    eval (App (App true (Var "a")) (Var "b")) `shouldBe` Var "a"
```

```
--
-- false ≡ λp.λq.q
--
-- and ≡ λp.λq.p q p
--
-- and true false → false
--
    eval (App (App and true) false) `shouldBe`
      Lambda "p" (Lambda "q" (Var "q"))
```

Simply Typed Lambda Calculus

Structure

$$
\begin{aligned}
e ::= & & \text{Expressions:} \\
& x & \text{Variable} \\
& \lambda x : \tau . e & \text{Abstraction} \\
& e\ e & \text{Application}
\end{aligned}
$$

τ Type of the parameter x

- `Bool`, `Int`, …

What's a Type?

A Type is a set of values that an expression may return:

Bool	True, False
Int	$[-2^{29}..2^{29}-1]$ (in Haskell, 'Data.Int')

Simple types don't have parameters, no polymorphism:

`Bool`, `Int`	have no parameters $\rightarrow$ simple types
`Maybe a`	takes a type parameter (*a*) $\rightarrow$ not a simple type
`a -> a`	is polymorphic $\rightarrow$ not a simple type

Type Safety = Progress + Preservation

Progress : If an expression is well typed then either it is a value, or it can be further evaluated by an available evaluation rule.

- A well typed (typable) program never gets "stuck".

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Progress : If an expression is well typed then either it is a value, or it can be further evaluated by an available evaluation rule.

- A well typed (typable) program never gets "stuck".

Preservation : If an expression e has type τ, and is evaluated to e', then e' has type τ.

- $e \equiv (\lambda x : Int.x)1$ and $e' \equiv 1$ have both the same type: `Int`

Not all meaningful Programs can be type checked

```haskell
id :: a -> a
id a = a
```

- It strongly depends on the type system if this is allowed or not.
- In Simply Typed Lambda Calculus it's not!
  - No polymorphic types ...

Evaluation

Evalution rules stay the same!

- Type checking is done upfront

Typing Rules - Variables

$$\frac{x : \sigma \in \Gamma}{\Gamma \vdash x : \sigma} \qquad \text{T-Var}$$

Meaning

Γ	The Typing Environment, a list of $(\mathit{Variable} : \mathit{Type})$ pairs (associations)
$x : \sigma \in \Gamma$	If (x, σ) is in the Typing Environment
$\Gamma \vdash x : \sigma$	x has type σ

Typing Rules - Variables - Example

$$\frac{x : \sigma \in \Gamma}{\Gamma \vdash x : \sigma} \qquad \text{T-Var}$$

Example

$$\underbrace{\lambda x : Int}_{\Gamma' = \Gamma, x : Int} . \underbrace{\lambda y : Bool}_{\Gamma'' = \Gamma', y : Bool} . \underbrace{x}_{\Gamma'' \vdash x : Int}$$

$\lambda x : Int$ Add $x : Int$ to the Typing Environment (Γ)

x We know from the Typing Environment (Γ'') that x has type Int

Typing Rules - Constants

$$\Gamma \vdash n : \text{Int} \qquad \text{T-Int}$$

$$\Gamma \vdash \text{True} : \text{Bool} \qquad \text{T-True}$$

$$\Gamma \vdash \text{False} : \text{Bool} \qquad \text{T-False}$$

Meaning

`True`, `False` literals / constants are of type `Bool`

n number literals / constants are of `Int`

Why do we need Γ here?

- We handle Type Constructors like variables
- Think: $\Gamma \equiv \emptyset, \mathit{True} : \mathit{Bool}, \mathit{False} : \mathit{Bool}, 0 : \mathit{Int}, 1 : \mathit{Int}, \ldots$

$$\Gamma \vdash \textsf{\textit{n}} : \textsf{Int} \qquad \text{T-Int}$$

$$\Gamma \vdash \textsf{True} : \textsf{Bool} \qquad \text{T-True}$$

Example

$$\Gamma \equiv \emptyset, \textit{True} : \textit{Bool}, \textit{False} : \textit{Bool}, 0 : \textit{Int}, 1 : \textit{Int}, \ldots$$

True

1

Typing Rules - Constants - Example

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$$\Gamma \equiv \emptyset, \mathit{True} : \mathit{Bool}, \mathit{False} : \mathit{Bool}, 0 : \mathit{Int}, 1 : \mathit{Int}, \ldots$$

True

1

Typing Rules - Lambdas

$$\frac{\Gamma, x : \tau_1 \vdash e : \tau_2}{\Gamma \vdash \lambda x : \tau_1 . e : \tau_1 \rightarrow \tau_2} \quad \text{T-Lam}$$

Meaning

Condition With $x : \tau_1$ in the Typing Environment, e has type τ_2

Conclusion $\lambda x : \tau_1 . e$ has type $\tau_1 \rightarrow \tau_2$

Because e has type τ_2 if x has type τ_1

Typing Rules - Lambdas - Example

$$\frac{\Gamma, x : \tau_1 \vdash e : \tau_2}{\Gamma \vdash \lambda x : \tau_1 . e : \tau_1 \to \tau_2} \quad \text{T-Lam}$$

Example

$$\lambda x : \overbrace{Int}^{\tau_1} . \overbrace{x}^{e} \qquad :?$$

Typing Rules - Lambdas - Example

$$\frac{\Gamma, x : \tau_1 \vdash e : \tau_2}{\Gamma \vdash \lambda x : \tau_1 . e : \tau_1 \to \tau_2} \qquad \text{T-Lam}$$

Example

$$\lambda x : \overbrace{Int}^{\tau_1} . \overbrace{x}^{e} \qquad :?$$

$$\frac{\Gamma, x : Int \vdash e : Int}{\Gamma \vdash \lambda x : Int . e : Int \to Int}$$

Typing Rules - Lambdas - Example

$$\frac{\Gamma, x : \tau_1 \vdash e : \tau_2}{\Gamma \vdash \lambda x : \tau_1 . e : \tau_1 \to \tau_2} \qquad \text{T-Lam}$$

Example

$$\lambda x : \overbrace{Int}^{\tau_1} . \overbrace{x}^{e} \qquad : \overbrace{Int}^{\tau_1} \to \overbrace{Int}^{\tau_2}$$

$$\frac{\Gamma, x : Int \vdash e : Int}{\Gamma \vdash \lambda x : Int . e : Int \to Int}$$

Typing Rules - Applications

$$\frac{\Gamma \vdash e_1 : \tau_1 \to \tau_2 \quad \Gamma \vdash e_2 : \tau_1}{\Gamma \vdash e_1 e_2 : \tau_2} \quad \text{T-App}$$

Meaning

Condition If e_1 is a function of type $\tau_1 \to \tau_2$ and e_2 has type τ_2

Conclusion Then the type of $e_1 e_2$ (function application) is τ_2

Typing Rules - Applications

$$\frac{\Gamma \vdash e_1 : \tau_1 \to \tau_2 \quad \Gamma \vdash e_2 : \tau_1}{\Gamma \vdash e_1 e_2 : \tau_2} \quad \text{T-App}$$

Meaning

Condition If e_1 is a function of type $\tau_1 \to \tau_2$ and e_2 has type τ_2

Conclusion Then the type of $e_1 e_2$ (function application) is τ_2

