Encapsulation

Programming Languages

CS 214

Review

A *type* consists of two things:

- a set of *values*; and
- a set of *operations* onto those values.

An *abstract data type (ADT)* consists of:

- a collection of *data*: $type_1 \cdot type_2 \cdot \ldots \cdot type_n$
- a collection of *operations* on the data:

$$F(type_1 \cdot type_2 \cdot \ldots \cdot type_n) \rightarrow ADT$$
$$G(ADT) \rightarrow type_1$$
$$\ldots$$
$$H(ADT) \rightarrow \emptyset$$

Obviously, these two are related...

Encapsulation

An encapsulation mechanism is a language’s construct for “wrapping” a type’s data and operations into a *single syntactic structure*.

Two different encapsulation mechanisms have evolved:

- The class, a mechanism that lets programmers create new types that encapsulate data and operations; and
- The *module* (aka *package*), a mechanism that lets programmers store new types and their operations in a distinct container.

The evolutionary history of these provides useful context, so we’ll examine the history of each separately...

ADTs

In the early 1970s, *imperative* programming languages had evolved to the point where much of programming was building *abstract data types (ADTs)*, which consisted of an abstract type and its supported *operations*.

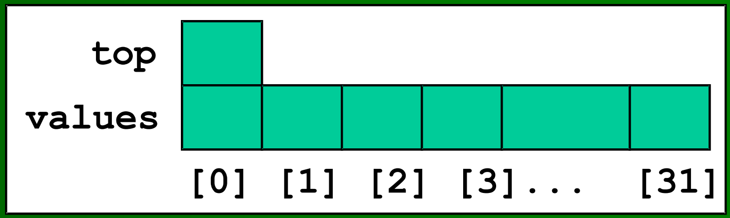
For example, a *Stack* ADT consists of:

- *Initialization(&Stack)* $\rightarrow \emptyset$
- *isEmpty(Stack)* $\rightarrow$ *bool*
- *isFull(Stack)* $\rightarrow$ *bool*
- *push(value · &Stack)* $\rightarrow \emptyset$
- *pop(&Stack)* $\rightarrow \emptyset$
- *top(Stack)* $\rightarrow$ *value*

The ADT's operations make up its *programmer's interface*, through which users are to interact with the ADT.

ADT Example in C

```c
/* IntStack.h (minus precondition checks)*/

#define STACK_MAX 32
typedef struct StackStruct {
  int myTop;
  int myValues[STACK_MAX];
} IntStack;

void init(IntStack* sRef) { sRef->myTop = -1; }

int isEmpty(IntStack s) { return s.myTop < 0; }

int isFull(IntStack s) {return s.myTop >= STACK_MAX-1;}

void push(int value, IntStack* sRef) {
  sRef->myTop++;
  sRef->myValues[sRef->myTop] = value;
}

void pop(IntStack* sRef) { sRef->myTop--; }

int top(IntStack s) { return s.myValues[s.myTop]; }
```



Problem 1

Nothing prevents a programmer from *bypassing* the interface:

Instead of writing:

```
while ( !isFull(s) )
 // … do something with s
```

a programmer can write:

```
while ( s.myTop < STACK_MAX )
 // … do something with s
```

If we upgrade our array-based stack to a linked stack:

```
/* IntStack.h … */

typedef struct Node {
  int value;
  struct Node * next;
} IntStackNode;

typedef struct StackStruct {
  IntStackNode * top;
} IntStack;
```

then the programmer's code *breaks* (↑ maintenance costs)!

Problem 2

Nothing prevents the programmer from *adding operations that violate the design of the ADT…*

```
#include "IntStack.h"

int peekUnderTop(IntStack s)
{
  return s.values[s.top-1];
}
```

Such operations will also “break” if we change the implementation details that underlie the *Stack* ADT (↑ maintenance costs)!

Recall: High maintenance costs led industry from *spaghetti coding* to *structured programming*.

Eliminating the maintenance costs of “broken” code led industry from *structured programming* to *modular programming*.

Modules and Packages

The problem with structured programming was that it did nothing to hide an ADT's *implementation details* .

In 1977, Wirth designed *Modula* with a new "container" construct in which a type and its operations could be stored.

- Wirth called this container the *module*.
- Rather than thinking of a type as values and operations, Wirth considered a type to be *just values* (i.e., data).
- The *module* was Wirth's construct for "wrapping" a type and its operations together (i.e., building an ADT).
- Fortran (90 and later) also provides a *Module* construct

In the 1980s, Ada adopted a similar approach for ADTs, but called their container the *package* instead of the module.

