Speaking C++ as a Native

(Multiparadigm Programming in Standard C++)

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Abstract

- Multi-paradigm programming is programming applying different styles of programming, such as object-oriented programming and generic programming, where they are most appropriate. This talk presents simple example of individual styles in ISO Standard C++ and examples where these styles are used in combination to produce cleaner, more maintainable code than could have been done using a single style only.

- 60 minutes, incl Q&A

Overview

- Standard C++
  - C++ aims, standardization, overview
- Abstraction: Classes and templates
  - Range example
  - Resource management
- Generic Programming: Containers and algorithms
  - Vector and sort example
  - Function objects
- Object-Oriented Programming: class hierarchies and interfaces
  - Ye olde shape example
- Multi-paradigm Programming
  - Algorithms on shapes example
- Implications for Large Systems
  - Libraries, coupling, and lock-in

Standard C++

- ISO/IEC 14882 – Standard for the C++ Programming Language
  - Core language
  - Standard library
- Implementations
  - Borland, Compaq, IBM, EDG, GNU, Metrowerks, Microsoft, SGI, Sun, Etc.
    - + many ports
  - All approximate the standard: portability is improving
  - Some are free
  - For all platforms: BeOS, Mac, IBM, Linux/Unix, Windows, embedded systems, etc.
- Probably the world's most widely used general-purpose programming language

Standard C++

- C++ is a general-purpose programming language with a bias towards systems programming that
  - is a better C
  - supports data abstraction
  - supports object-oriented programming
  - supports generic programming

- A multiparadigm programming language

  (if you must use long words)
  - The most effective styles use a combination of techniques

Elegant, direct expression of ideas

- Declarative information is key:

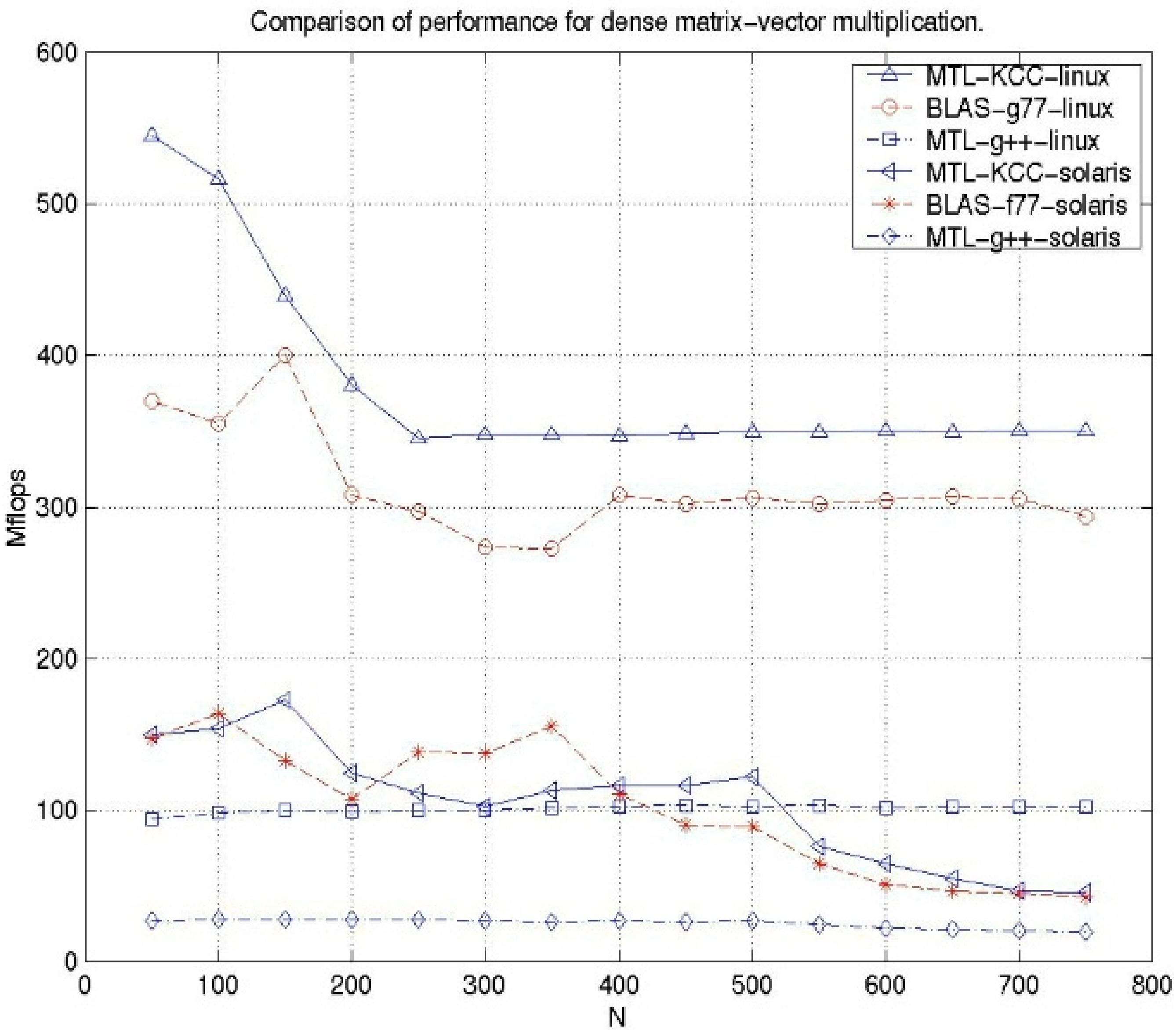
```
Matrix<double,100,50,Sparse> ms;
Matrix<Quad,100,50,Dense,Triangular<upper> > mt;
Matrix<double,100,50> m;     // defaults to rectangular and dense
```

