

Programming Paradigms

Lecture 11

Slides are from Prof. Chin Wei-Ngan from NUS

Stateful Programming

Overview

- Stateful programming
 - what is state?
 - cells as abstract datatypes
 - the stateful model
 - relationship between the declarative model and the stateful model
 - indexed collections:
 - array model
 - parameter passing:
 - system building
 - component-based programming

Maintaining State

Encapsulated State I

Box O

An **Interface** that hides
the state

State as a
group of
memory cells

Group of functions and
procedures that operate
on the state

- Box O can remember information between independent invocations, it has a memory
- Basic elements of explicit state
- Index datatypes
- Basic techniques and ideas of using state in program design

Encapsulated State II

Box O

An **Interface** that hides
the state

State as a
group of
memory cells

Group of functions and
procedures that operate
on the state

- What is the difference between implicit state and explicit state?
- What is the difference between state in general and encapsulated state?
- Component based programming and object-oriented programming
- Abstract data types using encapsulated state

What is a State?

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

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

{Show {Sum [1 2 3 4] 0}}
```

What is an Implicit State?

The two arguments `Xs` and `A`
represents an **implicit state**

<code>Xs</code>	<code>A</code>
<code>[1 2 3 4]</code>	0
<code>[2 3 4]</code>	1
<code>[3 4]</code>	3
<code>[4]</code>	6
<code>nil</code>	10

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

{Show {Sum [1 2 3 4] 0} }
```

What is an Explicit State?

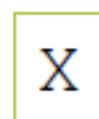
An *explicit state* (in a procedure) is a state whose lifetime extends over more than one procedure call without being present in the procedure's arguments.

Extends beyond declarative programming model

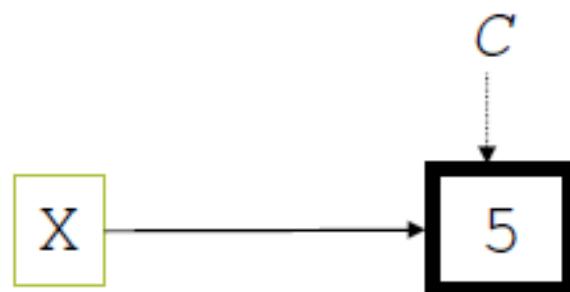
- support general concurrency
- support memory capability
- efficiency reasons

What is an Explicit State? Example

an unbound
variable



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

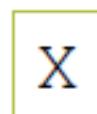


Cell C is assigned
the value 6,
 $@X$ is bound to 6

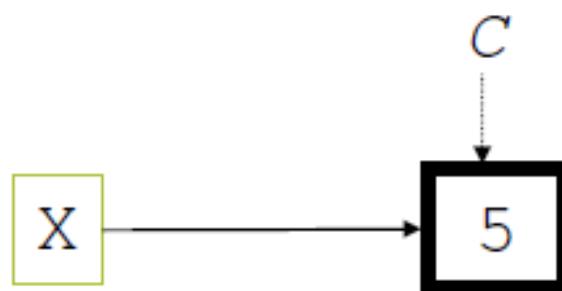


What is an Explicit State? Example

an unbound
variable



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



Cell C is assigned
the value 6,
 $@X$ is bound to 6



- The cell is a value container with a unique **identity/address**
- X is really bound to the **identity/address** of the cell
- When the cell is assigned, X does not change

Maintaining State

- Agents maintain ***implicit*** state
 - state maintained as values passed as arguments
- Agents ***encapsulate*** state
 - state is only available within one agent
 - in particular, only one thread
- With ***cells*** we can have ***explicit*** state
 - programs can manipulate state by manipulating cells

Explicit State

- So far, the considered models do not have explicit state
- Explicit state is of course useful
 - algorithms might require state (such as arrays)
 - the right model for some task

Modular Approach to State

- Programs should be modular
 - composed from components
- Some components can use state
 - use only, if necessary
- Components from outside (interface) can still behave like functions

State: Abstract Datatypes

- Many useful abstractions are abstract datatypes using encapsulated state
 - arrays
 - dictionaries
 - queues
 - ...

Cells

Cells as Abstract Datatypes

- $C = \{ \text{NewCell } X \}$
 - creates new cell C
 - with initial value X
- $X = \{ \text{Access } C \}$ or equivalently $x = @C$
 - returns current value of C
- $\{ \text{Assign } C \ X \}$ or equivalently $C := X$
 - assigns value of C to be X
- $\{ \text{Exchange } C \ X \ Y \}$ or equivalently $x = C := Y$
 - atomically assigns Y into C and bind old value to X

Cells

- Are a model for explicit state
- Useful in few cases on itself
- Device to explain other stateful datatypes such as arrays

