Environments

In virtually all programming languages, programmers create symbols (variables) and associate values with them. We discussed bindings earlier. What we want to show now is how to implement bindings. Our implementation allows us to implement *static scope rules*, since this is the most common binding method in programming languages today.

An *environment* is a data structure that associates a value with each element of a finite set of symbols – that is, it represents a set of bindings. We could think of an environment as a set of pairs

$$\{(s_1, v_1), \cdots, (s_n, v_n)\}$$

that encode the binding of symbol s_1 to value v_1, s_2 to value v_2, *etc.* The problem with this simple approach is that the same symbol may have different bindings in different parts of the program, and this approach doesn't make it clear how to determine which binding is the *current* binding.

Instead, we specify an environment as a Java object having a method called `applyEnv` that, when passed a symbol (a `String`) as a parameter, returns the current value bound to that symbol. So if `env` is an environment and `x` is a symbol,

```
env.applyEnv("x")
```

returns the value currently bound to the symbol `x`.

Environments (continued)

If there is no binding for the symbol `x` in the environment `env`, then `env.applyEnv("x")` throws an exception.

In addition to getting the current value bound to a symbol, our environment implementation provides a way to create an empty environment (one with no bindings), and a way to extend an existing environment (essentially to enter a new *block*) by adding new bindings.

But wait: what type does `applyEnv` return? In other words, what exactly is a "value"? For the time being, we assume that a "value" is an instance of a class aptly named `Val`. We will refine the notion of "value" later. If you're worried about this, just pretend that instances of the `Val` class represent integers.

Environments (continued)

Our environments are implemented as instances of a Java abstract class `Env`, a simple version of which we show here:

```
public abstract class Env {

    public static final Env empty = new EnvNull();

    public abstract Env add(Binding b);

    public static Env initEnv() {
        // initial environment with no bindings
        return new EnvNode(new Bindings(), empty);
    }

    public abstract Binding lookup(String sym); // only local bindings

    public abstract Val applyEnv(String sym);

    public Val applyEnv(Token tok) {
        return applyEnv(tok.toString());
    }

    public Env extendEnv(Bindings bindings) {
        return new EnvNode(bindings, this);
    }

}
```

Environments (continued)

We represent a binding as an instance of the class `Binding`. A `Binding` object has a `String` field named `id` that holds an identifier name (a symbol) and a `Val` field named `val` that holds the value bound to that variable.

```
public class Binding {

    public String id;
    publilc Val val;

    public Binding(String id, Val val) {
        this.id = id;
        this.val = val;
    }

}
```

Programming languages typically support many types of values – such as integers, floats, and booleans. The only `Val` type we are concerned with at this point is an integer value represented by a class `IntVal` that extends the `Val` abstract class. Think of an `IntVal` as a *wrapper* for the Java primitive type `int`. Later, we will add new `Val` types as needed to extend functionality.

Environments (continued)

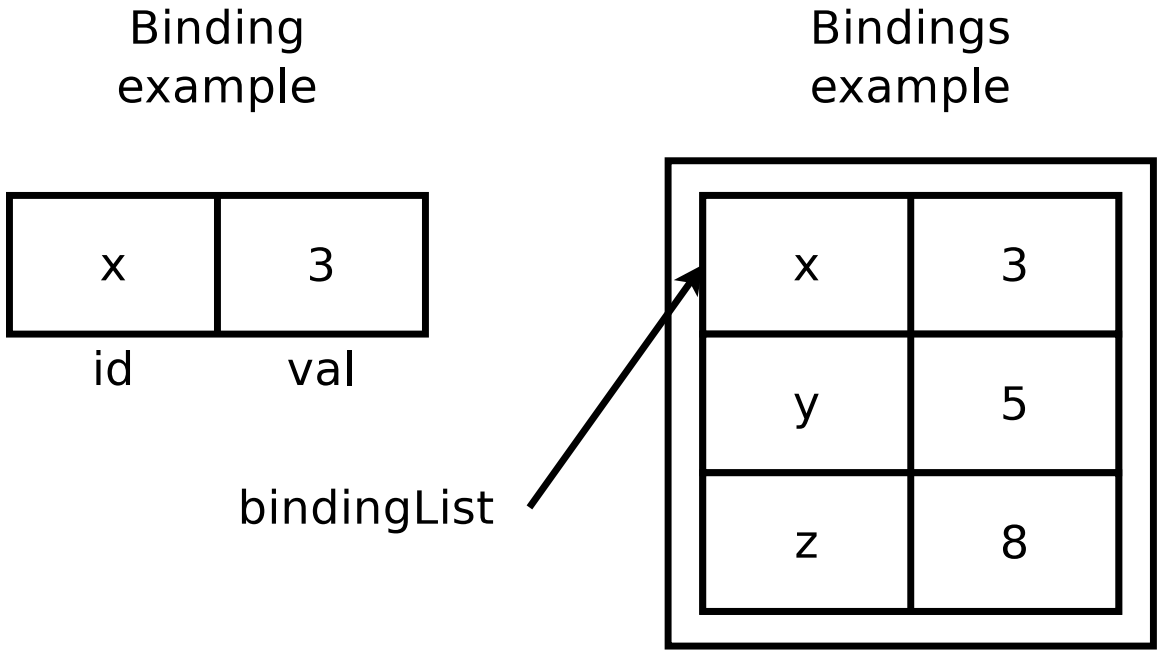
A *local environment* is a list of zero or more bindings. In the context of block-structured languages, you can think of a local environment as capturing all of the bindings defined in a particular block. We represent a local environment using the class `Bindings`. A `Bindings` object has a single field named `bindingList` which is a `List` of `Binding` objects.

```
public class Bindings {

    public List<Binding> bindingList;

    // create an empty list of bindings
    public Bindings() {
        bindingList = new ArrayList<Binding>();
    }

    public Bindings(List<Binding> bindingList) {
        this.bindingList = bindingList;
    }

    ... methods lookup() and add() are given later ...

}
```

