Dependent Types Made Difficult

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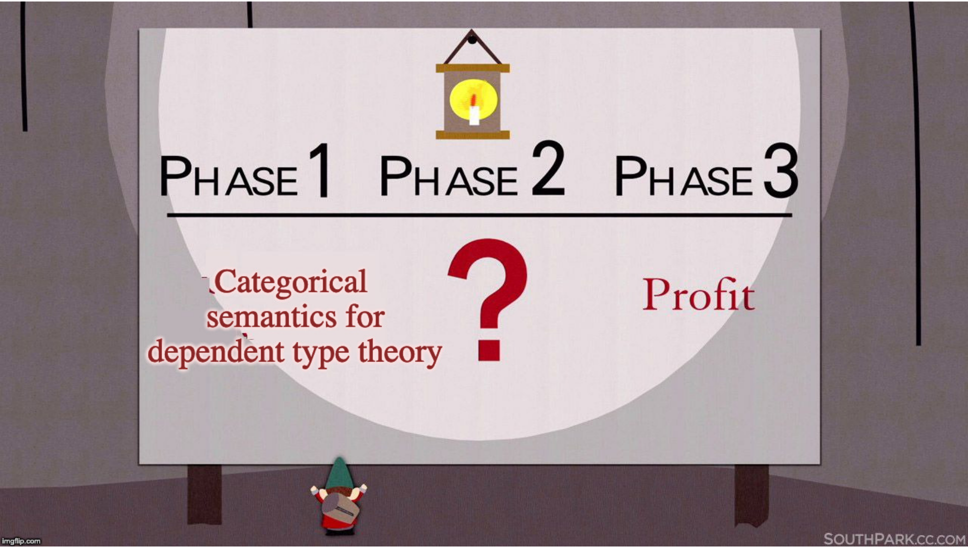
What is the categorical semantics of dependent type theory?


PHASE 1
PHASE 2
PHASE 3
Categorical semantics for dependent type theory
?
Profit
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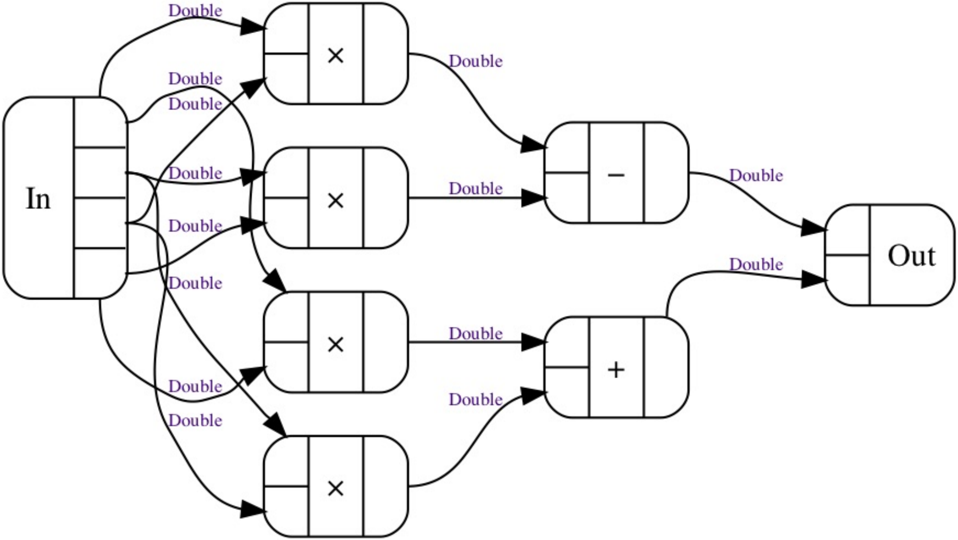
Compiling to Categories (Elliott, 2017)

Take in Haskell source and spit out . . .

Compiling to Categories (Elliott, 2017)

- computation graphs
  - diagrams
  - circuit descriptions (VHDL, Verilog)
- linear maps
- automatic differentiation
- incremental computation
- interval analysis
- Kleisli category for any monad e.g. probabilistic programming
- graphics (GLSL)
- syntax
- products of the above
- tons more . . . see https://github.com/conal/concat



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How does this work??

The simply-typed lambda calculus is the *internal language* of *Cartesian closed categories*.

which means

We can interpret the lambda calculus in any CCC.

Cartesian closed categories

A Cartesian closed category is a category with function objects.