Examples

```
X = {NewCell 0}
```

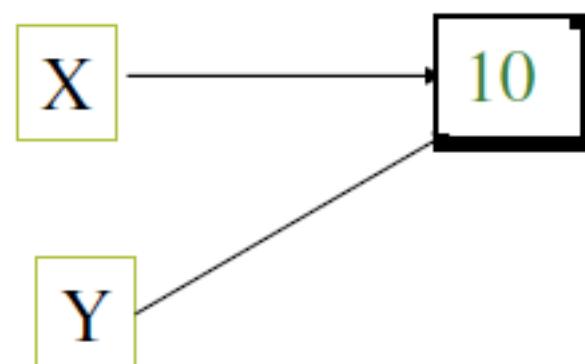
```
{Assign X 5}
```

```
Y = X
```

```
{Assign Y 10}
```

```
{Access X} == 10 → true
```

```
X == Y → true
```



Examples

```
X = {NewCell 0}
```



```
{Assign X 5}
```



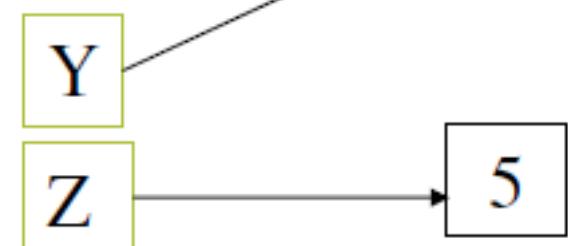
```
Y = X
```



```
{Exchange Y Z 10}
```

