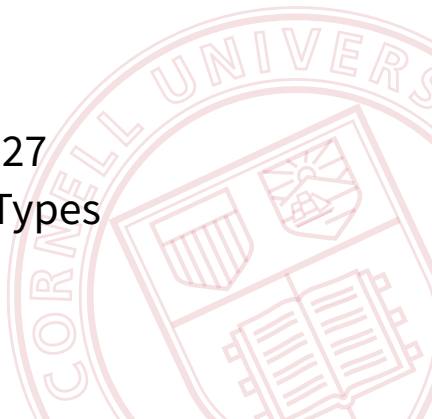


CS 4110

Programming Languages & Logics

Lecture 27
Recursive Types



Recursive Types

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Java

```
class Tree {  
    Tree leftChild, rightChild;  
    int data;  
}
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type tree = Leaf | Node of tree * tree * int
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λ -calculus?

$$tree = \mathbf{unit} + \mathbf{int} \times tree \times tree$$

Recursive Type Equations

We would like **tree** to be a solution of the equation:

$$\alpha = \mathbf{unit} + \mathbf{int} \times \alpha \times \alpha$$

However, no such solution exists with the types we have so far...

Unwinding Equations

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If we take the limit of this process, we have an infinite tree.

Infinite Types

Think of this as an infinite labeled graph whose nodes are labeled with the type constructors \times , $+$, **int**, and **unit**.

This infinite tree is a solution of our equation, and this is what we take as the type **tree**.

μ Types

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$$\mu\alpha. \tau$$

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Here's a **tree** type satisfying our original equation:

$$\mathbf{tree} \triangleq \mu\alpha. \mathbf{unit} + \mathbf{int} \times \alpha \times \alpha.$$

Static Semantics (Equirecursive)

We'll define two treatments of recursive types. With *equirecursive types*, a recursive type is equal to its unfolding:

$\mu\alpha. \tau$ is a solution to $\alpha = \tau$, so:

$$\mu\alpha. \tau = \tau\{\mu\alpha. \tau/\alpha\}$$

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Two typing rules let us switch between folded and unfolded:

$$\frac{\Gamma \vdash e : \tau\{\mu\alpha. \tau/\alpha\}}{\Gamma \vdash e : \mu\alpha. \tau} \mu\text{-INTRO}$$

$$\frac{\Gamma \vdash e : \mu\alpha. \tau}{\Gamma \vdash e : \tau\{\mu\alpha. \tau/\alpha\}} \mu\text{-ELIM}$$

Isorecursive Types

Alternatively, *isorecursive types* avoid infinite type trees.

The type $\mu\alpha. \tau$ is distinct but transformable to and from $\tau\{\mu\alpha. \tau/\alpha\}$.

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Converting between the two uses explicit **fold** and **unfold** operations:

$$\begin{aligned} \mathbf{unfold}_{\mu\alpha. \tau} &: \mu\alpha. \tau \rightarrow \tau\{\mu\alpha. \tau/\alpha\} \\ \mathbf{fold}_{\mu\alpha. \tau} &: \tau\{\mu\alpha. \tau/\alpha\} \rightarrow \mu\alpha. \tau \end{aligned}$$

Static Semantics (Isorecursive)

The typing rules introduce and eliminate μ -types:

$$\frac{\Gamma \vdash e : \tau\{\mu\alpha. \tau/\alpha\}}{\Gamma \vdash \mathbf{fold} e : \mu\alpha. \tau} \mu\text{-INTRO}$$

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Dynamic Semantics

We also need to augment the operational semantics:

$$\frac{}{\mathbf{unfold} (\mathbf{fold} e) \rightarrow e}$$

Intuitively, to access data in a recursive type $\mu\alpha. \tau$, we need to **unfold** it first. And the only way that values of type $\mu\alpha. \tau$ could have been created is via **fold**.

Example

Here's a recursive type for lists of numbers:

$$\mathbf{intlist} \triangleq \mu\alpha. \mathbf{unit} + \mathbf{int} \times \alpha.$$

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Here's how to add up the elements of an **intlist**:

let sum =

fix ($\lambda f: \mathbf{intlist} \rightarrow \mathbf{intlist}$

$\lambda l: \mathbf{intlist}$. case **unfold** l of

$(\lambda u: \mathbf{unit}. 0)$

| $(\lambda p: \mathbf{int} \times \mathbf{intlist}. (\#1 p) + f(\#2 p))$)

Encoding Numbers

Recursive types let us encode the natural numbers!

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The successor function has type $\mathbf{nat} \rightarrow \mathbf{nat}$:

$$(\lambda x : \mathbf{nat}. \mathbf{fold} (\mathbf{inr}_{\mathbf{unit}+\mathbf{nat}} x))$$

Self-Application and Ω

Recall Ω defined as:

$$\omega \triangleq \lambda x. x x$$

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So let's write a type equation:

$$\sigma = \sigma \rightarrow \tau$$

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Putting these pieces together, the fully typed ω term is:

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The type of ω is $(\mu\alpha. (\alpha \rightarrow \tau)) \rightarrow \tau$.

So the type of **fold** ω is $\mu\alpha. (\alpha \rightarrow \tau)$.

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So the type of **fold** ω is $\mu\alpha. (\alpha \rightarrow \tau)$.

Now we can define $\Omega = \omega (\mathbf{fold} \ \omega)$. It has type τ .

Self-Application and Ω

We can even write ω in OCaml:

```
# type u = Fold of (u -> u);;
type u = Fold of (u -> u)
# let omega = fun x -> match x with Fold f -> f x;;
val omega : u -> u = <fun>
# omega (Fold omega);;
...runs forever until you hit control-c
```

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With recursive types, we can type everything in the untyped lambda calculus!

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Every λ -term can be applied as a function to any other λ -term.
So let's define an “untyped” type:

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So let's define an “untyped” type:

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The full translation is:

$$\begin{aligned} \llbracket x \rrbracket &\triangleq x \\ \llbracket e_0 e_1 \rrbracket &\triangleq (\mathbf{unfold} \llbracket e_0 \rrbracket) \llbracket e_1 \rrbracket \\ \llbracket \lambda x. e \rrbracket &\triangleq \mathbf{fold} \lambda x : U. \llbracket e \rrbracket \end{aligned}$$

Every untyped term maps to a term of type U .