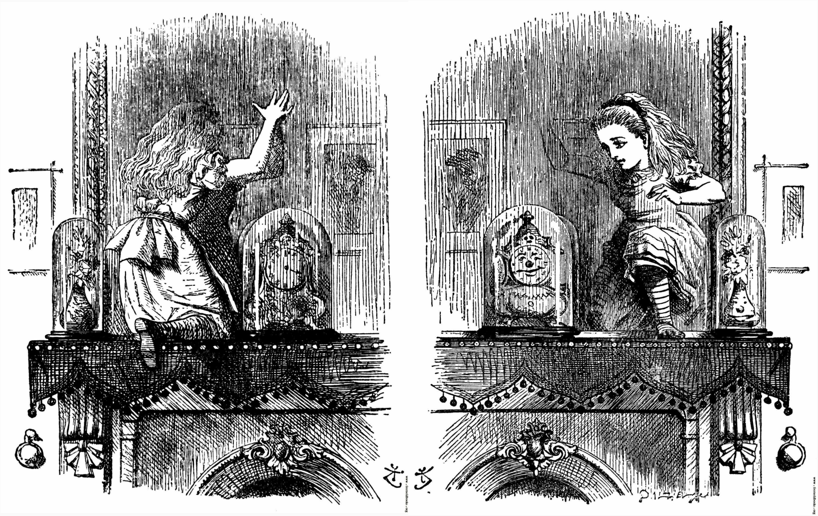
$$\mathcal{C}(A \times B, C) \cong \mathcal{C}(A, C^B)$$

In Haskell, this isomorphism is called "curry".

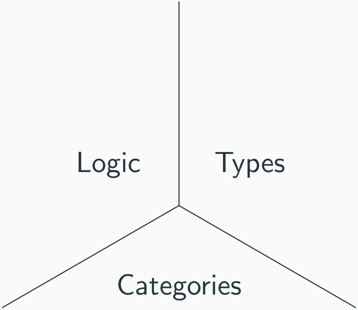
```
curry :: ((a,b) -> c) -> a -> b -> c
curry f a b = f (a, b)

uncurry :: (a -> b -> c) -> (a, b) -> c
uncurry f (a, b) = f a b
```

Categorical semantics

Curry-Howard correspondence



Curry-Howard-Lambek correspondence



Categorical semantics

$$\begin{tikzcd} \text{Type theories} \arrow[r, bend left, "\text{Syntactic category}"] \arrow[r, phantom, "\perp"] & \text{Categories} \arrow[l, bend left, "\text{Internal language}"] \end{tikzcd}$$

Advantages

- More easily prove properties about a type theory using CT
- CT proofs using the internal language can be easier
- Can use the internal language to define internal structures
- The CT can illuminate the TT, and vice versa
- The internal language is valid in every model

Adjunctions

Adjunctions

$$F \dashv U : \mathcal{C} \to \mathcal{D}$$

$$\begin{tikzcd} \mathcal{C} \arrow[r, bend left, "F"] \arrow[r, phantom, "\perp"] & \mathcal{D} \arrow[l, bend left, "U"] \end{tikzcd}$$

$$\mathcal{D}(Fc, d) \cong \mathcal{C}(c, Ud)$$

$$\frac{Fc \to d \text{ in } \mathcal{D}}{c \to Ud \text{ in } \mathcal{C}}$$

Example: free monoid

The free monoid on an alphabet Λ is the set Λ^* of words in Λ.

$$\frac{\Lambda^* \to m \text{ in } \mathbf{Mon}}{\Lambda \to m \text{ in } \mathbf{Set}}$$

Why?

A monoid homomorphism has to respect multiplication, so

$$f(abcd\cdots) = f(a)f(b)f(c)\cdots$$

Example: currying

The functor $- \times b$ is left adjoint to $(-)^b$.

$$\frac{a \times b \to c \text{ in } \textbf{Type}}{\overline{a \to c^b \text{ in } \textbf{Type}}}$$

```
curry :: ((a,b) -> c) -> a -> b -> c
curry f a b = f (a, b)

uncurry :: (a -> b -> c) -> (a, b) -> c
uncurry f (a, b) = f a b
```