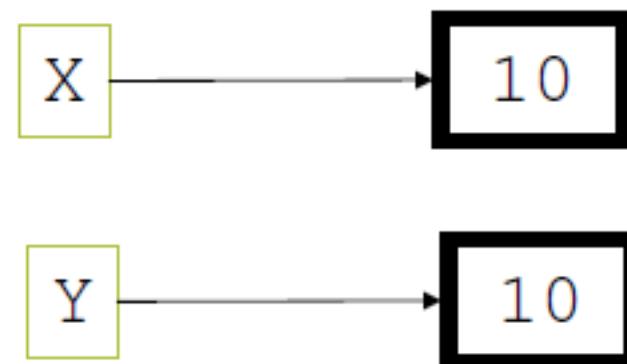


z is the old value of cell Y

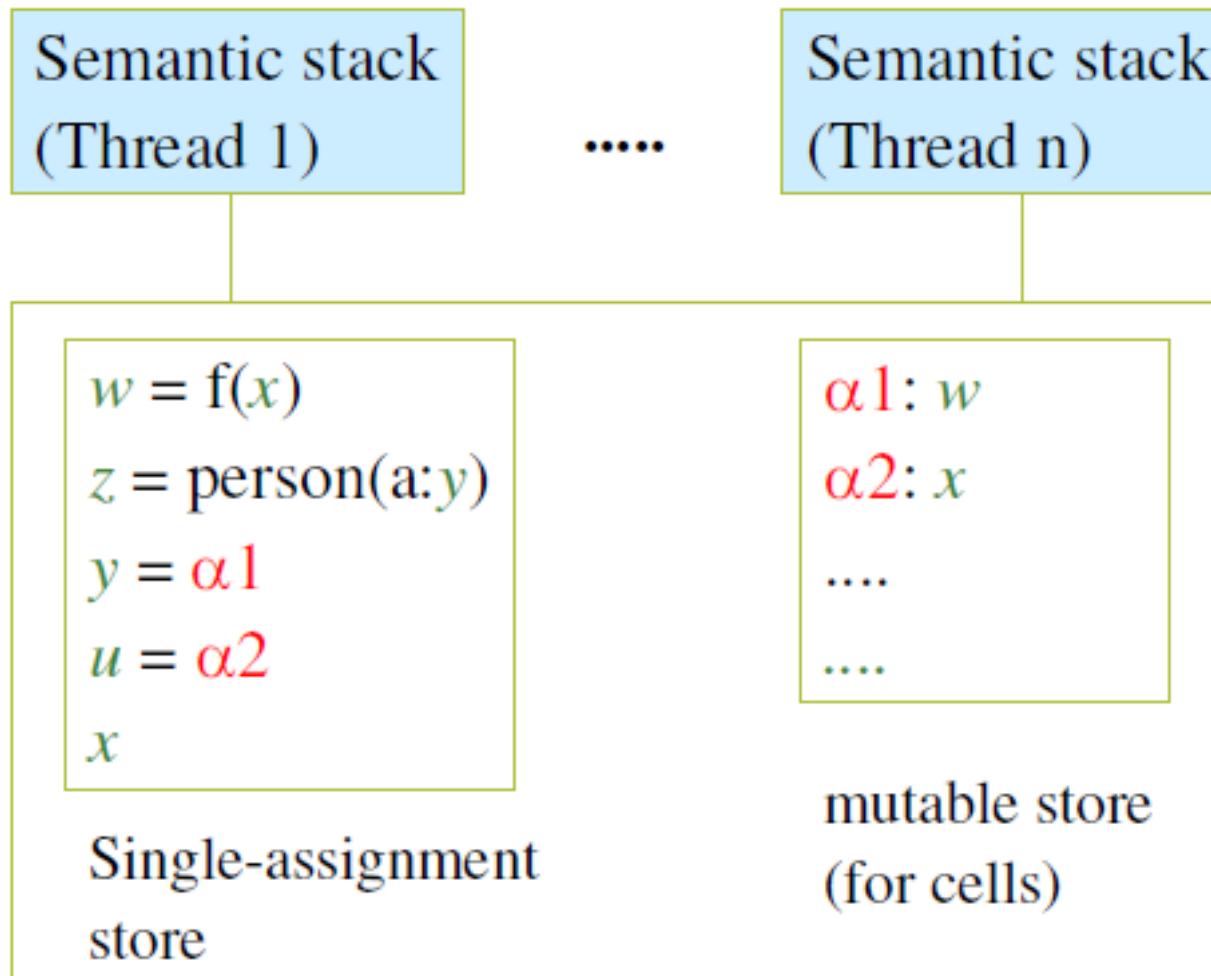


Examples

- `X = {NewCell 10}`
`Y = {NewCell 10}`
- `X == Y` % returns `false`
- Because `x` and `y` refer to different cells, with different identities
- `{Access X} == {Access Y}` returns `true`



Semantic Model Extended with Cells



The Stateful Model

$\langle S \rangle ::= \text{skip}$

| $\langle S_1 \rangle \langle S_2 \rangle$

| ...

| **thread** $\langle S_1 \rangle \text{end}$

| { NewCell $\langle X \rangle \langle C \rangle$ }

| { Exchange $\langle C \rangle \langle X \rangle \langle Y \rangle$ }

empty statement

statement sequence

thread creation

cell creation

cell exchange

The stateful model

- | {NewCell $\langle c \rangle$ } *cell creation*
- | {Exchange $\langle c \rangle \langle x \rangle \langle y \rangle$ } *cell exchange*

NewCell: Create a new cell $\langle c \rangle$ with initial content $\langle x \rangle$

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

```
proc {Assign C X} {Exchange C _ X} end
fun {Access C} local X in
    {Exchange C X X} X end end
```

Do We Need Explicit State?

- Up to now the computation model we introduced in the previous lectures did not have any notion of explicit state
- An important question is: do we need explicit state?
- There are a number of reasons for introducing state, we discuss some of them here

Modular Programs

- A system (program) is **modular** if changes (updates) in the program are confined to the components where the functionality are changed
- Here is an example where introduction of explicit state in a systematic way leads to program modularity compared to programs that are written using only the declarative model (where every component is a function)

Encapsulated State I

- Assume we have three persons: P, U1 and U2
- P is a programmer that developed a component M that provides two functions F and G
- U1 and U2 are system builders that use the component M

```
fun {MF}  
  fun {F ...}  
    <Definition of F>  
  end  
  fun {G ...}  
    <Definition of G>  
  end  
in 'export' (f:F g:G)  
end  
M = {MF}
```

Encapsulated State II

- Assume we have three persons: P, U1 and U2
- P is a programmer that developed a component M that provides two functions F and G
- U1 and U2 are system builders that use the component M

```
functor MF
  export f:F g:G
  define
    fun {F ...}
      <Definition of F>
    end
    fun {G ...}
      <Definition of G>
    end
  end
```

Encapsulated State III

- User U_2 has a demanding application
- He wants to extend the module M to enable him to monitor how many times the function F is invoked in his application
- He goes to P , and asks him to do so without changing the interface to M

```
fun {M}
  fun {F ...}
    <Definition of F>
  end
  fun {G ...}
    <Definition of G>
  end
in 'export' (f:F g:G)
end
```

Encapsulated State IV

- This cannot be done in the declarative model, because F cannot remember its previous invocations
- The only way to do it there is to change the interface to F by adding two extra arguments FIn and $FOut$

```
fun {F ... +FIn ?FOut} FOut = FIn+1 ... end
```

- The rest of the program always remembers the previous number of invocations (FIn and $FOut$) returns the new number of invocation
- But this **changes** the interface!

Encapsulated State V

- A cell is created when MF is called
- Due to lexical scoping the cell is only visible to the created version of F and Count
- The M.f did not change
- New function M.c is available
- **x is hidden only visible inside M (encapsulated state)**

```
fun {MF}
  X = {NewCell 0}
  fun {F ...}
    {Assign X {Access X}+1}
    ⟨Definition of F⟩
  end
  fun {G ...}
    ⟨Definition of G⟩
  end
  fun {Count} {Access X} end
in 'export' (f:F g:G c:Count)
end
M = {MF}
```

Relationship between the Declarative Model and the Stateful Model

- **Declarative programming** guarantees by construction that each procedure computes a function
- This means each component (and subcomponent) is a function
- It is possible to use encapsulated state (cells) so that a component is declarative from outside, and stateful from the inside
- Considered as a black-box the program procedure is still a function

Declarative versus Stateful

- Declarative:

```
declare X  
thread X=1 end  
thread X=2 end  
{Browse X}
```

→ 1 or 2, followed by a
“failure unification”

