Compiler Construction
SMD163

Lecture 15: Polymorphism

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Plan for This Lecture:

- A continuing look at type systems as an example of static analysis.
- How can we balance safety with flexibility?
  - One answer: Polymorphism
- How can we balance documentation with clutter?
  - One answer: Type Inference
- There's a lot we could talk about here, but we'll only be scraping the surface …

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Polymorphism:

- According to my dictionary:

  polymorphism [poli *mawr* fizm] *n* occurrence of several types of individual organism within one species.

- From the Greek:

  polymorphism = "many shapes".

- In programming languages:

  A single value/function/object can be used at many different types.

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Some Examples:

- Some operations work on only <u>one</u> type of value:

$$\frac{E \vdash e_1 : \text{boolean} \qquad E \vdash e_2 : \text{boolean}}{E \vdash e_1 \,\&\&\, e_2 : \text{boolean}}$$

- Some operations work on <u>any</u> type of value:

$$\frac{E \vdash e_1 : T[\,] \qquad E \vdash e_2 : \text{int}}{E \vdash e_1[e_2] : T}$$

- Some operations work only on <u>some</u> types of value:

$$\frac{E \vdash e_1 : t \qquad E \vdash e_2 : t \quad t \in \{\text{int,float}\}}{E \vdash e_1 < e_2 : \text{boolean}}$$

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Terminology:

- A monomorphic operator works on only one type of argument. (e.g., the && operator.)
- A polymorphic operator works on more than one type of argument.
  - Parametric polymorphism: essentially the same implementation/algorithm is used for all types of argument. (e.g., Array indexing.)
  - Ad-hoc polymorphism: different implementations are used for different types of value (e.g., numeric comparisons.)

Subtype Polymorphism:

- There is another kind of polymorphism in languages that allow implicit coercion of a value from one type to another.

$$\frac{E \vdash e : T \qquad T < S}{E \vdash e : S}$$

- For example, in C, Java, etc., any `int` value can be used where a `float` is expected. (`int < float`)
- In Java, using the code for the quick calculator as an example, any `IntExpr` or `BinExpr` can be used where an `Expr` is expected. (`IntExpr < Expr, BinExpr < Expr`)

Implementing Polymorphism:

- Each different kind of polymorphism requires different implementation techniques, both for type checking and for run-time/execution.
- Each different kind of polymorphism is useful.
- Combining multiple forms of polymorphism in a single language can be challenging.
- We will be focusing on parametric polymorphism in this lecture.

Enforced Monomorphism:

- Suppose that A is a Java class, and consider the following function:

```
void swap(A[] arr, int x, int y) {
    A temp = arr[x];
    arr[x] = arr[y];
    arr[y] = temp;
}
```

- This definition will work for any choice of A.
- The definition uses only polymorphic constructs.
- But Java restricts it to a particular choice of A.

Lifting the Restriction:

- Let's introduce a way to indicate that A is a generic type – a parameter, not a fixed class:

```
void swap<A>(A[] arr, int x, int y) {
    A temp = arr[x];
    arr[x] = arr[y];
    arr[y] = temp;
}
```

- `arr`, `x`, and `y` are value parameters: any values will do (provided they have the right type!) …
- `A` is a type parameter: any type will do …

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Using a Polymorphic Function:

- To use a polymorphic function, we just need to specify the type A as part of the call:

```
int[] intValues  = new Int[] {1,2,3};
Button[] buttons = new Button[] {
                                new
  Button("OK"),
                                new
  Button("Cancel")
                              };

… swap<int>(intValues, 1, 2) …

… swap<Button>(buttons, 0, 1) …
```

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Parameterized Types:

- Polymorphic functions start to become really useful in a language that has parameterized datatypes:
  - Arrays of A's
  - Pairs of A's and B's
  - Lists of A's …

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Linked Lists:

- Linked lists are a very useful data structure:

```
class List {
    Value data;
    List  next;
    List(Value data, List next) {
        this.data = data;
        this.next = next;
    }
}
```

- What's special about the Value type used here?
- … Nothing!   (i.e., any class would do)

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A Profusion of Linked Lists:

- But we often need lots of different Value types in a single program:

```
class StringList {
    String  data;
    StringList  next;
    StringList(String data,StringList next) {
        this.data = data;
        this.next = next;
    }
}
class IntegerList { … }
class ButtonList { … }
```

- It's irritating to repeat this "boilerplate" over and over again … and it makes the program harder to maintain …

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A Profusion of Functions too!