Example: quantifiers $\exists_y \dashv w_y \dashv \forall_y$

$$w_y : \mathrm{Form}(\bar{x}) \to \mathrm{Form}(\bar{x}, y)$$
$$\phi(\bar{x}) \mapsto \phi(\bar{x})$$

$$\frac{\bar{x}, y \vdash w_y\phi(\bar{x}) \Rightarrow \psi(\bar{x}, y)}{\bar{x} \vdash \phi(\bar{x}) \Rightarrow \forall_y \psi(\bar{x}, y)}$$

$$\frac{\bar{x} \vdash \exists_y \psi(\bar{x}, y) \Rightarrow \phi(\bar{x})}{\bar{x}, y \vdash \psi(\bar{x}, y) \Rightarrow w_y\phi(\bar{x})}$$

Compiling to CCCs

- Categorical semantics for STLC in CCCs
- Lots of CCCs
- GHC Core's System FC can (mostly) be converted to STLC
- GHC plugin, rewrite rules
- Convert Haskell src to VHDL, diagrams, etc

There's more to type theory than STLC!

- polymorphic types
- existential types
- universal types
- type classes
- union and intersection types
- quotient types
- dependent types
- refinement types
- homotopy type theory
- ...

Dependent types

Dependent types

A dependent type is one that contains free variables.

$$\tau : \mathrm{Type} \quad x : \tau \vdash P(x) : \mathrm{Type}$$

It *depends on* terms.

Dependent types

$$n : \mathrm{Nat} \vdash \mathrm{IsEven}\, n : \mathrm{Type}$$

```
data IsEven (n : Nat) : Type where
ZEven : IsEven 0
SSEven : IsEven n -> IsEven (n + 2)
```

Dependent types

$$n : \mathrm{Nat}, a : \mathrm{Type} \vdash \mathrm{Vect}_n(a) : \mathrm{Type}$$

```
data Vect (n : Nat) (a : Type) : Type where
Nil : Vect 0 a
(::) : a -> Vect n a -> Vect (n + 1) a
```

Dependent product type

```
replicate : (n : Nat) -> a -> Vect n a
```

$$\begin{aligned}\text{replicate} : & \prod_{a:\text{Type}} \prod_{n:\mathbb{N}} \prod_{x:a} \text{Vect}_n(a) \\ = & \prod_{a:\text{Type}} \prod_{n:\mathbb{N}} a \to \text{Vect}_n(a)\end{aligned}$$

$$a \to b \equiv \prod_{\_:a} b$$

Dependent sum type

```
evenLenLists = (l : List Int ** m : Nat ** length l = 2 * m)
```

$$\text{evenLenLists} = \sum_{l : \text{List}(a)} \sum_{m : \mathbb{N}} \text{length}(l) = 2m$$

$$(a, b) \equiv \sum_{\_ : a} b$$

Dependent types are the internal language of *locally Cartesian closed categories*.

Semantics

Semantics

Objects: closed types

Arrows: terms in context

also arrows: functions

$$f : a \to b$$
$$[[f]] : [[a]] \to [[b]]$$

Semantics for dependent types

$$\begin{aligned}
\mathsf{IsEven} &: \mathbb{N} \to \mathbf{Set} \\
\mathsf{IsEven}\,0 &= \{\mathrm{zeroEven}\} \\
\mathsf{IsEven}\,1 &= \{\} \\
\mathsf{IsEven}\,2 &= \{\mathrm{twoEven}\} \\
\mathsf{IsEven}\,3 &= \{\} \\
\mathsf{IsEven}\,4 &= \{\mathrm{fourEven}\} \\
&\vdots
\end{aligned}$$

Semantics for dependent types

$$\mathsf{CustomerOf} : \mathsf{Bank} \to \mathbf{Set}$$

$$\mathsf{CustomerOf}\ \mathsf{ANZ} = \{\text{Alice, Albert, Anne-Marie}\}$$

$$\mathsf{CustomerOf}\ \mathsf{CBA} = \{\text{Calvin, Colin}\}$$

$$\mathsf{CustomerOf}\ \mathsf{NAB} = \{\text{Nathan}\}$$

$$\mathsf{CustomerOf}\ \mathsf{Westpac} = \{\text{Wendy, Will}\}$$

Thinking backwards

$$p : \mathsf{IsEven}\ \_ \to \mathbb{N}$$
$$p\ \mathit{zeroEven} = 0$$
$$p\ \mathit{twoEven} = 2$$
$$p\ \mathit{fourEven} = 4$$
$$\vdots$$

$$p : \mathsf{CustomerOf}\ \_ \to \mathsf{Bank}$$
$$p\ \mathrm{Alice} = \mathsf{ANZ}$$
$$p\ \mathrm{Albert} = \mathsf{ANZ}$$
$$p\ \mathrm{Anne\text{-}Marie} = \mathsf{ANZ}$$
$$p\ \mathrm{Calvin} = \mathsf{CBA}$$
$$p\ \mathrm{Colin} = \mathsf{CBA}$$
$$p\ \mathrm{Nathan} = \mathsf{NAB}$$
$$p\ \mathrm{Wendy} = \mathsf{Westpac}$$
$$p\ \mathrm{Will} = \mathsf{Westpac}$$

