Semantic Analysis and Type checking

- A compiler has to do semantic checks in addition to syntactic checks.
- Semantic checks
  - Static – done during compilation
  - Dynamic – done during run-time
- ***Type checking*** is one of these static checking operations.
  - we may not do all type checking at compile-time.
  - Some systems also use dynamic type checking too.

The 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**

Errors

let y: Int in x + 3

Error?

let y: String ← "abc" in y + 3

Error?

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?

- Checks of many kinds . . . coolc checks:
  1. All identifiers are declared
  2. Types
  3. Inheritance relationships
  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

Scope

- **Matching identifier declarations with uses**
  - **Important static analysis step in most languages**
  - **Including COOL!**

```
fn main() {// Parent scope
let x = 1;{    // `x` in this nested scope shadows `x` in the parent scope.
    let x = "Hello, world";
    assert_eq!(x, 1);
    }
}
```

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 runtime behavior**
  - **Cool has static scope**

- **A few languages are dynamically scoped**
  - **Lisp, Perl**
  - **Lisp has changed to mostly static scoping**
  - **Scope depends on execution of the program**

Static Scope

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

Uses of x refer to closest enclosing definition

Dynamic Scope

- **A dynamically-scoped variable refers to the closest enclosing binding in the execution of the program**

Example

```
bar(x) = x+a
foo(y) = let a← 4 in bar(3);
baz(z) = let a← 5 in bar(3)
```

Scope in Cool

- Cool identifier names are introduced by
  1. Class declarations (introduce class names)
  2. Method definitions (introduce method names)
  3. Let expressions (introduce object id's)
  4. Formal parameters (introduce object id's)
  5. Attribute definitions in a class (introduce object id's)
  6. Case expressions (introduce object id's)

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**

```
Class Foo {
   . . .
   let y: Bar in . . .
};
Class Bar {
   . . .
};
```

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

More More Scope in Cool

- 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
- Methods may also be redefined (overridden)

SYMBOL TABLE AND SCOPE

- Symbol tables typically need to support multiple declarations of the same identifier within a program.

- We shall implement scopes by setting up a separate symbol table for each scope.

Who Creates Symbol Table??

- Identifiers and attributes are entered by the analysis phases when processing a definition (declaration) of an identifier

- In simple languages with only global variables and implicit declarations:
  - ✓ The scanner can enter an identifier into a symbol table if it is not already there

- In block-structured languages with scopes and explicit declarations:
  - ✓ The parser and/or semantic analyzer enter identifiers and corresponding attributes

USE OF SYMBOL TABLE

- Symbol table information is used by the analysis and synthesis phases
- To verify that used identifiers have been defined(declared)
- To verify that expressions and assignments are semantically correct -type checking
- To generate intermediate or target code

IMPLEMENTATION OF SYMBOL TABLE

- Each entry in the symbol table can be implemented as a record consisting of several field.
- These fields are dependent on the information to be saved about the name
- But since the information about a name depends on the usage of the name the entries in the symbol table records will not be uniform.
- Hence to keep the symbol tables records uniform some information are kept outside the symbol table and a pointer to this information is stored in the symbol table record.

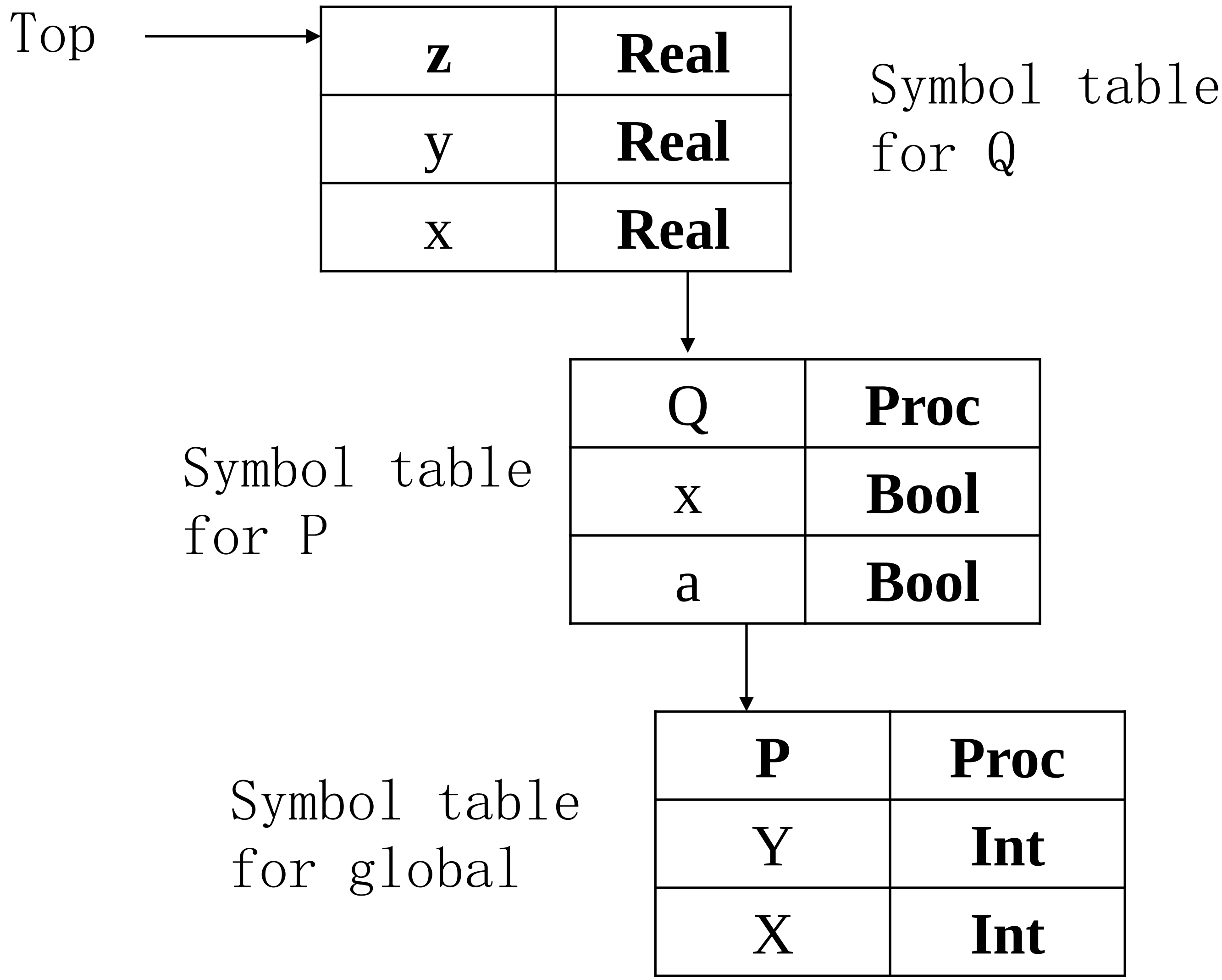
SYMBOL TABLE ORGANIZATION

```
Int x,y;

Procedure P:
    Bool x, a ;

    Procedure Q:
        Real x,y,z ;
        begin
        ......
         end
    begin

    end
```



