"NOBODY UNDERSTANDS ME."

Scoping and Type Checking

First, Written Assignments

- *Pick 'em up!* Even if you got a passing grade you'll want to see what we marked up.
- Derivations and parse trees are closely related, but if we ask you to draw a parse tree you must *draw the parse tree*.
- WA2#4 was *in the book* (Fig 2.34; you just had to substitute in k=3):

SLL(k) but not LL($k-1$):

$$S \longrightarrow \mathtt{a}^{k-1}\ \mathtt{b} \mid \mathtt{a}^{k}$$

Next. Semantic Fever: Catch it!

Course Goals and Objectives

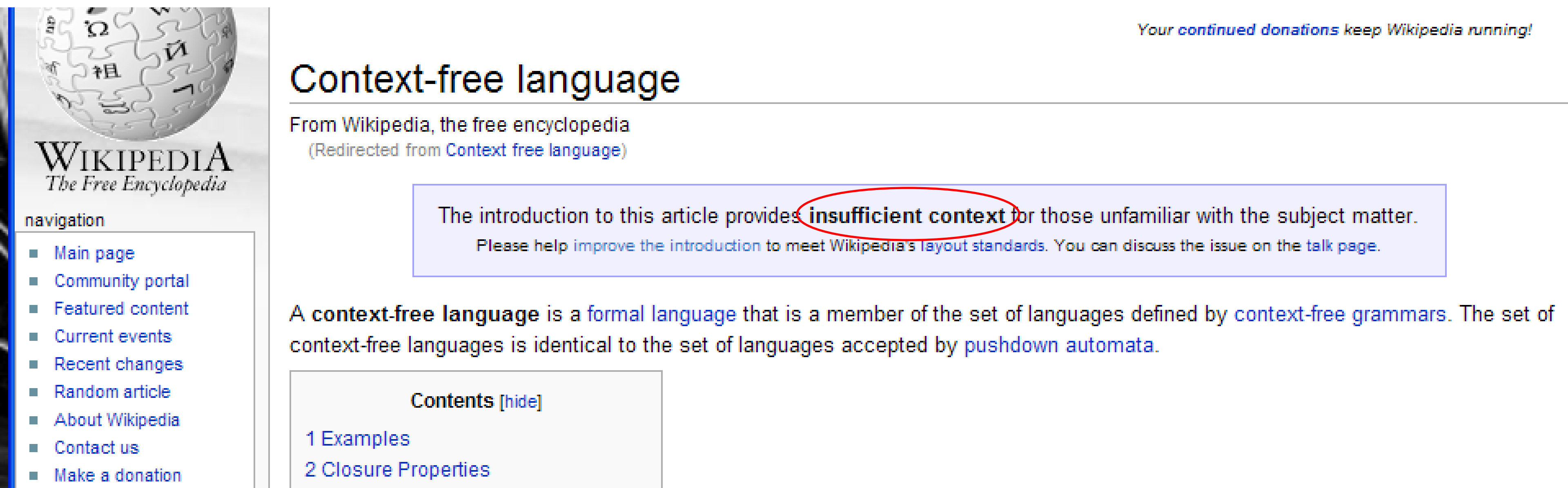
- At the end of this course, you will be acquainted with the fundamental concepts in the **design** and **implementation** of high-level programming **languages**. In particular, you will understand the **theory** and **practice** of **lexing**, **parsing**, **semantic** analysis, and **code** interpretation. You will also have gained practical experience programming in multiple **different** languages.

In One Slide

- **Scoping rules** match identifier uses with identifier definitions.
- A **type** is a set of values coupled with a set of operations on those values.
- A **type system** specifies which operations are valid for which types.
- **Type checking** can be done statically (at compile time) or dynamically (at run time).

Lecture Outline

- The role of semantic analysis in a compiler
  - A laundry list of tasks
- Scope
- Types



The Interpreter/Compiler So Far

- Lexical analysis
  - Detects inputs with illegal tokens
- Parsing
  - Detects inputs with ill-formed parse trees
- **Semantic analysis**
  - Last “front end” phase
  - Catches more errors

What's Wrong?

- Example 1

  let y: Int in x + 3

- Example 2

  let y: String ← "abc" in y + 3

Why a Separate Semantic Analysis?

- Parsing cannot catch some errors

- Some language constructs are **not context-free**
  - Example: All used variables must have been declared (i.e. scoping)
  - Example: A method must be invoked with arguments of proper type (i.e. typing)

What Does Semantic Analysis Do?