Thinking backwards

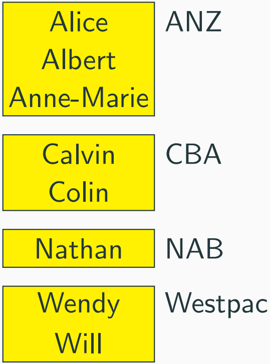
$$
\begin{aligned}
p &: \mathsf{IsEven}\ \_ \to \mathbb{N} \\
p\ \mathit{zeroEven} &= 0 \\
p\ \mathit{twoEven} &= 2 \\
p\ \mathit{fourEven} &= 4 \\
&\vdots
\end{aligned}
$$

Thinking backwards

$$
\begin{aligned}
p : \mathsf{CustomerOf}\ \_ &\to \mathsf{Bank} \\
p\,\mathrm{Alice} &= \mathsf{ANZ} \\
p\,\mathrm{Albert} &= \mathsf{ANZ} \\
p\,\mathrm{Anne\text{-}Marie} &= \mathsf{ANZ} \\
p\,\mathrm{Calvin} &= \mathsf{CBA} \\
p\,\mathrm{Colin} &= \mathsf{CBA} \\
p\,\mathrm{Nathan} &= \mathsf{NAB} \\
p\,\mathrm{Wendy} &= \mathsf{Westpac} \\
p\,\mathrm{Will} &= \mathsf{Westpac} \\
&\vdots
\end{aligned}
$$

Semantics for dependent types

$\mathbf{Set}/\mathbb{N}$



$\mathbf{Set}/\mathrm{Bank}$

Over-categories

$$X \in \mathcal{C}, \mathcal{C}/X$$

Objects:
$$\begin{tikzcd} A \arrow[d, "p"] \\ X \end{tikzcd}$$

fibre $(A)_x = p^{-1}x$ in **Set**

Arrows:
$$\begin{tikzcd} A \arrow[rr, "f"] \arrow[dr, "p"'] & & B \arrow[dl, "q"] \\ & X & \end{tikzcd}$$

section $s : X \to A$
such that $p \circ s = \mathrm{id}$

Over-categories

Alice Albert Anne-Marie	ANZ
Calvin Colin	CBA
Nathan	NAB
Wendy Will	Westpac

Artarmon Annandale Auburn	ANZ
Clovelly Curl Curl	CBA
Naremburn Nth Bondi	NAB
Wahroonga Woollahra	Westpac

fibre $(A)_x = p^{-1}x$

section $s : X \to A$ such that $p \circ s = \mathrm{id}$

Substitution

$$\text{bankOf} : \text{Branch} \to \text{Bank}$$

$$b : \text{Bank} \vdash \text{CustomerOf}\ b : \text{Type}$$

$$br : \text{Branch} \vdash \text{CustomerOf}(\text{bankOf}\ br) : \text{Type}$$

Alice Albert	Artarmon
	Annandale
Anne-Marie	Auburn
Calvin Colin	Clovelly
	Curl Curl
	Naremburn
Nathan	Nth Bondi
Will	Wahroonga
Wendy	Woollahra

$\vdots$

	"hello"
twoEven	"no"
eightEven	"icecream"
	"submarine"

$\vdots$

$$s : \mathsf{String} \vdash \mathsf{IsEven}(\mathsf{length}\, s) : \mathsf{Type}$$

Substitution = pullback aka change of base

$$\mathrm{bankOf} : \mathrm{Branch} \to \mathrm{Bank}$$

$$\mathrm{bankOf}^* : \mathbf{Set} \,/\, \mathrm{Bank} \to \mathbf{Set} \,/\, \mathrm{Branch}$$

