# OOP (Object Oriented Programming)

- So far the languages that we encountered treat data and computation separately.
- In OOP, the data and computation are combined into an “object”.

# Benefits of OOP

- more convenient: collects related information together, rather than distributing it.
  - Example: C++ iostream class collects all I/O related operations together into one central place.
  - Contrast with C I/O library, which consists of many distinct functions such as getchar, printf, scanf, sscanf, etc.
- centralizes and regulates access to data.
  - If there is an error that corrupts object data, we need to look for the error only within its class
  - Contrast with C programs, where access/modification code is distributed throughout the program

# Benefits of OOP (Continued)

header

c file

- Promotes reuse.
  - by separating interface from implementation.
    - We can replace the implementation of an object without changing client code.
    - Contrast with C, where the implementation of a data structure such as a linked list is integrated into the client code
  - by permitting extension of new objects via inheritance.
    - Inheritance allows a new class to reuse the features of an existing class.
    - Example: define doubly linked list class by inheriting/ reusing functions provided by a singly linked list.

# Encapsulation & Information hiding

- Encapsulation
  - centralizing/regulating access to data
- Information hiding
  - separating implementation of an object from its interface
- These two terms overlap to some extent.

# Classes and Objects

- Class is an (abstract) type
  - includes data
    - class variables (aka static variables)
      - shared (global) across all objects of this class
    - instance variables (aka member variables)
      - independent copy in each object
      - similar to fields of a struct
  - and operations
    - member functions
      - always take object as implicit (first) argument
    - class functions (aka static functions)
      - don't take an implicit object argument
- Object is an instance of a class
  - variable of class type

a.f(b)

# Access to Members

- Access to members of an object is regulated in C++ using three keywords
  - Private:
    - Accessibly only to member functions of the class
    - Can't be directly accessed by outside functions
  - Protected:
    - allows access from member functions of any subclass
  - Public:
    - can be called directly by any piece of code.

# Member Function

- Member functions are of two types
    - statically dispatched
    - dynamically dispatched.
- The dynamically dispatched functions are declared using the keyword “virtual” in C++
    - all member function functions are virtual in Java

# C++

- Developed as an *extension* to C

  by adding object oriented constructs originally found in Smalltalk (and Simula67).
- Most legal C programs are also legal C++ programs
  - “Backwards compatibility” made it easier for C++ to be accepted by the programming community
  - . . . but made certain features problematic (leading to “dirty” programs)
- Many of C++ features have been used in Java
  - Some have been “cleaned up”
  - Some useful features have been left out

# Example of C++ Class

- A typical convention is C++ is to make all data members private. Most member functions are public.
- Consider a list that consists of integers. The declaration for this could be :

```
class IntList {
   private:
      int elem; // element of the list
      IntList *next ; // pointer to next element
   public:
      IntList (int first); //"constructor"
      ~IntList () ; // "destructor".
      void insert (int i); // insert element i
      int getval () ; // return the value of elem
      IntList *getNext (); // return the value of next
}
```

# Example of C++ Class (Continued)

- We may define a subclass of IntList that uses doubly linked lists as follows:

```
class IntDList: IntList {
   private:
      IntList *prev;
   public:
      IntDlist(int first);
      // Constructors need to be redefined
       ~IntDlist();
      // Destructors need not be redefined, but
      // typically this is needed in practice.
      // Most operations are inherited from IntList.
      // But some operations may have to be redefined.
      insert (int);
      IntDList *prev();
 }
```

virtual

# C++ and Java: The Commonalities

- Classes, instances (objects), data members (fields) and member functions (methods).
- Overloading and inheritance.
  - base class (C++) → superclass (Java)
  - derived class (C++) → subclass (Java)
- Constructors
- Protection (visibility): `private`, `protected` and `public`
- Static binding for data members (fields)

# A C++ Primer for Java Programmers

Classes, fields and methods:

**Java:**

```
class A extends B {
  private int x;
  protected int y;
  public int f() {
      return x;
    }
  public void print() {
      System.out.println(x);
  }
}
```

**C++:**

```
class A : public B {
  private: int x;
  protected: int y;
  public: int f() {
      return x;
    }
  void print() {
      std::cout << x << std::endl;
  }
}
```

# A C++ Primer for Java Programmers

List a, b;
a = b;

List *a, *b;
a = b;

Primitive objects
int, floats
value semantics

Class objects
(Objects)
reference semantics

Declaring objects:

- In Java, the declaration `A va` declares va to be a *reference* to object of class A.
  - Object creation is always via the new operator
- In C++, the declaration `A va` declares va to be an object of class A.
  - Object creation may be automatic (using declarations) or via new operator:

```
A *va = new A;
```

pointers

int a, b;
b = 5
value
a = b
a = 6

List a, b;
reference
a = b;
... modify a ...
b is also modified

# Objects and References

- In Java, all objects are allocated on the heap; references to objects may be stored in local variables.
- In C++, objects are treated analogous to *C* `structs`: they may be allocated and stored in local variables, or may be dynamically allocated.
- Parameters to methods:
  - Java distinguishes between two sets of values: primitives (e.g. `ints`, `floats`, etc.) and objects (e.g `String`, `Vector`, etc.

    Primitive parameters are passed to methods *by value* (copying the value of the argument to the formal parameter)

    Objects are passed *by reference* (copying only the reference, not the object itself).
  - C++ passes all parameters *by value* unless specially noted.

# Type

- **Apparent Type:** Type of an object as per the declaration in the program.
- **Actual Type:** Type of the object at run time.

Let `Test` be a subclass of `Base`. Consider the following Java program:

```
Base b = new Base();
Test t = new Test();
...
b = t;
```

Actual type of b is Base

Actual type of t and b is Test.

| *Variable* | *Apparent type of object referenced* |
|---|---|
| b | `Base` |
| t | `Test` |

... throughout the scope of b and t's declarations

# Type (Continued)

Let `Test` be a subclass of `Base`. Consider the following Java program fragment:

```
Base b = new Base();
Test t = new Test();
...
b = t;
```

| *Variable* | *Program point* | *Actual type of object referenced* |
|---|---|---|
| `b` | **before** `b=t` | `Base` |
| `t` | **before** `b=t` | `Test` |
| `b` | **after** `b=t` | `Test` |
| `t` | **after** `b=t` | `Test` |

# Type (Continued)

Things are a bit different in C++, because you can have both objects and object references. Consider the case where variables are objects in C++:

```
Base b();
Test t();
...
b = t;
```

| *Variable* | *Program point* | *Actual type of object referenced* |
|---|---|---|
| `b` | **before** `b=t` | `Base` |
| `t` | **before** `b=t` | `Test` |
| `b` | **after** `b=t` | `Base` |
| `t` | **after** `b=t` | `Test` |

# Type (Continued)

Things are a bit different in C++, because you can have both objects and object references. Consider the case where variables are pointers in C++:

```
Base *b = new Base();
Test *t = new Test();
...
b = t;
```

| *Variable* | *Program point* | *Actual type of object referenced* |
|---|---|---|
| `b` | **before** `b=t` | `Base*` |
| `t` | **before** `b=t` | `Test*` |
| `b` | **after** `b=t` | `Test*` |
| `t` | **after** `b=t` | `Test*` |

# Subtype

- A is a subtype of B if every object of type A is also a B, i.e., every object of type A has
  - (1) all of the data members of B
  - (2) supports all of the operations supported by B, with the operations taking the same argument types and returning the same type.
  - (3) AND these operations and fields have the "same meaning" in A and B.
- It is common to view data field accesses as operations in their own right. In that case, (1) is subsumed by (2) and (3).

# Subtype Principle

- A key principle :
  - "For any operation that expects an object of type T, it is acceptable to supply object of type T', where T' is subtype of T."
- The subtype principle enables OOL to support subtype polymorphism:
  - client code that accesses an object of class C can be reused with objects that belong to subclasses of C.

# Subtype Principle (Continued)

- The following function will work with any object whose type is a subtype of IntList.

```
void q (IntList &i, int j) {
   ...
   i.insert(j) ;
}
```

- Subtype principle dictates that this work for IntList and IntDList.
  - This must be true even is the insert operation works differently on these two types.
  - Note that use of IntList::insert on IntDList object will likely corrupt it, since the prev pointer would not be set.

# Subtype Principle (Continued)

- Hence, `i.insert` must refer to
  - IntList::insert when `i` is an IntList object, and
  - IntDList::insert function when i is an IntDList.
- Requires dynamic association between the name “insert” and the its implementation.
  - achieved in C++ by declaring a function be virtual.
  - definition of insert in IntList should be modified as follows: `virtual void insert(int i);`
  - all member functions are by default virtual in Java, while they are nonvirtual in C++
    - equivalent of “virtual” keyword is unavailable in Java.