- We often need similar functions for each list type too:

```
int length(StringList list) {
    int len = 0;
    for (; list!=null; list=list.next) {
        len++;
    }
    return len;
}
int length(ButtonList list) {
    int len = 0;
    for (; list!=null; list=list.next) {
        len++;
    }
    return len;
}
```

Exactly the same code in each definition!

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But why not use class Object?

- The class Object is the ultimate parent of all classes:

```
class List {
    Object data;
    List  next;
    List(Object data, List next) {
        this.data = data;
        this.next = next;
    }
}
```

- Now we can easily build lists of Buttons as well as Strings…

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But why not use class Object?

- However, this freedom actually applies to each particular list:

```
List x = new List(new String("abc"), null);
…
x = new List(new Button(), x);
…
```

- Moreover, all we know about the elements of a list is that they are "objects"; their type is Object. Thus, downcasts are needed:

```
String s =  (String)(x.data);
```

- Now what if the data element of (the head of) x was accidentally a button? Such an error will not be caught until run-time!

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A Parameterized List Type:

- In principle, we could avoid code duplication as well as downcasts by <u>parameterizing</u> the definition of the `List` class:

```
class List<Value> {
    Value data;
    List  next;
    List(Value data, List<Value> next) {
        this.data = data;
        this.next = next;
    }
}
```

- This is an example of a <u>parameterized datatype</u>.

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A Parameterized List Type:

- Type parameters now indicate the contents of each list:

```
List<String> x = new List<String>(new
  String("abc"),null);
…
List<Button> y = new List<Button>(new Button(), null);
…
```

- Lists of different type cannot be confused:

```
…
List<Button> y = new List<Button>(new Button(),x);
```

- Elements have their right type without casting:

```
String s = x.data;
Button b = y.data;
```

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A Polymorphic Length Function:

- Moreover, we need only one definition for the length function:

```
int length<Value>(List<Value> list) {
    int len = 0;
    for (; list!=null; list=list.next) {
        len++;
    }
    return len;
}
```

- One concept, one definition.
- Less code to write, less code to understand, less code to maintain.

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So how can this feature be implemented?

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Types:

- Previously, we have assumed we have a small collection of primitive types (int, boolean, …), the array type constructor (int[], …), as well as an extensible set of simple class types (Button, List, …)

- Now we have added:
  - Parameterized types of the form $T\langle A_1,\ldots,A_n\rangle$
  - Type parameters (or "type variables"), which are placeholders for arbitrary types that will be supplied later.

Type Checking Functions:

- Write $R(A_1,\ldots,A_n)$ for the type of a function that returns a result of type R given arguments of type $A_1,\ldots,A_n$.

- We will assume that an environment F is provided mapping function names to function types.

- Here is a rule for type checking a function call:

$$\frac{F(f)=R(A_1,\ldots,A_n) \quad E,F \vdash e_1:A_1 \;\ldots\; E,F \vdash e_n:A_n}{E,F \vdash f(e_1,\ldots,e_n) : R}$$

Continued …

- Note that we have extended our typing rules to use hypotheses of the form $E,F \vdash e : A$ with two environments:
  - E, which records the names and types of variables;
  - F, which records the names and types of functions.

- We choose to keep these to environments separate because functions are not "first-class" values in our language. (They cannot be stored in data structures, or used as function parameters.)

Extending our Earlier Rules:

- Technically, all of the type checking rules that we have given previously need to be extended:

$$\frac{E,F \vdash e_1 : \text{boolean} \quad E,F \vdash e_2 : \text{boolean}}{E,F \vdash e_1 \,\&\&\, e_2 : \text{boolean}}$$

$$\frac{E,F \vdash e_1 : T[] \quad E,F \vdash e_2 : \text{int}}{E,F \vdash e_1[e_2] : T}$$

etc…

- None of these rules actually uses F … but it might be needed in one of their hypotheses. This is why we need to propagate the new environment.