Substitution = pullback aka change of base

$$
\begin{tikzcd}
T \arrow[drr, bend left, "f"] \arrow[dr, dashed, "\exists!" description] \arrow[ddr, bend right, "g"'] & & \\
& \mathrm{Branch} \times_{\mathrm{Bank}} \mathrm{Customer} \arrow[r] \arrow[d, "p^*"] & \mathrm{Customer} \arrow[d, "p"] \\
& \mathrm{Branch} \arrow[r, "\mathrm{bankOf}"] & \mathrm{Bank}
\end{tikzcd}
$$

$$
\begin{aligned}
\mathrm{Branch} \times_{\mathrm{Bank}} \mathrm{Customer} &= \mathrm{bankOf}^* \, \mathrm{Customer} \\
&= \{(br, c) | \mathrm{bankOf}(br) = p(c)\}
\end{aligned}
$$

Dependent sum

$$f : X \to Y$$

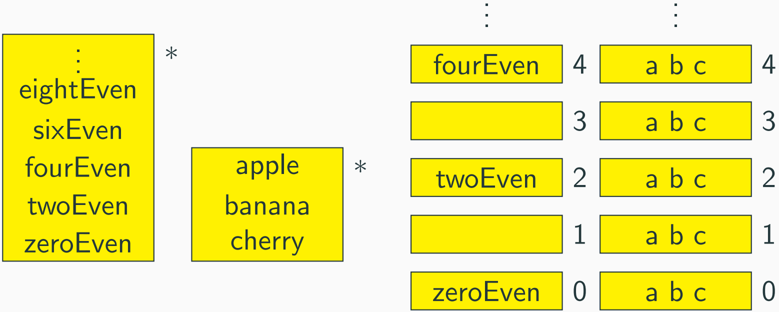
$$\sum_f : \mathbf{Set}/X \to \mathbf{Set}/Y$$

$$\begin{tikzcd} A \arrow[d, "p"] \\ X \arrow[d, "f"] \\ Y \end{tikzcd}$$

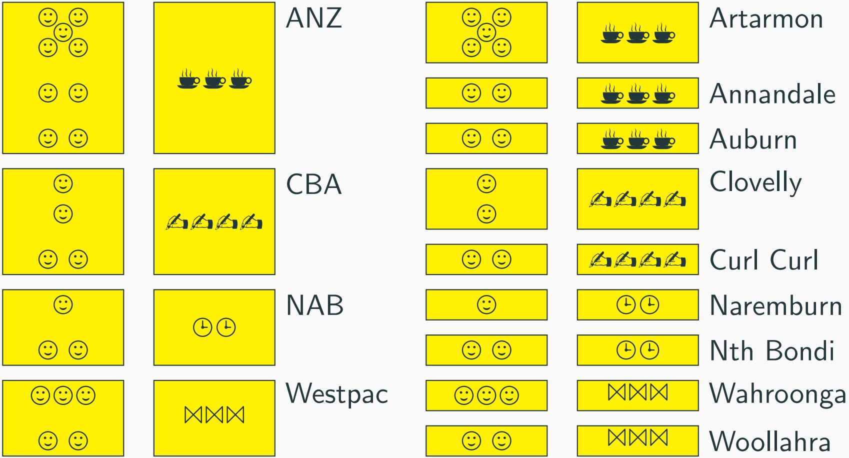
$$\sum_f \dashv f^*$$

$\sum_{x:X} := \sum_{!_X} \quad !_X : X \to *$

$$\mathbf{Set}/*\left(\sum_f p, q\right) \cong \mathbf{Set}/X(p, f^* q)$$



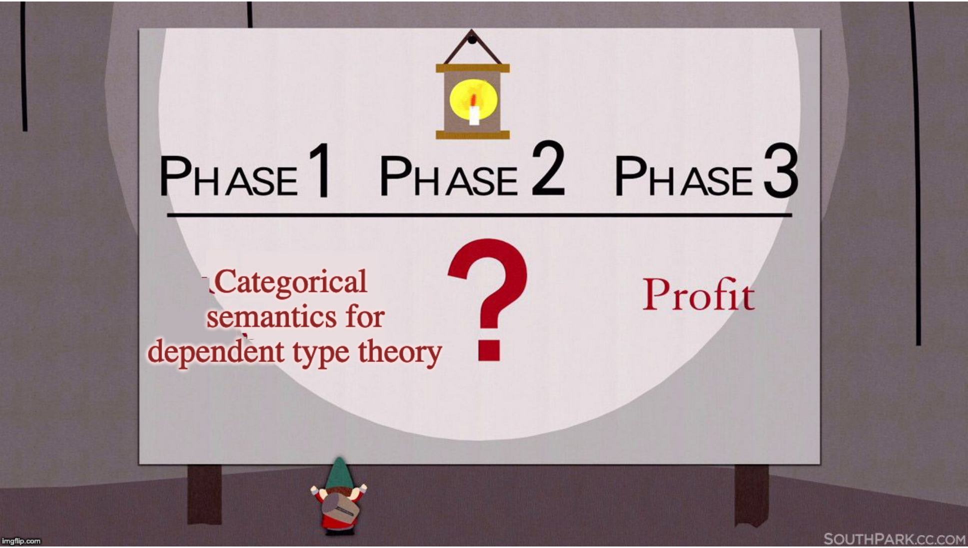
$\sum_{\text{bankOf}}$: **Set** / Branch $\rightarrow$ **Set** / Bank



Dependent product

A category is **locally Cartesian closed**
if f^* also has a right adjoint
for all arrows f.