# Reuse of Code

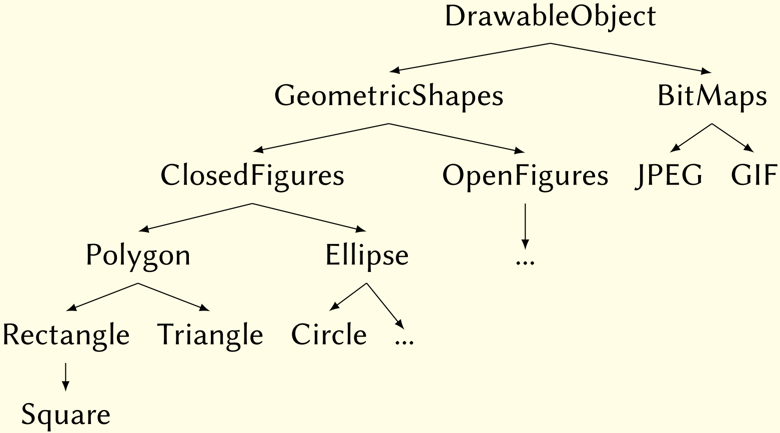
- Reuse achieved through subtype polymorphism
  - the same piece of code can operate on objects of different type, as long as:
    - Their types are derived from a common base class
    - Code assumes only the interface provided by base class.
- Polymorphism arises due to the fact that the implementation of operations may differ across subtypes.

# Reuse of Code (Continued)

- Example:
  - Define a base class called DrawableObject
    - supports draw() and erase().
  - DrawableObject just defines an interface
    - no implementations for the methods are provided.
    - this is an abstract class — a class with one or more abstract methods (declared but not implemented).
    - also an interface class — contains only abstract methods subtypes.

# Reuse of Code: example (Continued)

- The hierarchy of DrawableObject may look as follows:



# Reuse of Code: example (Continued)

- The subclasses support the draw() and erase() operation supported by the base class.
- Given this setting, we can implement the redraw routine using the following code fragment:

```
void redraw(DrawableObject* objList[], int size){
   for (int i = 0; i < size; i++)
   objList[i]->draw();
}
```

# Reuse of Code: example (Continued)

- objList[i].draw will call the appropriate method:
  - for a square object, Square::draw
  - for a circle object, Circle:draw
- The code need not be changed even if we modify the inheritance hierarchy by adding new subtypes.

# Reuse of Code: example (Continued)

- Compare with implementation in C:

```
void redraw(DrawableObject *objList[], int size) {
   for (int i = 0; i < size; i++){
      switch (objList[i]->type){
         case SQUARE: square_draw((struct Square *)objList[i]);
            break;
         case CIRCLE: circle_draw((struct Circle *)objList[i]);
            break;
         ........
         default: ....
      }
   }
}
```

- Differences:
  - no reuse across types (e.g., Circle and Square)
  - need to explicitly check type, and perform casts
  - will break when new type (e.g., Hexagon) added

# Reuse of Code (Continued)

- Reuse achieved through subtype polymorphism
  - the same piece of code can operate on objects of different type, as long as:
    - Their types are derived from a common base class
    - Code assumes only the interface provided by base class.
- Polymorphism arises due to the fact that the implementation of operations may differ across subtypes.

# Dynamic Binding

- Dynamic binding provides overloading rather than parametric polymorphism.
    - the draw function implementation is not being shared across subtypes of DrawableObject, but its name is shared.
- Enables client code to be reused
- To see dynamic binding more clearly as overloading:
    - Instead of a.draw(),
    - view as draw(a)

# Reuse of Code (Continued)

- Subtype polymorphism = function overloading
- Implemented using dynamic binding
  - i.e., function name is resolved at runtime, rather than at compile time.
- Conclusion: just as overloading enables reuse of client code, subtype polymorphism enables reuse of client code.

# Inheritance

- language mechanism in OO languages that can be used to implement subtypes.
- The notion of interface inheritance corresponds conditions (1), (2) and (3) in the definition of Subtype
- but provision (3) is not checked or enforced by a compiler.

# Subtyping & interface inheritance

- The notion of subtyping and interface inheritance coincide in OO languages.
  OR
- Another way to phrase this is to say that “interface inheritance captures an ’is-a’ relationship”
  OR
- If A inherits B’s interface, then it must be the case that every A is a B.

# Implementation Inheritance

- If A is implemented using B, then there is an implementation inheritance relationship between A and B.
  - However A need not support any of the operations supported by B

    OR
  - There is no `is-a` relationship between the two classes.
- Implementation inheritance is thus “irrelevant” from the point of view of client code.
- Private inheritance in C++ corresponds to implementation-only inheritance, while public inheritance provides both implementation and interface inheritance.

