State, Object-Oriented Programming
Explicit State, Polymorphism (CTM 6.1-6.4.4)
Objects, Classes and Inheritance (CTM 7.1-2)

Carlos Varela
Rensselaer Polytechnic Institute
October 31, 2014

Adapted with permission from:
Seif Haridi
KTH
Peter Van Roy
UCL
What is state?

• State is a **sequence of values in time** that contains the intermediate results of a desired computation
• Declarative programs can also have state according to this definition
• Consider the following program

```plaintext
fun {Sum Xs A}
  case Xs
    of X|Xr then {Sum Xr A+X}
      [] nil then A
  end
end

{Browse {Sum [1 2 3 4] 0}}
```
What is implicit state?

The two arguments Xs and A represent an implicit state.

<table>
<thead>
<tr>
<th>Xs</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1 2 3 4]</td>
<td>0</td>
</tr>
<tr>
<td>[2 3 4]</td>
<td>1</td>
</tr>
<tr>
<td>[3 4]</td>
<td>3</td>
</tr>
<tr>
<td>[4]</td>
<td>6</td>
</tr>
<tr>
<td>nil</td>
<td>10</td>
</tr>
</tbody>
</table>

```plaintext
fun {Sum Xs A}
  case Xs of X|Xr then {Sum Xr A+X}
  [] nil then A
end
end

{Browse {Sum [1 2 3 4] 0}}
```
An unbound variable

A cell $C$ is created with initial value 5
$X$ is bound to $C$

The cell $C$, which $X$ is bound to, is assigned the value 6
What is explicit state: Example?

An unbound variable

A cell $C$ is created with initial value 5

$X$ is bound to $C$

The cell $C$, which $X$ is bound to, is assigned the value 6

- The cell is a value container with a unique **identity**
- $X$ is really bound to the **identity** of the cell
- When the cell is assigned, $X$ does not change
What is explicit state?

- **X = {NewCell I}**
  - Creates a cell with initial value I
  - Binds X to the identity of the cell

- **Example: X = {NewCell 0}**

- **{Assign X J}**
  - Assumes X is bound to a cell C (otherwise exception)
  - Changes the content of C to become J

- **Y = {Access X}**
  - Assumes X is bound to a cell C (otherwise exception)
  - Binds Y to the value contained in C
Examples

- $X = \{\text{NewCell 0}\}$
- $\{\text{Assign X 5}\}$
- $Y = X$
- $\{\text{Assign Y 10}\}$
- $\{\text{Access X}\} == 10 \% \text{ returns true}$
- $X == Y \% \text{ returns true}$
Examples

• $X = \{\text{NewCell 10}\}$
  $Y = \{\text{NewCell 10}\}$

• $X == Y$ % returns false
  Because $X$ and $Y$ refer to
different cells, with
different identities

• $\{\text{Access } X\} == \{\text{Access } Y\}$
  returns true
The model extended with cells

Semantic stack

\[ w = f(x) \]
\[ z = \text{person}(a:y) \]
\[ y = \alpha_1 \]
\[ u = \alpha_2 \]
\[ x \]

single assignment store

\[ \alpha_1: w \]
\[ \alpha_2: x \]

....

mutable store
The stateful model

\[ \langle s \rangle ::= \text{skip} \]
\[ \quad | \quad \langle s_1 \rangle \langle s_2 \rangle \]
\[ \quad | \quad ... \]
\[ \quad | \quad \{ \text{NewCell} \langle x \rangle \langle c \rangle \} \]
\[ \quad | \quad \{ \text{Exchange} \langle c \rangle \langle x \rangle \langle y \rangle \} \]

- empty statement
- statement sequence
- cell creation
- cell exchange

Exchange: bind \( \langle x \rangle \) to the old content of \( \langle c \rangle \) and set the content of the cell \( \langle c \rangle \) to \( \langle y \rangle \)
The stateful model

\[
\begin{align*}
\text{cell creation} & \quad \{\text{NewCell} \, \langle x \rangle \, \langle c \rangle \} \\
\text{cell exchange} & \quad \{\text{Exchange} \, \langle c \rangle \, \langle x \rangle \, \langle y \rangle \}
\end{align*}
\]

Exchange: bind \( \langle x \rangle \) to the old content of \( \langle c \rangle \) and set the content of the cell \( \langle c \rangle \) to \( \langle y \rangle \)

\[
\begin{align*}
\text{proc} & \quad \{\text{Assign} \, \langle C \rangle \, \langle X \rangle \} \quad \{\text{Exchange} \, \langle C \rangle \, \_ \, \langle X \rangle \} \quad \text{end} \\
\text{fun} & \quad \{\text{Access} \, \langle C \rangle \} \, \langle X \rangle \quad \text{in} \quad \{\text{Exchange} \, \langle C \rangle \, \langle X \rangle \, \langle X \rangle \} \quad \text{X \ end}
\end{align*}
\]