ADT Example in Ada

```
-- IntStackPackage.ads is the IntStackPackage specification
--  the Ada equivalent of a C header file

package IntStackPackage is
  type IntStack is private;

  procedure init(s: in out IntStack);
  function  isEmpty(s: in IntStack) return Boolean;
  function  isFull(s: in IntStack) return Boolean;
  procedure push(value: in Integer; s: in out IntStack);
  procedure pop(s: in out IntStack);
  function  top(s: in IntStack) return Integer;
 private
  STACK_MAX: constant Integer := 32;

  type IntStack is
   record
    myTop: Integer;
    myValues: array(1..STACK_MAX) of Integer;
  end Stack;
end IntStackPackage;
```

All declarations before *private* are visible externally; those after *private* are local to the package.

ADT Example in Ada (ii)

```
-- IntStackPackage.adb is the IntStackPackage body
--   the Ada equivalent of a C implementation file

package body IntStackPackage is
  procedure init(s: in out IntStack) is
  begin
      s.myTop:= 0;
  end init;

  function  isEmpty(s: in IntStack) return Boolean is
  begin
      return s.myTop < 1;
  end isEmpty;

  procedure push(value: in Integer; s: in out IntStack) is
  begin
      s.myTop:= s.myTop + 1; s.myValues(s.myTop):= value;
  end;

   -- … definitions of isFull(), pop(), top(), …

end IntStackPackage;
```


Package Specifications

The "public section" of the specification creates its *interface*

- Nothing else in the package is accessible;
- If a programmer wishes to use the ADT, they must do so using the declarations in its interface.

An Ada package specification differs from a C header file:

- Its private section allows the package to *hide implementation details* from the programmer (everything in a header file is public).
- The specification file *must be compiled* before it can be used (and before the package body can be compiled).

By separating the ADT's *public interface* from its *private implementation*, *a programmer cannot write programs that depend upon the ADT's implementation details*.

Example Usage

Given such an ADT, a programmer can write:

```
-- IntStackTest.adb
with TextIO, IntStackPackage; use TextIO, IntStackPackage;

procedure IntStackTest is
  s1, s2: IntStack;
  i: Integer;
begin
  init(s1);

  while (not isFull(s1)) loop
    get(i); push(i, s1);
  end loop;

  s2:= s1;

  while (not isEmpty(s2)) loop
    put(top(s2)); pop(s2);
  end loop;

end IntStackTest;
```

In modular programming, ADT operations are subprograms that receive the ADT as an argument.

Used in this way, a package/ module is a container in which an ADT can be "wrapped".

Modules/Packages As “Objects”

Modules/packages can also be used as “objects”:

```
-- IntStack.ads is the IntStack specification

package IntStack is
  function  isEmpty() return Boolean;
  function  isFull() return Boolean;
  procedure push(value: in Integer);
  procedure pop;
  function  top() return Integer;
end IntStack;
```

All of these identifiers are public (there is no *private* section).

The operations do *not* receive the ADT via a parameter.

There is no *init* subprogram in this kind of module/package (we’ll see why shortly).

“Object” Package Bodies

```
-- IntStack.adb is the IntStack body

package body IntStack is

 STACK_MAX: constant Integer := 32;
 myTop: Integer;
 myValues: array(1..STACK_MAX) of Integer;

 function isEmpty() return Boolean is
 begin
   return myTop < 1;
 end;

 procedure push(value: in Integer) is
 begin
   myTop:= myTop+1; myValues(myTop):= value;
 end push;

 -- … definitions of isFull, pop, top, …
begin
  myTop:= 0;
end IntStack;
```

Note 1: All of the implementation details are here in the body, making them *private*.

Note 2: A package may have an *initialization block* at its end that is executed when a program using the package is run...

"Object" Modules in Use

Such modules/packages can be used in an object-like way:

```
-- IntStackTest.adb tests the IntStack package

with Text_IO, IntStack; use Text_IO;

procedure IntStackTest is
  i: Integer;
begin

  while (not IntStack.isFull()) loop
    get(i);
    IntStack.push(i);
  end loop;

  while (not IntStack.isEmpty()) loop
    put(IntStack.top());
    IntStack.pop;
  end loop;

end IntStackTest;
```

In this approach, a module/package superficially resembles an OO-language object (created from a class)…

But a module/package is ***not a type***, so it cannot be used to create variables.

→*Only one such "object" can exist at a time*.

Generic Packages

Ada also allows packages to be given *type-parameters*, providing a way to circumvent the "one object" problem:

```
-- Stack.ads is the generic Stack specification
generic
  type Item is private;          -- Item is a type parameter
  Integer size;                  -- size is a data parameter
package Stack is
  function isEmpty() return boolean;
  function isFull() return boolean;
  procedure push(v: in Item);
  procedure pop();
  function top() return Item;
end Stack;
```

Ada's keyword *generic* tells the compiler that the parameters *Item* and *size* will be supplied by the ADT's user (ideal for containers).