Environments (continued)

A local environment should not have two different bindings with the same symbol, although our simple implementation does not enforce this. We will see later how to we can achieve this restriction when we build our local environments.

The following diagram gives an example of a `Binding` object that binds the symbol `"x"` to the integer (`IntVal`) value `3`, and a `Bindings` object with a `bindingList` of size three.



For the sake of simplicity, we omit drawing the extra box around the `bindingList` in future `Bindings` diagrams.

Environments (continued)

Given a local environment, we want to be able to look up the `Binding` associated with a particular symbol and to add `Binding` objects to the local environment. It is also convenient to consider adding a `Binding` obtaind from a symbol and a value. The following methods are part of the `Bindings` (local environment) class:

```
// look up the Binding associated with a given symbol
public Binding lookup(String sym) {
    for (Binding b: bindingList)
        if (sym.equals(b.id))
            return b;
    return null;
}

// add a Binding object to this local environment
public void add(Binding b) {
    bindingList.add(b);
}

// add a binding (s, v) to this local environment
public void add(String s, Val v) {
    add(new Binding(s, v));
}
```

Environments (continued)

A nonempty environment is an instance of the class `EnvNode`. An `EnvNode` object has two fields: a `Bindings` object named `bindings` that holds the local bindings and an `Env` object named `env` that refers to an enclosing (in the sense of static scope rules) environment.

In the `EnvNode` class, making a call to `lookup` for a symbol always means looking for it in the local bindings.

When we call `applyEnv` in the `EnvNode` class, we search for the symbol in the local bindings using `lookup`:

- if that returns a non-`null` `Binding` object, `applyEnv` returns the `Val` field in the `Binding`.
- if that returns `null`, `applyEnv` returns the result of calling `applyEnv` (recursively) on the enclosing environment.

The `EnvNode` class is given on the following slide.

Environments (continued)


```
public class EnvNode extends Env {

    public Bindings bindings; // list of local bindings
    public Env env;           // enclosing scope

    public EnvNode(Bindings bindings, Env env) {
        this.bindings = bindings;
        this.env = env;
    }

    public Binding lookup(Symbol sym) {
        return bindings.lookup(sym);
    }

    public Val applyEnv(String sym) {
        Binding b = bindings.lookup(sym);
        if (b == null)
            return env.applyEnv(sym);
        return b.val;
    }

}
```

Environments (continued)

An empty environment is an instance of the class `EnvNull`. An `EnvNull` object has no fields. The `lookup` method in the `EnvNull` class returns `null` (no `Binding` can be found in the empty environment), and the `applyEnv` method in this class throws a `PLCCException`.

```
public class EnvNull extends Env {

    // create an empty environment
    public EnvNull() {
    }

    // find the Val corresponding to a given id
    public Val applyEnv(String sym) {
        throw new PLCCException("no binding for "+sym);
    }

    public Binding lookup(String sym) {
        return null;
    }

}
```

Environments (continued)