SYMBOL TABLE DATA STRUCTURES

Issues to consider : Operations required

- Insert :Add symbol to symbol table
- Look UP: Find symbol in the symbol table (and get its attributes)
- Insertion is done only once
- Look Up is done many times
- Need Fast Look Up
- The data structure should be designed to allow the compiler to find the record for each name quickly and to store or retrieve data from that record quickly.

A Fancier Symbol Table

1. **enter_scope() start a new nested scope**
2. **find_symbol(x) finds current x (or null)**
3. **add_symbol(x) add a symbol x to the table**
4. **check_scope(x) true if x defined in current scope**
5. **exit_scope() exit current scope**

We will supply a symbol table manager for your project ,e.g., symtab.h, a list of scope, a scope is a list of entries <id, data>

Scopes - Summary

- Scoping rules match uses of identifiers with their declarations
  - Static scoping is the most common form
- Scoping rules can be implemented using symbol tables
  - In one or more passes over the AST

Class Definitions

- **Class names can be used before being defined**
- **We can't check class names**
  - **using a symbol table**
  - **or even in one pass**
- **Solution**
  - **Pass 1: Gather all class names**
  - **Pass 2: Do the checking**
- **Semantic analysis requires multiple passes**
  - **Probably more than two**

Types

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

Types and Operations

- Certain operations are legal 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!

E.g.

```
add $r1, $r2, $r3
```

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!**
- **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 (Rust):**
  - ✓ Data races
  - ✓ Dereferencing a null/dangling raw pointer
  - ✓ Reads of undef (uninitialized) memory
  - ✓ 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, Rust, Cool,)
  - Dynamically typed: Almost all checking of types is done as part of program execution (Scheme, Python)
  - Untyped: No type checking (machine code)

```
>>> x =1
>>> def f():
        print(x)
        x(1)
>>> f()
1
TypeError: 'int' object is not callable
```

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
- 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, unsafe code in Rust
  - ➢ Some dynamically typed languages support “pragmas” or “advice”
    - type declarations

Type Checking in Cool

- Type concepts in COOL
- Notation for type rules
  - Logical rules of inference
- COOL type rules
- General properties of type systems

Cool Types

- The types are:
  - Class names
  - Base classes: object, IO, Int, String, Bool
  - SELF_TYPE
  - Note: there are no base types (as int in C)

- **The user declares types for all identifiers**
- **The compiler infers types for expressions**
  - Infers a type for every sub-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 the terms are often used interchangeably**
- **We have seen two examples of formal notation specifying parts of a compiler**
  - **Regular expressions**
  - **Context-free grammars**
- **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 E1 and E2 have certain types, then E3 has a certain type**
- **Rules of inference are a compact notation for "If-Then" statements**
- **Start with a simplified system and gradually add features by type inference**
- **Building blocks**
  - **Symbol $\wedge$ is "and", $\vee$ is "or",**
  - **Symbol ➔ is "if-then"**
  - **x:T is "x has type T"**

From English to an Inference Rule

If e1 has type Int and e2 has type Int,
then e1 + e2 has type Int

(e1 has type Int $\wedge$ e2 has type Int) $\rightarrow$
(e1 + e2 has type Int)

(e1:Int $\wedge$ e2:Int) $\rightarrow$ (e1 + e2 : Int)

General inference rule:

Hypothesis$_1$ $\wedge$ Hypothesis$_2$ $\wedge \ldots \wedge$ Hypothesis$_n$ $\rightarrow$ Conclusion

Notation for Inference Rules

- **General inference rule:**
  $\textbf{Hypothesis}_1 \wedge \textbf{Hypothesis}_2 \wedge \ldots \wedge \textbf{Hypothesis}_n \Rightarrow \textbf{Conclusion}$

- **By tradition inference rules are written**

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

- **|- means "we can prove that…"**

Two Rules

$$\frac{}{\vdash i:Int}\ [int]$$

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

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

- These rules give templates describing how to type integers and + expressions
- By filling in the templates, we can produce complete types for expressions
- Example: 1+2

Soundness

- A type system is sound if
  - Whenever $\vdash e : T$
  - Then e evaluates to a value of type T
- We only want sound rules
  - But some sound rules are better than others

$$\frac{}{\vdash i : Object} \quad \text{(i is an integer constant)}$$

In Cool, class Int inherits from Object

Soundness and Completeness

- A type-system is **sound** implies that all of type-checked programs are correct (in the other words, all of the incorrect program can't be type checked), i.e. there won't be any *false negative*.

