CSE 505: Programming Languages

Lecture 17 — The Curry-Howard Isomorphism

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Language Design

What have we been up to?

▶ Define a programming language
  ▶ we’ve been fairly formal
  ▶ pretty close to SML if you squint real hard
Language Design

What have we been up to?
- Define a programming language
  - we’ve been fairly formal
  - pretty close to SML if you squint real hard
- Define a type system
  - outlaw bad programs that “get stuck”
  - sound: no typable programs get stuck
  - incomplete: knocked out some OK programs too, oh well
Elsewhere in the Universe (or the other side of campus)

What do logicians do?
- Define formal logics
  - tools to precisely state propositions
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- Define formal logics
  - tools to precisely state propositions

- Define proof systems
  - tools to figure out which propositions are true

Turns out, we did that too!
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What do logicians do?

- Define formal logics
  - tools to precisely state propositions

- Define proof systems
  - tools to figure out which propositions are true

Turns out, we did that too!
Punchline

We are accidental logicians!
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The Curry-Howard Isomorphism

- Proofs : Propositions :: Programs : Types
- proofs are to propositions as programs are to types
Woah. Back up a second. Logic?!
Woah. Back up a second. Logic?!

Let’s trim down our (explicitly typed) simply-typed \( \lambda \)-calculus to:

\[
e ::= x | \lambda x. \ e | e \ e
| (e, e) | e.1 | e.2
| A(e) | B(e) | \text{match } e \text{ with } A x. \ e | B x. \ e
\]

\[
\tau ::= b | \tau \rightarrow \tau | \tau \ast \tau | \tau + \tau
\]

- Lambdas, Pairs, and Sums
- Any number of base types \( b_1, b_2, \ldots \)
- No constants (can add one or more if you want)
- No fix
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e ::= x \mid \lambda x. e \mid ee
\mid (e, e) \mid e.1 \mid e.2
\mid A(e) \mid B(e) \mid \text{match } e \text{ with } A x. e \mid B x. e
\]

\[
\tau ::= b \mid \tau \to \tau \mid \tau * \tau \mid \tau + \tau
\]

- Lambdas, Pairs, and Sums
- Any number of base types \(b_1, b_2, \ldots\)
- No constants (can add one or more if you want)
- No fix

What good is this?!

Well, even sans constants, plenty of terms type-check with \(\Gamma = \cdot\).
\[ \lambda x : b . \ x \]

has type
\( \lambda x : b. \; x \)

has type

\( b \rightarrow b \)
\[ \lambda x : b_1. \lambda f : b_1 \rightarrow b_2. \ f \ x \]

has type
\[ \lambda x : b_1. \lambda f : b_1 \rightarrow b_2. \ f \ x \]

has type

\[ b_1 \rightarrow (b_1 \rightarrow b_2) \rightarrow b_2 \]
\[ \lambda x : b_1 \rightarrow b_2 \rightarrow b_3. \lambda y : b_2. \lambda z : b_1. x \ z \ y \]

has type
\[ \lambda x : b_1 \to b_2 \to b_3. \lambda y : b_2. \lambda z : b_1. \ x \ z \ y \]

has type

\[ (b_1 \to b_2 \to b_3) \to b_2 \to b_1 \to b_3 \]
\[ \lambda x: b_1. \ (A(x), A(x)) \]

has type
\[ \lambda x : b_1. \ (A(x), A(x)) \]

has type

\[ b_1 \rightarrow ((b_1 + b_7) \ast (b_1 + b_4)) \]
\[ \lambda f : b_1 \to b_3. \lambda g : b_2 \to b_3. \lambda z : b_1 + b_2. \]
\[(\text{match } z \text{ with } A x. f x \mid B x. g x) \]

has type
\[ \lambda f: b_1 \to b_3. \lambda g: b_2 \to b_3. \lambda z: b_1 + b_2. \]
\((\text{match } z \text{ with } A x. \ f \ x \ \mid B x. \ g \ x)\)

has type

\[(b_1 \to b_3) \to (b_2 \to b_3) \to (b_1 + b_2) \to b_3\]
\[
\lambda x : b_1 \ast b_2. \lambda y : b_3. ((y, x.1), x.2)
\]

has type
\[ \lambda x : b_1 \ast b_2. \quad \lambda y : b_3. \quad ((y, x.1), x.2) \]

has type

\[(b_1 \ast b_2) \to b_3 \to ((b_3 \ast b_1) \ast b_2)\]
Empty and Nonempty Types