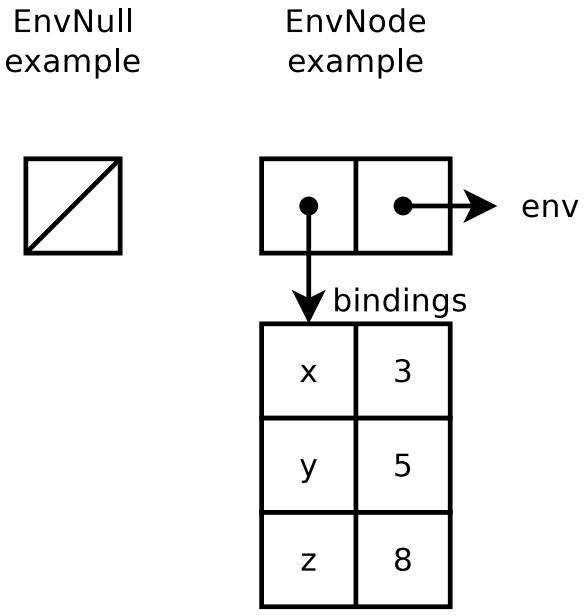
Both the `EnvNode` and `EnvNull` classes define an `add` method – declared as an abstract method in the `Env` class – that takes a `Binding` object as a parameter. In the `EnvNode` class, this method adds the binding to its local environment. In the `EnvNull` class, this method throws an exception (because there is no local environment to add to).

Attempting to `add` a binding to an `Env` object should be considered an error if the binding's symbol already appears in the local bindings, although this error is not checked in the `Env` classes.

Environments (continued)

The following diagrams give examples of an `EnvNull` object and an `EnvNode` object.

The `EnvNull` object has no fields – we always draw such an environment as shown below. The `EnvNode` object in this example has a `bindings` field as shown on slide 2.6 and an `env` field referring to some enclosing environment (not shown).



In the right-hand `EnvNode` example, a call to `lookup("x")` returns the `Binding` object `("x", 3)` (think of this as a pair), a call to `applyEnv("x")` returns an `IntVal` object with value 3, and a call to `lookup("w")` returns `null`.

Environments (continued)

In summary, an environment is a linked list of nodes, where a node is either an instance of `EnvNode` (with its corresponding local bindings) or an instance of `EnvNull`, which terminates the list.

The `extendEnv` procedure, defined in the `Env` class, takes a set of local bindings and uses them to return a new `EnvNode` that becomes the head of a new environment list, extending the current environment list. Here is the definition of `extendEnv`:

```
public Env extendEnv(Bindings bindings) {
    return new EnvNode(bindings, this);
}
```

Environments (continued)

In some cases, we may want to create a `Bindings` object from a `List` of symbols and a `List` of values by binding each symbol to its corresponding value. The resulting `Bindings` object can then be used to extend an environment. Here is a constructor for a `Bindings` object that does this pairing.

```
public Bindings (List<?> idList, List<Val> valList) {
    // idList.size() and valList.size() must be the same
    bindingList = new ArrayList<Binding>();
    Iterator<?> idIterator = idList.iterator();
    Iterator<Val> valIterator = valList.iterator();
    while (idIterator.hasNext()) {
        String s = idIterator.next().toString();
        Val v = valIterator.next();
        this.add(new Binding(s, v));
    }
}
```

The purpose of the '`?`' wildcard in the `List<?>` parameter declaration is to allow for a `List` of either `Strings` or `Tokens`.

This constructor relies on the two `List` parameters having the same size. It is the responsibility of the caller to ensure that this is the case.

Environments (continued)

For the remainder of these materials, we use the representation for environments that we have described here:

- an environment is a (possibly empty) linked list of local environments
- a local environment is a `List` of bindings
- a binding is an association of an identifier (symbol) to a value

Our implementation defines the following classes: `Env` (with subclasses `EnvNull` and `EnvNode`), `Binding`, and `Bindings` as summarized on the next slide.

Environments (continued)

Class/method summary:

```
abstract class Env
    public abstract Binding lookup(String sym)
    public Val applyEnv(String sym)
    public Env extendEnv(Bindings bindings)
    public Env add(Binding b)

class EnvNode extends Env
    public Binding lookup(String sym)

class EnvNull extends Env

class Bindings
    public Binding lookup(String sym)
    public void add(Binding b)

class Binding

abstract class Val

class IntVal extends Val
```