- Stateful

```
declare X={NewCell 0}  
thread X:=1 end  
thread X:=2 end  
{Browse @X}
```

→ 0, 1, or 2 depending on the
order of threads execution

Programs with Accumulators

```
local
  fun {Sum1 Xs A}
    case Xs of X|Xr
      then {Sum1 Xr A+X}
    [] nil then A
  end
end
in
  fun {Sum Xs}
    {Sum1 Xs 0}
  end
```

Programs with Accumulators

```
fun {Sum Xs}
  fun {Sum1 Xs A}
    case Xs of X|Xr
      then {Sum1 Xr A+X}
    [] nil then A
    end
  end
in
{Sum1 Xs 0}
end
```

```
fun {Sum Xs}
  fun {Sum1 Xs}
    case Xs of X|Xr
      then
        {Assign A X+{Access A}}
        {Sum1 Xr}
    [] nil then {Access A}
    end
  end
A = {NewCell 0}
in
{Sum1 Xs}
end
```

Programs with Accumulators

```
fun {Sum Xs}
  fun {Sum1 Xs}
    case Xs of X|Xr then
      {Assign A X+{Access A}}
      {Sum1 Xr}
    [] nil then
      {Access A}
    end
  end
  A = {NewCell 0}
in
  {Sum1 Xs}
end
```

```
fun {Sum Xs}
  A = {NewCell 0}
in
  {ForAll Xs
    proc {$ X}
      {Assign A
        X+{Access A}}
    end}
    {Access A}
  end
```

Programs with Accumulators

```
fun {Sum Xs}
  A = {NewCell 0}
in
{ForAll Xs
  proc {$ X}
    {Assign A
      X+{Access A}}
  end}
{Access A}
end
```

```
fun {Sum Xs}
  A = {NewCell 0}
in
  for X in Xs do
    {Assign A
      X+{Access A}}
  end
  {Access A}
end
```

- The state is encapsulated inside each procedure invocation

Another Declarative Function with State

```
fun {Reverse Xs}
    Rs={NewCell nil}
in
    for X in Xs do
        Rs:=X | @Rs end
    @Rs
end
```

Rs is a hidden internal state that do not live beyond the lifetime of above method.

Indexed Collections

- Indexed collections groups a set of (partial) values
- The individual elements are accessible through an index
- The declarative model provides:
 - tuples, e.g. date(17 december 2001)
 - records, e.g. date(day:17 month:december year:2001)
- We can now add state to the fields
 - arrays
 - dictionaries

Arrays

- An array is a **mapping** from integers to (partial) values
- The **domain** is a set of consecutive integers, with a *lower bound* and an *upper bound*
- The range can be mutated (change)
- A good approximation is to think of arrays as a tuple of cells

Array Model

- Simple array
 - fields indexed from 1 to n
 - values can be accessed, assigned, and exchanged
- Model: tuple of cells

Arrays

- `A={NewArray L H I}`
 - create array with fields from `L` to `H`
 - all fields initialized to value `I`
- `X={ArrayAccess A N}`
 - return value at position `N` in array `A`
- `{ArrayAssign A N X}`
 - set value at position `N` to `X` in array `A`
- `{ArrayExchange A N X Y}`
 - change value at position `N` in `A` from `X` to `Y`
- `A2={Array.clone A}`
 - returns a new array with same indices and contents as `A`

Example 1

- $A = \{\text{MakeArray } L \ H \ F\}$
- Creates an array A where for each index I is mapped to $\{F \ I\}$

```
fun {MakeArray L H F}
  A = {NewArray L H unit}
  in
    for I in L..H do
      A.I := {F I}
    end
  A
end
```

Array2Record

- $R = \{Array2Record\ L\ A\}$
- Define a function that takes a label L and an array A , it returns a record R whose label is L and whose features are from the lower bound of A to the upper bound of A
- We need to know how to make a record
- $R = \{Record.make\ L\ Fs\}$
 - creates a record R with label L and a list of features (selector names), returns a record with distinct fresh variables as values
- $L = \{Array.low\ A\}$ and $H = \{Array.high\ A\}$
 - Return lower bound and higher bound of array A

Array2Record. Example

```
fun {Array2Record LA A}
    L = {Array.low A}
    H = {Array.high A}
    R = {Record.make LA {From L H} }
in
    for I in L..H do
        R.I = A.I
    end
    R
end
```

