Language SET

In this version of our source language, we allow for the assignment o
ables. Languages that allow for the mutation of variables are called
Compared to functional programming (`V6` is an example), such la
herently more difficult to reason about, which accounts for why func
ming has received so much attention and also for why it is so diffi
high-quality software in most side-effecting programming language

So far, Languages `V1` through `V6` have treated denoted values (the t
ables are bound to) as being the same as expressed values (the valu
sions can have). For example, a variable `x` in one of these language
ates to the same thing no matter where it appears in its scope.

When we add variable mutation (also called "assignment"), such as

```
set x = add1(x)
```

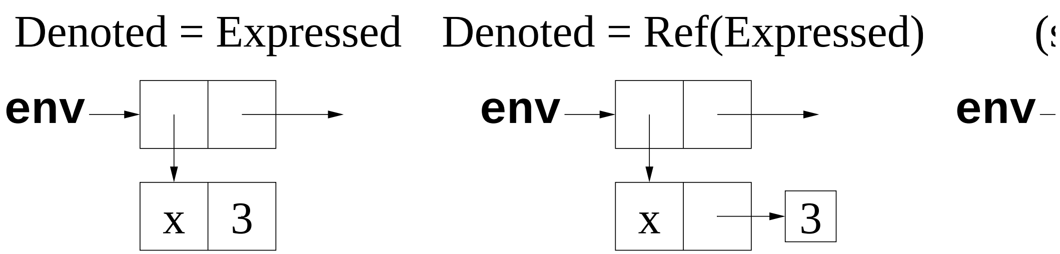
the meaning of `x` on the LHS is different from its meaning on the RH
sion `x` in the RHS of this "assignment" represents an expressed va
on the LHS represents a denoted value that can be modified. In orde
variable assignment, we need to find a way to disconnect denoted v
pressed values.

Language SET (continued)

We introduce the notion of a *reference*, something that *refers to* a m
in memory. Instead of binding a variable directly to an expressed val
variable to a reference containing an expressed value. From a compu
point of view, a reference is simply the address of a memory locati
never changes, but the memory contents at the address can change.

Expressed value = Val = IntVal+ProcVal
Denoted value = Ref(Expressed)

To mutate a variable bound to a reference, we change the *contents* o
the variable is still bound to the same reference.



The two right-hand diagrams depict the same environment. The righ
a more compact representation.

Language SET (continued)

References will also be used to implement various parameter-passi
as described later in these notes.

We choose the following concrete and abstract syntax for variable m

```
<exp>:SetExp ::=␣SET␣<VAR>␣EQUALS␣<exp>
              SetExp(Token␣var,␣Exp␣exp)
```

We can now write the following program in our newly extended sou

```
let
  x = 42
in
  { set x = add1(x) ; x }
```

This evaluates to 43.

Language SET (continued)

The ability to modify the value bound to a variable allows us to "ca
ronment in a procedure and use the procedure to modify its capture
For example, consider:

```
define g = let
             count = 0
           in
             proc() set count = add1(count)
.g() % => 1
.g() % => 2
.g() % => 3
```

The value of `count` is captured in the local `let` bindings that define
Each time we evaluate `.g()`, the procedure increments the value of
turns this newly incremented value. The variable `count` persists fr
tion to the other because the `proc` captures the environment in whi
namely the one with the variable `count`.

In this example, the `count` variable is unbound in the top-level envi
attempt to evaluate it throws an exception:

```
count % unbound variable
```

Language SET (continued)

In our Java implementation, we want a reference to be a Java object
can be mutated. When we bind a variable to a reference object (its
this binding does not change, but the contents of the reference itsel
refers to – can change.

The `Ref` abstract class embodies our notion of a reference – the thing
can be bound to. For now, the only subclass of the `Ref` class is the

```
ValRef(Val␣val)
```

The contents of a `ValRef` object is a `Val`, and we say that such
reference to a value. (Recall that a `Val` object is either an `IntVal`
– the only two `Val` types that we currently have.)

A `Ref` object has two methods:

```
public abstract Val deRef();
public abstract Val setRef(Val v);
```

In the `ValRef` class, The `deRef` (dereference) method simply re
object stored in the object's `val` field, and the `setRef` (set refe
modifies the `val` field by changing it to the `Val` parameter `v` (an
new `Val` object as well).