\( C := \langle X \rangle \) is syntactic sugar for \{\text{Assign} \, \langle C \rangle \, \langle X \rangle \} \\
\( @C \) is syntactic sugar for \{\text{Access} \, \langle C \rangle \} \\
\( X=C:=\langle Y \rangle \) is syntactic sugar for \{\text{Exchange} \, \langle C \rangle \, \langle X \rangle \, \langle Y \rangle \}
Abstract data types (revisited)

• For a given functionality, there are many ways to package the ADT. We distinguish three axes.
  • Open vs. secure ADT: is the internal representation visible to the program or hidden?
  • Declarative vs. stateful ADT: does the ADT have encapsulated state or not?
  • Bundled vs. unbundled ADT: is the data kept together with the operations or is it separable?
• Let us see what our stack ADT looks like with some of these possibilities
Stack: Open, declarative, and unbundled

• Here is the basic stack, as we saw it before:

  fun {NewStack} nil end
  fun {Push S E} E|S end
  fun {Pop S E} case S of X|S1 then E=X  S1 end end
  fun {IsEmpty S} S==nil end

• This is completely unprotected. Where is it useful? Primarily, in small programs in which expressiveness is more important than security.
Stack: Secure, declarative, and unbundled

- We can make the declarative stack secure by using a wrapper:

```plaintext
local Wrap Unwrap
in
  {NewWrapper Wrap Unwrap}
  fun {NewStack} {Wrap nil} end
  fun {Push S E} {Wrap E|{Unwrap S}} end
  fun {Pop S E} case {Unwrap S} of X|S1 then E=X {Wrap S1} end end
  fun {IsEmpty S} {Unwrap S} ==nil end
end

- Where is this useful? In large programs where we want to protect the implementation of a declarative component.
```
Stack: Secure, *stateful*, and unbundled

- Let us combine the wrapper with state:
  
  ```
  local Wrap Unwrap
  in
  {NewWrapper Wrap Unwrap}
  fun {NewStack} {Wrap {NewCell nil}} end
  proc {Push W X} C={Unwrap W} in {Assign C X|{Access C}} end
  fun {Pop W} C={Unwrap W} in
    case {Access C} of X|S then {Assign C S} X end
  end
  fun {IsEmpty W} {Access {Unwrap W}}==nil end
  end
  ```

  This version is stateful but lets us store the stack separate from the operations.

  The same operations work on all stacks.
• This is the simplest way to make a secure stateful stack:

\[
\text{proc} \{\text{NewStack} ?\text{Push} ?\text{Pop} ?\text{IsEmpty}\}
\]
\[
\quad C = \{\text{NewCell} \text{ nil}\}
\]
\[
in
\quad \text{proc} \{\text{Push} \ X\} \{\text{Assign} \ C \ X\|\{\text{Access} \ C\}\} \quad \text{end}
\]
\[
\quad \text{fun} \{\text{Pop}\} \quad \text{case} \ \{\text{Access} \ C\} \ \text{of} \ X\|S \ \text{then} \ \{\text{Assign} \ C \ S\} \ X \ \text{end} \ \text{end}
\]
\[
\quad \text{fun} \{\text{IsEmpty}\} \quad \{\text{Access} \ C\} == \text{nil} \ \text{end}
\quad \text{end}
\]
• Compare the declarative with the stateful versions: the declarative version needs two arguments per operation, the stateful version uses higher-order programming (instantiation)
• With some syntactic support, this is \textit{object-based programming}
Four ways to package a stack

• Open, declarative, and unbundled: the usual declarative style, e.g., in Prolog and Scheme

• Secure, declarative, and unbundled: use wrappers to make the declarative style secure

• Secure, stateful, and unbundled: an interesting variation on the usual object-oriented style

• Secure, stateful, and bundled: the usual object-oriented style, e.g., in Smalltalk and Java

• Other possibilities: there are four more possibilities! Exercise: Try to write all of them.
Encapsulated stateful abstract datatypes ADT