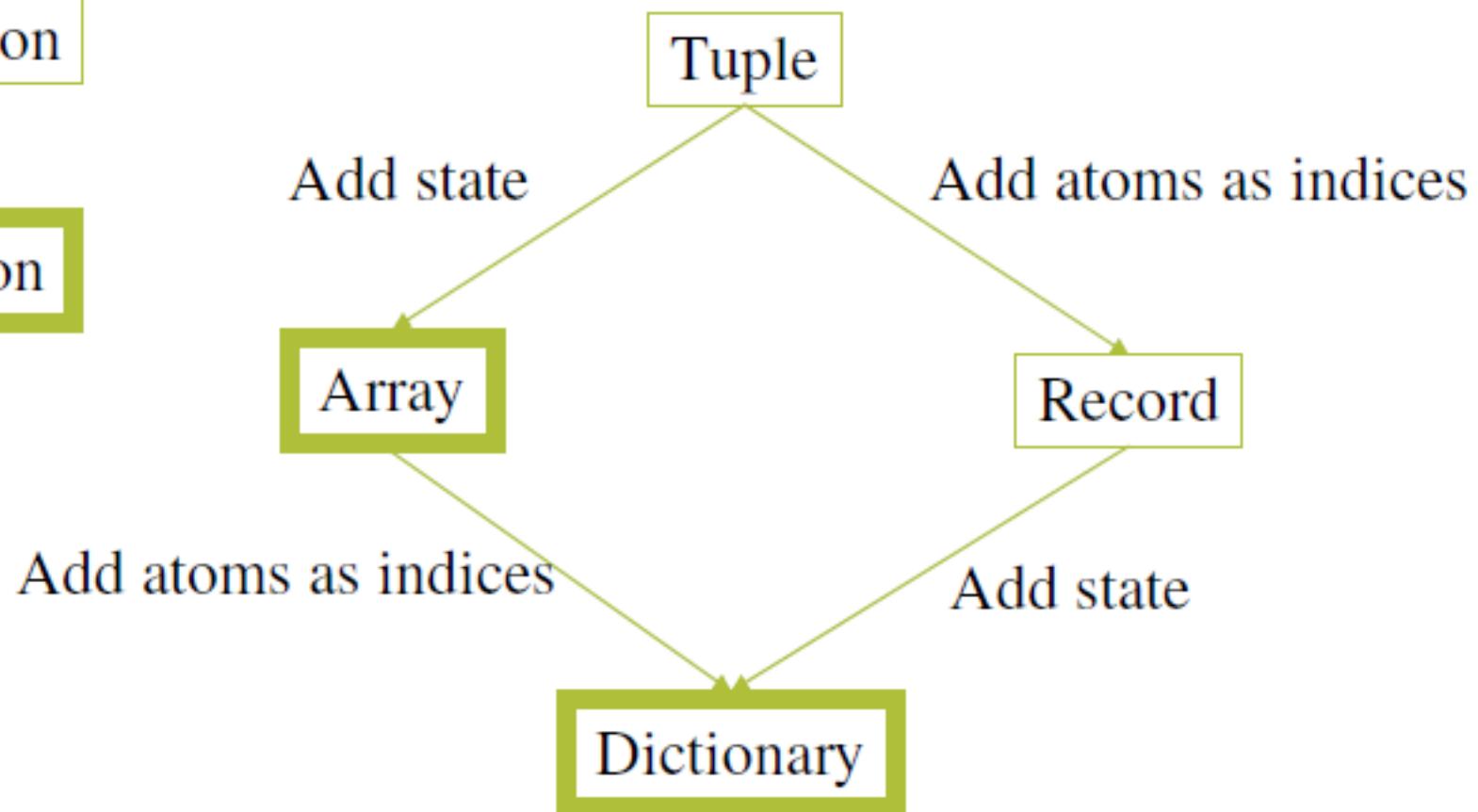
Tuple to Array. Example

```
fun {Tuple2Array T}
    H = {Width T}
in
    {MakeArray 1 H
        fun {$ I} T.I end}
end
```