Language SET (continued)

```
Ref
%%%
public abstract class Ref {

    public abstract Val deRef();
    public abstract Val setRef(Val v);

}
%%%
```

Language SET (continued)

```
ValRef
%%%
public class ValRef extends Ref {

    public Val val;

    public ValRef(Val val) {
        this.val = val;
    }

    public Val deRef() {
        return val;
    }

    public Val setRef(Val v) {
        return val = v;
    }
}
%%%
```

Language SET (continued)

Our denoted values (the things that variables are bound to) are now stead of values, so we need to change our `Binding` objects to bi to a reference. (Notice that we use the terms “variable”, “identifier” interchangeably.)

```
Binding(String id, Ref ref)
```

In the `Env` class, we want `applyEnv` to continue to return the `Va` rectly) bound to a symbol. Since we now bind identifiers to referen the responsibilities as follows:

```
// returns the reference bound to sym
public abstract Ref applyEnvRef(String sym);

public Val applyEnv(String sym) {
    return applyEnvRef(sym).deRef();
}
```

The `applyEnvRef` method behaves exactly like the `V6 applyE` turning the thing (now a `Ref`) bound to the symbol and throwing there is nothing bound to the given symbol. The `applyEnv` metho turn a `Val`: it simply gets the `Ref` object using `applyEnvRef` ar it to return its corresponding value.

Language SET (continued)

In our semantics code, we need to modify all of the instances of `Bindings` objects so that they use references instead of values. To ing” of a variable to a value, first wrap the value into a new referenc the variable to the newly created reference. Here’s an example of binding of the variable named `x` to (a reference to) an integer `10`:

```
String var = "x";
Val val = new IntVal(10);
Binding b = new Binding(var, new ValRef(val));
```

The `valsToRefs` static method in the `Ref` class takes a list of `Va` a corresponding list of `Refs`. This is used, for example, in the coc objects (which need to bind formal parameter symbols to references parameter values) and for `LetExp` objects (which need to bind thei symbols to reference to their RHS expression values).

```
public static List<Ref> valsToRefs(List<Val> valList
    List<Ref> refList = new ArrayList<Ref>(valList.s
    for (Val v : valList)
        refList.add(new ValRef(v));
    return refList;
}
```

Language SET (continued)

```
<exp>:SetExp ::=␣SET␣<VAR>␣EQUALS␣<exp>
              SetExp(Token␣var,␣Exp␣exp)
```

So far, we have dealt only with the implementation details of envir
do we implement the semantics of `set` expressions? Coding this is

```
SetExp
%%%
    public Val eval(Env env) {
        Val val = exp.eval(env); // the RHS express:
        Ref ref = env.applyEnvRef(var); // the LHS :
        return ref.setRef(val);  // sets the ref anc
    }
%%%
```

Remember that an expression (<exp>) always evaluates to a val
a `SetExp` is no exception: the value of a `SetExp` is the value of
assignment. This means that multiple `set` operations can appear in

Language SET (continued)

Let's look the three lines in the `eval` method shown on the previou

```
Val val = exp.eval(env); // the RHS express:
Ref ref = env.applyEnvRef(var); // the LHS :
return ref.setRef(val);  // sets the ref anc
```

Notice that the `exp.eval(env)` expression returns a `Val` ob
whereas the `env.applyEnvRef(var)` expression returns a `Re`
erence). We use the terms **value semantics** to refer to obtaining the
thing and **reference semantics** to refer to obtaining a reference to s
code above shows that *we use value semantics for the RHS of a* `set`
reference semantics for its LHS.

Because we need to modify the value denoted by the LHS variable
(as shown above), we must use reference semantics for the LHS. V
would have been useless here, since we regard "values" – instances o
– as immutable: things that cannot be modified.

In a `set` expression, the LHS variable must exist in the environment
expression occurs, otherwise we could find no reference to modify
to the LHS variables occurring in `let` expressions. A `let` expressi
bindings to the LHS variables: we don't *modify* these variables, we

Language SET (continued)

A variable that occurs on the LHS of a `set` *expression is not an* particular, observe that the grammar rule for a `set` expression us `VarExp`, to the left of `EQUALS`, and we use reference semantics, nc tics, for such an occurrence, because we are not treating the LHS expression.

When we evaluate a `VarExp` (this *is* an expression), either by itse another expression, we use value semantics in Language SET. Thi you examine the `eval` semantics for a `VarExp`:

```
public Val eval(Env env) {
    return env.applyEnv(var); // value semantics!
}
```

Even though all variables are bound to references in an `Env`, tl method de-references the reference bound to `var` to return its value

Observe that expressed values (instances of `Val`) get wrapped into stances of `Ref`) when they are bound to variables in creating env example, when evaluating the RHS expressions in a `let/letrec` ating the actual parameter expressions during a procedure applicatic these expressions using value semantics in Language SET before into `ValRef` objects.

Language SET (continued)

To illustrate how `set` expressions evaluate to something, conside `let` expression in Language SET:

```
let
  t = 3
  u = 42
  v = 0
in
  { set v = set u = set t = add1(t) ; +(t,+(u,v)) }
```

This expression evaluates to 12. The first expression in the body sequence expression) gets evaluated like this:

```
set v = { set u = { set t = add1(t) } }
```

The innermost `set` expression sets `t` to 4 and evaluates to 4. Procee the next `set` expression sets `u` to 4 (the value of the innermost `set` to 4. Finally, the outermost `set` expression sets `v` to 4 and evaluates value gets discarded by the sequence expression, but the last express body uses the modified values of `t`, `u`, and `v`.