Just saw a few “nonempty” types

- $\tau$ nonempty if closed term $e$ has type $\tau$
- $\tau$ empty otherwise
Empty and Nonempty Types

Just saw a few “nonempty” types

- $\tau$ *nonempty* if closed term $e$ has type $\tau$
- $\tau$ *empty* otherwise

Are there any empty types?
Empty and Nonempty Types

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- \( \tau \) nonempty if closed term \( e \) has type \( \tau \)
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Are there any empty types?

Sure! \( b_1 \rightarrow b_2 \rightarrow (b_2 \rightarrow b_1) \rightarrow b_2 \)
Empty and Nonempty Types

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- \( \tau \) nonempty if closed term \( e \) has type \( \tau \)
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Are there any empty types?

Sure! \( b_1 \quad b_1 \rightarrow b_2 \quad b_1 \rightarrow (b_2 \rightarrow b_1) \rightarrow b_2 \)

What does this one mean?

\[ b_1 + (b_1 \rightarrow b_2) \]
Empty and Nonempty Types

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- $\tau$ nonempty if closed term $e$ has type $\tau$
- $\tau$ empty otherwise

Are there any empty types?

Sure! $b_1 \ b_1 \rightarrow b_2 \ b_1 \rightarrow (b_2 \rightarrow b_1) \rightarrow b_2$

What does this one mean?

$$b_1 + (b_1 \rightarrow b_2)$$

I wonder if there’s any way to distinguish empty vs. nonempty...
Empty and Nonempty Types

Just saw a few “nonempty” types

- $\tau$ nonempy if closed term $e$ has type $\tau$
- $\tau$ empty otherwise

Are there any empty types?

Sure! $b_1$ $b_1 \rightarrow b_2$ $b_1 \rightarrow (b_2 \rightarrow b_1) \rightarrow b_2$

What does this one mean?

$b_1 + (b_1 \rightarrow b_2)$

I wonder if there’s any way to distinguish empty vs. nonempty...

Ohwell, now for a totally irrelevant tangent!
Totally irrelevant tangent.
Propositional Logic

Suppose we have some set \( b_1, b_2, \ldots \) of basic propositions. Using standard operators \( \supset, \land, \lor \), we can define formulas:

- \( p ::= b | p \supset p | p \land p | p \lor p \)

Some formulas are tautologies: by virtue of their structure, they are always true regardless of the truth of their constituent propositions.

- e.g. \( p_1 \supset p_1 \)

Not too hard to build a proof system to establish tautologyhood.
Propositional Logic

Suppose we have some set $b$ of basic propositions $b_1, b_2, \ldots$

- e.g. “ML is better than Haskell”
Propositional Logic

Suppose we have some set $b$ of basic propositions $b_1, b_2, \ldots$

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Then, using standard operators $\supset, \land, \lor$, we can define formulas:

$$p ::= b \mid p \supset p \mid p \land p \mid p \lor p$$

- e.g. “ML is better than Haskell” $\land$ “Haskell is not pure”
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Not too hard to build a proof system to establish tautologyhood.
Proof System

\[ \Gamma ::= \cdot \mid \Gamma, p \]
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\[ \Gamma ::= \cdot \mid \Gamma, p \]

\[\Gamma \vdash p\]

\[\begin{array}{c}
\Gamma \vdash p_1 \\
\Gamma \vdash p_2
\end{array}\]

\[\Gamma \vdash p_1 \land p_2\]
Proof System

\[ \Gamma ::= \cdot \mid \Gamma, p \]

\[ \Gamma \vdash p \]

\[ \frac{\Gamma \vdash p_1 \quad \Gamma \vdash p_2}{\Gamma \vdash p_1 \land p_2} \quad \frac{\Gamma \vdash p_1 \land p_2}{\Gamma \vdash p_1} \]
Proof System

\[ \Gamma ::= \cdot \mid \Gamma, p \]

\[ \begin{array}{c}
\Gamma \vdash p \\
\hline
\Gamma \vdash p_1 \quad \Gamma \vdash p_2 \\
\hline
\Gamma \vdash p_1 \land p_2 \\
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\Gamma \vdash p_1 \\
\end{array} \]