- Many kinds of checks . . . **cool** checks:
  1. All identifiers are declared
  2. Static Types
  3. Inheritance relationships (no cycles, etc.)
  4. Classes defined only once
  5. Methods in a class defined only once
  6. Reserved identifiers are not misused

  And others . . .
- The requirements depend on the language
  - Which of these are checked by Ruby? Python?

Scope

- **Scoping rules** match identifier uses with identifier declarations
  - Important semantic analysis step in most languages
  - Including COOL!

Scope (Cont.)

- The **scope** of an identifier is the portion of a program in which that identifier is accessible
- The same identifier may refer to different things in different parts of the program
  - Different scopes for same name don't overlap
- An identifier may have restricted scope

Static vs. Dynamic Scope

- Most languages have **static** scope
  - Scope depends only on the program text, not run-time behavior
  - Cool has static scope
- A few languages are **dynamically** scoped
  - Lisp, SNOBOL, Tex
  - Lisp has changed to mostly static scoping
  - Scope depends on execution of the program

Static Scoping Example

```
let x: Int <- 0 in
  {
     x;
     { let x: Int <- 1 in
          x; } ;
     x;
  }
```

Static Scoping Example (Cont.)

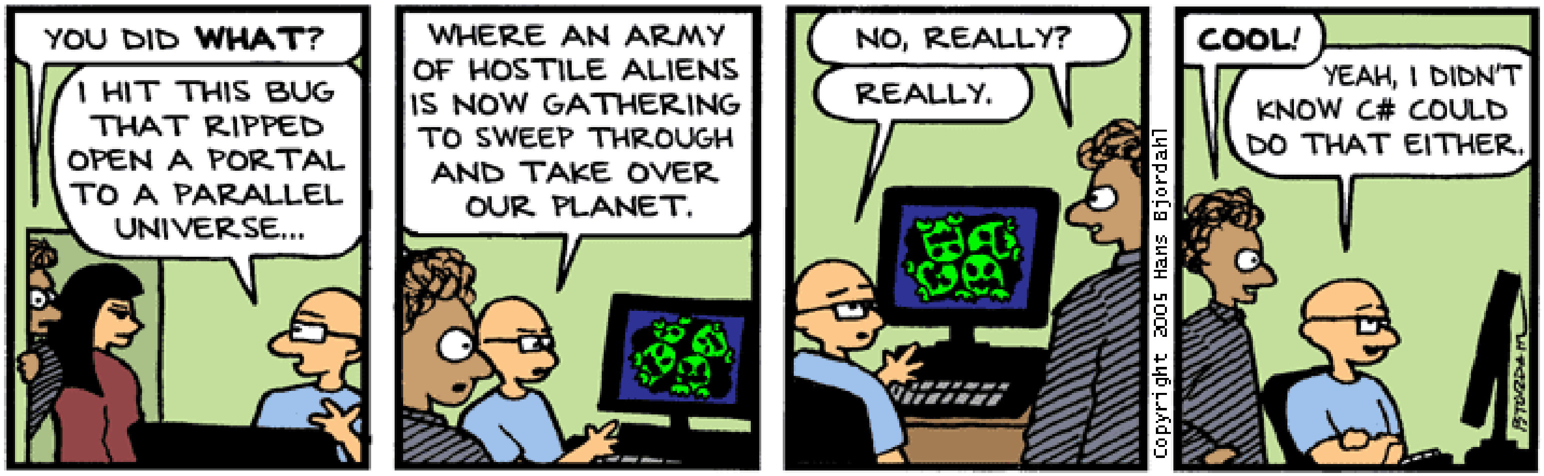
```
let x: Int <- 0 in
  {
     x;
     { let x: Int <- 1 in
           x; } ;
     x;
  }
```

Uses of x refer to closest enclosing definition

Scope in Cool

- Cool identifier bindings are **introduced** by
  - Class declarations (introduce class names)
  - Method definitions (introduce method names)
  - Let expressions (introduce object id's)
  - Formal parameters (introduce object id's)
  - Attribute definitions in a class (introduce object id's)
  - Case expressions (introduce object id's)

Implementing the Most-Closely Nested Rule



Bug Bash by Hans Bjordahl http://www.bugbash.net/

- Much of semantic analysis can be expressed as a **recursive descent** of an AST
  - Process an AST node *n*
  - Process the children of *n*
  - Finish processing the AST node *n*

Implementing . . . (Cont.)