- A type-system is **complete** implies that all of the correct program can be accepted by the type checker, i.s. there won't be any *false positive*.

Type Checking Proofs

- Type checking proves facts e:T
  - Proof is on the structure of the AST e
  - Proof has the shape of the AST
  - One type rule is used for each AST node (sub-expressive)

- In the type rule used for a node e
  - The hypotheses are the proofs of types of e's subexpressions
  - The conclusion is the proof of type of e

- Types are computed in a bottom-up pass over the AST

Rules for Constants

$$\frac{}{\vdash \text{false:Bool}}\ [\text{False}] \qquad \frac{}{\vdash \text{True:Bool}}\ [\text{True}]$$

$$\frac{}{\vdash \text{s:String}}\ [\text{String}] \qquad \frac{}{\vdash \text{i:Int}}\ [\text{Int}]$$

Rule for New

- new T produces an object of type T
  - Ignore SELF_TYPE for now . . .

$$\frac{}{\vdash \text{new } T : T} \quad \textbf{[New]}$$

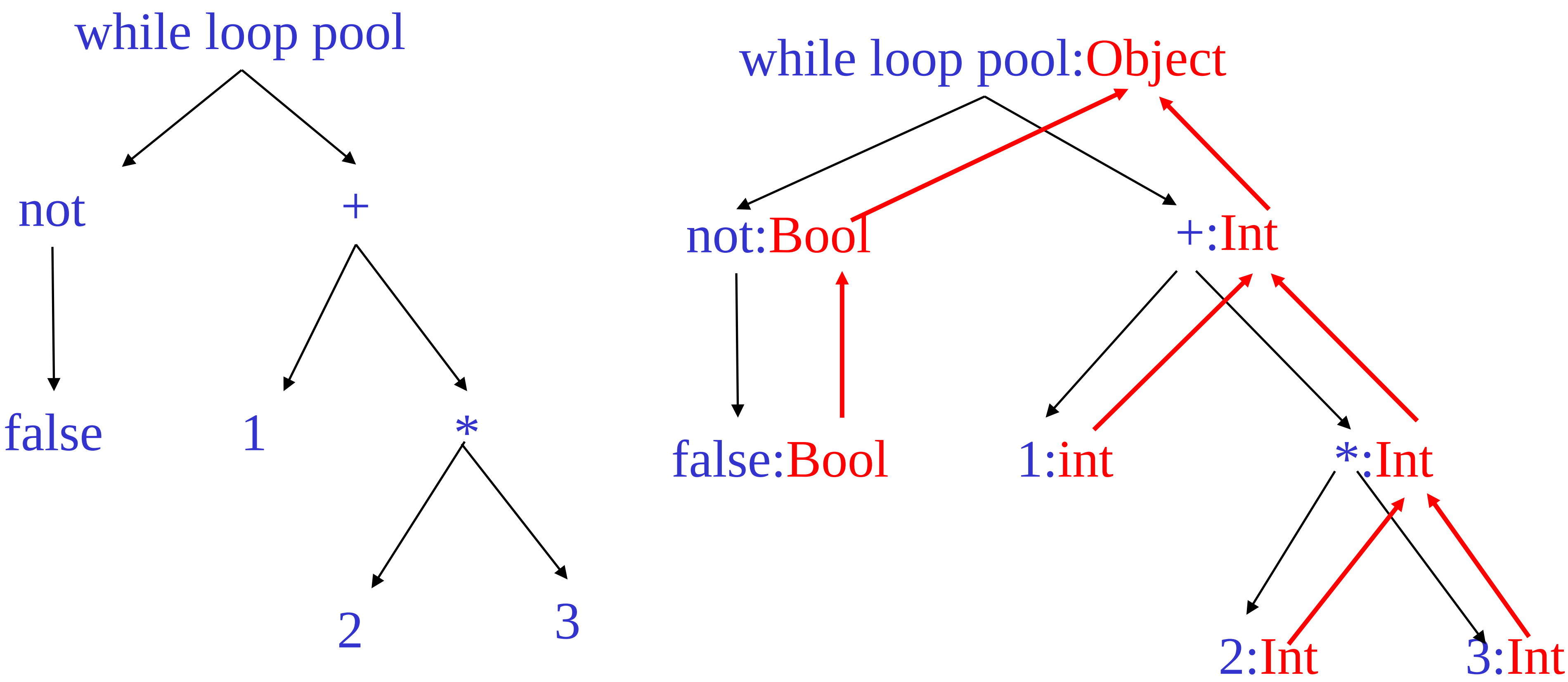
Two More Rules

$$\frac{\vdash e:Bool}{\vdash\ !\ e: Bool}\ [Not]$$

$$\frac{\vdash e_1:Bool \quad \vdash e_2:T}{\vdash \text{while } e_1 \text{ loop } e_2 \text{ pool}:Object}\ [While]$$

Typing: Example

- Typing for while not false loop 1 + 2 * 3 pool



Typing Derivations

- The typing reasoning can be expressed as an inverted tree:
  - ➢ The root of the tree is the whole expression
  - ➢ Each node is an instance of a typing rule
  - ➢ Leaves are the rules with no hypotheses

$$\dfrac{\dfrac{\vdash \text{false} : \text{Bool}}{\vdash \text{not false} : \text{Bool}} \qquad \dfrac{\vdash 1 : \text{Int} \qquad \dfrac{\vdash 2 : \text{Int} \qquad \vdash 3 : \text{Int}}{\vdash 2 * 3 : \text{Int}}}{\vdash 1 + 2 * 3 : \text{Int}}}{\vdash \text{while not false loop } 1 + 2 * 3 : \text{Object}}$$

A Problem

- What is the type of a variable reference?

$$\frac{}{\vdash x : ?}\ \textbf{[Var]}$$

- The local, structural rule does not carry enough information to give a type.
- We need a hypothesis of the form "we are in the scope of a declaration of x with type T")

A Solution: Put more information in the rules!