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\hline
\Gamma \vdash p_2 \\
\end{array} \]
Proof System

\[ \Gamma ::= \cdot \mid \Gamma, p \]

\[ \Gamma \vdash p \]

\[ \frac{\Gamma \vdash p_1 \quad \Gamma \vdash p_2}{\Gamma \vdash p_1 \land p_2} \]

\[ \frac{\Gamma \vdash p_1 \land p_2}{\Gamma \vdash p_1} \quad \frac{\Gamma \vdash p_1 \land p_2}{\Gamma \vdash p_2} \]

\[ \frac{\Gamma \vdash p_1}{\Gamma \vdash p_1 \lor p_2} \]
Proof System

\[ \Gamma ::= \cdot \mid \Gamma, p \]

\[ \Gamma \vdash p \]

\[\begin{align*}
\frac{\Gamma \vdash p_1 \quad \Gamma \vdash p_2}{\Gamma \vdash p_1 \land p_2} & & \frac{\Gamma \vdash p_1 \land p_2}{\Gamma \vdash p_1} & & \frac{\Gamma \vdash p_1 \land p_2}{\Gamma \vdash p_2} \\
\frac{\Gamma \vdash p_1}{\Gamma \vdash p_1 \lor p_2} & & \frac{\Gamma \vdash p_2}{\Gamma \vdash p_1 \lor p_2} & & \frac{\Gamma \vdash p_2}{\Gamma \vdash p_1 \lor p_2}
\end{align*}\]
Proof System

\[ \Gamma ::= \cdot \mid \Gamma, p \]

\[ \Gamma \vdash p \]

\[ \frac{\Gamma \vdash p_1 \quad \Gamma \vdash p_2}{\Gamma \vdash p_1 \wedge p_2} \quad \frac{\Gamma \vdash p_1}{\Gamma \vdash p_1 \wedge p_2} \quad \frac{\Gamma \vdash p_2}{\Gamma \vdash p_1 \wedge p_2} \]

\[ \frac{\Gamma \vdash p_1}{\Gamma \vdash p_1 \vee p_2} \quad \frac{\Gamma \vdash p_2}{\Gamma \vdash p_1 \vee p_2} \]

\[ \frac{\Gamma \vdash p_1 \vee p_2 \quad \Gamma, p_1 \vdash p_3 \quad \Gamma, p_2 \vdash p_3}{\Gamma \vdash p_3} \]
Proof System

\[ \Gamma ::= \cdot \mid \Gamma, p \]

\[ \Gamma \vdash p \]

\[ \frac{\Gamma \vdash p_1 \quad \Gamma \vdash p_2}{\Gamma \vdash p_1 \land p_2} \]

\[ \frac{\Gamma \vdash p_1 \land p_2}{\Gamma \vdash p_1} \quad \frac{\Gamma \vdash p_1 \land p_2}{\Gamma \vdash p_2} \]

\[ \frac{\Gamma \vdash p_1}{\Gamma \vdash p_1 \lor p_2} \quad \frac{\Gamma \vdash p_2}{\Gamma \vdash p_1 \lor p_2} \]

\[ \frac{\Gamma \vdash p_1 \lor p_2 \quad \Gamma, p_1 \vdash p_3 \quad \Gamma, p_2 \vdash p_3}{\Gamma \vdash p_3} \]

\[ p \in \Gamma \]

\[ \frac{\Gamma \vdash p}{\cdot \vdash p} \]
\[ \Gamma ::= \cdot \mid \Gamma, p \]

\[ \Gamma \vdash p \]

\[ \frac{\Gamma \vdash p_1 \quad \Gamma \vdash p_2}{\Gamma \vdash p_1 \land p_2} \]