Language SET (continued)

What happens if you try to mutate the value of an identifier that is or
parameters to a procedure? For example, what value is returned by
program?

```
let
  x = 3
  p = proc(t) set t = add1(t)
in
  { .p(x) ; x }
```

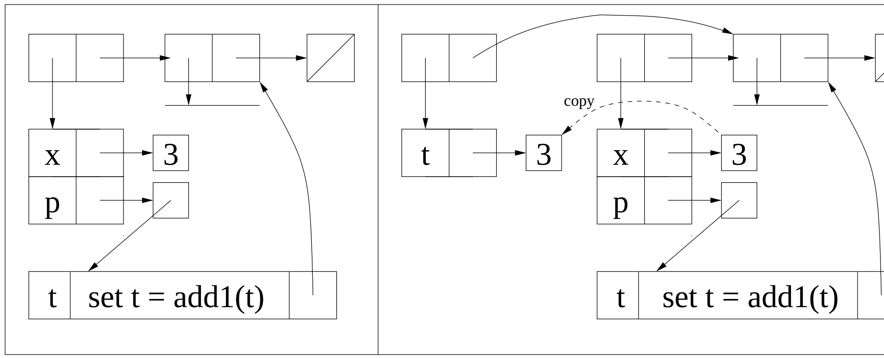
In our procedure application semantics (see the AppExp code), the
eters are bound to (references to) the *values* of the actual parame
value of the actual parameter x in the expression .p(x) is 3, this
variable t in the procedure application is bound to *a new referenc*
and evaluating the body of the procedure modifies this reference to t
it's the reference to variable t, not the variable x, that gets modified.
of this entire expression is 3.

Language SET (continued)

```
let
  x = 3
  p = proc(t) set t = add1(t)
in
  { .p(x) ; x }
```

The following illustration shows

- the environment immediately before the procedure application .
ticular, the binding of x to a reference to the value 3, and
- the environment during the procedure application .p(x), bind
parameter t to a *new* reference containing a copy of the value
by the dashed line).

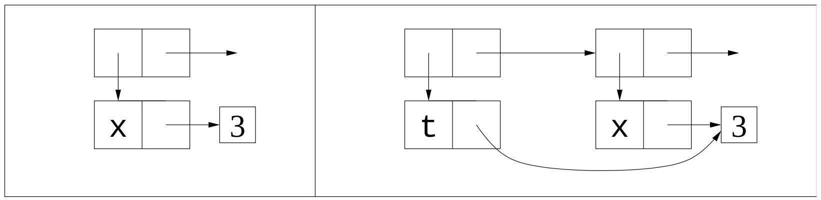


Language REF

A parameter passing approach that evaluates actual parameters usin
tics and that binds the formal parameters to these actual parameter
call-by-value. This is what we use in languages V1 to V6.

In the language SET, where bindings are to references instead of v
the actual parameter values into *new* references, and these referenc
the formal parameters. Though denoted values are references in Lan
parameter passing approach is still call-by-value.

Considering the illustration in the previous slide, Suppose we *want*
binds the formal parameter t to the *same* reference that is bound to
new reference containing a copy of the value. The following diagr
the bindings in the previous diagram change when t is bound to the
as x:



Such a parameter passing semantics is called *call-by-reference*. W
by-reference next, along with variants on this theme.

Language REF (continued)

To repeat:

- The parameter passing semantics that we have been using up t
  call-by-value. In call-by-value semantics – which we have refe
  semantics, when an actual parameter expression in a procedure
  variable, the procedure's corresponding formal parameter deno
  ence to the expressed value of the actual parameter.
- In *call-by-reference* semantics – which we have referred to as *re*
  tics, when an actual parameter expression in a procedure applic
  able, the procedure's corresponding formal parameter denotes
  ence as the actual parameter.

The differences between call-by-value and call-by-reference seman
when the actual parameter expression is a variable. When the ac
expression is not a variable, the corresponding formal parameter de
erence to the expressed value of the actual parameter, just as in Lan

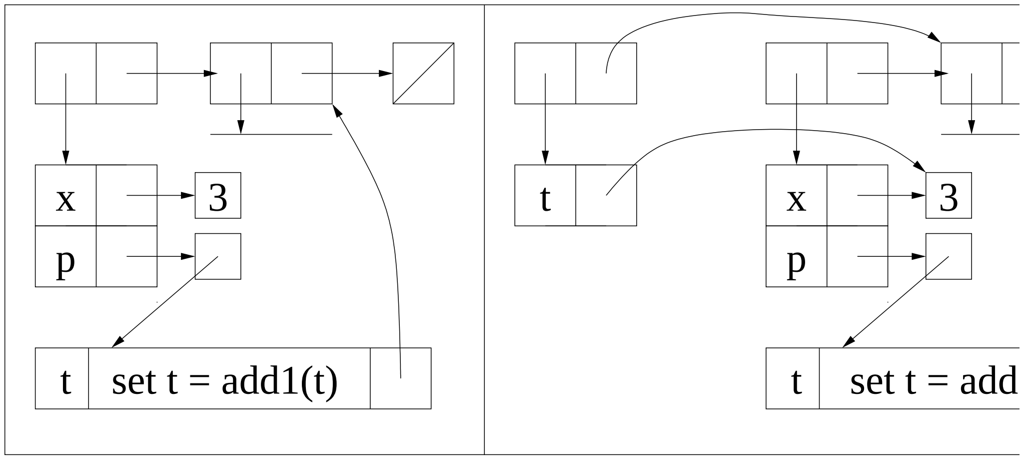
Observe that in let and letrec expressions, we always use valu
the variable bindings. This means that each LHS variable in a le
pression always denotes a new reference to the expressed value of its
RHS expression.