- A type environment gives types for free variables
- A variable is free in an expression

  if it is not defined within the expression
- A type environment is a function

O: ObjectIds → Types

E.g.:

1. **x** and **y** are free in the expression **x *y**
2. **x** is **not** free, **y** is free in **let x: Int x + y**
3. **x** and **y** are free in the expression **x + let x: Int in x + y**

Type Environments

- Let **O** be a type environment function **O: ObjectIds → Types**

The sentence **$O \vdash e : T$**

is read: Under the type environment **O**, it is provable that the expression **e** has the type **T**

Modified Rules for Constants

$$\frac{}{O \vdash false:Bool} \text{[False]}$$

$$\frac{}{O \vdash True:Bool} \text{[True]}$$

$$\frac{}{O \vdash s:String} \text{[String]}$$

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

$$\frac{O \vdash e_1:Int \quad O \vdash e_2:Int}{O \vdash e_1+e_2:Int} \text{[Add]}$$

$$\frac{O \vdash e_1:Bool \quad O \vdash e_2:T}{O \vdash \text{while } e_1 \text{ loop } e_2 \text{ pool}:Object} \text{[While]}$$

New Rule

- And we can write new rules:

$$\frac{O(x) = T}{O \vdash x : T} \text{ [Var]}$$

Let Rule

$$\frac{O(T_0/x) \mid\!- e_1 : T_1}{O \mid\!- \text{let } x: T_0 \text{ in } e : T_1} \quad \text{[Let-No-Init]}$$

$O(T_0/x)$ is an new environment obtained from O by assigning T_0 to x

$$O(T_0/x)(x)=T_0$$
$$O(T_0/x)(y)=O(y) \text{ if } x!=y$$

Note that the let-rule enforces variable scope

Let Example

- Consider the Cool expression

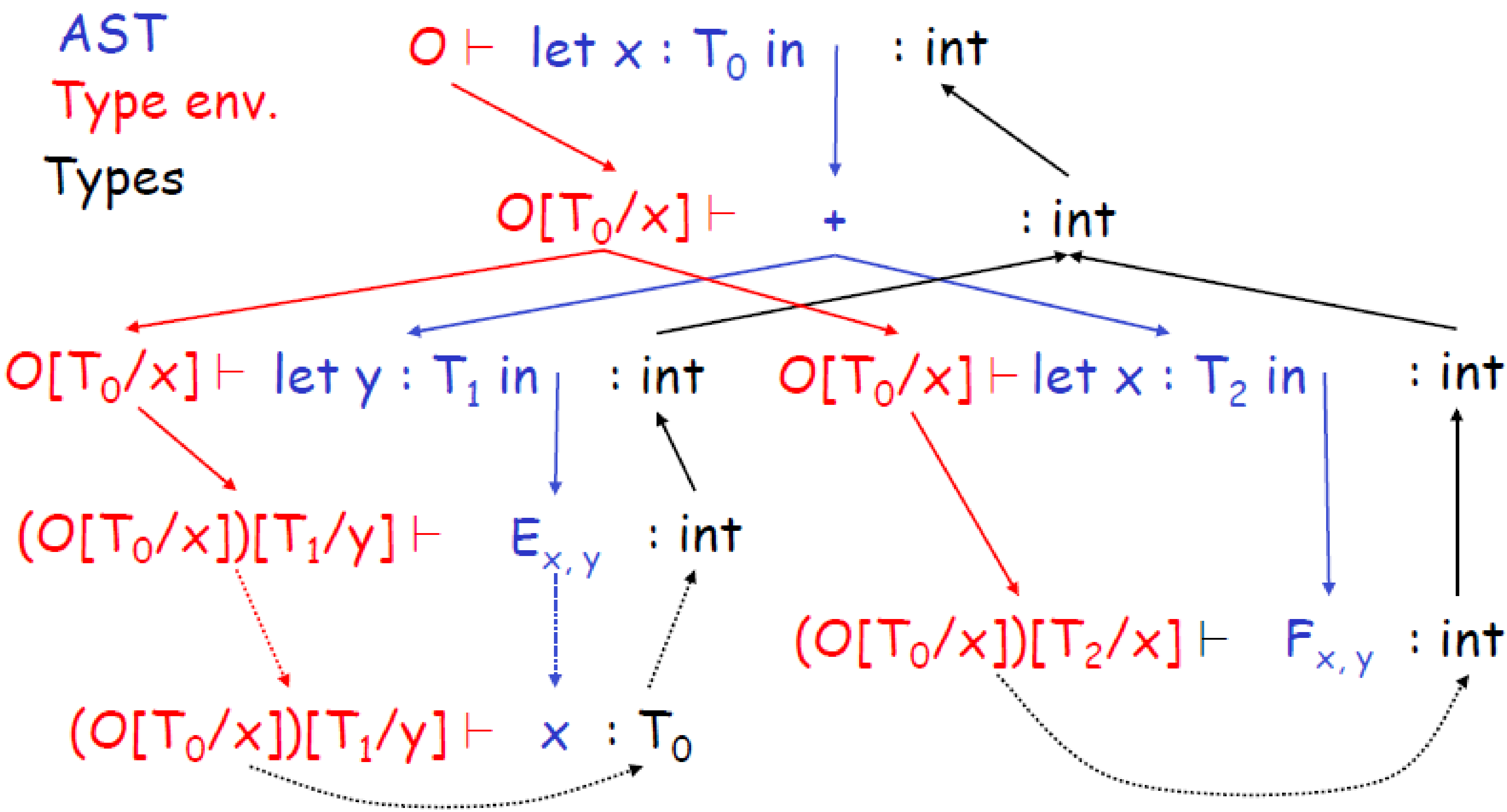
$$\textbf{let } x : T_0 \textbf{ in } (\textbf{let } y : T_1 \textbf{ in } E_{x,y}) + (\textbf{let } x : T_2 \textbf{ in } F_{x,y})$$