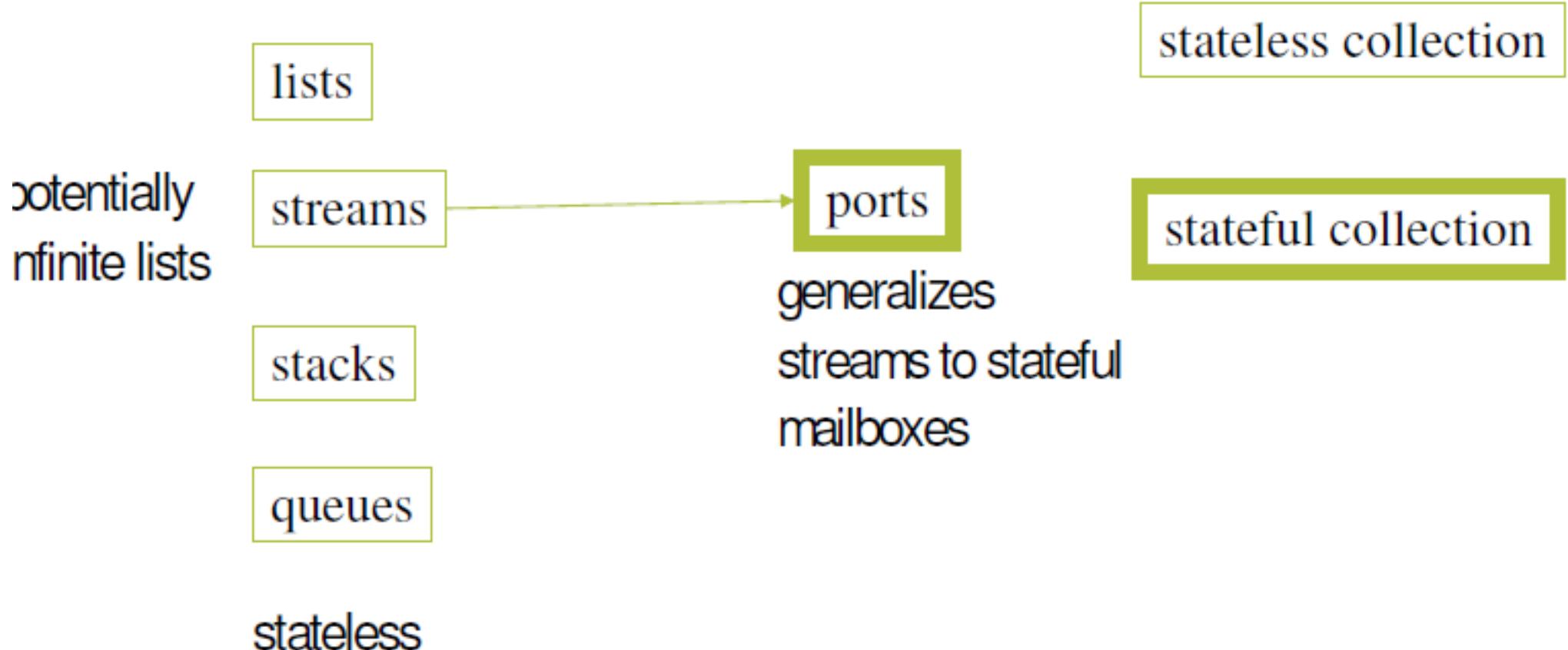
Indexed Collections

stateless collection

stateful collection



Other Collections



Parameter Passing

- Variety of parameter passing mechanisms can be simulated using cells, e.g.
 - Call by Reference
 - Call by Variable
 - Call by Value
 - Call by Value-Result
 - Call by Name
 - Call by Need

Call by Reference

- Pass language entity to methods
- What is a language entity?
 - single-assignment variable
 - cell
 - local variable (in C)
 - Is it address? &v
 - Is it its value? v

Call by Variable

- Identity of cell is passed
- (special case of call by reference)

```
proc {Sqr A}  
  A:=@A+1  
  A:=@A * @A  
end
```

```
local C={NewCell 0} in  
  C:=5  
  {Sqr C}  
  {Browse @C}  
end
```

Call by Value

- A value is passed and put into a local cell.

```
proc {Sqr A}          local C={NewCell 0} in
  D={NewCell A}        C:=5
  in   D:=@D+1         {Sqr @C}
      D:=@D*@D        {Browse @C}
end                      end
```

Call by Value-Result

- A value is passed into local cell on entry of method, and passed out on exit of method.

```
proc {Sqr A}          local C={NewCell 0} in
    D={NewCell @A}      C:=5
    in   D:=@D+1        {Sqr C}
        D:=@D*@D        {Browse @C}
    A:=@D                end
end
```

Call by Name

- A function for each argument that returns a cell on invocation.

```
proc {Sqr A}  
  {A} := @ {A} + 1  
  {A} := @ {A} * @ {A}  
end
```

```
local C={NewCell 0} in  
C:=5  
{Sqr fun {$} C end}  
{Browse @C}  
end
```

Call by Need

- The function is called once and used multiple times.

```
proc {Sqr A}  
  D={A}  
in  D:=@D+1  
    D:=@D*@D  
end
```

```
local C={NewCell 0} in  
C:=5  
{Sqr fun {$} C end}  
{Browse @C}  
end
```

System Building

- Abstraction is the best tool to build complex system
- Complex systems are built by layers of abstractions
- Each layer have two parts:
 - Specification, and
 - Implementation
- Any layer uses the specification of the lower layer to implement its functionality

Properties Needed to Support the Principle of Abstraction

- Encapsulation

- Hide internals from the interface

- Compositionality

- Combine parts to make new parts

- Instantiation/invocation

- Create new instances of parts

Component-Based Programming

- Supports
 - Encapsulation
 - Compositionality
 - Instantiation

Object-Oriented Programming

- Supports
 - Encapsulation
 - Compositionality
 - Instantiation
- Plus
 - Inheritance

Maintainability Issues

- Component design
 - Encapsulate design decisions
 - Avoid changing component interfaces
- System design
 - Reduce external dependency
 - Reduce levels of indirection
 - Predictable dependencies
 - Make decisions at right level
 - Document violations

