

Introduction

Welcome to Hype for Types!

- Instructors:

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- Attendance

- ▶ In general, you have to come to lecture to pass
- ▶ Let us know if you need to miss a week

- Homework

- ▶ Every lecture will have an associated homework
- ▶ Graded on effort (*not* correctness)
- ▶ If you spend more than an hour, please stop¹

¹Unless you're having fun!

Other Stuff

- Please join the Discord and Gradescope if you haven't
- We assume everyone has 150 level knowledge of functional programming and type systems
 - ▶ If you don't have this and feel really lost, talk to us after class

Motivation

Programming is Hard

There are many common classes of mistakes/bugs/errors in code:



<https://xkcd.com/327/>

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- `A[len(A)]`



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- `1 + "hello"`
- `fun f x = f x`
- `malloc(sizeof(int)); return;`
- `free(A); free(A);`
- `A[len(A)]`
- `@requires is_sorted(A)`



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Types are... hype!

Types are *descriptions* of how some piece of data can be used.


² Foreshadowing: “a literary device in which a writer gives an advance hint of what is to come later in the story.” [Wikipedia, “Foreshadowing,” retrieved 30 Aug 2022](#) 

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Guiding Question

How can we use types to catch errors at compile-time?

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Can we use types for more than just bug-catching?²

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Lambda Calculus

Building a tiny language

The *simply-typed lambda calculus* is simple. It only has four features:

- Unit (“empty tuples”)
- Booleans
- Tuples
- Functions

Expressions

We represent our expressions using a *grammar*:

$e ::= x$	variable
$\langle \rangle$	unit
false	false boolean
true	true boolean
if e_1 then e_2 else e_3	boolean case analysis
$\langle e_1, e_2 \rangle$	tuple
fst (e)	first tuple element
snd (e)	second tuple element
$\lambda x : \tau. e$	function abstraction (lambda)
$e_1 e_2$	function application

Types

Similarly, we define our types as follows:

$$\begin{array}{l} \tau ::= \mathbf{unit} \\ \quad | \mathbf{bool} \\ \quad | \tau_1 \times \tau_2 \\ \quad | \tau_1 \rightarrow \tau_2 \end{array}$$

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Question

How do we check if $e : \tau$?

Inference Rules

In logic, we use *inference rules* to state how facts follow from other facts.

$$\frac{\text{premise}_1 \quad \text{premise}_2 \quad \dots}{\text{conclusion}}$$

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For example:

$$\frac{\text{you are here} \quad \text{you are hyped}}{\text{you are hyped for types}}$$

functions are values

$$\frac{\text{it's raining} \quad x \text{ is outside}}{x \text{ is getting wet}}$$

$$\frac{\text{Socrates is a man} \quad \text{All men are mortal}}{\text{Socrates is mortal}}$$

$$\frac{n \text{ is a number}}{n + 1 \text{ is a number}}$$

$$\frac{f \text{ total} \quad x \text{ valuable}}{f \ x \text{ valuable}}$$

Typing Rules: First Attempt

Consider the judgement $e : \tau$ (“ e has type τ ”). Let’s try to express some simple typing rules.

$$\frac{}{\langle \rangle : \mathbf{unit}}$$

$$\frac{}{\mathbf{false} : \mathbf{bool}}$$

$$\frac{}{\mathbf{true} : \mathbf{bool}}$$

$$\frac{e_1 : \mathbf{bool} \quad e_2 : \tau \quad e_3 : \tau}{\mathbf{if } e_1 \mathbf{ then } e_2 \mathbf{ else } e_3 : \tau}$$

$$\frac{e_1 : \tau_1 \quad e_2 : \tau_2}{\langle e_1, e_2 \rangle : \tau_1 \times \tau_2}$$

$$\frac{e : \tau_1 \times \tau_2}{\mathbf{fst}(e) : \tau_1}$$

$$\frac{e : \tau_1 \times \tau_2}{\mathbf{snd}(e) : \tau_2}$$

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Question

How do we write rules for functions?