- Scope:
  - of y is $E_{x,y}$
  - of outer x is $E_{x,y}$
  - of inner x is $F_{x,y}$

- This is captured precisely in the let-rule

Let Example

$$\textbf{let } x : T_0 \textbf{ in } (\textbf{let } y : T_1 \textbf{ in } E_{x,y}) + (\textbf{let } x : T_2 \textbf{ in } F_{x,y})$$



Notes

- **The type environment gives types to the free identifiers in the current scope**
- **The type environment is passed down the AST from the root towards the leaves**
- **Types are computed up the AST from the leaves towards the root**

Let with Initialization

- Now consider let with initialization:

$$\frac{O \vdash e_0 : T_0 \qquad O(T_0/x) \vdash e_1 : T_1}{O \vdash \text{let } x : T_0 \leftarrow e_0 \text{ in } e_1 : T_1} \text{ [Let-Init]}$$

This rule is weak. Why?

```
class C inherits P { … }
…
let x : P ← new C in …
…
```

The previous let rule does not allow this code

Subtyping

- Define a relation $X \leq Y$ on classes (types) to say that:
  - An object of type X could be used when one of type Y is acceptable, or equivalently
  - X conforms with Y
  - In Cool this means that X is a subclass of Y

- Define a relation $\leq$ on classes (reflexive transitive closure)
  1. **$X \leq X$**
  2. **$X \leq Y$ if X inherits from Y**
  3. **$X \leq Z$ if $X \leq Y$ and $Y \leq Z$**

Let with Initialization

$$\frac{O \vdash e_0 : T_0 \qquad O(T_0/x) \vdash e_1 : T_1}{O \vdash \text{let } x: T_0 \leftarrow e_0 \text{ in } e_1 : T_1} \quad \text{[Let-Init]}$$

$$\frac{O \vdash e_0 : T \qquad T \le T_0 \qquad O(T_0/x) \vdash e_1 : T_1}{O \vdash \text{let } x: T_0 \leftarrow e_0 \text{ in } e_1 : T_1} \quad \text{[Let-Init]}$$

- Both rules for let are sound
  - Flexible rules that do not constrain programming
  - Restrictive rules that ensure safety of execution
- But more programs type check with the latter

Expressiveness of Static Type Systems

- A static type system enables a compiler to detect many common programming errors
- The cost is that some correct programs are disallowed
  – Some argue for dynamic type checking instead
  – Others argue for more expressive static type checking
- But more expressive type systems are also more complex

Dynamic And Static Types

- The dynamic type of an object is the class C that is used in the “new C” expression that creates the object
  - A run-time notion
  - Even languages that are not statically typed have the notion of dynamic type

- The static type of an expression is a notation that captures all possible dynamic types the expression could take
  - A compile-time notion

Dynamic and Static Types. (Cont.)

- In early type systems the set of static types correspond directly with the dynamic types
- Soundness theorem: for all expressions E

  dynamic_type(E) = static_type(E)

  (in **all** executions, E evaluates to values of the type inferred by the compiler)
- This gets more complicated in advanced type systems

Dynamic and Static Types in COOL

```
class A { … }
class B inherits A {…}
class Main {
   A x ← new A;
   …
   x ← new B;
   …
}
```

x has static type A

Here, x's value has dynamic type A

Here, x's value has dynamic type B

A variable of static type A can hold values of static type B, if B $\leq$ A

Dynamic and Static Types

Soundness theorem for the Cool type system:

$\forall$ E. dynamic_type(E) $\leq$ static_type(E)

Why is this Ok?

– For E, compiler uses static_type(E) (call it C)

– All operations that can be used on an object of type C can also be used on an object of type C' $\leq$ C

- Such as fetching the value of an attribute
- Or invoking a method on the object

– Subclasses can only add attributes or methods

– Methods can be redefined but with same type !

Let Example

- Consider the following Cool class definitions

  Class A { a() : Int { 0 }; }

  Class B inherits A { b() : Int { 1 }; }

- An instance of B has methods "a" and "b"
- An instance of A has method "a"
  - A type error occurs if we try to invoke method "b" on an instance of A
  - It is OK to invoke method "a" on an instance of B

  Let a: A← new B (OK)

  Let b: B← new A (error)

Let Example

$$\frac{O \vdash e_0 : T \quad T \leq T_0 \quad O \vdash e_1 : T_1}{O \vdash \text{let } x : T_0 \leftarrow e_0 \text{ in } e_1 : T_1} \text{[Let-Init]}$$

Any error?

$$\frac{O \vdash e_0 : T \quad T_0 \leq T \quad O(T_0/x) \vdash e_1 : T_1}{O \vdash \text{let } x : T_0 \leftarrow e_0 \text{ in } e_1 : T_1} \text{[Let-Init]}$$

Any error?