Features of Data Abstraction

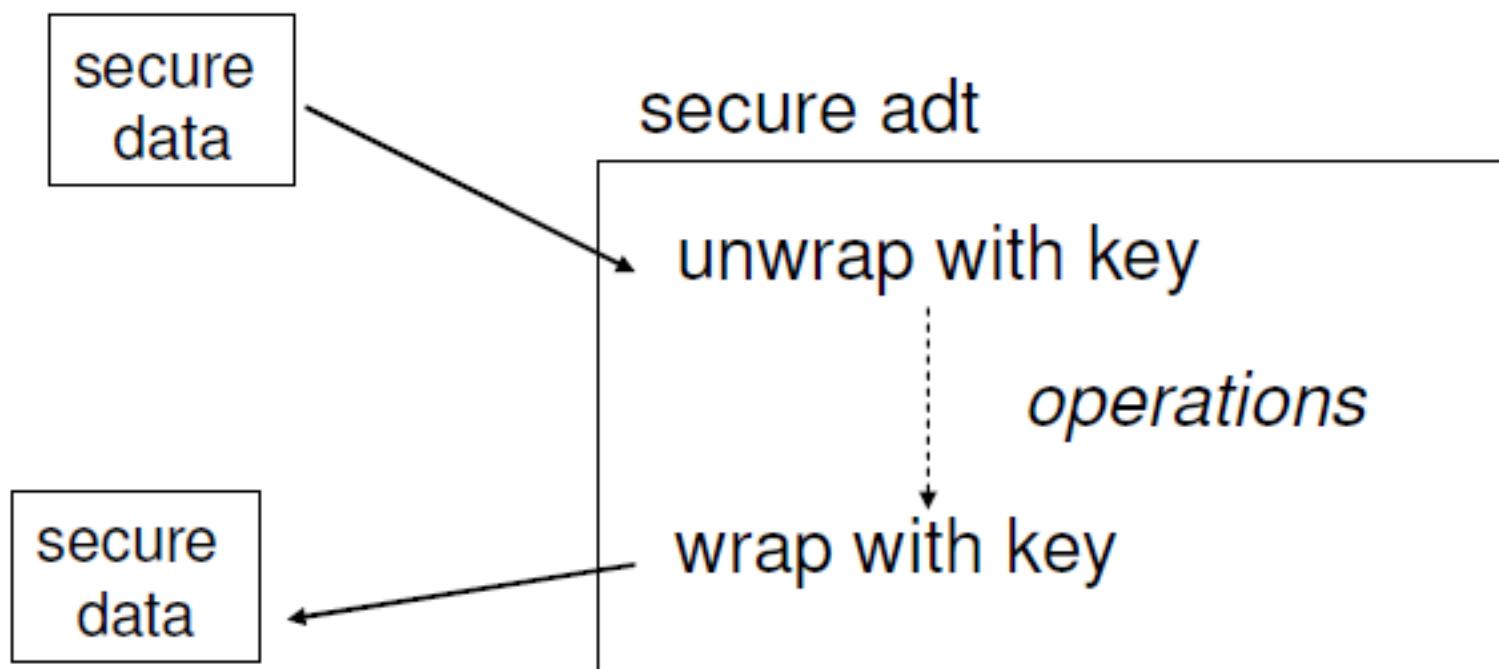
- Open/secure
 - Open – encapsulation enforced by programmer
 - Secure – implementation details not accessible to user
- Unbundled/bundled
 - Value/operations defined separately
 - Value/operation together, e.g. objects
- Explicit state/declarative
 - declarative – no mutable state
 - e.g. `push :: {Stack A, A} → State A`

Making ADT Secure in Oz

- Make values secure using keys

{ NewName } return a fresh name

N1==N2 compares names N1 and N2



Making ADT Secure in Oz

```
proc {NewWrapper ?Wrap ?Unwrap}
    Key={NewName}
in
    fun {Wrap X}
        fun {$ K} if K==Key then X
                  else raise error end end
    end
    fun {Unwrap W}
        {W Key}
    end
end
```