Such a *Stack* stores "generic" *Items*, instead of "hardwired" Integers.

Generic Package Bodies

```
-- Stack.adb is the generic Stack body

package body Stack is

 myCapacity: Integer := size;
 myTop: Integer;
 myValues: array(1..myCapacity) of Item;

 function isEmpty() return Boolean is
 begin
   return myTop < 1;
 end;

 procedure push(value: in Item) is
 begin
  myTop:= myTop+1; myValues(myTop):= value;
 end push;

 -- … definitions of isFull, pop, top, …
begin
  myTop:= 0;
end Stack;
```

This far more elegant than C++ *templates:* the compiler already knows that *Stack* is a generic package because the spec. is compiled first.

Recent versions of Fortran's *module* have added this *generic* mechanism.

Generic Instantiation

Now we can dynamically create multiple *Stack* “objects”:

```
-- StackTest.adb tests the generic Stack package

with Text_IO, Stack; use Text_IO;
procedure StackTest is
  i: Integer;
  package intStack1 is new Stack(integer, 8);
  package intStack2 is new Stack(integer, 8);
begin
  while (not intStack1.isFull()) loop
    get(i);
    intStack1.push(i);
  end loop;

  intStack2:= intStack1;

  while (not intStack2.isEmpty()) loop
    put(intStack2.top());
    intStack2.pop;
  end loop;
end StackTest;
```

This permits generic Ada packages to be constructed and operated on in a way similar to objects.

History: Simula

Back in 1967, *Dahl & Nygaard* noted that at its simplest, *programming consists of operating on variables*.

That is, variables are *typed objects*, and since types consist of values and operations, programming can be reduced to operating on variables.

Dahl & Nygaard were working on constructs to simplify the representation of *"real world" objects* in software, so that real-world processes could be more easily *simulated*.

Their language was *Simula* (*Sim*ple *u*niversal *la*nguage) and it provided useful *Simulation* and *Process* constructs...

Simula Classes

Dahl & Nygaard reasoned that if types are *values plus operations*, then a language should provide a syntactic structure that explicitly combines data and operations.

They took the *record* construct, extended it to store *subprograms* as well as *data* and christened it the *class* (from mathematics).

Subprograms (operations)
Data (state information)

Their *class* construct provided for creating *new types*, which could then be used to *declare variables*.

In time, variables were replaced by *objects* and object-oriented programming (OOP), culminating in *Smalltalk*.

Example: An *IntStack* Class

```
! IntStack.sim (minus precondition checks);

Class IntStack(Size);                 ! Classes can have parameters;
  Integer Size;                       ! Params precede 'Begin';
Begin
                                      ! Attribute variables;
  Integer myTop;                      !  Data encapsulated;
  Integer Array myValues(1:Size);!      but not hidden

                                      ! Methods;
                                      !  Operations encapsulated;
  Procedure Init;                     ! Initialization;
    myTop:= 0;                        ! 1-line methods need no 'end';

  Boolean Procedure IsEmpty;          ! Functions are typed procs;
   IsEmpty:= myTop < 1;               ! Assign RV to function name;

  Boolean Procedure IsFull;
   IsFull:= myTop >= Size;


  ! … continued on next page … ;
```


Example: An *IntStack* Class (ii)

```
! IntStack.sim (continued)

  Procedure Push(Value);      ! Methods can have parameters;
    Integer Value;            ! Parameters precede 'Begin';
  Begin                       ! Methods with multiple statements;
    myTop:= myTop + 1;        !  must be 'wrapped' in a block;
    myValues(myTop):= Value;
  End of Push;

 Procedure Pop;
   myTop:= myTop - 1;

 Integer Procedure Top;
   Top:= myValues(myTop);
                              ! Life: code following methods;
 Init;                        !  is executed on object creation;
End of Stack;
```

Simula-67 did not hide the data: nothing prevented code from:

– *accessing the class's implementation details*; or

– *violating the intent of the creator of the class*.