Comments

- The typing rules use very concise notation
- They are very carefully constructed
- Virtually any change in a rule either:
  - Makes the type system unsound

    (bad programs are accepted as well typed)
  - Or, makes the type system less usable

    (good programs are rejected)
- But some good programs will be rejected anyway
  - The notion of a good program is undecidable

Assignment

- More uses of subtyping:

$$\frac{\begin{array}{c} O(x)=T_0 \\ T_1 \leq T_0 \\ O \vdash e_1 : T_1 \end{array}}{O \vdash x \leftarrow e_1 : T_1} \quad \text{[Assign]}$$

Initialized Attributes

- Let $O_C(x) = T$ for all attributes x:T in class C
- Attribute initialization is similar to let, except for the scope of names

$$\frac{O_C(x)=T_0 \quad T_1 \leq T_0 \quad O_C \vdash e_1 : T_1}{O_C \vdash x : T_0 \leftarrow e_1;} \quad \text{[Attr-Init]}$$

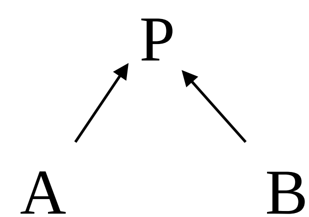
$$\frac{O_C(x)=T_0}{O_C \vdash x : T_0;} \quad \text{[Attr-No-Init]}$$

If-Then-Else

- Consider:

    if e_0 then e_1 else e_2 fi

- The result can be either e_1 or e_2,
- The dynamic type is either e_1's or e_2's type
- The best we can do statically is the smallest supertype larger than the type of e_1 and e_2



- Consider the class hierarchy

if e_0 then new A else new B fi

- Its type should allow for the dynamic type to be both A or B
    - Smallest supertype is P

Least Upper Bounds

- lub(X,Y), the least upper bound of X and Y, is Z if
  - $X \leq Z \wedge Y \leq Z$

    Z is an upper bound
  - $X \leq Z' \wedge Y \leq Z' \Rightarrow Z \leq Z'$

    Z is least among upper bounds
- In COOL, the least upper bound of two types is their least common ancestor in the inheritance tree

$$\frac{\begin{array}{l} O \vdash e_0 : Bool \\ O \vdash e_1 : T_1 \\ O \vdash e_2 : T_2 \end{array}}{O \vdash \text{if } e_0 \text{ then } e_1 \text{ else } e_2 \text{ fi} : lub(T_1, T_2)} \quad \text{[If-Then-Else]}$$

Case

- The rule for case expressions takes a lub over all branches

$$\frac{\begin{array}{l} O \vdash e_0 : T_0 \\ O[T_1/x_1] \vdash e_1 : T_1` \\ \quad \ldots\ldots \\ O[T_n/x_n] \vdash e_n : T_n` \end{array}}{\begin{array}{l} O \vdash \text{case } e_0 \text{ of} \\ \qquad x_1 : T_1 \rightarrow e_1; \\ \qquad \ldots\ldots \\ \qquad x_n : T_n \rightarrow e_n; \\ \quad \text{esac} : lub(T_1`, \ldots, T_n`) \end{array}} \text{[If-Then-Else]}$$

Method Dispatch

- There is a problem with type checking method calls:

$$\frac{\begin{array}{l} O \vdash e_0 : T_0 \\ O \vdash e_1 : T_1 \\ \ldots\ldots \\ O \vdash e_n : T_n \end{array}}{O \vdash e_0.f(e_1,\ldots,e_n) : ?} \quad [\text{Dispatch}]$$

- We need information about the formal parameters and return type of f

Notes on Dispatch

- In Cool, method and object identifiers live in different name spaces
  - A method foo and an object foo can coexist in the same scope
- In the type rules, this is reflected by a separate mapping M for method signatures

$$M(C,f) = (T_1,\ldots T_n,T)$$

means in class C there is a method f: $f(x_1{:}T_1,\ldots,x_n{:}T_n){:}\ T_n$

- Now we have two environments O and M
- The form of the typing judgment is:

$$\mathbf{O,M|\text{-}\ e{:}T}$$

read as: "with the assumption that the object identifiers have types as given by O and the method identifiers have signatures as given by M, the expression e has type T"

The Method Environment

- The method environment must be added to all rules
- In most cases, M is passed down but not actually used
  - Example of a rule that does not use M:

$$\frac{}{O,M \vdash \text{false} : \text{Bool}} \text{[False]} \qquad \frac{}{O,M \vdash 1 : \text{Int}} \text{[Int]}$$

$$\frac{O,M \vdash e_1 : \text{Int} \quad O,M \vdash e_2 : \text{Int}}{O,M \vdash e_1 + e_2 : \text{Int}} \text{[Add]}$$

$$\frac{O,M \vdash e_1 : \text{Bool} \quad O,M \vdash e_2 : T}{O,M \vdash \text{while } e_1 \text{ loop } e_2 \text{ pool} : \text{Object}} \text{[While]}$$

  - Only the dispatch rules use M

Method Dispatch

- There is a problem with type checking method calls:

$$\frac{\begin{array}{c} O,M \vdash e_0:T_0 \\ O,M \vdash e_1:T_1 \\ \ldots\ldots \\ O,M \vdash e_n:T_n \\ M(T_0, f)=(T_1`,\ldots,T_n`,T) \\ T_i \leq T_i` \text{ for all } 1 \leq i \leq n \end{array}}{O,M \vdash e_0.f(e_1,\ldots,e_n):T} \quad [\text{Dispatch}]$$

- We need information about the formal parameters and return type of f

Static Dispatch

- Static dispatch is a variation on normal dispatch
- The method is found in the class explicitly named by the programmer
- The inferred type of the dispatch expression must conform to the specified type

$$\frac{\begin{array}{c} O,M \vdash e_0 : T_0 \\ O,M \vdash e_1 : T_1 \\ \ldots\ldots \\ O,M \vdash e_n : T_n \\ M(T, f) = (T_1`, \ldots, T_n`, T_{n+1}) \\ T_i \leq T_i` \text{ for all } 1 \leq i \leq n \\ T_0 \leq T \end{array}}{O,M \vdash e_0@T.f(e_1, \ldots, e_n) : T_{n+1}} \quad \text{[StaticDispatch]}$$

Handling the SELF_TYPE

- Recall that type systems have two conflicting goals:
  - Give flexibility to the programmer
  - Prevent valid programs to "go wrong"

