Programming Languages

Generics, Containers and Iterators

CSCI-GA.2110-003
Fall 2011
Allows for type-independent data structures and functions.

Examples:

- A sorting algorithm has the same structure, regardless of the types being sorted
- Stack primitives have the same semantics, regardless of the objects stored on the stack.

One common use:

- algorithms on containers: updating, iteration, search

Language models:

- C: macros (textual substitution) or unsafe casts
- Ada: generic units and instantiations
- C++, Java, C#: templates
- ML: parametric polymorphism, functors
**Parameterizing software components**

<table>
<thead>
<tr>
<th>Construct</th>
<th>generic parameter(s) are:</th>
</tr>
</thead>
<tbody>
<tr>
<td>array</td>
<td>bounds, element type</td>
</tr>
<tr>
<td>Ada generic package</td>
<td>values, types, packages</td>
</tr>
<tr>
<td>Ada generic subprogram</td>
<td>values, types</td>
</tr>
<tr>
<td>C++ class template</td>
<td>values, types</td>
</tr>
<tr>
<td>C++ function template</td>
<td>values, types</td>
</tr>
<tr>
<td>Java generics (all)</td>
<td>classes, interfaces</td>
</tr>
<tr>
<td>ML function</td>
<td>implicit</td>
</tr>
<tr>
<td>ML type constructor</td>
<td>types</td>
</tr>
<tr>
<td>ML functor</td>
<td>structures (containing types, values)</td>
</tr>
</tbody>
</table>
template <typename T>
class Vector {
public:
    explicit Vector (size_t);  // constructor
    T& operator[] (size_t);    // subscript operator
    ...  // other operations
private:
    ...  // a size and a pointer to an array
};

Vector<int> V1(100);    // instantiation
Vector<int> V2;          // use default constructor

typedef Vector<employee> Dept;  // named instance
template <typename T, unsigned int i>
class Buffer {
    T v[i];    // storage for buffer
    unsigned int sz;  // total capacity
    unsigned int count;  // current contents

public:
    Buffer () : sz(i), count(0) { }
    T read ();
    void write (const T& elem);
};

Buffer<Shape *, 100> picture;
template <typename T> class List {
    struct Link { // for a list node
        Link *pre, *succ; // doubly linked
        T val;
        Link (Link *p, Link *s, const T& v)
            : pre(p), succ(s), val(v) { }
    };
    Link *head;
public:
    void print (std::ostream& os) {
        for (Link *p = head; p; p = p->succ)
            // operator<< must exist for T
            // if print will be used.
            os << p->val << "\n";
    }
};
Instantiated implicitly at point of call:

```cpp
template <typename T>
void sort (vector<T>&) { ... }

void testit (vector<int>& vi) {
    sort(vi); // implicit instantiation
    // can also write sort<int>(vi);
}
```
Template types are not initially not known.

Uninstantiated templates are not & cannot be compiled.

Generic definitions must be written completely in header files.

Once fully instantiated, all types become known.

Compiler generates classes, functions from the template.

Compilation proceeds in the usual manner after this.

Compiler may optimize by reusing multiple occurrences of a fully instantiated template.
Templates and regular functions overload each other:

```cpp
template <typename T> class Complex {...};
template <typename T> T sqrt (T); // template
template <typename T> Complex<T> sqrt (Complex<T>); // partial specialization
double sqrt (double); // explicit specialization

void testit (Complex<double> cd) {
    sqrt(2); // sqrt<int>
    sqrt(2.0); // sqrt (double): regular function
    sqrt(cd); // sqrt<complex<double>>
}
```

Partial specialization narrows the set of acceptable template parameters. Compiler will select the most specialized (specific) type.
Containers are data structures to manage collections of items

- Typical operations: insert, delete, search, count
- Typical algorithms over collections use:
  - imperative languages: iterators
  - functional languages: map, fold

```java
interface Iterator<E> {
    boolean hasNext (); // returns true if there are
    // more elements
    E next (); // returns the next element
    void remove (); // removes the current element
    // from the collection
}
```
**STL**: A set of useful data structures and algorithms in C++, mostly to handle collections.