Checking Polymorphic Functions:

- To deal with polymorphic functions, we must extend our notation to allow function types of the form:

$$\langle P_1,\ldots,P_m\rangle\ R\ (A_1,\ldots,A_n)$$

Type parameters ($m\geq 0$) | Result type | Value parameters ($n\geq 0$)

- For example, the `length` function has type: <Value> int (List<Value>).

Instantiation:

- Polymorphic types are <u>instantiated</u> by picking a type to replace each of the parameters P_i.
- The instantiation of a polymorphic type $\langle P_1,\ldots,P_m\rangle\ R\ (A_1,\ldots,A_n)$, with types $T_1, \ldots, T_m$:
  - Is written: $[T_1/P_1,\ldots,T_m/P_m]\ R\ (A_1,\ldots,A_n)$;
  - Is obtained by replacing each occurrence of a P_i in $R(A_1,\ldots,A_n)$ with the corresponding T_i.
- We can instantiate the type of `length` to work on Strings. The result is int (List<String>).

Type Checking & Polymorphism:

- It is quite easy to extend our previous rule for type checking functions to work with polymorphic functions:

$$F(f) = \langle P_1,\ldots,P_m\rangle R\ (A_1,\ldots,A_n)$$

$$R'\ (A'_1,\ldots,A'_n) = [T_1/P_1,\ldots,T_m/P_m]\ R\ (A_1,\ldots,A_n)$$

$$\frac{E,F \vdash e_1 : A'_1 \qquad \ldots \qquad E,F \vdash e_n : A'_n}{E,F \vdash f\langle T_1,\ldots,T_m\rangle(e_1,\ldots,e_n) : R'}$$

- This might look like a big mess of symbols …
- Read carefully, and it will start to make sense!

The Hacker's Perspective:

To type check a call: $f\langle T_1,\ldots,T_m\rangle(e_1,\ldots,e_n)$

- Look up f in the function environment;
- Suppose that f has type $\langle P_1,\ldots,P_m\rangle R\ (A_1,\ldots,A_n)$;
- Replace each use of P_i in $R\ (A_1,\ldots,A_n)$ with the corresponding T_i. Call the result $R'\ (A'_1,\ldots,A'_n)$;
- Check that each argument e_i has type A'_i;
- The result type of the call is just R'.

Implementing Types:

```
class Type {
    abstract boolean equal(Type other);
    …
}
```

Test for equality of types in the “obvious” way.

```
class ParamType extends Type {
    String  name;
    Type[]  params;
    …
}
class TypeVar extends Type {
    String name;
    …
}
```

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Testing for Equality:

```
class ParamType extends Type { …
    boolean equal(Type other) {
       if (other instanceof ParamType) {
          ParamType that = (ParamType)other;
          if (name.equal(that.name)
              && params.length ==
  that.params.length) {
             for (int i=0;i<params.length; i++) {
                if
  (!params[i].equal(that.params[i]))
                   return false;
             }
             return true;
          }
       }
       return false;
    }
```

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Implementing Instantiation:

```
class Type {
    abstract Type inst(Type[] given, Type[] ps);
    …
}
```

Instantiate a polymorphic type.

```
class TypeVar extends Type {
    String name;
    Type inst(Type[] given, Type[] ps) {
       for (int i=0; i<ps.length; i++) {
          if (this.equal(ps[i])) {
             return given[i];
          }
       }
       return this;
    }
}
```

$[T_i/P_i]\ P_i = T_i$

$[T_i/P_i]\ X = X$

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Pragmatics:

- Although it is flexible, this type system can be rather cumbersome in practice:

```
List<Integer> state;
List<List<Integer>> states;
states = new
  List<List<Integer>>(state,states);
…
```

- Type names can quickly become very long, making them harder to write, and harder to get right.
- Can we get by without writing types?

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Explicit vs Implicit Typing:

- In many languages, types are specified <u>explicitly</u>:

```
int f(int a, int b) {
   int c = a + b;
   int d = a - b;
   return c*d;
}
```

- Imagine what this might look like if types were <u>implicit</u>:

```
function f(a, b) {
   var c = a + b;
   var d = a - b;
   return c*d;
}
```

Valuable documentation … or restrictive clutter?