• These are stateful entities that can be accessed only by the external interface
• The implementation is not visible outside
• We show two methods to build stateful abstract data types:
  – The functor based approach (record interface)
  – The procedure dispatch approach
The functor-based approach

fun {NewCounter I}
  \( S = \{\text{NewCell I}\} \)
proc {Inc} \( S := @S + 1 \) end
proc {Dec} \( S := @S - 1 \) end
fun {Get} @S end
proc {Put I} \( S := I \) end
proc {Display} {Browse @S} end

in o(inc:Inc dec:Dec get:Get put:Put display:Display)
end
The functor-based approach

fun {NewCounter I}
  \( S \) = \{NewCell I\}

proc {Inc} \( S := @S + 1 \) end

proc {Dec} \( S := @S - 1 \) end

fun {Get} \( @S \) end

proc {Put I} \( S := I \) end

proc {Display} \{Browse \( @S \)\} end

in  o(inc:Inc dec:Dec get:Get put:Put browse:Display)
end

The state is collected in cell \( S \)
The state is completely encapsulated
i.e. not visible outside
The functor-based approach

The interface is created for each instance Counter

fun {NewCounter I}
  \( S = \{\text{NewCell } I\} \)
  \[
  \text{proc \{Inc\} } S := \@S + 1 \text{ end} \\
  \text{proc \{Dec\} } S := \@S - 1 \text{ end} \\
  \text{fun \{Get\} } @S \text{ end} \\
  \text{proc \{Put I\} } S := I \text{ end} \\
  \text{proc \{Display\} } \{\text{Browse } @S\} \text{ end}
\]

in  o(inc:Inc dec:Dec get:Get put:Put display:Display)
end
The functor-based approach

fun \{NewCounter I\}
  \[ S = \{NewCell I\} \]

proc \{Inc\} \[ S := @S + 1 \] end

proc \{Dec\} \[ S := @S - 1 \] end

fun \{Get\} @S end

proc \{Put I\} \[ S := I \] end

proc \{Display\} {Browse S.v} end

\[ \text{in } o(\text{inc:Inc dec:Dec get:Put display:Display}) \]

end

functions that access the state by lexical scope
Call pattern

declare C1 C2
C1 = {NewCounter 0}
C2 = {NewCounter 100}

{C1.inc}
{C1.display}

{C2.dec}
{C2.display}
Defined as a functor

functor Counter
export inc:Inc dec:Dec get:Get put:Put display:Display init:Init
define
    S
    proc {Init init(I)}  S = {NewCell I}  end
    proc {Inc}  S := @$S + 1$  end
    proc {Dec}  S := @$S - 1$  end
    fun {Get}  @$S$  end
    proc {Put I}  S := I  end
    proc {Display}  {Browse @$S$}  end
end
Functors

• Functors have been used as a specification of modules
• Also functors have been used as a specification of abstract datatypes
• How to create a stateful entity from a functor?
Explicit creation of objects from functors

• Given a variable F that is bound to a functor
  
  \[ [O] = \{\text{Module.apply } [F]\} \]
  
  creates stateful ADT object O that is an instance of F

• Given the functor F is stored on a file ’f.ozf’
  
  \[ [O] = \{\text{Module.link } [’f.ozf’]\} \]
  
  creates stateful ADT object O that is an instance of F
functor Counter
export inc:Inc dec:Dec get:Put display:Display init:Init

define

S
   proc {Init init(I)}  S = {NewCell I}  end
   proc {Inc}  S := @S + 1  end
   proc {Dec}  S := @S - 1  end
   fun {Get}  @S  end
   proc {Put I}  S := I  end
   proc {Display}  {Browse @S}  end

end
Pattern of use

fun \{New Functor Init\}
    M in
    [M] = \{Module.apply \[Functor\]\}
    \{M.init Init\}
    M
End

declare C1 C2
C1 = \{New Counter init(0)\}
C2 = \{New Counter init(100)\}
\{C1.inc\} \{C1.put 50\} \{C1.display\}
\{C2.dec\} \{C2.display\}
The procedure-based approach

fun {Counter}
   \texttt{S}
   \begin{align*}
   \text{proc } \{\text{Inc inc(Value)}\} & \quad S \assign @S + \text{Value} \end{align*} \text{ end} \\
   \text{proc } \{\text{Display display}\} & \quad \{\text{Browse } @S\} \end{align*} \text{ end} \\
   \text{proc } \{\text{Init init(I)}\} & \quad S \assign \{\text{NewCell I}\} \end{align*} \text{ end} \\
D = o(inc:Inc \; \text{display:Display} \; \text{init:Init}) \\
\text{in } \text{ proc } \{M\} \quad \{D.\{\text{Label M}\} \; M\} \end{align*} \text{ end} \\
\text{end}
The procedure-based approach

fun \{Counter\}
   S
...
   D = o(inc:Inc display:Display init:Init)
end

fun \{New Class InitialMethod\}
   O = \{Class\}
end
Example

• The following shows how an object is created from a class using the procedure \texttt{New/3}, whose first argument is the class, the second is the initial method, and the result is the object.