- Sequential containers: `list`, `vector`, `deque`
- Associative containers: `set`, `map`

We can *iterate* over these using (what else?) *iterators*.

Iterators provided (for `vector<T>`):

- `vector<T>::iterator`
- `vector<T>::const_iterator`
- `vector<T>::reverse_iterator`
- `vector<T>::const_reverse_iterator`

Iterator concepts: trivial, input, output, forward, bidirectional, and random access.
For standard collection classes, we have member functions `begin` and `end` that return iterators.

We can do the following with an iterator `p`:

- `*p` "Dereference" it to get the element it points to (trivial)
- `++p`, `p++` Advance it to point to the next element (forward)
- `--p`, `p--` Retreat it to point to the previous element (bidirectional)
- `p+i`, `p-i` Advance/retreat it `i` times (random access)
- `p[i]` Access index `i` (random access)

A sequence is defined by a pair of iterators:

- the first points to the first element in the sequence.
- the second points to *one past* the last element in the sequence. Cannot deference, but must still be a valid memory address.

There are a wide variety of operations that work on sequences.
```cpp
#include <vector>
#include <string>
#include <iostream>

int main () {
    using namespace std;
    vector<string> ss(20); // initialize to 20 empty strings
    for (int i = 0; i < 20; i++)
        ss[i] = string(1, 'a'+i); // assign "a", "b", etc.
    vector<string>::iterator loc =
        find(ss.begin(), ss.end(), "d"); // find first "d"
    cout << "found: " << *loc
        << " at position " << loc - ss.begin() << endl;
}
```
STL provides a wide variety of standard “algorithms” on sequences.

Example: finding an element that matches a given condition

```cpp
// Find first 7 in the sequence
list<int>::iterator p = find(c.begin(), c.end(), 7);
```

```cpp
// Find first number less than 7 in the sequence
bool less_than_7(int v) {
    return v < 7;
}
```

```cpp
list<int>::iterator p = find_if(c.begin(), c.end(), less_than_7);
```

```cpp
// C++11:
auto p = find_if(c.begin(), c.end(), less_than_7);
```
Example: doing something for each element of a sequence

It is often useful to pass a function *or something that acts like a function*:

```cpp
template <typename T>
class Sum {
    T res;
public:
    Sum (T i = 0) : res(i) { } // initialize
    void operator() (T x) { res += x; } // accumulate
    T result () const { return res; } // return sum
};

void f (list<double>& ds) {
    Sum<double> sum;
    sum = for_each(ds.begin(), ds.end(), sum);
    cout << "the sum is " << sum.result() << "\n";
}
```
Function objects

template <typename Arg, typename Res> struct unary_function {
    typedef Arg argument_type;
    typedef Res result_type;
};

struct R { string name; ... }

class R_name_eq : public unary_function<R, bool> {
    string s;
public:
    explicit R_name_eq (const string& ss) : s(ss) { } 
    bool operator() (const R& r) const { return r.name == s; } 
};

void f (list<R>& lr) {
    list<R>::iterator p = find_if(lr.begin(), lr.end(),
        R_name_eq("Joe");
    ...
}
template <typename Arg, typename Arg2, typename Res>
struct binary_function {
    typedef Arg first_argument_type;
    typedef Arg2 second_argument_type;
    typedef Res result_type;
};

template <typename T>
struct less : public binary_function<T,T,bool> {
    bool operator() (const T& x, const T& y) const {
        return x < y;
    }
};
template <typename BinOp>
class binder2nd
  : public unary_function<typename BinOp::first_argument_type,
                           typename BinOp::result_type> {
protected:
  BinOp op;
  typename BinOp::second_argument_type arg2;
public:
  binder2nd (const BinOp& x,
             const typename BinOp::second_argument_type& v)
    : op(x), arg2(v) { }
  return_type operator() (const argument_type& x) const {
    return op(x, arg2);
  }
};

template <typename BinOp, typename T>
binder2nd<BinOp> bind2nd (const BinOp& op, const T& v) {
  return binder2nd<BinOp> (op, v);
}
```cpp
void f (const list<int>& xs, int limit) {
    list<int>::const_iterator it =
        find_if(xs.begin(), xs.end(),
            bind2nd(less<int>(), limit));
    int num = it != xs.end() ? *it : limit;
    ...
}
```