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Typed and Safe:

Safety

```
int f(int a, int b) {
   int c = a + b;
   int d = a - b;
   return c*d;
}
```

Checked at compile-time, so we know it won't be called with the wrong type of arguments … but limited to integers…

```
function f(a, b) {
   var c = a + b;
   var d = a - b;
   return c*d;
}
```

Flexibility

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Untyped and Flexible:

Safety

```
int f(int a, int b) {
   int c = a + b;
   int d = a - b;
   return c*d;
}
```

Could work with more than just integers … but might crash at run-time if we pass the wrong type of value …

```
function f(a, b) {
   var c = a + b;
   var d = a - b;
   return c*d;
}
```

Flexibility

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Safety and Flexibility?

Safety

```
int f(int a, int b) {
   int c = a + b;
   int d = a - b;
   return c*d;
}
```

```
function f(a, b) {
   var c = a + b;
   var d = a - b;
   return c*d;
}
```

Can we have type safety without having to write types?

```
function f(a, b) {
   var c = a + b;
   var d = a - b;
   return c*d;
}
```

Flexibility

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Type Inference:

- Take a language that:
  - Doesn't require you to declare the return type of each function;
  - Doesn't require you to declare the type of each function argument;
  - Doesn't require you to declare the type of each local variable.
- Try to <u>infer</u> the information that you need by looking at the context.
- In effect, get the compiler (static analysis) to add the type information, instead of the programmer.

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For Example:

- Consider the following definition:

```
function choose(c, x, y) {
    return (c ? x : y);
}
```

- It's clear that c must be a boolean, and that x and y must have the same type.
- So we can treat `choose` as a polymorphic function:

```
A choose<A>(boolean c, A x, A y) {
    return (c ? x : y);
}
```

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New Type Variables:

- The first time we encounter a variable like x or y, we won't know what type to use for it.
- So let's make up a "new" (or "fresh") type as a first guess …
- … but be prepared to adjust our guess as we see how the variable is actually used.

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Type Checking `choose`:

When we first see the definition of choose, we know that it will have a type of the form R(U,V,W) for some types R, U, V, W, but we don't know what those types will be …

```
function choose(c, x, y) {
    return c ? x : y;
}
```

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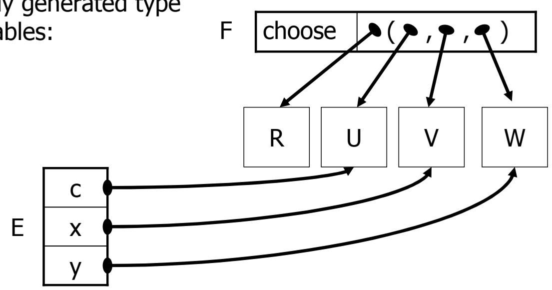
Type Checking `choose`:

So we will initialize our environments to use types that contain newly generated type variables:

```
function choose(c, x, y) {
    return c ? x : y;
}
```



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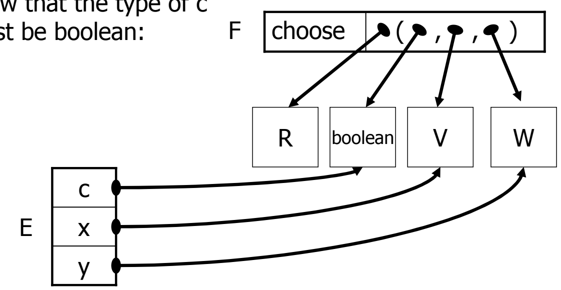
Type Checking `choose`:

Now we see c used as the first argument of a ?: expression, so we know that the type of c must be boolean:

```
function choose(c, x, y) {
    return c ? x : y;
}
```



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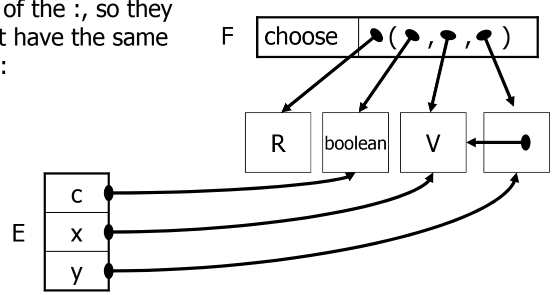
Type Checking `choose`:

Next we see that x and y are used as the two arguments on either side of the :, so they must have the same type:

```
function choose(c, x, y) {
    return c ? x : y;
}
```



