

# Constructive Logic

Hype for Types

September 14, 2021

# Proofs

# Existence

I want to prove there exists a set with property  $P$ .

Is one of these more useful?

- Proof by contradiction: If such a set did not exist, we'd have a contradiction (insert proof here), therefore it must exist
- Direct proof: The set  $S$  has property  $P$  (insert proof here)

# Existence

I want to prove there exists an algorithm to convert SML into x86 assembly.

Is one method more useful now?

# Existence

I want to prove there exists an algorithm to convert SML into x86 assembly.

Is one method more useful now?

- Proof by contradiction: If such a compiler did not exist, we'd have a contradiction (insert proof here), therefore it must exist
- Direct proof : CakeML (formally verified SML compiler)

# To Construct or Not To Construct

Two kinds of proofs

- *Non-Constructive* : demonstrate the existence of a mathematical object, but *without* telling you what it is
- *Constructive* : demonstrate the existence of a mathematical object precisely by presenting an object and proving it has the desired properties

# A Concrete but Boring Example

Does there exist  $a, b : \mathbb{R}$  such that  $a, b$  irrational but  $a^b$  rational?

- *Non-Constructive*

If  $\sqrt{2}^{\sqrt{2}}$  rational, we're done. Otherwise  $(\sqrt{2}^{\sqrt{2}})^{\sqrt{2}} = 2$ .

- *Constructive*

Take  $a = \sqrt{2}$  and  $b = \log_2 9$ . Then  $\sqrt{2}^{\log_2 9} = 9^{\log_2 \sqrt{2}} = 9^{\frac{1}{2}} = 3$

# Constructive proofs are useful to computer scientists

Constructive proofs provide *algorithms*!

A proof that all natural numbers have property  $P$  must describe a way to construct a proof of  $P(n)$  for each  $n : \mathbb{N}$



## Formalization B)

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- How do we formalize what it means for a proof to be constructive?

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- "You have to construct something" is pretty vague
- How do we formalize what it means for a proof to be constructive?
  - 1 Decide what kinds of proposition we want to talk about
  - 2 Inference rules!

# Formalization B)

A few reasonable kinds of proposition

- $\top$
- $\perp$
- $A \wedge B$
- $A \vee B$
- $A \Rightarrow B$
- $\neg A$

# Constructive Logic: Inference Rules

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Given  $A \wedge B$ , we can extract two facts (*elimination*)...  $A$  and  $B$ :

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Given  $A \Rightarrow B$  and  $A$ , we can extract...  $B$ :

$$\frac{\Gamma \vdash A \Rightarrow B \quad \Gamma \vdash A}{\Gamma \vdash B} (\Rightarrow E)$$

# Disjunction ( $\vee$ )

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Given  $A \vee B$ , we can extract... nothing? But if we *also* have “given  $A$ , then  $C$ ” and “given  $B$ , then  $C$ ,” we can get  $C$ :

$$\frac{\Gamma \vdash A \vee B \quad \Gamma, A \vdash C \quad \Gamma, B \vdash C}{\Gamma \vdash C} (\vee E)$$



# Truth ( $\top$ ) and Falsehood ( $\perp$ )

To get  $\top$ , we need...

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To get  $\top$ , we need... nothing!

$$\frac{}{\Gamma \vdash \top} (\top I)$$

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To get  $\top$ , we need... nothing!

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Can we get any information out of  $\top$ ?

# Truth ( $\top$ ) and Falsehood ( $\perp$ )

To get  $\top$ , we need... nothing!

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Can we get any information out of  $\top$ ? No!

How can we get  $\perp$ ?

# Truth ( $\top$ ) and Falsehood ( $\perp$ )

To get  $\top$ , we need... nothing!

$$\frac{}{\Gamma \vdash \top} (\top I)$$

Can we get any information out of  $\top$ ? No!

How can we get  $\perp$ ? We can't!

# Truth ( $\top$ ) and Falsehood ( $\perp$ )

To get  $\top$ , we need... nothing!

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Can we get any information out of  $\top$ ? No!

How can we get  $\perp$ ? We can't!

But given  $\perp$ , we can obtain a proof of...

# Truth ( $\top$ ) and Falsehood ( $\perp$ )

To get  $\top$ , we need... nothing!

$$\frac{}{\Gamma \vdash \top} (\top I)$$

Can we get any information out of  $\top$ ? No!

How can we get  $\perp$ ? We can't!

But given  $\perp$ , we can obtain a proof of... anything!

$$\frac{\Gamma \vdash \perp}{\Gamma \vdash A} (\perp E)$$

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Do we need new inference rules?

No!

$$\neg A \equiv A \Rightarrow \perp$$

$\neg A$  means "If we can prove  $A$ , we can do something impossible".

# All the rules!

$$\frac{\Gamma \vdash A \quad \Gamma \vdash B}{\Gamma \vdash A \wedge B} (\wedge I)$$

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## Question

Does this seem familiar...?

# Programs are Proofs

# Back to the Simply-Typed Lambda Calculus

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$$\frac{\Gamma \vdash \perp}{\Gamma \vdash A} (\perp E)$$

$$\frac{\Gamma \vdash A \vee B \quad \Gamma, A \vdash C \quad \Gamma, B \vdash C}{\Gamma \vdash C} (\vee E)$$

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Let's Prove Some Stuff!

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Prove  $A \Rightarrow A$ .

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$\lambda f : A \times B \rightarrow C. \lambda a : A. \lambda b : B. f \langle a, b \rangle$ , or `Fn.curry` in SML

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Prove  $A \wedge (B \vee C) \leftrightarrow (A \wedge B) \vee (A \wedge C)$ .

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$\lambda x : A \times (B + C)$ . **case**  $\text{snd}(x)$  **of**  $x_1 \Rightarrow$  **Left**  $\langle \text{fst}(x), x_1 \rangle \mid x_2 \Rightarrow$

**Right**  $\langle \text{fst}(x), x_2 \rangle$

$\lambda x : (A \times B) + (A \times C)$ . **case**  $x$  **of**  $x_1 \Rightarrow \langle \text{fst}(x_1), \text{Left } \text{snd}(x_1) \rangle \mid x_2 \Rightarrow$   
 $\langle \text{fst}(x_2), \text{Right } \text{snd}(x_2) \rangle$

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# Is there anything we can't prove constructively?

- Law of Excluded Middle :  $P \vee \neg P$
- Double Negation Elimination :  $\neg\neg P \Rightarrow P$

(These are actually equivalent)

So what?

## Practical Implications



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## Question

These proofs seem pretty boring, can a type system express more complicated propositions?