    Milner, 1981: "Well-typed programs do not go wrong"
- An active line of research is in the area of inventing more flexible type systems while preserving soundness

An Example

```
class Count {
    i : Int ← 0;
    inc () : Count {
        {
            i ← i + 1;
            self;
        }
    };
};
```

Any error?

```
class Stock inherits Count {
    name() : String { …};
};

class Main {
a : Stock ← (new Stock).inc ();
… a.name() …
};
```

- (new Stock).inc() has dynamic type Stock,
- So it is legitimate to write a : Stock ← (new Stock).inc ()
- But this is not well-typed: (new Stock).inc() has static type Count
- The type checker "looses" type information
- This makes inheriting inc useless
  - So, we must redefine inc for each of the subclasses, with a specialized return type

SELF_TYPE to the Rescue

- Insight:
  - inc returns "self"
  - Therefore the return value has same type as "self"
  - Which could be Count or any subtype of Count !
  - In the case of (new Stock).inc () the type is Stock
- We introduce the keyword SELF_TYPE to use for the return value of such functions
- SELF_TYPE allows the return type of inc to change when inc is inherited
- Modify the declaration of inc to read

  inc() : SELF_TYPE { … }

- The type checker can now prove:

  O, M |- (new Count).inc() : Count

  O, M |- (new Stock).inc() : Stock

- The program from before is now well typed

Notes About SELF_TYPE

- SELF_TYPE is not a dynamic type. It is a static type
- It helps the type checker to keep better track of types
- It enables the type checker to accept more correct programs
- In short, having SELF_TYPE increases the expressive power of the type system

- What can be the dynamic type of the object returned by inc?
  – Answer: whatever could be the type of "self"

    class A inherits Count { } ;
    class B inherits Count { } ;
    class C inherits Count { } ;
    (inc could be invoked through any of these classes)

– Answer: Count or any subtype of Count

SELF_TYPE and Dynamic Types

- In general, if SELF_TYPE appears textually in the class C as the declared type of E then it denotes the dynamic type of the "self" expression:

$$\text{dynamic\_type}(E) = \text{dynamic\_type}(\text{self}) \leq C$$

- Note: The meaning of SELF_TYPE depends on where it appears
  - We write SELF_TYPE_C to refer to an occurrence of SELF_TYPE in the body of C

$$\textbf{SELF\_TYPE}_C \leq \textbf{C}$$

Type Checking

- This suggests a typing rule:

$$SELF\_TYPE_C \leq C$$

- This rule has an important consequence:
  – In type checking it is always safe to replace $SELF\_TYPE_C$ by C
- This suggests one way to handle SELF_TYPE :
  – Replace all occurrences of $SELF\_TYPE_C$ by C
- This would be correct but it is like not having SELF_TYPE at all

Operations on SELF_TYPE

- Recall the operations on types
  - $T_1 \leq T_2$ T_1 is a subtype of T_2
  - $lub(T_1,T_2)$ the least-upper bound of T_1 and T_2
- We must extend these operations to handle SELF_TYPE
- Let T and T' be any types but SELF_TYPE
- Four cases:
  1. $SELF\_TYPE_C \leq T$ if $C \leq T$
     - $SELF\_TYPE_C$ can be any subtype of C including C itself
     - Thus this is the most flexible rule we can allow
  2. $SELF\_TYPE_C \leq SELF\_TYPE_C$
  3. $T \leq SELF\_TYPE_C$ always false
     - Note: $SELF\_TYPE_C$ can denote any subtype of C.
  4. $T \leq T'$ (according to the rules from before)

Extending lub(T,T')

- Let T and T' be any types but SELF_TYPE
- Again there are four cases:

1. $\text{lub}(\text{SELF\_TYPE}_C, \text{SELF\_TYPE}_C) = \text{SELF\_TYPE}_C$

2. $\text{lub}(\text{SELF\_TYPE}_C, T) = \text{lub}(C, T)$

This is the best we can do because $\text{SELF\_TYPE}_C \leq C$

3. $\text{lub}(T, \text{SELF\_TYPE}_C) = \text{lub}(C, T)$

4. lub(T, T') defined as before

Where Can SELF_TYPE Appear in COOL?

- The parser checks that SELF_TYPE appears only where a type is expected
- But SELF_TYPE is not allowed everywhere a type can appear:

1. class T inherits T' {…}: T, T' cannot be SELF_TYPE

- Because SELF_TYPE is never a dynamic type

2. m@T(E1,…,En)

- T cannot be SELF_TYPE

3. x : T.

- T can be SELF_TYPE, an attribute whose type is $SELF\_TYPE_C$

4. let x : T in E

- T can be SELF_TYPE, x has type $SELF\_TYPE_C$

5. new T

- T can be SELF_TYPE, creates an object of the same type as self

6. m(x : T) : T' { … } Only T' can be SELF_TYPE !

Typing Rules for SELF_TYPE

- Since occurrences of SELF_TYPE depend on the enclosing class, we need to know the class in which an expression occurs.
- We need to carry more context during type checking
- New form of the typing judgment:

O,M,C |- e : T

  – A mapping O giving types to object id's
  – A mapping M giving types to methods
  – The current class C where e occurs

Type Checking Rules

- The next step is to design type rules using SELF_TYPE for each language construct
- Most of the rules remain the same except that $\leq$ and lub are the new ones
- Example:

$$\frac{O,M,C \vdash e_1 : Int \quad O,M,C \vdash e_2 : Int}{O,M,C \vdash e_1 + e_2 : Int} \text{[Add]}$$

$$\frac{O(x) = T_0 \quad O,M,C \vdash e_1 : T_1 \quad T_1 \leq T_0}{O,M,C \vdash x \leftarrow e_1 : T_1} \text{[Assign]}$$

What's Different?