```
id' :: Int -> Int
id' i = i

1 :: Int
(id' 1) :: Int
```

Typing Rules - Applications - Example

$$\frac{\Gamma \vdash e_1 : \tau_1 \to \tau_2 \quad \Gamma \vdash e_2 : \tau_1}{\Gamma \vdash e_1 e_2 : \tau_2} \quad \text{T-App}$$

Example

$$\overbrace{(\lambda x : Int.True)}^{e_1}\ \overbrace{42}^{e_2} \qquad :?$$

Typing Rules - Applications - Example

$$\frac{\Gamma \vdash e_1 : \tau_1 \to \tau_2 \quad \Gamma \vdash e_2 : \tau_1}{\Gamma \vdash e_1 e_2 : \tau_2} \qquad \text{T-App}$$

Example

$$\overbrace{(\lambda x : \mathit{Int}.\mathit{True})}^{e_1}\overbrace{42}^{e_2} \qquad :$$

$$\frac{\Gamma \vdash \overbrace{(\lambda x : \mathit{Int}.\mathit{True})}^{e_1} : \overbrace{\mathit{Int} \to \mathit{Bool}}^{\tau_1 \to \tau_2} \quad \Gamma \vdash \overbrace{42}^{e_2} : \overbrace{\mathit{Int}}^{\tau_1}}{\Gamma \vdash \underbrace{(\lambda x : \mathit{Int}.\mathit{True})}_{e_1}\underbrace{42}_{e_2} : \underbrace{\mathit{Bool}}_{\tau_2}}$$

Typing Rules - Applications - Example

$$\frac{\Gamma \vdash e_1 : \tau_1 \rightarrow \tau_2 \quad \Gamma \vdash e_2 : \tau_1}{\Gamma \vdash e_1 e_2 : \tau_2} \qquad \text{T-App}$$

Example

$$\overbrace{(\lambda x : \mathit{Int}.\mathit{True})}^{e_1}\overbrace{42}^{e_2} \quad : \quad \overbrace{\mathit{Bool}}^{\tau_2}$$

$$\frac{\Gamma \vdash \overbrace{(\lambda x : \mathit{Int}.\mathit{True})}^{e_1} : \overbrace{\mathit{Int} \rightarrow \mathit{Bool}}^{\tau_1 \rightarrow \tau_2} \quad \Gamma \vdash \overbrace{42}^{e_2} : \overbrace{\mathit{Int}}^{\tau_1}}{\Gamma \vdash \underbrace{(\lambda x : \mathit{Int}.\mathit{True})}_{e_1}\underbrace{42}_{e_2} : \underbrace{\mathit{Bool}}_{\tau_2}}$$

Type Checker - Expressions