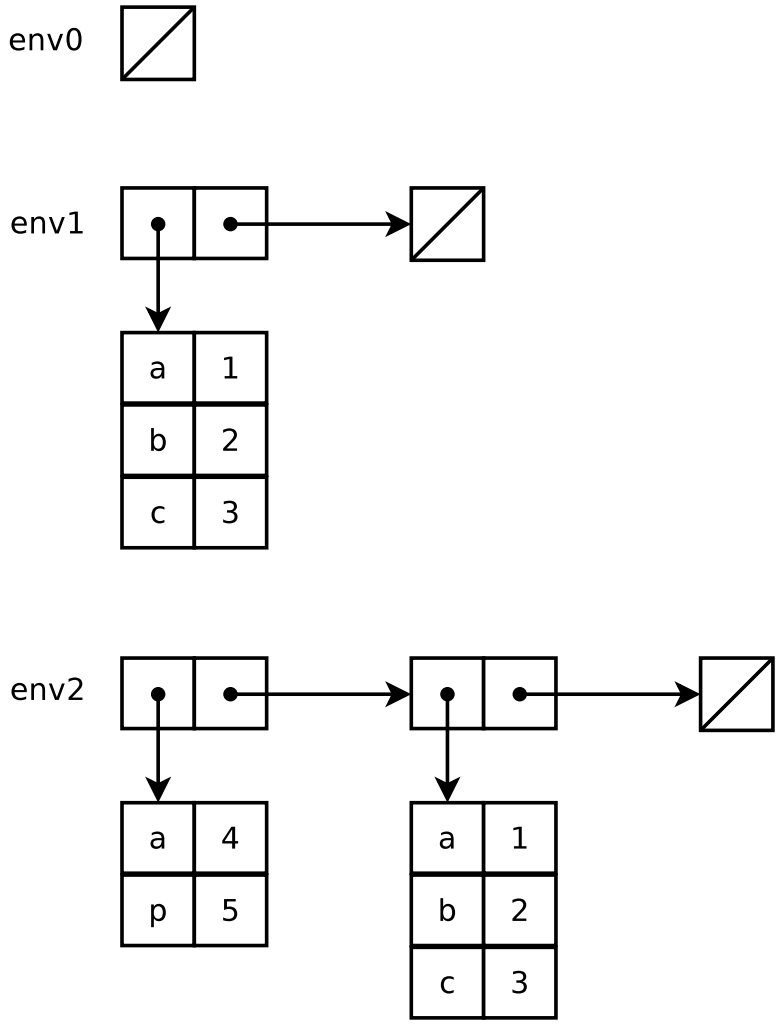
Environments (continued)

Here is a test program in the `Env` class. This program illustrates how to use the two constructor versions in the `Bindings` class.

```
public static void main(String [] args) {
    Env env0 = empty;
    Env env1 = env0.extendEnv(
        new Bindings(Arrays.asList(
            new Binding("a", new IntVal(1)),
            new Binding("b", new IntVal(2)),
            new Binding("c", new IntVal(3)))));
    List<String> i2 = Arrays.asList("a", "p");
    List<Val> v2 = Arrays.asList((Val)new IntVal(4), (Val)new IntVal(5));
    Env env2 = env1.extendEnv(new Bindings(i2, v2));
    System.out.println("env0:\n" + env0.toString(0));
    System.out.println("env1:\n" + env1.toString(0));
    System.out.println("env2:\n" + env2.toString(0));
    System.out.print("a(env2) => "); System.out.println(env2.applyEnv("a"));
    System.out.print("a(env1) => "); System.out.println(env1.applyEnv("a"));
    System.out.print("p(env2) => "); System.out.println(env2.applyEnv("p"));
    System.out.print("p(env1) => "); System.out.println(env1.applyEnv("p"));
}
```

Environments (continued)

We show these environments in diagram form as follows:



Environments (continued)

We can include Java code for environments into our PLCC specification file (usually called `grammar`) in the same way that we include Java code into our Java classes generated by PLCC. However, the environment-related classes `Env`, `EnvNode`, `EnvNull`, `Binding`, and `Bindings` do not appear in our BNF grammar, so PLCC doesn't generate stubs for them automatically.

As noted in Slide Set 1a, PLCC makes it possible to create stand-alone Java source files in exactly the same way as it adds methods to generated files, except that the *entire* code for each stand-alone Java source file – including `import` lines and the class constructor – must appear in the language specification section following the BNF rules.

For example, to create a Java source file named `Env.java`, use the following template:

```
Env
%%%
... code for the entire Env.java source file ...
%%%
```

Environments (continued)

We will encounter language definitions that end up creating dozens of Java source files. To manage these complex languages, we separate the contents of the semantics section of the grammar file into separate files grouped by purpose. In many cases, different languages may share some of the same source files. The semantics section then simply identifies the names of these files using an `include` feature that treats the contents of these files as if they were part of the entire grammar file.

For example, one of our early languages `V1` has the following grammar file structure:

```
# lexical specification
...
%
# BNF grammar
...
%
include code              # BNF grammar semantics
include prim              # primitive operations (PLUS, MINUS, etc.)
include ../Env/envRN      # environment code (Env, Binding, etc.)
include val               # value semantics (IntVal, etc.)
```