# Implementation Inheritance (Continued)

- Implementation-only inheritance is invisible outside a class
  - not as useful as interface inheritance.
  - can be simulated using composition.

```
class B{
   op1(...)
   op2(...)
}
class A: private class B {
   op1(...) /* Some operations supported by B may also be supported
               A (e.g., op1), while others (e.g., op2) may not be */
   op3(...) /* New operations supported by A */
}
```

# Implementation Inheritance (Continued)

- The implementation of op1 in A has to explicitly invoke the implementation of op1 in B:

```
A::op1(...){
    B::op1(...)
}
```

- So, we might as well use composition:

```
class A{
    B b;
    op1(...) {  b.op1(...) }
    op3(...)...
}
```

# Polymorphism

"*The ablilty to assume different forms*"

- A function/method is polymorphic if it can be applied to values of many types.
- Class hierarchy and inheritance provide a form of polymorphism called *subtype polymorphism.*
- As dicussed earlier, it is a form of overloading.
  - Overloading based on the first argument alone.
  - Overloading resolved dynamically rather than statically.
- Polymorphic functions increase code reuse.

# Polymorphism (Continued)

- Consider the following code fragment: `(x < y)? x : y`
- "Finds the minimum of two values".
- The same code fragment can be used regardless of whether `x` and `y` are:
  - integers
  - floating point numbers
  - objects whose class implements operator "<".
- *Templates* lift the above form of polymorphism (called *parametric* polymorphism) to functions and classes.

# Parametric polymorphism Vs Interface Inheritance

- In C++,
  - template classes support parametric polymorphism
  - public inheritance support interface + implementation inheritance.
- Parametric polymorphism is more flexible in many cases.

```
template class List<class ElemType>{
   private:
      ElemType *first; List<ElemType> *next;
   public:
      ElemType *get(); void insert(ElemType *e);
}
```

- Now, one can use the List class with any element type:

```
void f(List<A> alist, List<B> blist){
   A a = alist.get();
   B b = blist.get();
}
```

# Parametric polymorphism Vs Inheritance (Continued)

- If we wanted to write a List class using only subtype polymorphism:
  - We need to have a common base class for A and B
  - e.g., in Java, all objects derived from base class “Object”

```
class AltList{
   private:
      Object first; AltList next;
   public:
      Object get(); void insert(Object o);
}

void f(AltList alist, AltList blist) {
   A a = (A)alist.get();
   B b = (B)blist.get();
}
```

# Parametric polymorphism Vs Interface Inheritance (Continued)

- Note: get() returns an object of type Object, not A.
- Need to explicitly perform runtime casts.
  - type-checking needs to be done at runtime, and type info maintained at runtime
  - potential errors, as in the following code, cannot be caught at compile time

```
List alist, blist;
A a; A b;//Note b is of type A, not B
alist.insert(a);
blist.insert(b);
f(alist, blist);//f expects second arg to be list of B's, but we are giving a list of A's.
```

# Overloading, Overriding, and Virtual Functions

- Overloading is the ability to use the same function NAME with different arguments to denote DIFFERENT functions.
- In C++
  - void add(int a, int b, int& c);
  - void add(float a, float b, float& c);
- Overriding refers to the fact that an implementation of a method in a subclass supersedes the implementation of the same method in the base class.

# Overloading, Overriding, and Virtual Functions (Continued)

- Overriding of non-virtual functions in C++:

```
class B {
   public:
      void op1(int i) { /* B’s implementation of op1 */ }
}
class A: public class B {
   public:
      void op1(int i) { /* A’s implementation of op1 */ }
}
main() {
   B b; A a;
   int i = 5; b.op1(i); // B’s implementation of op1 is used
   a.op1(i); // Although every A is a B, and hence B’s implementation of
             // op1 is available to A, A’s definition supercedes B’s defn,
             // so we are using A’s implementation of op1.
   ((B)a).op1(); // Now that a has been cast into a B, B’s op1 applies.
   a.B::op1(); // Explicitly calling B’s implementation of op1
}
```

# Overloading, Overriding, and Virtual Functions (Continued)

- In the above example the choice of B’s or A’s version of op1 to use is based on compile-time type of a variable or expression. The runtime type is not used.
- Overloaded (non-member) functions are also resolved using compile-time type information.