```haskell
module TypedSyntax where

import qualified Data.Map.Strict as Map

type Name = String
type Error = String

data Expr                  -- e ::=                    Expressions :
  = IntValue Int           --       [−2^29..2^29 − 1]        Integer Literal
  | BoolValue Bool         --       True | False             Boolean Literal
  | Var Name               --       x                        Variable
  | App Expr               --       e e                      Application
        Expr
  | Lambda Name            --       λx: τ.e                  Abstraction
           Type
           Expr
  deriving (Eq, Show)
```

Type Checker - Types

```haskell
type Environment = Map.Map Name Type

data Type                          -- τ ::=          Types :
  = TInt                           --      Int        Integer
  | TBool                          --      Bool       Boolean
  | TArr Type                      --      τ1 → τ2    Abstraction / Function
         Type
  deriving (Eq, Show)
```

Type Checker - Literals

```haskell
module TypedCheck where

import Data.Either.Extra
import qualified Data.Map.Strict as Map

import TypedSyntax

check :: Environment -> Expr -> Either Error Type
--
-- Γ ⊢ n : Int   (T-Int)
--
check _ (IntValue _) = Right TInt
--
-- Γ ⊢ True : Bool   (T-True)
--
check _ (BoolValue True) = Right TBool
--
-- Γ ⊢ False : Bool   (T-False)
--
check _ (BoolValue False) = Right TBool
```

Type Checker - Lambda Abstraction

```
--
-- Γ,x:τ1⊢e:τ2 / Γ⊢λx:τ1.e:τ1→τ2   (T-Lam)
--
check env (Lambda name atype e) = do
  t <- check (Map.insert name atype env) e
  return $ TArr atype t
```

$$\frac{\Gamma, x{:}\tau_1 \vdash e{:}\tau_2}{\Gamma \vdash \lambda x{:}\tau_1 . e{:}\tau_1 \to \tau_2} \quad \textit{(T-Lam)}$$

Type Checker - Application

```
--
-- \frac{\Gamma \vdash e_1 : \tau_1 \rightarrow \tau_2 \quad \Gamma \vdash e_2 : \tau_1}{\Gamma \vdash e_1\, e_2 : \tau_2}   (T-App)
--
check env (App e1 e2) = do
  t1 <- check env e1
  case t1 of
    (TArr ta1 ta2) -> do
      t2 <- check env e2
      if ta1 == t2
        then Right ta2
        else Left $ "Expected " ++ (show ta1) ++ " but got : " ++ (show t2)
    _ -> Left $ "Expected TArr but got : " ++ (show t1)
```

Type Checker - Variables

```haskell
--
-- x:σ∈Γ / Γ⊢x:σ   (T-Var)
--
check env (Var name) = find env name

find :: Environment -> Name -> Either Name Type
find env name = maybeToEither "Var not found!" (Map.lookup name env)
```

$$\frac{x:\sigma \in \Gamma}{\Gamma \vdash x:\sigma} \quad (\textit{T-Var})$$

Tests

```haskell
module TypedCheckExamplesSpec where

import Test.Hspec
import TypedCheck
import TypedSyntax

import qualified Data.Map.Strict as Map

main :: IO ()
main = hspec spec
```

Tests

```haskell
spec :: Spec
spec = do
  describe "check" $
    it "should type check these terms" $
--
-- (λx : Int.x) 42 :: Int
--
     do
      check Map.empty (App (Lambda "x" TInt (Var "x")) (IntValue 5))
        `shouldBe` Right TInt
```

```haskell
--
-- Does not type check: (λx : Bool.x) 42
--
      check Map.empty (App (Lambda "x" TInt (Var "x")) (IntValue 5))
        `shouldBe` Right TInt
```

Tests

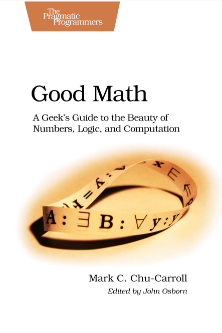
```haskell
--
-- Does not type check: 42 False
--
      check Map.empty (App (IntValue 42) (BoolValue False)) `shouldBe`
        Left "Expected TArr but got : TInt"
```

End

Thanks

- Hope you enjoyed this talk and learned something new.
- Hope it wasn't too much math and dusty formulas ... :)

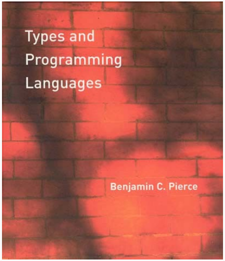
Good Math



A Geek's Guide to the Beauty of Numbers, Logic, and Computation

- Easy to understand

Types and Programming Languages



- Types systems explained by building interpreters / checkers and proving properties
- Very "mathematical", but very complete and self-contained

Write you a Haskell

Building a modern functional compiler from first principles.

- Starts with the Lambda Calculus and goes all the way down to a full Haskell compiler
- Available for free - Not finished, yet