\[ \frac{\Gamma \vdash p_1 \land p_2}{\Gamma \vdash p_1} \quad \frac{\Gamma \vdash p_1 \land p_2}{\Gamma \vdash p_2} \]

\[ \frac{\Gamma \vdash p_1}{\Gamma \vdash p_1 \lor p_2} \]

\[ \frac{\Gamma \vdash p_1 \lor p_2 \quad \Gamma, p_1 \vdash p_3 \quad \Gamma, p_2 \vdash p_3}{\Gamma \vdash p_3} \]

\[ p \in \Gamma \quad \Gamma, p_1 \vdash p_2 \]

\[ \Gamma \vdash p \quad \Gamma \vdash p_1 \supset p_2 \]
Proof System

\[ \Gamma ::= \cdot \mid \Gamma, p \]

\[ \Gamma \vdash p \]

\[\frac{\Gamma \vdash p_1 \quad \Gamma \vdash p_2}{\Gamma \vdash p_1 \land p_2}\]
\[\frac{\Gamma \vdash p_1 \land p_2}{\Gamma \vdash p_1}\]
\[\frac{\Gamma \vdash p_1 \land p_2}{\Gamma \vdash p_2}\]

\[\frac{\Gamma \vdash p_1}{\Gamma \vdash p_1 \lor p_2}\]
\[\frac{\Gamma \vdash p_2}{\Gamma \vdash p_1 \lor p_2}\]
\[\frac{\Gamma \vdash p_1 \lor p_2 \quad \Gamma, p_1 \vdash p_3 \quad \Gamma, p_2 \vdash p_3}{\Gamma \vdash p_3}\]

\[\frac{p \in \Gamma}{\Gamma \vdash p}\]
\[\frac{\Gamma, p_1 \vdash p_2}{\Gamma \vdash p_1 \supset p_2}\]
\[\frac{\Gamma \vdash p_1 \supset p_2 \quad \Gamma \vdash p_1}{\Gamma \vdash p_2}\]
Wait a second...
Wait a second…
Wait a second... ZOMG!

That’s exactly our type system! Just erase terms, change each $\tau$ to a $p$, and translate $\to$ to $\supset$, $*$ to $\land$, $+$ to $\lor$.

\[
\begin{align*}
\Gamma \vdash e : \tau \\
\Gamma \vdash e_1 : \tau_1 & \quad \Gamma \vdash e_2 : \tau_2 \\
& \quad \Gamma \vdash (e_1, e_2) : \tau_1 \ast \tau_2 \\
\Gamma \vdash e : \tau_1 \ast \tau_2 & \quad \Gamma \vdash e : \tau_1 \ast \tau_2 \\
& \quad \Gamma \vdash e.1 : \tau_1 \\
& \quad \Gamma \vdash e.2 : \tau_2 \\
\Gamma \vdash e : \tau_1 & \quad \Gamma \vdash e : \tau_2 \\
& \quad \Gamma \vdash A(e) : \tau_1 \lor \tau_2 \\
& \quad \Gamma \vdash B(e) : \tau_1 \lor \tau_2 \\
\Gamma \vdash e : \tau_1 \lor \tau_2 & \quad \Gamma, x:\tau_1 \vdash e_1 : \tau \\
& \quad \Gamma, y:\tau_2 \vdash e_2 : \tau \\
& \quad \Gamma \vdash \text{match } e \text{ with } Ax. \ e_1 \mid By. \ e_2 : \tau \\
\Gamma(x) = \tau & \quad \Gamma, x : \tau_1 \vdash e : \tau_2 \\
& \quad \Gamma \vdash \lambda x. \ e : \tau_1 \to \tau_2 \\
& \quad \Gamma \vdash e_1 : \tau_2 \to \tau_1 \\
& \quad \Gamma \vdash e_2 : \tau_2 \\
\end{align*}
\]
What does it all mean? The Curry-Howard Isomorphism.

- Given a well-typed closed term, take the typing derivation, erase the terms, and have a propositional-logic proof.

- Given a propositional-logic proof, there exists a closed term with that type.

- A term that type-checks is a *proof* — it tells you exactly how to derive the logical formula corresponding to its type.
What does it all mean? The Curry-Howard Isomorphism.