# Overriding In The Presence Of Virtual Function

```
class B {
   public:
      virtual void op1(inti){/* B's implementation of op1 */ }
}
class A: public class B {
   public:
      void op1(int i) {// op1 is virtual in base class, so it is virtual here too
      /* A's implementation of op1 */ }
}
main() {
   B b; A a;
   int i = 5;
   b.op1(i); // B's implementation of op1 is used
   a.op1(i); // A's implementation of op1 is used.
   ((B)a).op1(); // Still A's implementation is used
   a.B::op1(); // Explicitly requesting B's definition of op1
}
```

# Overriding In The Presence Of Virtual Function (Continued)

```
void f(B x, int i) {
   x.op1(i);
}
```

- which may be invoked as follows:

```
B b;
A a;
f(b, 1); // f uses B's op1
f(a, 1); // f still uses B's op1, not A's
```

```
void f(B& x, int i) {
   x.op1(i);
}
```

- which may be invoked as follows:

```
B b;
A a;
f(b, 1); // f uses B's op1
f(a, 1); // f uses A's op1
```

# Function Template

- Declaring function templates:

```
template <typename T>
T min (  T x,   T y  ) {
return (x < y)? x : y;
}
```

- `typename` parameter can be name of any type (e.g. `int`, `long`, `Base`, ...)
- Using template functions:
  - `z = min(x, y)`
  - Compiler fills out the template's typename parameter using the types of arguments.
  - Can also be explicitly used as: min<float>(x, y)

# Class Templates

- Of great importance in implementing data structures (say list of elements, where all elements have to be of the same type).
- Java does not provide templates:
  - Some uses of templates can be replaced by using Java `interfaces`.
  - Many other uses would require "type casting"

    e.g.:

    ```
    Iterator e = ...
    Int x = (Integer) e.next();
    ```
  - Inherently dangerous since it skirts around compile-time type checking.

# Dynamic Binding

- A function f may take parameters of class C1
- The actual parameter passed into the function may be of class C2 that is a subclass of C1
- Methods invoked on this parameter within f will be the member function supported by C2, rather than C1
- To do this, we have to identify the appropriate member function at runtime, based on the actual type C2 of the parameter, and not the (statically) determined type C1

# Dynamic Binding (Continued)

- Dynamic binding provides overloading rather than parametric polymorphism.

```
void q (IntList &i, int j) {
   ...
   i.insert(j) ;
}
```

  - the `insert` function implementation is not being shared across subtypes of IntList, but its name is shared.
- enables client code to be reused
- To see dynamic binding as overloading, we need to eliminate the “syntactic sugar” used for calling member functions in OOL:
  - Instead of viewing it as `i.insert(...)`, we would think of it as a simple function `insert(i,...)` that explicitly takes an object as an argument.

# Implementation of OO-Languages

- Data
  - nonstatic data (aka instance variables) are allocated within the object
    - the data fields are laid out one after the other within the object
    - alignment requirements may result in “gaps” within the object that are unused
    - each field name is translated at compile time into a number that corresponds to the offset within the object where the field is stored
  - static data (aka class variables) are allocated in a static area, and are shared across all instances of a class.
    - Each class variable name is converted into an absolute address that corresponds to the location within the static area where the variable is stored.

# Implementation of Dynamic Binding

- All virtual functions corresponding to a class C are put into a virtual method table (VMT) for class C
- Each object contains a pointer to the VMT corresponding to the class of the object
- This field is initialized at object construction time
- Each virtual function is mapped into an index into the VMT. Method invocation is done by
  - access the VMT table by following the VMT pointer in the object
  - look up the pointer for the function within this VMT using the index for the member function

# Implementation of Inheritance

- Key requirement to support subtype principle:
  - a function f may expect parameter of type C1, but the actual parameter may be of type C2 that is a subclass of C1
  - the function f must be able to deal with an object of class C2 as if it is an object of class C1
    - this means that all of the fields of C2 that are inherited from C1, including the VMT pointer, must be laid out in the exact same way they are laid out in C1
    - all functions in the interface of C1 that are in C2 must be housed in the same locations within the VMT for C2 as they are located in the VMT for C1

# Impact of subtype principle on Implementation (Continued)

- In order to satisfy the constraint that VMT (Virtual Method Table) ptr appear at the same position in objects of type A and B, it is necessary for the data field f in A to appear after the VMT field.
- A couple of other points:
  - non-virtual functions are statically dispatched, so they do not appear in the VMT table
  - when a virtual function f is NOT redefined in a subclass, the VMT table for that class is initialized with an entry to the function f defined its superclass.

# Summary

- The key properties of OOL are:
  - encapsulation
  - inheritance+dynamic binding