Typing Rules: Functions

Let's give it a shot.

$$\frac{e_1 : \tau_1 \rightarrow \tau_2 \quad e_2 : \tau_1}{e_1 e_2 : \tau_2}$$

Looks good so far...

Typing Rules: Functions

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$$\frac{e_1 : \tau_1 \rightarrow \tau_2 \quad e_2 : \tau_1}{e_1 \ e_2 : \tau_2}$$

Looks good so far...

$$\frac{e : \tau_2 \text{ (?)}}{\lambda x : \tau_1. e : \tau_1 \rightarrow \tau_2}$$

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Looks good so far...

$$\frac{e : \tau_2 \text{ (?)}}{\lambda x : \tau_1. e : \tau_1 \rightarrow \tau_2}$$

Key Idea

Expressions only have types *given a context!*

Contexts

Intuition

If, given $x : \tau_1$, we know $e : \tau_2$, then $\lambda x : \tau_1. e : \tau_1 \rightarrow \tau_2$.

Therefore, we need a context (denoted Γ) which associates types with variables.

$$\frac{\Gamma, x : \tau_1 \vdash e : \tau_2}{\Gamma \vdash \lambda x : \tau_1. e : \tau_1 \rightarrow \tau_2}$$

What types does some variable x have? It depends on the previous code!

$$\frac{x : \tau \in \Gamma}{\Gamma \vdash x : \tau}$$

All the rules!

$$\frac{x : \tau \in \Gamma}{\Gamma \vdash x : \tau} \text{ (VAR)}$$

$$\frac{}{\Gamma \vdash \langle \rangle : \mathbf{unit}} \text{ (UNIT)}$$

$$\frac{}{\Gamma \vdash \mathbf{false} : \mathbf{bool}} \text{ (FALSE)}$$

$$\frac{}{\Gamma \vdash \mathbf{true} : \mathbf{bool}} \text{ (TRUE)}$$

$$\frac{\Gamma \vdash e_1 : \mathbf{bool} \quad \Gamma \vdash e_2 : \tau \quad \Gamma \vdash e_3 : \tau}{\Gamma \vdash \mathbf{if } e_1 \mathbf{ then } e_2 \mathbf{ else } e_3 : \tau} \text{ (IF)}$$

$$\frac{\Gamma \vdash e_1 : \tau_1 \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash \langle e_1, e_2 \rangle : \tau_1 \times \tau_2} \text{ (TUP)}$$

$$\frac{\Gamma \vdash e : \tau_1 \times \tau_2}{\Gamma \vdash \mathbf{fst}(e) : \tau_1} \text{ (FST)}$$

$$\frac{\Gamma \vdash e : \tau_1 \times \tau_2}{\Gamma \vdash \mathbf{snd}(e) : \tau_2} \text{ (SND)}$$

$$\frac{\Gamma, x : \tau_1 \vdash e : \tau_2}{\Gamma \vdash \lambda x : \tau_1. e : \tau_1 \rightarrow \tau_2} \text{ (ABS)}$$

$$\frac{\Gamma \vdash e_1 : \tau_1 \rightarrow \tau_2 \quad \Gamma \vdash e_2 : \tau_1}{\Gamma \vdash e_1 e_2 : \tau_2} \text{ (APP)}$$

Example: what's the type?

Let's derive that

$$\cdot \vdash (\lambda x : \mathbf{unit}. \langle x, \mathbf{true} \rangle) \langle \rangle : \mathbf{unit} \times \mathbf{bool}$$

by using the rules.

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Homework Foreshadowing

That looks like a trace of a typechecking algorithm!

Get Hype.

The Future is Bright

- How can you use basic algebra to manipulate types?
- How do types and programs relate to logical proofs?
- How can we automatically fold (and unfold) any recursive type?
- How can types allow us to do safe imperative programming?
- Can we make it so that programs that typecheck iff they're correct?