- Given a well-typed closed term, take the typing derivation, erase the terms, and have a propositional-logic proof.

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- A term that type-checks is a proof — it tells you exactly how to derive the logical formula corresponding to its type.

- Constructive (hold that thought) propositional logic and simply-typed lambda-calculus with pairs and sums are the same thing.
  - Computation and logic are deeply connected.
  - \( \lambda \) is no more or less made up than implication.

- Revisit our examples under the logical interpretation...
\[ \lambda x : b. \ x \]

is a proof that

\[ b \rightarrow b \]
\[ \lambda x : b_1. \lambda f : b_1 \to b_2. \ f \ x \]

is a proof that

\[ b_1 \to (b_1 \to b_2) \to b_2 \]
\[
\lambda x: b_1 \to b_2 \to b_3. \lambda y: b_2. \lambda z: b_1. \ x \ z \ y
\]

is a proof that

\[
(b_1 \to b_2 \to b_3) \to b_2 \to b_1 \to b_3
\]
\[ \lambda x: b_1. \ (A(x), A(x)) \]

is a proof that

\[ b_1 \to ((b_1 + b_7) \ast (b_1 + b_4)) \]
\[ \lambda f : b_1 \rightarrow b_3. \lambda g : b_2 \rightarrow b_3. \lambda z : b_1 + b_2. \]

\[(\text{match } z \text{ with } A x. \ f \ x \mid B x. \ g \ x)\]

is a proof that

\[(b_1 \rightarrow b_3) \rightarrow (b_2 \rightarrow b_3) \rightarrow (b_1 + b_2) \rightarrow b_3\]
\( \lambda x : b_1 \ast b_2 . \ \lambda y : b_3 . \ ((y, x.1), x.2) \)

is a proof that

\[(b_1 \ast b_2) \rightarrow b_3 \rightarrow ((b_3 \ast b_1) \ast b_2)\]
So what?

Because:

- This is just fascinating (glad I’m not a dog)
- Don’t think of logic and computing as distinct fields
- Thinking “the other way” can help you know what’s possible/impossible
- Can form the basis for theorem provers
- Type systems should not be *ad hoc* piles of rules!
So what?

Because:

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- Can form the basis for theorem provers
- Type systems should not be *ad hoc* piles of rules!

So, every typed $\lambda$-calculus is a proof system for some logic...

Is STLC with pairs and sums a *complete* proof system for propositional logic? Almost...
Classical vs. Constructive

Classical propositional logic has the “law of the excluded middle”:

$$\Gamma \vdash p_1 + (p_1 \rightarrow p_2)$$

(Think “$p + \neg p$” – also equivalent to double-negation $\neg\neg p \rightarrow p$)
Classical vs. Constructive

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STLC does not support this law; for example, no closed expression has type $b_1 + (b_1 \rightarrow b_2)$
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Logics without this rule are called constructive. They’re useful because proofs “know how the world is” and “are executable” and “produce examples”
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Logics without this rule are called constructive. They’re useful because proofs “know how the world is” and “are executable” and “produce examples”

Can still “branch on possibilities” by making the excluded middle an explicit assumption:

$$((p_1 + (p_1 \to p_2)) \ast (p_1 \to p_3) \ast ((p_1 \to p_2) \to p_3)) \to p_3$$
Classical vs. Constructive, an Example

Theorem: There exist irrational numbers $a$ and $b$ such that $a^b$ is rational.

Classical Proof:

Let $x = \sqrt{2}$. Either $x$ is rational or it is irrational.

If $x$ is rational, let $a = b = \sqrt{2}$, done.

If $x$ is irrational, let $a = x$ and $b = x$. Since $(\sqrt{2} \sqrt{2}) = \sqrt{2}(\sqrt{2} \cdot \sqrt{2}) = \sqrt{2}^2 = 2$, done.

Well, I guess we know there are some $a$ and $b$ satisfying the theorem...

but which ones?

LAME.

Constructive Proof:

Let $a = \sqrt{2}, b = \log_2 9$.