Simula: Using the *IntStack* Class

To use the class, we write something like this:

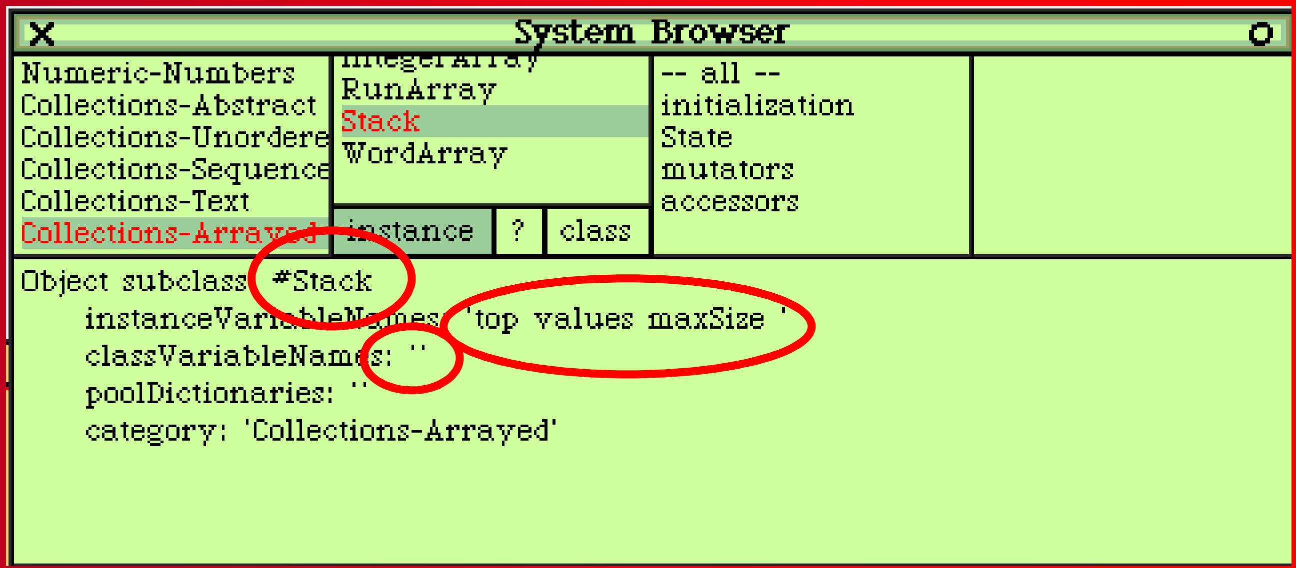
```
! IntStackTest.sim

Begin
  Ref(IntStack) S1, S2;              ! Reference (pointer) variables;
  Integer value;                     ! Normal variable;

  S1 :- New IntStack(8);             ! Special reference assignment;

  While Not S1.IsFull Do Begin       ! Dot-notation for messages;
    Value:= InInt;                   !  no args, no parentheses;
    S1.Push(Value);                  !  args require parentheses;
  End;

  S2 :- S1;                          ! Reference assignment

  While Not S2.IsEmpty Do Begin
    OutInt(S2.Top);
    S2.Pop;
  End;
End of Program;
```


Smalltalk

Smalltalk took the ideas of Simula and extended them:

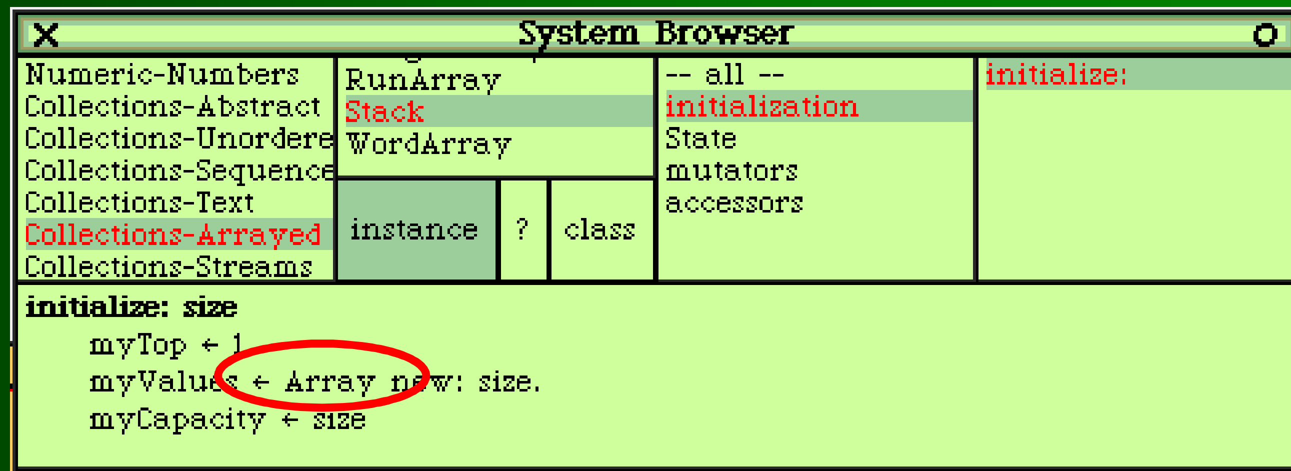
- Everything (including programs) are *objects or methods*
- Attribute variables are *hidden* (private) by default
- A large predefined *class library* is provided
- A GUI *integrated development environment (IDE)* is provided