- Example: the scope of let bindings is one subtree

  let x: Int ← 0 in e

- x can be used in subtree e

Symbol Tables

- Consider again: let x: Int $\leftarrow$ 0 in e
- Idea:
  - Before processing e, add definition of x to current definitions, overriding any other definition of x
  - After processing e, remove definition of x and restore old definition of x
- A **symbol table** is a data structure that tracks the current bindings of identifiers
  - You'll need to make one for PA4
  - OCaml's Hashtbl is designed to be a symbol table, so if you saved OCaml … no, wait …

Scope in Cool (Cont.)

- Not all kinds of identifiers follow the most-closely nested rule
- For example, class definitions in Cool
  - Cannot be nested
  - Are **globally visible** throughout the program
- In other words, a class name can be **used before it is defined**

Example: Use Before Definition

Class Foo {

. . . let y: **Test** in . . .

};

Class **Test** {

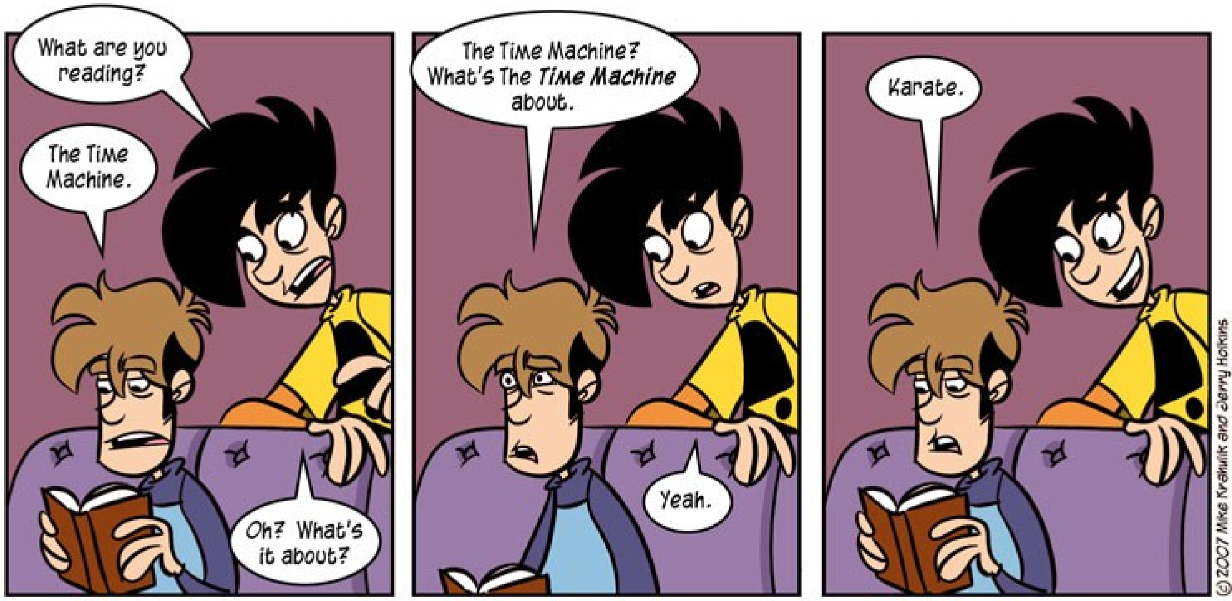
. . .

};

More Scope in Cool

Attribute names are **global** *within* the class in which they are defined

```
Class Foo {
  f(): Int { tm };
  tm: Int ← 0;
}
```



More Scope (Cont.)

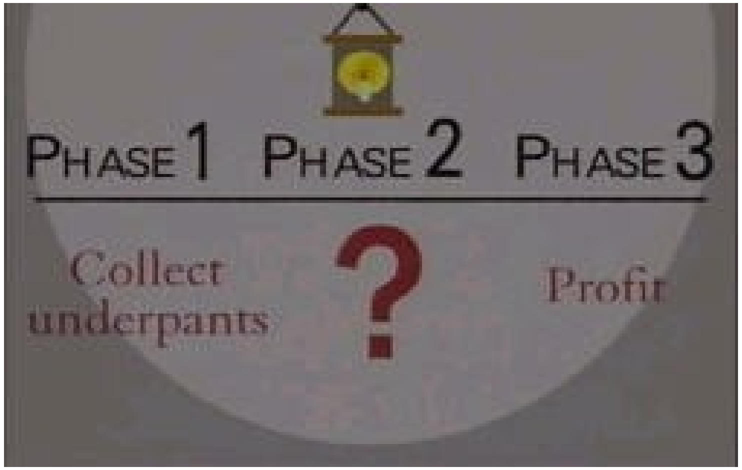
- Method and attribute names have complex rules

- A method need not be defined in the class in which it is used, but in some parent class
  - This is standard **inheritance**!