“Is this readable? ... The notation is logical, but it takes some getting used to.” – Stroustrup, p. 520

Equivalent to the following in ML:

```ml
fun f xs limit =
    let val optNum = List.find (fn x => x < limit) xs
    val num = Option.getOpt (optNum, limit)
    in ...
end
```
Templates in C++ allow for arbitrary computation to be done at compile time!

```cpp
template <int N> struct Factorial {
    enum { V = N * Factorial<N-1>::V }
};

template <> struct Factorial<1> {
    enum { V = 1 }
};

void f () {
    const int fact12 = Factorial<12>::V;
    cout << fact12 << endl;  // 479001600
}
```
Only class parameters (no value)

Implementation by *type erasure*: all instances share the same code

Unlike C++, generics are fully compilable (uninstantiated).

```java
interface Collection <E> {
    public void add (E x);
    public Iterator<E> iterator ();
}
```

Collection <Thing> is a parametrized type

Collection *(by itself)* is a raw type!
class Collection<A extends Comparable<A>> {
    public A max() {
        Iterator<A> xi = this.iterator();
        A biggest = xi.next();
        while (xi.hasNext()) {
            A x = xi.next();
            if (biggest.compareTo(x) < 0)
                biggest = x;
        }
        return biggest;
    }
    ...
}
Functors yield *structures*, similar to the way C++ templates yield concrete classes.

Why functors, when we have parametric polymorphic functions and type constructors (e.g., containers)?

- Functors can take structures as arguments. This is not possible with functions or type constructors.
- Sometimes a type needs to be parameterized on a *value*. This is not possible with type constructors.
Example functor: the signature

Similar to an interface (Java) or forward declaration (C++).

```
signature SET =
  sig
    type elem
    type set
    val empty : set
    val singleton : elem -> set
    val member : elem * set -> bool
    val union : set * set -> set
    ...
  end
```
functor SetFn (type elem
  val compare : elem * elem -> order) : SET =
structure
  type elem = elem
  datatype set = EMPTY
      | SINGLE of elem
      | PAIR of set * set

  val empty = EMPTY
  val singleton = SINGLE

  fun member (e, EMPTY) = false
        | member (e, SINGLE e') = compare (e, e') = EQUAL
        | member (e, PAIR (s1,s2)) = member (e, s1) orelse member (e, s2)

  ...
end
Example functor: the instantiation

structure IntSet = 
    SetFn (type elem = int 
           compare = Int.compare)

structure StringSet = 
    SetFn (type elem = string 
           compare = String.compare)

fun cmp (is1, is2) = ...

structure IntSetSet = SetFn (type elem = IntSet.set 
                               compare = cmp)

Compare functor implementation with a polymorphic type: how are element comparisons done?
I/O for integer types.

Identical implementations, but need separate procedures for strong-typing reasons.

generic
  type Elem is range <>;  -- any integer type
package Integer_IO is
  procedure Put (Item: Elem);
  ...
end Integer_IO;
generic
type Elem is private; -- parameter
package Stacks is
type Stack is private;
procedure Push (X: Elem; On: in out Stack);
...
private
type Cell; -- linked list
type Stack is access Cell; -- representation
type Cell is record
  Val: Elem;
  Next: Ptr;
end record;
end Stacks;
with Stacks;
procedure Test_Stacks is
  package Int_Stack
    is new Stacks (Integer); -- list of integers
  package Float_Stack
    is new Stacks (Float); -- list of floats

  S1: Int_Stack.Stack; -- stack objects
  S2: Float_Stack.Stack;

  use Int_Stack, Float_Stack; -- OK, regular packages
begin
  Push(15, S1);
  Push(3.5 * Pi, S2);
  ...
end Test_Stacks;
Type parameter restrictions