Language REF (continued)

Using call-by-reference semantics, the program

```
let
  x = 3
  p = proc(t) set t = add1(t)
in
  { .p(x) ; x }
```

returns the value 4, since `t` denotes the same reference as `x`. The
created by the `let` and then during evaluation of the application `.p`
to evaluating the procedure body) are illustrated in the following fig



Language REF (continued)

In Language REF, when actual parameter expressions are not thems
we use value semantics. To illustrate this, consider the value retur
lowing program:

```
let
  x = 3
  p = proc(t) set t = add1(t)
in
  { .p(+(x,0)) ; x }
```

Clearly the expressed value of the actual parameter `+(x,0)` is th
of `x`, but the expression `+(x,0)` is not a variable, so value sem
this actual parameter. This means that when we apply the procedur
parameter `t` denotes a *new* reference to the value of this expression
`t` and `x` have the same expressed values, but they have different den
modifying `t` does not affect the value of `x`. This expression evaluate

Language REF (continued)

The term *L-value* refers to a semantic entity that can be considered
It's called an L-value because it is the sort of thing that can appe
the '=' in a `set` expression. In Languages SET and REF, a variabl
considered as an L-value (because variables are always bound to ref
expression like `+(x,0)` can only be considered as a value, never a

Whether we consider a semantic entity as an L-value depends on w
In the expression

```
set x = 3
```

the occurrence of `x` is considered as an L-value. On the other hand, in

```
set y = x
```

the occurrence of `x` is not considered as an L-value.

In Languages SET and REF, only variables can be considered as L-
guage SET, actual parameter expressions (even variables) *in procedu*
are never considered as L-values. In Language REF, only actual pa
sions that are variables are considered as L-values.

Language REF (continued)

*To summarize: for procedure applications that appear in Language
tual parameter is a variable (and therefore denotes a reference), th
corresponding formal parameter to the same reference. If an actu
something other than a variable, then the corresponding formal par
to a* ***new*** *temporary reference containing the expressed value of the
ter.*

Language REF (continued)

Our `REF` language has exactly the same grammar rules as our `SET`
only differences are in the bindings of formal parameters during pr
cation. As the discussion on the previous slides show, we need to
parameters that are variables differently from actual paramemeters t
sions. The idea here is to define an `evalRef` method for instanc
classes that takes care of how to translate themselves into a referenc
but a `VarExp`, `evalRef` evaluates the expression and returns a ne
the value. For a `VarExp`, `evalRef` returns the same reference tha
rameter denotes.

So in the `Exp` class, the `evalRef` method has the following *defaul*

```
public Ref evalRef(Env env) {
    return new ValRef(eval(env)); // value semantics
}
```

For the `VarExp` subclass – *and only for this class*, `evalRef` is im

```
public Ref evalRef(Env env) {
    return env.applyEnvRef(var); // reference semant
}
```

The `evalRef` method in the `VarExp` class overrides the `evalRef`
`Exp` class. In all other classes that extend the `Exp` class, the defau
the parent `Exp` class is used.

Language REF (continued)

The other change is in the `Rands` code. In the `SET` language, the
method was used in the implementation of `eval` for both a `LetExp`
`AppExp` object, since both created new bindings to values. In the `RE`
`AppExp` object needs new bindings to values except for actual par
are variables – a situation that is described in the previous slides.
implement the correct `eval` semantics for an `AppExp` object, we
`evalRef` references instead of `eval` values to bind them to the f
ters. The method `evalRandsRef` in the `Rands` class does this w
`eval` method in the `AppExp` class uses the `evalRandsRef` meth
bindings of the formal parameters to their appropriate references. Th
`evalRandsRef` follows:

```
public List<Ref> evalRandsRef(Env env) {
    List<Ref> refList = new ArrayList<Ref>(expLi
    for (Exp exp : expList)
        refList.add(exp.evalRef(env));
    return refList;
}
```

Language REF (continued)

Remember that we always use value semantics for `let` bindings. T
a Language REF program such as

```
let
  x = 3
in
  let
    y = x
  in
    { set y = add1(y) ; x }
```

evaluates to 3.