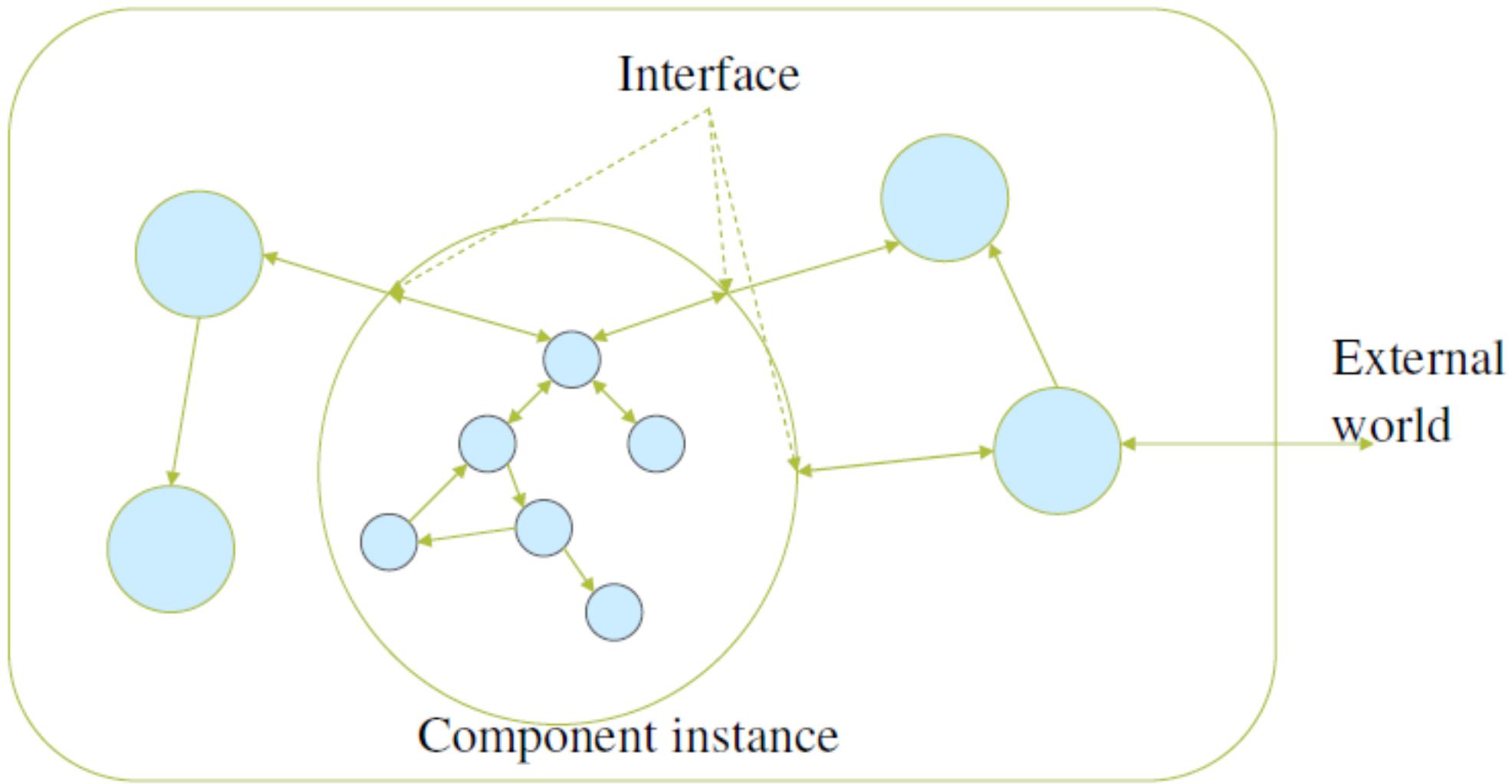
Using Security Wrapper in Stack ADT

```
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
```

Component-Based Programming

- "Good software is good in the large and in the small, in its high level architecture and in its low-level details". In Object-oriented software construction by Bernard Meyer
- What is the best way to build big applications?
- A large application is (almost) always built by a team
- How should the team members communicate?
- This depends on the application's structure (architecture)
- One way is to structure the application as a hierarchical graph

Component-Based Programming



Component-Based Design

- Team members are assigned individual components
- Team members communicate at the interface
- A component, can be implemented as a record that has a name, and a list of other component instances it needs, and a higher-order procedure that returns a component instance with the component instances it needs
- A component instance has an interface and an internal entities that serves the interface

Model Independence Principle

- As the system evolves, a component implementation might change or even the model changes
 - declarative (functional)
 - stateful sequential
 - concurrent, or
 - relational
- The interface of a component should be independent of the computation model used to implement the component
- The interface should depend only on the externally visible functionality of the component

What Happens at the Interface?

- The power of the component based infrastructure depends to a large extent on the expressiveness of the interface
- How does components communicate with each others?
- We have three possible case:
 - The components are written in the same language
 - The components are written in different languages
 - The components are written in different computation model

Components in the Same Language

- This is easy
- In Mozart/Oz, component instances are modules (records whose fields contain the various services provided by the component-instance part)
- In Java, interfaces are provided by objects (method invocations of objects)
- In Erlang, component instances are mainly concurrent processes (threads), communication is provided by sending asynchronous messages

Components in Different Languages

- An intermediate common language is defined to allow components to communicate given that the language provide the same computation model
- A common example is CORBA IDL (Interface Definition Language) which maps a language entity to a common format at the client component, and does the inverse mapping at the service-provider component
- The components are normally reside on different operating system processes (or even on different machines)
- This approach works if the components are relatively large and the interaction is relatively infrequent

Illustration (one way)

A component C1
calling the function
(method) $f(x)$ in the
Component C2

Translate $f(x)$ from
language L1 (structured
data) to IDL
(sequence of bytes)

Translate $f(x)$ from
language IDL
(sequence of bytes) to
language L2 (structured
data)

A component C2
invoking the function
(method) $f(x)$

Summary

- Stateful programming
 - what is state?
 - cells as abstract datatypes
 - the stateful model
 - relationship between the declarative model and the stateful model
 - indexed collections:
 - array model
 - system building
 - component-based programming