- Methods may also be redefined (overridden)

Class Definitions

- Class names can be used before being defined
- We can't check this property
  - using a symbol table
  - or even in one pass :-(
- Solution
  - Pass 1: Collect all class names
  - Pass 2: Do the checking
  - ?
  - Pass 4: Profit!



- Semantic analysis requires **multiple passes**
  - Probably more than two

Q: Advertising (832 / 842)

- Translate the last line in this French **M&Ms** jingle: *Nous sommes les M&Ms / Nous sommes les M&Ms / Des belles coleurs en choix / Des belles coleurs en choix / Tout le monde nous aime / C'est nous, les M&Ms / M&Ms fondent dans la bouche, pas dans la main.*

Real-World Languages

- This Asian language, sometimes called Siamese, is mutually intelligible with Lao and is spoken by 26+ million. It is tonal and has a complex writing system. The language's literature is influenced by India; its literature epic is a version fo the Ramayana.
  - Example: สวัสดี

Q: Games (575 / 842)

- This line of female dolls with fruit-dessert names was initially introduced in 1980 and included sidekicks Blueberry Muffin and Crepe Suzette to help fight against Sour Grapes.

Types

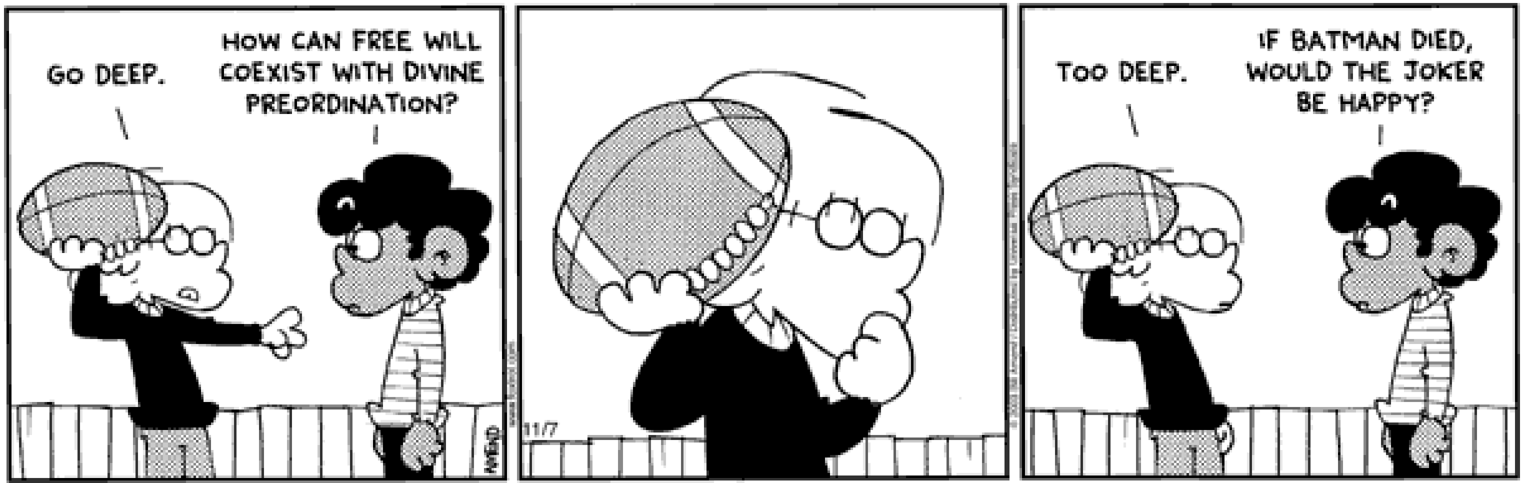
- What is a **type**?
  - The notion varies from language to language
- Consensus
  - A set of values
  - A set of valid operations on those values
- Classes are one instantiation of the modern notion of type

Why Do We Need Type Systems?

Consider the assembly language fragment

addi $r1, $r2, $r3

What are the types of $r1, $r2, $r3?



Types and Operations

- Certain operations are **legal** or **valid** for values of each type

  - It doesn't make sense to add a function pointer and an integer in C

  - It does make sense to add two integers

  - But both have the same assembly language implementation!

Type Systems

- A language's **type system** specifies which operations are valid for which types
- The goal of type checking is to ensure that operations are used with the correct types
  - Enforces intended interpretation of values, because nothing else will!
    - Our last, best hope … for victory!
- Type systems provide a concise formalization of the semantic checking rules

What Can Types do For Us?