Our observation (see Slide 3.79) that any `let` can be re-written a
procedure application no longer applies with languages that impl
reference semantics. Specifically, if we attempt to re-write the in
above Language REF program as a procedure application using the a
on Slide 3.79, we get

```
let
  x = 3
in
  .proc(y) {set y = add1(y) ; x } (x)
```

which evaluates to 4.

Language REF (continued)

We want literals (`LIT`s) always to have value semantics. For exar
appears in an expression should always evaluate to the integer 4.
following code in Language REF:

```
define square = proc(x) set x=*(x,x)
define four = 4
{ .square(four) ; four }
```

By the time the variable `four` gets evaluated the second time in th
pression, its value has changed to 16, because Language REF use
mantics for the actual parameter `four`. Thus the value of the seque
is 16. Consider now what happens if we replace the sequence ex
with the following:

```
{ .square(4) ; 4 }
```

Of course, this sequence expression evalautes to 4, because Langu
value semantics for everything but variables. However, languages
TRAN IV (in the 1970s) treated numeric literals (like '4') as vari
reference semantics when passing them to procedures. The equiv
expression, if written FORTRAN IV, would evaluate to 16. Furth
quent statements such as

```
IF 4 = 16 THEN CALL YIKES
```

(not really a legal FORTRAN IV statement) would end up calling Y

Language NAME

We now turn to a different parameter passing mechanism, *call-by-*
by-name procedure application, we bind each procedure's formal p
corresponding *un-evaluated actual parameter expression*. Each tim
formal parameter in the procedure body, we evaluate its correspon
rameter expression *in the environment where the procedure was call*
environment, and this value becomes the expressed value of the forn

Call-by-name has behaviors that differ from call-by-reference: (1) i
erence the formal parameter in the procedure body, we never eval
parameter expression; and (2) every time we evaluate the formal pa
procedure body, we re-evaluate the actual parameter expression.

In the presence of side-effects, call-by-name has interesting prope
it very powerful but often difficult to reason about. The language A
call-by-value and call-by-name as its parameter passing mechanism
had its greatest influence on languages such as Pascal, C/C++, and .
call-by-name has been all but abandoned by modern imperative
programming languages – mostly because of its inefficiency, it st
in functional programming: Scheme supports a variant, *call-by-nee*
`promise/force`; Haskell also supports call-by-need. We procee
both call-by-name and call-by-need.

Language NAME (continued)

We implement Language NAME with call-by-name semantics. It is
guage REF.

Two actual parameter expressions that can appear in procedure ap
constant behavior: They are `LitExp` and `ProcExp`. Evaluating
sions do not produce any side-effects, and their expressed values
`ProcVal`, respectively) can never change. (Don't confuse evaluting
rameters of a procedure application with applying the procedure.) E
in call-by-name, we can evaluate these actual parameter expressio
can bind their corresponding formal parameters to new references
In other words, we use value semantics for these actual parameter
Language NAME.

Evaluating variables that appear as actual parameter expressions (`Va`
not produce any side-effects, but such variables may have expressed
change, perhaps in `set` expressions. We therefore use reference se
tual parameter expressions that are variables in Language NAME.

Language NAME (continued)

In the presence of side-effects, call-by-reference and call-by-name n
ent results. Consider evaluating the following expression in Langua

```
let
  x = 1
  f = proc(t,u)
        { set t = add1(t) ; u }
in
  .f(x, +(x,5))
```

With call-by-reference, when we evaluate the application `.f(x,␣`
formal parameter `t` in the definition of `f` denotes the same reference
(initially containing 1), whereas the formal parameter `u` denotes a
to the value 6 (using value semantics for the `+(x,5)` expression)
in the body of `f` changes the expressed value of `x` (because `t` an
same reference) but does not change the expressed value of `u`. Thus
evaluates to 6.

Language NAME (continued)

Now consider the same expression in Language NAME.

```
let
  x = 1
  f = proc(t,u)
        { set t = add1(t) ; u }
in
  .f(x, +(x,5))
```

Consider what happens when we evaluate `.f(x,␣+(x,5))` using
The formal parameter `t` still denotes the same reference that `x` de
containing 1), but the formal parameter `u` denotes the (un-evaluat
`+(x,5)`.

The `set` operation in the body of this procedure increments the fo
`t`; but since `t` denotes the same reference as `x`, the value of `x` chang
When we then evaluate the formal parameter `u` at the end of the p
evaluate the expression `+(x,5)` denoted by `u` *in the environmen*
Since this expression gets evaluated after the `set`, and the value
the value of the expression `+(x,5)` (and thus the value returned by
application) is `+(2,5)` or 7. Thus the entire expression evaluates to

Language NAME (continued)

Consider the following definition in Language NAME:

```
define while = proc(test?, do, result)
  letrec loop = proc()
    if test? then {do ; .loop()} else result
  in .loop()
```

Using call-by-name, the expression

```
let x = 0 sum = 0 in
  .while(
    <=?(x,10),                                            % t
    { set sum=+(sum,*(x,x)) ; set x = add1(x) },  % c
    sum                                                   % :
  )
```

evaluates to the sum

$$\sum_{x=0}^{10} x^2 = 385$$

Suppose we were to consider these in Language REF. In this cas pression evaluation would never terminate. This is because the ac expression `<=?(x,10)` is evaluated only once, to 1 (true) when so the `test?` parameter is bound permanently to (a reference to) `test?` repeatedly always returns 1 (true), so the "loop" never termi

Language NAME (continued)

We proceed to implement call-by-name. We take our Language reference) implementation as a starting point.