Lemma
In this case all the slice categories $\mathcal{C}/X$ are Cartesian closed.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Compiling to LCCCs

- Categorical semantics for DTs in LCCCs
- Lots of LCCCs
- Something something Agda, Idris, Lean, ...
- **Profit**

LCCCs

Set is locally Cartesian closed.

Dependent product

$$f : X \to Y$$

$$\prod_f : \mathbf{Set}/X \to \mathbf{Set}/Y$$

$$f^* \dashv \prod_f$$

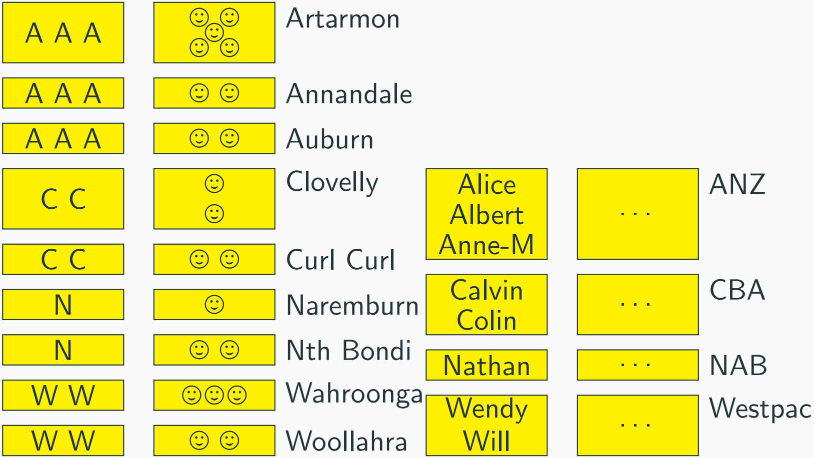
$\prod_{x:X} := \prod_{!_X} \quad !_X : X \to *$

$$\mathbf{Set}/X(f^*p, q) \cong \mathbf{Set}/*(p, \prod_f q)$$

⋮	⋮					
a b c	Iris Archibald	H	apple banana cherry	$*$	$\prod_{n=0}^{\infty}\{\mathrm{m}, \mathrm{f}\}$	$*$
a b c	Shirley Norman	G				
a b c	Helen Garry	me				

$$\frac{p : \mathit{Person} \vdash \mathit{Fruit} \to \mathit{ParentOf}(p)}{\vdash \mathit{Fruit} \to \prod_{p:\mathit{Person}} \mathit{ParentOf}(p)}$$

$\prod_{\mathsf{bankOf}}$: **Set** / Branch $\to$ **Set** / Bank



$$\left(\prod_{\mathsf{bankOf}} \mathsf{Staff}\right)_{ANZ} = \{ s : (\mathsf{Branch})_{\mathsf{ANZ}} \to \mathsf{Staff} \mid \forall br.\ \mathsf{branchOf}(s(br)) = br \}$$

Subtleties

$$c : \mathsf{Customer} \vdash \mathsf{IsEven}(\mathsf{length}(\mathsf{firstName}(c)))$$

- substitute $s := \mathsf{firstName}(c)$ into $\mathsf{IsEven}(\mathsf{length}(s))$
- substitute $n := \mathsf{length}(\mathsf{firstName}(c))$ into $\mathsf{IsEven}\ n$

Subtleties

- display map categories
- contextual categories
- categories with families
- categories with attributes
- Awodey's "natural model"

References

R. A. G. Seely, *Locally cartesian closed categories and type theory*

Martin Hofman, *Syntax and semantics of dependent types*

Alexandre Buisse, *Categorical models of dependent type theory*

Awodey, *Category Theory*, 7.29 and 9.7

MacLane and Moerdijk, *Sheaves in Geometry and Logic*, IV.7

The nLab, ncatlab.org/nlab