Building a Smalltalk *Stack* class is simple, as most of the syntax is auto-generated by the IDE:



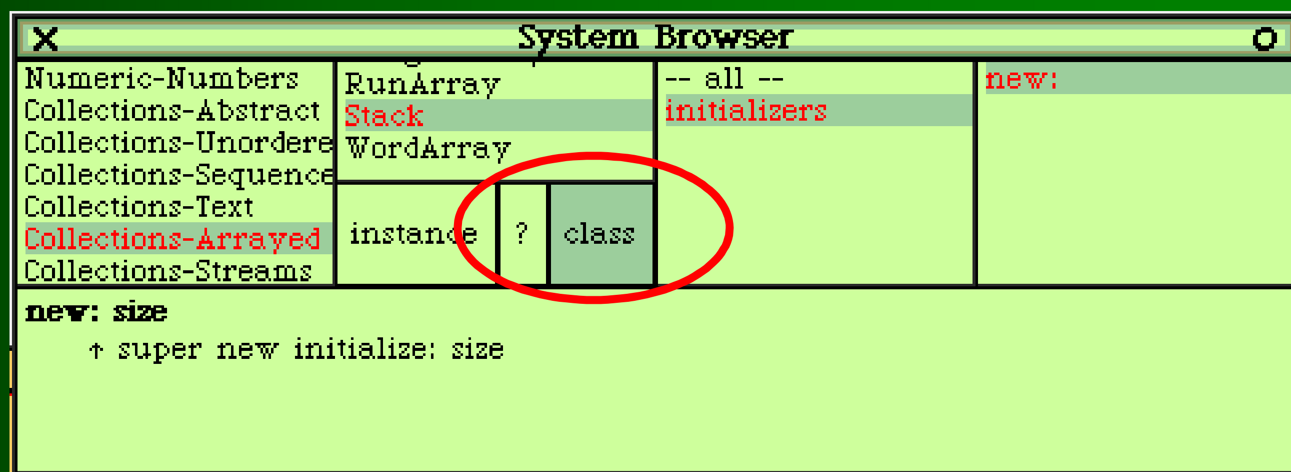
Smalltalk Operations

Adding *Stack* operations to our class is also easy: as the IDE makes templates for us



Smalltalk *Arrays* store *Objects* (more later)...

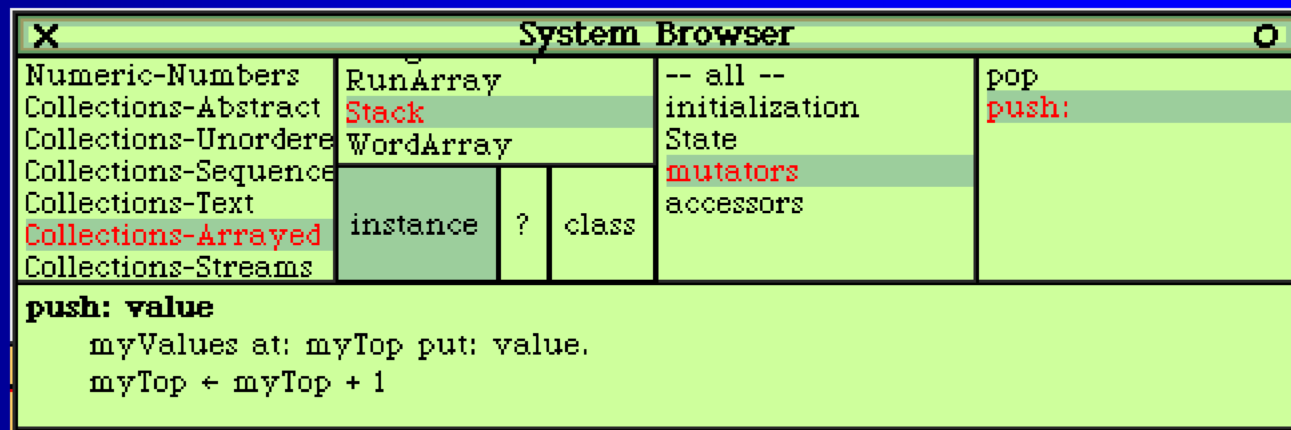
new: is a message we send the class (i.e., a *class method*):