If an actual parameter is a literal expression (such as `4`), we bind the eter to (a reference to) the literal value. If an actual parameter is a bind the formal parameter to (a reference to) the procedure's closur environment. If an actual parameter is an identifier, we bind the fo to the same reference as the actual parameter, using reference sema

If an actual parameter is any other kind of expression, we bind the ter to a `Ref` object that captures the expression in the environment called and that can be evaluated, when needed, by the called proc such an object a *thunk*.

Following our terminology for defining *value semantics* and *refer* discussed earlier, we call this *name semantics*.

Language NAME (continued)

A thunk amounts to a parameterless procedure that consists of an ex
environment in which the expression is to be evaluated. It looks just
except that there is no formal parameter list.

```
ThunkRef(Exp exp, Env env)
```

A `ThunkRef` is a `Ref`, since we want to de-reference (`deRef`) i
refer to the corresponding actual parameter. We bind a formal paran
reference only during procedure application. Thunks will otherwise
in expression semantics.

Language NAME (continued)

To change from call-by-reference to call-by-name, we need to cha
`evalRef` behavior of the `Exp` objects so that `evalRef` returns a
expressions *except for* `LitExp`, `ProcExp`, and `VarExp`. This
define `evalRef` in the `Exp` class with its default behavior as follo

```
public Ref evalRef(Env env) {
    return new ThunkRef(this, env);
}
```

For a `LitExp` and a `ProcExp`, a thunk is not necessary, so we retu
`ValRef` as in the `REF` language:

```
public Ref evalRef(Env env) {
    return new ValRef(eval(env));
}
```

Finally, for a `VarExp`, we simply use reference semantics as in the

```
public Ref evalRef(Env env) {
    return env.applyEnvRef(var);
}
```

Language NAME (continued)

The `ThunkRef` class is straight-forward:

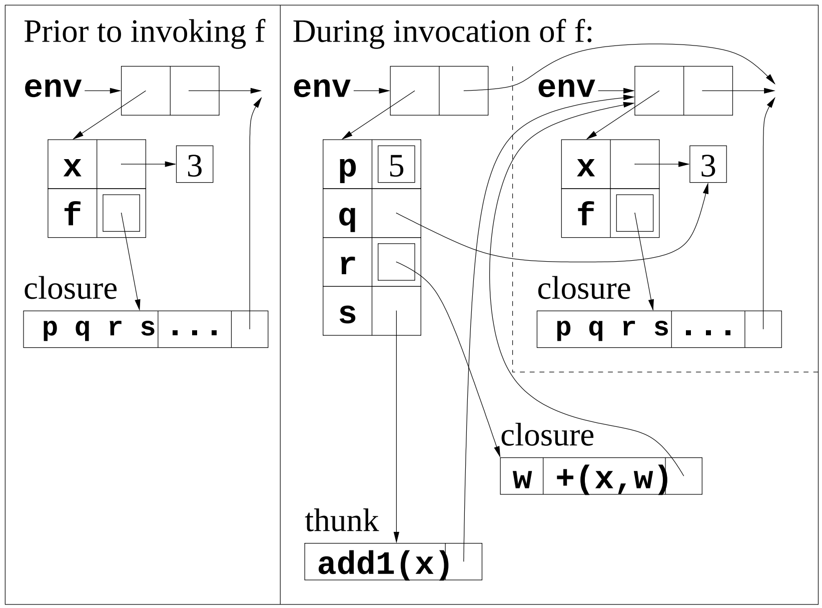
```
ThunkRef
%%%
public class ThunkRef extends Ref {

    public Exp exp;
    public Env env;

    public ThunkRef(Exp exp, Env env) {
        this.exp = exp;
        this.env = env;
    }

    public Val deRef() {
        return exp.eval(env);
    }

    public Val setRef(Val v) {
        throw new PLCCException("cannot modify a read-only exp
    }
}
%%%
```

Observe that the `setRef` method throws an exception. The `set`
only used with LHS variable references during evaluation of `set` e

Language NAME (continued)

The following illustration may help you to understand how these
The example shows all four possible cases of actual parameter expr
variable, procedure, and other:

```
let x = 3
    f = proc(p,q,r,s) ...
in .f(5, x, proc(w) +(x,w), add1(x))
```



Language NEED

The call-by-need parameter passing mechanism is the same as call-b
that a thunk is called at most once, and its value is remembered (*me*

Suppose a procedure with formal parameter `x` is invoked with ac
`set␣z␣=␣add1(z)`, using call-by-need semantics. As with cal
formal parameter `x` is bound to the thunk with `set␣z␣=␣add1(`
in an enclosing environment that we will assume has `z` bound to (
the value 8. When `x` is referenced in the body of calling procedure,
ing thunk is dereferenced, producing a result of 9 for `set␣z␣=␣a`
thunk now remembers (*memoizes*) the value 9, and any further refere
mal parameter `x` in the body of the procedure will continue to evalu
making any further changes to the variable `z`.