The syntax is: `type T is ...;`

<table>
<thead>
<tr>
<th>Restriction</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>private</td>
<td>any type with basic operations (e.g., assignment, equality)</td>
</tr>
<tr>
<td>limited private</td>
<td>any type (no required operations)</td>
</tr>
<tr>
<td>range &lt;&gt;</td>
<td>any integer type (arithmetic operations)</td>
</tr>
<tr>
<td>(&lt;&gt;())</td>
<td>any discrete type (enumeration or integer)</td>
</tr>
<tr>
<td>digits &lt;&gt;</td>
<td>any floating-point type</td>
</tr>
<tr>
<td>delta &lt;&gt;</td>
<td>any fixed-point type</td>
</tr>
</tbody>
</table>

Within the generic, the operations that apply to any type of the class can be used.

The instantiation must use a specific type of the class.
A generic function


generic
  type T is range <>; -- parameter of some integer type
  type Arr is array (Integer range <>) of T;
    -- parameter is array of those
function Sum_Array (A: Arr) return T;

-- Body identical to non-generic version
function Sum_Array (A: Arr) return T is
  Result: T := 0; -- some integer type
begin
  for J in A’range loop -- array: ’range available
    Result := Result + A(J); -- integer: "+" available
  end loop;
  return Result;
end;
type Apple is range 1..2**15 - 1;
type Production is array (1..12) of Apple;

type Sick_Days is range 1..5;
type Absences is array (1..52) of Sick_Days;

function Get_Crop is new Sum_Array (Apple, Production);
function Lost_Work is new Sum_Array (Sick_Days, Absences);
The only available operations are basic operations, which include assignment and equality.

generic
type T is private;
procedure Swap (X, Y: in out T);

procedure Swap (X, Y: in out T) is
  Temp: constant T := X;
begin
  X := Y;
  Y := Temp;
end Swap;
A generic sorting routine should apply to any array whose components are comparable, i.e., for which an ordering predicate exists. This class includes more than the numeric types:

```pascal
generic
  type T is -- parameter
    private;
  with function "<" (X, Y: T) -- parameter
    return Boolean;
  type Arr is -- parameter
    array (Integer range <>) of T;
procedure Sort (A: in out Arr);
```
The actual must have a matching signature, not necessarily the same name:

```plaintext
procedure Sort_Up is
    new Sort (Integer, "<", ...);

procedure Sort_Down is
    new Sort (Integer, ">", ...);

type Employee is record ... end record;
function Senior (E1, E2: Employee) return Boolean;
function Rank is new Sort (Employee, Senior, ...);
```
Useful to parameterize containers by size:

generic
type Elem is private;  -- type parameter
Size: Positive;        -- value parameter
package Queues is
type Queue is private;
procedure Enqueue (X: Elem; On: in out Queue);
procedure Dequeue (X: out Elem; From: in out Queue);
function Full (Q: Queue) return Boolean;
function Empty (Q: Queue) return Boolean;
private
type Contents is array (Natural range <>) of Elem;
type Queue is record
  Front, Back: Natural;
  C: Contents (0 .. Size);
end record;
end Queues;
generic
  type Real is digits <>; -- any floating type
package Generic_Complex_Types is
  -- complex is a record with two real components
  -- package declares all complex operations:
  --      +, -, Re, Im...
...
end Generic_Complex_Types;

We also want to define a package for elementary functions (\texttt{sin}, \texttt{cos}, etc.) on complex numbers. This needs the complex operations, which are parameterized by the corresponding real value.
with Generic_Complex_Types;
generic
with package Compl is
    new Generic_Complex_Types (<>);
package Generic_Complex_Functions is
    -- trigonometric, exponential,
    -- hyperbolic functions.
...
end Generic_Complex_Functions;

- Instantiate complex types with long_float components:

    package Long_Complex is
        new Generic_Complex_Types (long_float);

- Instantiate complex functions for long_complex types:

    package Long_Complex_Functions is
        new Generic_Complex_Functions (long_complex);