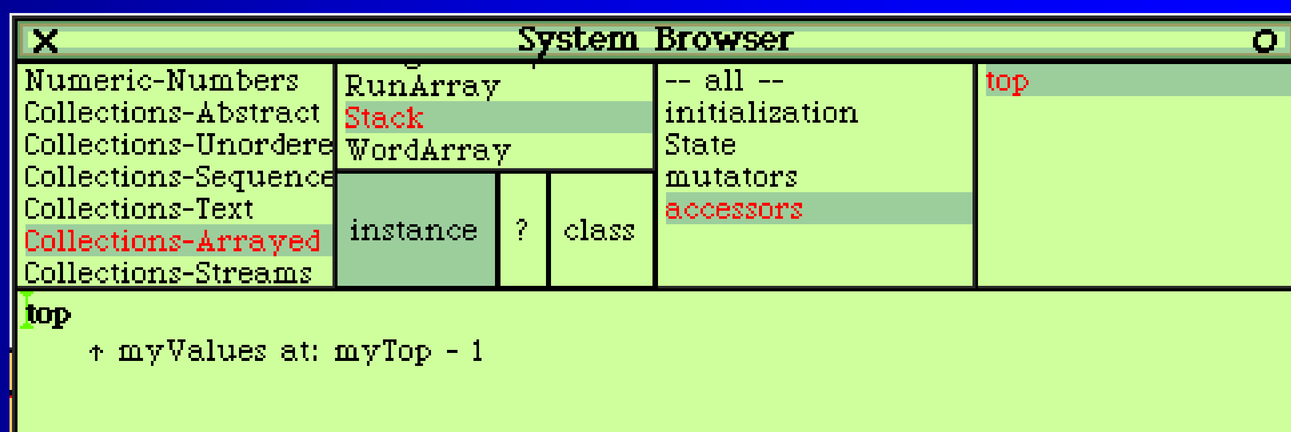
Smalltalk Operations (ii)

Messages that are sent to an object are *instance methods*; messages that are sent to the class are *class methodss*.

Mutators like *push* and *pop* are equally easy:

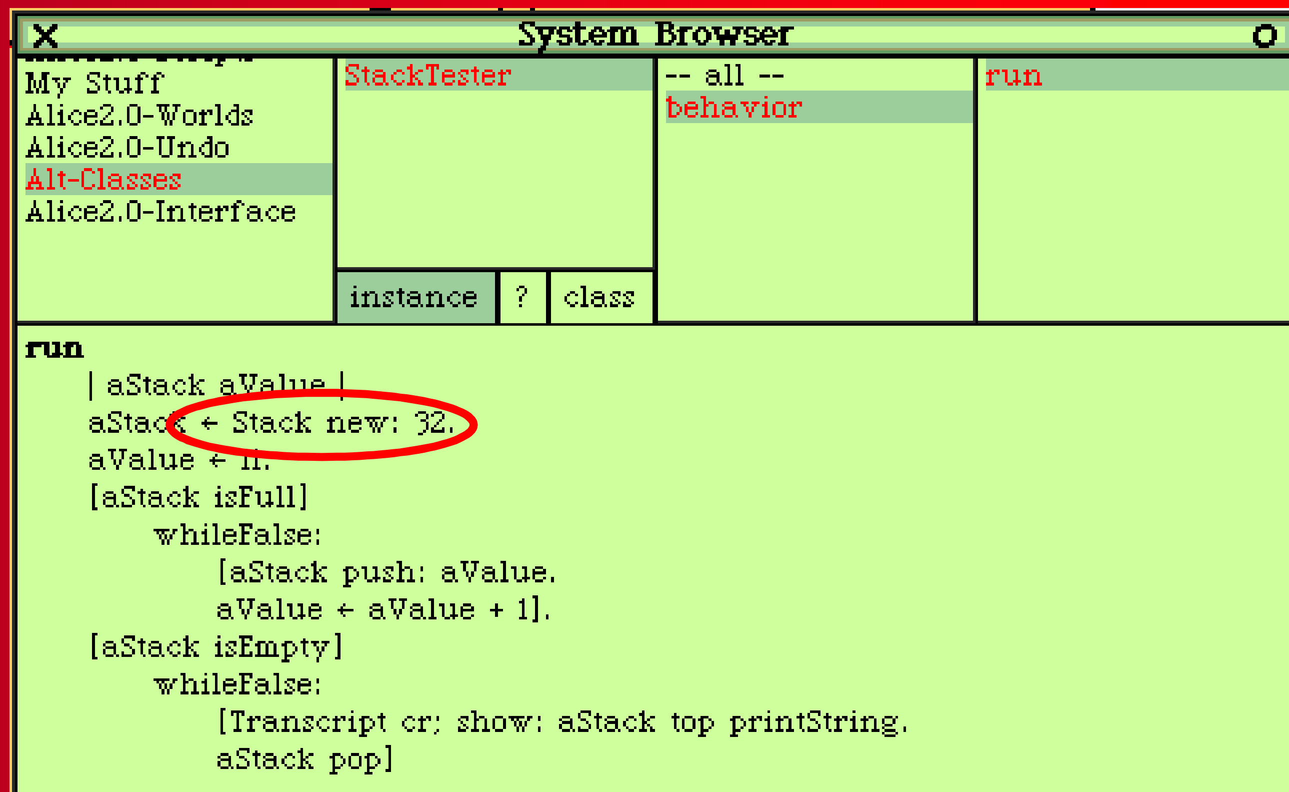


Other *Stack* operations (*isEmpty*, *isFull*, *top*) are just as easy...