If call-by-name had been used in the above example, additional eval
the body of the procedure would result in evaluating the body of the
such evaluation, further modifying `z` and yielding values 10, 11, 12,

In both call-by-need and call-by-name (and unlike call-by-reference
parameter is never referenced in the body of the procedure, the thun
uated. Compared to call-by-name, call-by-need reduces the overhea
evaluating a thunk when evaluating the corresponding formal param

Language NEED (continued)

Implementing call-by-need is easy, starting from the call-by-name i
principal change is to have a `Val` field named `val` in the `ThunkR`
used to memoize the value of the body of the thunk. This field is initi
when the thunk is created. When the thunk's `deRef` method is invok
see if the `val` field has been memoized (*i.e.*, is non-null). If so, the
simply returns the memoized value. Otherwise, it evaluates the bod
saves the value in the `val` field (thereby memoizing it), and then ret
subsequent `deRef` calls simply use the resulting memoized value.

In the NEED language, the `ThunkRef` *constructor initializes th*
`null`*, indicating that the thunk has not been memoized. This fi*
when the thunk's `deRef` *method is called.*

Language NEED (continued)

Here are the appropriate changes to `ThunkRef` ...

```
ThunkRef
%%%
public class ThunkRef extends Ref {

    public Exp exp;
    public Env env;
    public Val val; // memoized value

    public ThunkRef(Exp exp, Env env) {
        this.exp = exp;
        this.env = env;
        this.val = null;
    }

    public Val deRef() {
        if (val == null)
            val = exp.eval(env);
        return val;
    }

...

}
%%%
```

Language NEED (continued)

You might have noticed in the `code` file that an instance of the class
constructed by the `evalRef` methods in the `LitExp` and `ProcEx`
is a slight change from the `NAME` language, where the instances w
The `RO` part stands for "Read Only". We do this because it doesn't
a literal or procedure to be modified.

Consider, for example, the following code:

```
let
  f = proc(x) set x=add1(x)
in
  .f(3)
```

One's intuition would be to think of the procedure application `.f(3`

```
set 3=add1(3)
```

But of course this doesn't make any sense.

We have already seen that the `setRef` method in the `ThunkRef`
exception. What we are now doing is to have this same behavior
parameter expression except for a variable (where call-by-reference

Language NEED (continued)

The following example illustrates the difference between call-by-nai
need:

```
let
  x = 3
  p = proc(t) {t;t;t}
in
  .p(set x=add1(x))
```

With call-by-name, when we apply the procedure `p`, its formal param
to a thunk containing the expression `set␣x=add1(x)`. Each tir
the formal parameter `t` in the body of the procedure `p`, its thunk i:
resulting in evaluation of the expression `set␣x=add1(x)`. So sir
`t` three times in the body of `p`, the expression `set␣x=add1(x)`
three times, incrementing `x` from 3 to 6. Consequently, the entire ex
ates to 6.

With call-by-need, the first time we evaluate `t` in the body of `p`, its
actual parameter expression `set␣x=add1(x)` is evaluated, whic
effect of incrementing the value of `x` to 4 and evaluates to 4. How
memoizes the expressed value of 4, so any further references we mal
to 4. Consequently, the entire expression evaluates to 4.

Language NEED (continued)

Here's another example illustrating the difference between call-by
call-by-name/need. Examine the definition of `seq`, which seems
finitely but doesn't with call-by-name (why?).

```
define pair = proc(x,y)
  proc(t) if t then y else x
define first = proc(p) .p(0)
define rest = proc(p) .p(1)
define nth = proc(n,lst)    % zero-based
  if n then .nth(sub1(n),.rest(lst)) else .
define seq = proc(n) .pair(n,.seq(add1(n)))
define natno = .seq(0)      % all the natur
%% The above never terminates with call-by-
%% With call-by-name or call-by-need, we ge
.first(natno)               % => 0
.first(.rest(natno))        % => 1
.first(.rest(.rest(natno))) % => 2, and so
.nth(100,natno)             % => 100
```

Order of evaluation

Let's examine the following example in Language SET (or REF):

```
let
  x = 3
in
  let
    y = {set x = add1(x)}
    z = {set x = add1(x)}
  in
    z
```

Consider the inner `let`. We know that the right-hand side expressions (here wr
braces for clarity) are evaluated before their values are bound to the left-hand var
SET and REF *specify* the order in which the right-hand side expressions are evalu
to last. (In Language V6, the RHS expressions in a `let` cannot produce side effe
evaluation of RHS expressions wouldn't matter. However, when side-effects are p
of evaluation does matter.)