$$\frac{\begin{array}{c} O,M,C \vdash e_0:T_0 \\ O,M,C \vdash e_1:T_1 \\ \ldots\ldots \\ O,M,C \vdash e_n:T_n \\ M(T_0, f)=(T_1`,\ldots,T_n`,T_{n+1}`) \\ T_i \leq T_i` \text{ for all } 1 \leq i \leq n \\ T_{n+1}` \neq SELF\_TYPE \end{array}}{O,M,C \vdash e_0.f(e_1,\ldots,e_n):T_{n+1}`}$$

$$\frac{\begin{array}{c} O,M,C \vdash e_0:T_0 \\ O,M,C \vdash e_1:T_1 \\ \ldots\ldots \\ O,M,C \vdash e_n:T_n \\ M(T_0, f)=(T_1`,\ldots,T_n`, SELF\_TYPE) \\ T_i \leq T_i` \text{ for all } 1 \leq i \leq n \end{array}}{O,M,C \vdash e_0.f(e_1,\ldots,e_n):T_0}$$

> If the return type of the method is SELF_TYPE then the type of the dispatch is the type of the dispatch expression

An Example

```
class Count {
    i : int ← 0;
    inc () : SELF_TYPE{
        {
            i ← i + 1;
            self;
        }
    };
};
```

```
class Stock inherits Count {
    name() : String { …};
};

class Main {
a : Stock ← (new Stock).inc ();
… a.name() …
};
```

- (new Stock).inc() has dynamic type Stock,
- (new Stock).inc() has static type Stock,

- So this is well-typed

Static Dispatch

- Recall the original rule for static dispatch

$$\frac{\begin{array}{c} O,M \vdash e_0:T_0 \\ O,M \vdash e_1:T_1 \\ \ldots\ldots \\ O,M \vdash e_n:T_n \\ M(T, f)=(T_1`,\ldots,T_n`,T_{n+1}`) \\ T_i \leq T_i` \text{ for all } 1 \leq i \leq n \\ T_0 \leq T \\ T_{n=1}` \neq SELF\_TYPE \end{array}}{O,M \vdash e_0@T.f(e_1,\ldots,e_n):T_{n+1}`}$$

$$\frac{\begin{array}{c} O,M \vdash e_0:T_0 \\ O,M \vdash e_1:T_1 \\ \ldots\ldots \\ O,M \vdash e_n:T_n \\ M(T, f)=(T_1`,\ldots,T_n`, SELF\_TYPE) \\ T_i \leq T_i` \text{ for all } 1 \leq i \leq n \\ T_0 \leq T \end{array}}{O,M \vdash e_0@T.f(e_1,\ldots,e_n):T_0}$$

New Rules

- There are two new rules using SELF_TYPE

$$\frac{}{O,M,C \vdash \text{self} : \text{SELF\_TYPE}_C}$$

$$\frac{}{O,M,C \vdash \text{new SELF\_TYPE} : \text{SELF\_TYPE}_C}$$

- There are a number of other places where SELF_TYPE is used

Attributes and Methods

$$\frac{O_C(x)=T_0 \quad O_C \mid\!- e_1:T_1 \quad T_1 \le T_0}{O_C \mid\!- x:T_0 \leftarrow e_1;}\ [\text{Attr-Init}]$$

$$\frac{O_C(x)=T_0}{O_C \mid\!- x:T_0;}\ [\text{Attr-No-Init}]$$

$$\frac{M(C,f)=(T_1,\ldots,T_n,T_0) \quad T_0 \ne SELF\_TYPE \quad T_0' \le T_0 \quad O_C[SELF\_TYPE_C/self][T_1/x_1]\ldots[T_n/x_n], M, C \mid\!- e: T_0'}{O_C,M,C \mid\!- f(x_1:T_1,\ldots,x_n:T_n):T_0\ \{\ e\ \}}\ [\text{Method}]$$

$$\frac{M(C,f)=(T_1,\ldots,T_n, SELF\_TYPE) \quad T_0' \le SLEF\_TYPE_C \quad O_C[SELF\_TYPE_C/self][T_1/x_1]\ldots[T_n/x_n], M, C \mid\!- e: T_0'}{O_C,M,C \mid\!- f(x_1:T_1,\ldots,x_n:T_n): SELF\_TYPE\ \{\ e\ \}}\ [\text{Method}]$$

Summary of SELF_TYPE

- The extended $\leq$ and lub operations can do a lot of the work. Implement them to handle SELF_TYPE
- SELF_TYPE can be used only in a few places. Be sure it isn't used anywhere else.
- A use of SELF_TYPE always refers to any subtype in the current class
  - The exception is the type checking of dispatch.
  - SELF_TYPE as the return type in an invoked method might have nothing to do with the current class

Why Cover SELF_TYPE ?

- SELF_TYPE is a research idea
  - It adds more expressiveness to the type system
- SELF_TYPE is itself not so important
  - except for the project
- Rather, SELF_TYPE is meant to illustrate that type checking can be quite subtle
- In practice, there should be a balance between the complexity of the type system and its expressiveness

Type Systems

- The rules in these lecture were COOL-specific
  - Other languages have very different rules
- General themes
  - Type rules are defined on the structure of expressions
  - Types of variables are modeled by an environment
- Types are a play between flexibility and safety

One-Pass Type Checking

- COOL type checking can be implemented in a single traversal over the AST
- Type environment is passed down the tree
  - From parent to child
- Types are passed up the tree
  - From child to parent

$$\frac{O,M,C \vdash e_1:Int \quad O,M,C \vdash e_2:Int}{O,M,C \vdash e_1+e_2:Int}\ [Add]$$

```
TypeCheck(Environment, n) // node n denotes the expression e1 + e2
{
   T1 = TypeCheck(Environment, n.leftchild);
   T2 = TypeCheck(Environment, n.rightchild);
   Check T1 == T2 == Int;
   return Int;
}
```