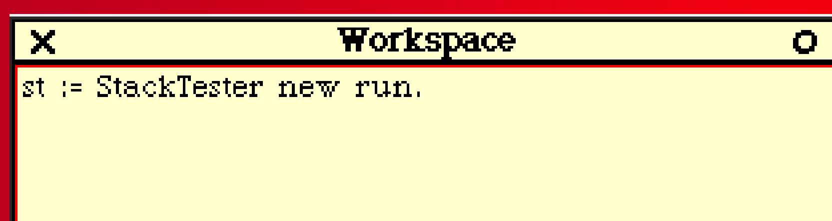
Smalltalk "Programs"

"Programs" are classes with *new* and *run* methods:



Note that we send *new:* to the *class*, not an *instance* of the class (i.e., an *object*)...

To run such programs:



C++ Classes

In 1986, Stroustrup added the *class* construct to C...

```
// IntStack.h

class IntStack {
 public:
   IntStack(int size);
   bool isEmpty() const;
   bool isFull() const;
   void push(int value);
   void pop();
   int top() const;
 private:
   int myTop, myCapacity;
   int * myValues;
};
```

```
// IntStack.h (cont'd)
inline IntStack::IntStack(int size){
  myTop = -1;
  myCapacity = size;
  myValues = new int[size];
}
inline
bool IntStack::isEmpty() const{
  return myTop < 0;
}
inline void
IntStack::push(int value) const {
  myValues[++myTop] = value;
}

 // … other operation definitions …
```

More complex operations can be separately compiled...

Using C++ Classes

C++ objects can be either statically or dynamically allocated:

```
// IntStackTest1.cpp

#include "IntStack.h"

int main() {
  IntStack s(8);
  int aValue;

  while ( !s.isFull() ) {
   cin >> aValue;
   s.push(aValue);
  }

  while ( !s.isEmpty() ) {
   cout << s.top() << ' ';
   s.pop();
  }
}
```

```
// IntStackTest2.cpp

#include "IntStack.h"

int main() {
 IntStack* s = new IntStack(8);
 int aValue;

 while ( !s->isFull() ) {
   cin >> aValue;
   s->push(aValue);
 }

 while ( !s->isEmpty() ) {
   cout << s->top() << ' ';
   s->pop();
 }
}
```

In Smalltalk, objects *must* be dynamically allocated.

Java Classes

In 1993, Gosling designed *Java*, based on C++ and Smalltalk.

```
// IntStack.java

public class IntStack {
 public IntStack(int size) {
   myTop = -1;
   myCapacity = size;
   myValues = new int[size];
 }

 public boolean isEmpty() {
   return myTop < 0;
 }

 public boolean isFull() {
   return myTop >= myCapacity;
 }
```

```
// IntStack.java (cont'd)

 public void push(int value) {
   myValues[++myTop] = value;
 }

 public void pop() {
   --myTop;
 }

 public int top() {
   return myValues[myTop];
 }
 private int    myTop,
                myCapacity;
 private int [] myValues;
}
```

Java mixes C++ syntax with Smalltalk philosophy...

Using Java Classes

- Like Smalltalk, Java objects *must* be dynamically allocated:
- Class variables are *reference variables*, so dot notation is used (vs. C++ ->)
- Also like Smalltalk, every Java subprog. must be a member of a class.

```
// IntStackTest.java

import IntStack;

class IntStackTest {
  public static void main(String [] args) {
  IntStack s = new IntStack(8);
  int aValue = 11;

  while ( !s.isFull() ) {
    s.push(aValue);
    aValue++;
  }

  while ( !s.isEmpty() ) {
   System.out.println( s.top() );
   s.pop();
  }
}
```

But most of Java's *syntax* is more similar to C++ than Smalltalk...

C++ Templates

C++ classes can have *parameters* (→ Ada *generic packages*):

```
// Stack.h
template<class Item>
class Stack {
 public:
   Stack(int size);
   bool isEmpty() const;
   bool isFull() const;
   void push(Item value);
   void pop();
   Item top() const;
 private:
   int myTop, myCapacity;
   Item * myValues;
};

#include "Stack.tpp"
```

```
// Stack.tpp
template<class Item>
inline Stack<Item>::Stack(int size){
   myTop = -1;
   myCapacity = size;
   myValues = new Item[size];
}
template<class Item>
inline bool Stack<Item>::isEmpty(){
   return myTop < 0;
}
template<class Item>
inline Item Stack<Item>::top() {
   return myValues[myTop];
}
// … isFull, push, pop, …
```

This is pretty clunky compared to Ada's *generic* mechanism...