Suppose we did not specify this order of evaluation. In the above example, if the
to be evaluated first, then `z` becomes 4 and `y` becomes 5, so the entire expressio
the value of `z`. If the order of evaluation were reversed, the entire expression eva
Languages SET and REF specify the order of evaluation, we have an unambiguou
the value of the above expression. In the absence of such a specification, the value
is ambiguous. *Do you know what your favorite language does?*

Order of evaluation (continued)

A similar situation exists when evaluating actual parameter express
by this example, assuming call-by-value semantics.

```
let
  x = 3
  p = proc(t,u) t
in
  .p(set x = add1(x), set x = add1(x))
```

When the actual parameters are evaluated left-to-right as specified in
`t` would be bound to 4 and `u` to 5, so the entire expression evalua
evaluation order had been right-to-left, the entire expression would

Order of evaluation (continued)

You can see that both `evalRands` and `evalRandsRef` use `fo`
(also called enhanced `for` loops) to traverse and evaluate the expres
of actual parameters. The traversal is guaranteed by the Java API
be "natural", in the sense that the elements of the list are visited in
number order. Here is the code for `evalRands` in the `Rands` clas

```
public List<Val> evalRands(Env env) {
    List<Val> valList = new ArrayList<Val>();
    for (Exp e : expList)
        valList.add(e.eval(env));
    return valList;
}
```

Our order of evaluation semantics depends on the behavior of Jav
order of evaluation mechanism, which is guaranteed to be left-to-ri
chosen right-to-left semantics, we could, instead, explicitly traverse
from last to first if we wished.

The point is that, to make any language semantics well-defined and
it is necessary to specify the order of evaluation. Unless the langua
clearly addresses the issue of order of evaluation, the language in
choose any evaluation order. *Let the buyer beware!*

Order of evaluation (continued)

Both Java and Python specify that actual parameter expressions are
to-right. However, the C language specification explicitly states th
which actual parameter expressions are evaluated is *undefined* – wh
the evaluation order is implementation dependent. In the following
output is 3 (using the GCC compiler on the date this file was last m
shows that the the operand expressions `foo(3)` and `foo(5)` are e
to-left. Your mileage may vary!

```
#include <stdio.h>
#include <stdlib.h>
static int xx = 0;
void foo2(int x1, int x2) {
    return;
}
int foo(int x) {
    xx = x;
    return x;
}
int main(int argc, char ** argv) {
    foo2(foo(3), foo(5));
    printf("xx=%d\n", xx);
    return 0;
}
```

Order of evaluation (continued)

Order of evaluation does not matter in languages without side-
makes functional languages immune to order of evaluation
http://en.wikipedia.org/wiki/Evaluation_strat
information about order of evaluation.

Another way to avoid order of evaluation problems is to require that
have at most one formal parameter. In languages that use this app
with with call-by-need, there is never an "order of evaluation" issu
is never more than one actual parameter to evaluate.

While you may think that a language with procedures having only
rameter might be limited, it's possible for such a language to beh
multiple formal parameters using an approach called "Currying",
the Haskell programming language – named after Haskell Curry.
slide gives an example.

Order of evaluation (continued)

Here is an example without currying:

```
let
  x = 3
  y = 5
  p = proc(t,u) +(t,u)
in
  .p(x,y) % => 8
```

Here is semantically equivalent code that has exactly one formal
`proc`:

```
let
  x = 3
  y = 5
  p = proc(t) proc(u) +(t,u)
in
  ..p(x)(y)
```

In the second example above, `x` must be evaluated first, so that
`.p(x)` can then be applied to the value of `y`.

Aliasing

Side-effecting languages that use call-by-reference suffer from a
Consider, for example, the following program using the REF langua

```
let
  addplus1 = proc(x,y) {set x = add1(x) ; +
in
  .addplus1(3,3)
```

It's clear that this program returns 7. But what about the following p

```
let
  a = 3
  addplus1 = proc(x,y) {set x = add1(x) ; +
in
  .addplus1(a,a)
```

Aliasing (continued)

```
let
  a = 3
  addplus1 = proc(x,y) {set x = add1(x) ; +
in
  .addplus1(a,a)
```

Using call-by-reference, when `addplus1` is applied to the actua and `a`, both formal parameters `x` and `y` of `addplus1` refer to th `a`. Therefore the `set␣x␣=␣add1(x)` expression is equivalent to `set␣a␣=␣add1(a)` which increments `a` to 4, and the next expre is essentially equivalent to the expression `+(a,a)` which now evalu the value of the program is 8.

Aliasing occurs when two different formal parameters refer to the s rameter. As this example shows, aliasing can lead to unexpected s should be avoided. **Of course, the best way to avoid problems of evaluation ambiguities and aliasing is to avoid using langau effects!**