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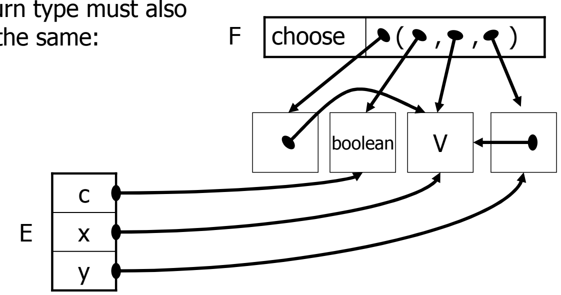
Type Checking `choose`:

Because this is the value that is returned from the function, the return type must also be the same:

```
function choose(c, x, y) {
    return c ? x : y;
}
```



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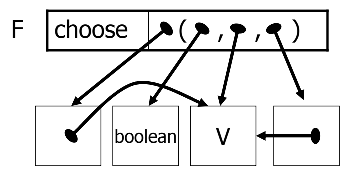
Type Checking `choose`:

Now we're done!

We leave the scope in which E was valid, and read off the inferred type for choose from F:

V(boolean, V, V).

```
function choose(c, x, y) {
    return c ? x : y;
}
```

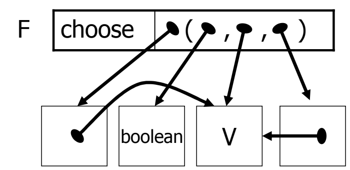


Type Checking `choose`:

Because V was a new variable, we can now infer that our function is polymorphic:

<V> V(boolean, V, V).

```
function choose(c, x, y) {
    return c ? x : y;
}
```



Implementing Type Variables:

```
class TypeVar extends Type {
   String name;

   static int nextNew = 0;
   static TypeVar fresh() {
      return new TypeVar("new" +
  nextNew++);
   }

   Type boundTo = null;
   …
}
```

This is the code we use to make "fresh" types …

We set this pointer to indicate when this type variable has been bound

Unification:

- It's no longer sufficient just to test two types for equality …
- The types might point to distinct type variables, and hence look like distinct types.
- But we can make the two types equal by <u>unifying</u> the variables; that is, by arranging for one variable to point to the other.
- Thus, <u>unification</u> plays a central role in type inference.

Implementing Unification:

```
class TypeVar extends Type {
   String name;

   Type boundTo = null;

   boolean unify(Type other) {
      if (boundTo!=null) {
         return boundTo.unify(other);
      }  else if (!other.equal(this)) {
         boundTo = other;
      }
      return true;
   }
}
```

What to do if this variable has already been bound …

Otherwise we can force the two types to be equal by binding this variable.

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What Happens at Runtime:

- How are polymorphic operations dealt with when a program is executed?
- There are two main strategies:
  - Heterogeneous;
  - Homogeneous.
- What are the main ideas? What are the tradeoffs?

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The Heterogeneous Strategy:

- The compiler generates a different piece of code for each different use of a polymorphic function.
  - A glorified macro preprocessor?
  - Bigger programs …
  - But at least the programmer doesn't have to maintain them all.
  - Separate compilation creates problems … you won't know all of the ways that a polymorphic function will be used when you compile its definition.

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The Homogeneous Strategy:

- Use *exactly* the same code for all versions of a polymorphic function.
  - Easier to implement, smaller programs.
  - A program may therefore manipulate data without knowing its type …
  - … but if you don't know it's type, then you won't know how much memory it takes, and you won't be able to move it around …
  - … unless every single data item takes exactly the same amount of storage.
  - The need for such "uniform representations" can make this implementation strategy more expensive.

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A Real Language:

- The syntax we've been using in this lecture is (almost) the syntax of a real language, GJ ("Generic Java", but, for legal reasons, they can't actually use that name …).
- The syntax is horrible … but that's because they didn't want to change the existing syntax of Java.
- Think "templates" in C++ … (but better)
- Think "generics" in Ada …
- Think typed functional languages …
- This was implemented as "generics" in Java 1.5.
- The compiler in Sun's previous JDK release was actually the GJ compiler … with the generic bits turned off! With Java 1.5 this changed…

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Summary:

- Polymorphic type systems increase flexibility without compromising on safety.
- Type checking an explicitly typed polymorphic language is straightforward. (But the backend may need more work!)
- We can use type inference so that programmers don't have to write types explicitly.

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