C++ Template Instantiation

A *template* is a *factory for creating classes*...

```
// StackTest1.cpp

#include "Stack.h"

int main() {
  Stack<int> s(32);
  int aValue;

  while ( !s.isFull() ) {
   cin >> aValue;
   s.push(aValue);
  }

  while ( !s.isEmpty() ) {
   cout << s.top() << ' ';
   s.pop();
  }
}
```

```
// StackTest1.cpp

#include "Stack.h"
#include "Student.h"
int main() {
  Stack<Student> s(32);
  Student aValue;

  while ( !s.isFull() ) {
   cin >> aValue;
   s.push(aValue);
  }

  while ( !s.isEmpty() ) {
   cout << s.top() << ' ';
   s.pop();
  }
}
```

Templates are esp. useful in creating classes that *contain* other objects.

Old Java Containers

Prior to Java 1.5, Java had no generics, but all classes have a common ancestor *Object*, so *Object containers* were used:

```
// Stack.java

public class Stack {
 public Stack(int size) {
  myTop = -1;
  myCapacity = size;
  myValues = new Object[size];
 }

 public boolean isEmpty() {
  return myTop < 0;
 }

 public boolean isFull() {
  return myTop >= myCapacity-1;
 }
```

```
// Stack.java (cont'd)

public void push(Object value){
  myValues[++myTop] = value;
}

public void pop() {
  --myTop;
}

public Object top() {
  return myValues[myTop];
}
 private int       myTop,
                   myCapacity;
 private Object [] myValues;
}
```

This can store *any object whose type is a subclass of Object.*

Old Java: Using *Object* Containers

Since our *Stack* stores *Objects*...

1. We can't store a primitive type (e.g., *int*) directly, but Java provides a "*wrapper class*" for each primitive type…

2. *Casting* must be used to retrieve the stored values…

```
// StackTest.java

import Stack;

class StackTest {
  public static void main(String [] args) {
  Stack s = new Stack(8);
  int aValue = 11;

  while ( !s.isFull() ) {
    s.push( new Integer(aValue) );
    aValue++;
  }

  while ( !s.isEmpty() ) {
   Integer anInteger = (Integer) s.top();
   int anInt = anInteger.intValue();
   System.out.println(anInt);
   s.pop();
  }
}
```

Newer Java Containers

Java 1.5 added *generics* and auto-boxing unboxing:

```
// Stack.java

public class Stack<Item> {
 public Stack(int size) {
  myTop = -1;
  myCapacity = size;
  myValues = (Item[])
               new Object[size];
 }
 public boolean isEmpty() {
  return myTop < 0;
 }

 public boolean isFull() {
  return myTop >= myCapacity-1;
 }
```

```
// Stack.java (cont'd)

public void push(Item value){
  myValues[++myTop] = value;
}

public void pop() {
  --myTop;
}

public Item top() {
  return myValues[myTop];
}

 private int        myTop,
                    myCapacity;
 private Item []    myValues;
}
```

Such a *Stack* can still store anything derived from Object...

Java: Using *Generic* Containers

Since *Stack<Item>* stores *Objects*...

1. We can't pass a primitive type arg (e.g., *int*), but we can pass a *wrapper-arg*.
2. *Auto-boxing* lets us pass primitive-type-values as args.
3. *Auto-unboxing* lets us retrieve *Items* as primitive type-vals.

```
// StackTester.java

import Stack;

class StackTester {
  public static void main(String [] args) {
  Stack<Integer> s = new Stack<>(8);
  int aValue = 11;

  while ( !s.isFull() ) {
    s.push( aValue );     // int auto-boxed
    aValue++;
  }

  while ( !s.isEmpty() ) {
   int anInt = s.top();   // auto-unboxed
   System.out.println(anInt);
   s.pop();
  }
}
```

Summary

To achieve the goals of abstract data typing, we need:

- *Encapsulation*: data and operations in 1 syntactic unit
- *Data hiding*: the ability to restrict access to ADT data.

Two different mechanisms have evolved for doing so:

- *The module:* a container for storing a data-type and its operations (aka the *package*).
- *The class:* a type-constructor that stores data and operations.

The class is better for flexibility, reuseability, and maintenance; the module is better for time-efficiency and performance.

Containers are packages or classes that store data-values.

- *Generic packages* and *templates* support strongly typed containers.
- *Generic containers* can be built in most modern languages.