Since $\sqrt{2} \log_2 9 = 9 \log_2 \sqrt{2} = 9 \log_2 2^{0.5} = 3$, done.

To prove that something exists, we actually had to produce it. SWEET.
Classical vs. Constructive, an Example

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If $x^x$ is rational, let $a = b = \sqrt{2}$, done.

If $x^x$ is irrational, let $a = x^x$ and $b = x$. Since

$$\left(\sqrt{2}^{\sqrt{2}}\right)^{\sqrt{2}} = \sqrt{2}^{(\sqrt{2} \cdot \sqrt{2})} = \sqrt{2}^2 = 2,$$ done.
Classical vs. Constructive, an Example

Theorem: There exist irrational numbers \( a \) and \( b \) such that \( a^b \) is rational.

Classical Proof:

Let \( x = \sqrt{2} \). \textit{Either} \( x^x \) \textit{is rational or it is irrational.}

\emph{If} \( x^x \) \emph{is rational}, let \( a = b = \sqrt{2} \), done.

\emph{If} \( x^x \) \emph{is irrational}, let \( a = x^x \) and \( b = x \). \textit{Since}
\[
\left( \sqrt{2}^{\sqrt{2}} \right)^{\sqrt{2}} = \sqrt{2}^{(\sqrt{2} \cdot \sqrt{2})} = \sqrt{2}^2 = 2, \text{ done.}
\]

Well, I guess we know there are \emph{some} \( a \) and \( b \) satisfying the theorem... but which ones?

Constructive Proof:

Let \( a = \sqrt{2} \), \( b = \log_2{9} \).

Since \( \sqrt{2}^{\log_2{9}} = 9^{\log_2{\sqrt{2}}} = 9^{0.5 \log_2{2}} = 3 \), done.

To prove that something exists, we actually had to produce it. \textit{SWEET.}
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Theorem: There exist irrational numbers $a$ and $b$ such that $a^b$ is rational.

Classical Proof:

Let $x = \sqrt{2}$. *Either $x^x$ is rational or it is irrational.*

*If $x^x$ is rational, let $a = b = \sqrt{2}$, done.*

*If $x^x$ is irrational, let $a = x^x$ and $b = x$. Since*

\[
\left(\sqrt{2}^{\sqrt{2}}\right)^{\sqrt{2}} = \sqrt{2}^{(\sqrt{2}\cdot\sqrt{2})} = \sqrt{2}^2 = 2, \text{ done.}
\]

Well, I guess we know there are some $a$ and $b$ satisfying the theorem... but which ones? LAME.

Constructive Proof:

Let $a = \sqrt{2}$, $b = \log_2 9$.

*Since* $\sqrt{2}^{\log_2 9} = 9^{\log_2 \sqrt{2}} = 9^{\log_2 (2^{0.5})} = 9^{0.5} = 3$, *done.*
**Classical vs. Constructive, an Example**

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Since $\sqrt{2}^{\log_2 9} = 9^{\log_2 \sqrt{2}} = 9^{\log_2 (2^{0.5})} = 9^{0.5} = 3$, done.

To prove that something exists, we actually had to produce it. SWEET.
Classical vs. Constructive, a Perspective

Constructive logic allows us to distinguish between things that classical logic lumps together.

Consider "$P$ is true." vs. "It would be absurd if $P$ were false." Those are different things, but classical logic can't tell.

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A “non-terminating proof” is no proof at all.

Remember the typing rule for fix:

\[
\Gamma \vdash e : \tau \rightarrow \tau \\
\Gamma \vdash \text{fix } e : \tau
\]

That let’s us prove anything! Example: \text{fix } \lambda x: b. x has type b

So the “logic” is inconsistent (and therefore worthless)

Related: In ML, a value of type \(\tau\)a never terminates normally (raises an exception, infinite loop, etc.)

```plaintext
let rec f x = f x
let z = f 0
```
Last word on Curry-Howard

It’s not just STLC and constructive propositional logic

*Every* logic has a corresponding typed \( \lambda \) calculus (and no consistent logic has something as “powerful” as \texttt{fix}).
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If you remember one thing: the typing rule for function application is $modus$ $ponens$