- Can detect certain kinds of errors
- Memory errors:
  - Reading from an invalid pointer, etc.
- Violation of **abstraction** boundaries:

```
class FileSystem {
   open(x : String) : File {
        …
   }
…
}
```

```
class Client {
   f(fs : FileSystem) {
      File fdesc <- fs.open("foo")
      …
   } -- f cannot see inside fdesc !
}
```

Type Checking Overview

- Three kinds of languages:
  - **Statically typed**: All or almost all checking of types is done as part of compilation (C, Java, Cool, OCaml, C#, C++, ...)
  - **Dynamically typed**: Almost all checking of types is done as part of program execution (Scheme, Ruby, Python, PHP, JavaScript, …)
  - **Untyped**: No type checking (machine code)

The Type Wars

- Competing views on static vs. dynamic typing
- Static typing proponents say:
  - Static checking catches many programming errors at compile time
  - Avoids overhead of runtime type checks
- Dynamic typing proponents say:
  - Static type systems are restrictive
  - Rapid prototyping easier in a dynamic type system

The Type Wars (Cont.)

- In practice, most code is written in statically typed languages with an “escape” mechanism
  - Unsafe casts in C, native methods in Java, unsafe modules in Modula-3
- Dynamic typing (sometimes called “duck typing”) is big in the scripting / glue world

Cool Types

- The **types** are:
  - Class names
  - SELF_TYPE
- There are *no* unboxed base types (int in Java)
- The user declares types for all identifiers
- The compiler **infers** types for expressions
  - Infers a type for *every* expression

Type Checking and Type Inference

- **Type Checking** is the process of verifying fully typed programs
- **Type Inference** is the process of filling in missing type information
- The two are different, but are often used interchangeably

Rules of Inference

- We have seen two examples of formal notation specifying parts of a compiler
  - Regular expressions (for the lexer)
  - Context-free grammars (for the parser)
- The appropriate formalism for type checking is **logical rules of inference**

Why Rules of Inference?

- **Inference rules** have the form

  If Hypothesis is true, then Conclusion is true

- Type checking computes via reasoning

  If E_1 and E_2 have certain types,

  then E_3 has a certain type

- **Rules of inference** are a compact notation for "If-Then" statements

From English to an Inference Rule

- The notation is easy to read (with practice)

- Start with a simplified system and gradually add features

- Building blocks
  - **Symbol $\wedge$ is "and"**
  - **Symbol $\Rightarrow$ is "if-then"**
  - **$x{:}T$ is "x has type T"**

English to Inference Rules (2)

If e_1 has type Int and e_2 has type Int,
then $e_1 + e_2$ has type Int

(e_1 has type Int $\wedge$ e_2 has type Int) $\Rightarrow$
$e_1 + e_2$ has type Int

$(e_1\text{: Int} \wedge e_2\text{: Int}) \Rightarrow e_1 + e_2\text{: Int}$

English to Inference Rules (3)

The statement

$$(e_1 : \text{Int} \wedge e_2 : \text{Int}) \Rightarrow e_1 + e_2 : \text{Int}$$

is a special case of

$$(\text{ Hypothesis}_1 \wedge \ldots \wedge \text{Hypothesis}_n) \Rightarrow \text{Conclusion}$$

This is an inference rule

Notation for Inference Rules

- By tradition inference rules are written

$$\frac{\vdash \text{Hypothesis}_1 \quad \ldots \quad \vdash \text{Hypothesis}_n}{\vdash \text{Conclusion}}$$

- Cool type rules have hypotheses and conclusions of the form:

$$\vdash e : T$$

- $\vdash$ means "we can prove that . . ."

Two Rules

$$\frac{}{\vdash i : \text{Int}} \; [\text{Int}]$$

(i is an integer)

$$\frac{\vdash e_1 : \text{Int} \qquad \vdash e_2 : \text{Int}}{\vdash e_1 + e_2 : \text{Int}} \; [\text{Add}]$$

Two Rules (Cont.)

- These rules give templates describing how to type integers and + expressions
- By filling in the templates, we can produce complete typings for expressions
- We can fill the template with ANY expression!

$$\frac{\vdash \text{true} : \text{Int} \qquad \vdash \text{false} : \text{Int}}{\vdash \text{true} + \text{false} : \text{Int}}$$

Example: 1 + 2

$$\dfrac{\dfrac{}{\vdash 1 : \text{Int}} \qquad \dfrac{}{\vdash 2 : \text{Int}}}{\vdash 1 + 2 : \text{Int}}$$

Homework

- **Compilers: PA6c Checkpoint Due**
- **Spring Break!**
- **Guest Lecture on Return: Claire Le Goues**
- Should I put off PA4c?