• \texttt{New/3} is a generic procedure for creating objects from classes.

\begin{verbatim}
declare C = {New Counter init(0)}
{C display}
{C inc(1)}
{C display}
\end{verbatim}

Object interface is as a procedure of one argument, which expects a record
Object-oriented programming

• Supports
  – Encapsulation
  – Compositionality
  – Instantiation

• Plus
  – Inheritance
Inheritance

- Programs can be built in hierarchical structure from ADT’s that depend on other ADT’s (Components)
- Object-oriented programming (inheritance) is based on the idea that ADTs have so much in common
- For example, sequences (stacks, lists, queues)
- Object oriented programming enables building ADTs incrementally, through *inheritance*
- An ADT can be defined to *inherit* from another abstract data type, substantially sharing functionality with that abstract data type
- Only the difference between an abstract datatype and its ancestor has to be specified
What is object-oriented programming?

- OOP (Object-oriented programming) = encapsulated state + inheritance
- Object
  - An entity with unique identity that encapsulates state
  - State can be accessed in a controlled way from outside
  - The access is provided by means of methods (procedures that can directly access the internal state)
- Class
  - A specification of objects in an incremental way
  - Incrementality is achieved inheriting from other classes by specifying how its objects (instances) differ from the objects of the inherited classes
<table>
<thead>
<tr>
<th>Instances (objects)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interface (what methods are available)</td>
</tr>
<tr>
<td>State (attributes)</td>
</tr>
<tr>
<td>Procedures (methods)</td>
</tr>
</tbody>
</table>
A class is a statement

class 〈ClassVariable〉

attr
〈AttrName1〉

〈AttrNameN〉

meth 〈Pattern1〉 〈Statement〉 end

meth 〈PatternN〉 〈Statement〉 end

end
A class can also be a value that can be in an expression position

class $
  \text{attr} \\
  \langle \text{AttrName1} \rangle \\
  : \\
  \langle \text{AttrNamen} \rangle \\
  \text{meth} \langle \text{Pattern} \rangle \langle \text{Statement} \rangle \text{ end} \\
  : \\
  \text{meth} \langle \text{Pattern} \rangle \langle \text{Statement} \rangle \text{ end} \\
\text{end}
Classes in Oz

The class Counter has the syntactic form

```oz
class Counter
  attr val
  meth display
    {Browse @val}
end
meth inc(Value)
  val := @val + Value
end
meth init(Value)
  val := Value
end
end
```
Attributes of Classes

The class Counter has the syntactic form

```
class Counter
    attr val

    end

    meth display
        {Browse @val}
    end

    meth inc(Value)
        val := @val + Value
    end

    meth init(Value)
        val := Value
    end
end
```

val is an attribute: a modifiable cell that is accessed by the atom val
Attributes of classes

The class Counter has the syntactic form

```plaintext
class Counter
    attr val
    meth display
        {Browse @val}
    end
    meth inc(Value)
        val := @val + Value
    end
    meth init(Value)
        val := Value
    end
end
```

the attribute val is accessed by the operator @val
The class Counter has the syntactic form

```
class Counter
  attr val
  meth display
    {Browse @val}
  end
  meth inc(Value)
    val := @val + Value
  end
  meth init(Value)
    val := Value
  end
end
```

the attribute val is assigned by the operator := as val := ...
The class Counter has the syntactic form

```plaintext
class Counter
    attr val
    meth display
        {Browse @val}
    end
    meth inc(Value)
        val := @val + Value
    end
    meth init(Value)
        val := Value
    end
end
```

methods are statements
method head is a record (tuple) pattern
Classes in Oz

The class Counter has the syntactic form

```
class Counter
  attr val
  meth display
    {Browse @val}
  end
  meth inc(Value)
    val := @val + Value
  end
  meth init(Value)
    val := Value
  end
end
```
Example

• An object is created from a class using the procedure `New/3`, whose first argument is the class, the second is the initial method, and the result is the object (such as in the functor and procedure approaches)

• `New/3` is a generic procedure for creating objects from classes.

```
declare C = {New Counter init(0)}
{C display}
{C inc(1)}
{C display}
```
A class $X$ is defined by:

- \texttt{class } X \ldots \texttt{ end}

Attributes are defined using the attribute-declaration part before the method-declaration part:

- \texttt{attr } A_1 \ldots A_N

Then follows the method declarations, each has the form:

- \texttt{meth } E \ S \texttt{ end}

The expression $E$ evaluates to a method head, which is a record whose label is the method name.
Summary

• An attribute $A$ is accessed using $\@ A$.
• An attribute is assigned a value using $A := E$.
• A class can be defined as a value:
  $X = \texttt{class} \ ... \ \texttt{end}$
Attribute Initialization

• Stateful (may be updated by :=)
• Initialized at object creation time, all instances have the initial balance = 0

```
class Account
  attr balance: 0
  meth ...
end
```

In general the initial value of an attribute could be any legal value (including classes and objects)
Attribute Initialization

- Initialization by instance

```ruby
class Account
  attr balance
  meth init(X) balance := X end
...
```

- O1 = {New Account init(100)}
- O2 = {New Account init(50)}
Attribute Initialization

• Initialization by brand

```ruby
declare L=linux

class RedHat
  attr ostype:L
  meth get(X) X = @ostype end
end

class SuSE
  attr ostype:L
  meth get(X) X = @ostype end
end

class Debian
  attr ostype:L
  meth get(X) X = @ostype end
end
```
Example

class Queue
    attr front back count
    meth init
        Q in
        front := Q  back := Q  count := 0
    end
    meth put(X)
        Q in
        @back = X|Q
        back := Q
        count := @count + 1
    end
    ...
end
Example

class Queue

attr front back count

meth init
    Q in
    front := Q  back := Q  count := 0
end

meth put(X)
    Q in
    @back = X|Q
    back := Q
    count := @count + 1
end

...
class Queue
    attr front back count
    ...
    meth get(?X)
        Q in
        X|Q = @front
        front := @count - 1
    end
    meth count(?X) X = @count end
    ...
end
Classes as incremental ADTs

• Object-oriented programming allows us to define a class by extending existing classes

• Three things have to be introduced
  – How to express inheritance, and what does it mean?
  – How to access particular methods in the new class and in preexisting classes
  – Visibility – what part of the program can see the attributes and methods of a class

• The notion of delegation as a substitute for inheritance
Inheritance

• Inheritance should be used as a way to specialize a class while retaining the relationship between methods
• In this way it is a just an extension of an ADT
• The other view is inheritance is just a (lazy) way to construct new abstract data types!
• No relationships are preserved
Inheritance

class Account
  attr balance:0
  meth transfer(Amount)
    balance := @balance+Amount
  end
  meth getBal(B)
    B = @balance
  end
end

A={New Account transfer(100)}
Inheritance II

The class VerboseAccount has the methods:
transfer, getBal, and
verboseTransfer

Conservative extension

```ruby
class VerboseAccount
  from Account
  meth verboseTransfer(Amount)
  ...
end
end
```
Inheritance II

Non-Conservative extension

```ruby
class AccountWithFee
  from VerboseAccount
  attr fee:5
  meth transfer(Amount)
  ...
end
```

The class `AccountWithFee` has the methods: `transfer`, `getBal`, and `verboseTransfer`.

The method `transfer` has been redefined (overridden) with another definition.
Inheritance II

Non-Conservative extension

```ruby
class AccountWithFee
  from VerboseAccount
  attr fee: 5
  meth transfer(Amount)
  ...
end
```
Polymorphism

The ability for operations to take objects (instances) of different types.

For example, the transfer method can be invoked in account object instances of three different classes.

The most specific behavior should be executed.
Dynamic binding
- Inside an object $O$ we want to invoke a method $M$
- This is written as \{self $M$\}, and chooses the method visible in the current object ($M$ of $D$)
Static and dynamic binding

Static binding
- Inside an object $O$ we want to invoke a method $M$ in a specific (super) class
- This is written as $C, M$ and chooses the method visible in the super class $C$ (M of $C$)
Static method calls

• Given a class $C$ and a method head $m(...)$, a static method-call has the following form:
  $C, m(...)$

• Invokes the method defined in the class argument.

• A static method call can only be used inside class definitions.

• The method call takes the current object denoted by `self` as implicit argument.

• The method $m$ could be defined in the class $C$, or inherited from a super class.
Exercises

66. Do Java and C++ object abstractions completely encapsulate internal state? If so, how? If not, why?
67. Do Java and C++ enable static access to methods defined in classes arbitrarily high in the inheritance hierarchy? If so, how? If not, why?
68. Exercise CTM 7.9.1 (pg 567)
69. Exercise CTM 7.9.7 (pg 568)