- Write expressions using “natural” notation:

```
m3 = add(mul(m,v),v2);       // functional
m2 = m*v+v2;                 // algebraic
```

- Execute without spurious function calls or temporaries

Uncompromising performance



My aims for this presentation

- Here, I want to show small, elegant, examples
  - building blocks of programs
  - building blocks of programming styles
- Elsewhere, you can find
  - huge libraries
    - Foundation libraries: vendor libs, Threads++, ACE, QT, boost.org, …
    - Scientific libraries: POOMA, MTL, Blitz++, ROOT, …
    - Application-support libraries: Money++, C++SIM, BGL, …
    - Etc.: C++ Libraries FAQ: http://www.trumphurst.com
  - powerful tools and environments
  - in-depth tutorials
  - reference material

C++'s weakness: poor use

- C style
  - Arrays, pointers, casts, macros, complicated use of free store (heap)
- Reinventing the wheel
  - Strings, vectors, lists, maps, GUI, graphics, numerics, concurrency, persistence, …
- Smalltalk-style hierarchies
  - "brittle" base classes
  - Overuse of hierarchies

Here, I focus on alternatives

  - Primarily relying on abstract classes, templates, and function objects

C++ Classes

- Primary tool for representing concepts
  - Represent concepts directly
  - Represent independent concepts independently
- Play a multitude of roles
  - Value types
  - Function types (function objects)
  - Constraints
  - Resource handles (e.g. containers)
  - Node types
  - Interfaces

Classes as value types

- Built-in types
  - bool, char, int, float, double, unsigned char, long int, pointers, arrays, …
- Standard-library types
  - string, vector, list, map, set, ostream, complex, priority_queue, auto_ptr, …
- User-defined types
  - Date, Socket, hash_map, Point, Range, Real, Buffer, Line_segment, Person, …

Classes as value types

```
void f(Range arg)           // Range: y in [x,z)
try
{
    Range v1(0,3,10);       // 3 in range [0,10)
    Range v2(7,9,100);      // 9 in range [7,100)
    v1 = v2;        // ok: 9 is in [0,10)
    v2 = v1;        // will throw exception: 3 is not in [7,100)
    v1 = v2-v1;     // ok: 9-3 is in [0,10)
    arg = v1;       // may throw exception
    v2 = arg;       // may throw exception
}
catch(Range_error) {
    cerr << “Oops: range error in f()”;
}
```

Classes as value types

```
class Range {                          // simple value type
    int value, low, high;              // invariant: low <= value < high
    void check(int v) { if (v<low || high<=v) throw Range_error(); }
public:
    Range(int lw, int v, int hi) : low(lw), value(v), high(hi) { check(v); }
    Range(const Range& a) :low(a.low), value(a.value), high(a.high) { }

    Range& operator=(const Range& a) { check(a.value); value=a.value; }
    Range& operator=(int a) { check(a); value=a; }

    operator int() const { return value; }    // extract value
};
```

Classes as value types: Generalize

```
template<class T> class Range {                 // simple value type
    T value, low, high;                         // invariant: low <= value < high
    void check(T v) { if (v<low || high<=v) throw Range_error(); }
public:
    Range(T lw,T v, T hi) : low(lw), value(v), high(hi) { check(v); }
    Range(const Range& a) :low(a.low), value(a.value), high(a.high) { }

    Range& operator=(const Range& a) { check(a.value); value=a.value; }
    Range& operator=(const T& a) { check(a); value=a; }

    operator T() const { return value; }        // extract value
};
```

Classes as value types

```
Range<int> ri(10, 10, 1000);
Range<double> rd(0, 3.14, 1000);
Range<char> rc(‘a’, ’a’, ’z’);
Range<string> rs(“Algorithm”, “Function”, “Zero”);
Range< complex<double> > rc(0,z1,100);  // error: < is not defined for complex
```

Templates: Constraints

```
Template<class T> struct Comparable {
    static void constraints(T a, T b) { a<b; a<=b; }  // the constraint check
    Comparable() { void (*p)(T,T) = constraints; }  // trigger the constraint check
};

Template<class T> struct Assignable { /* … */ };

template<class T> class Range
    : private Comparable<T>, private Assignable<T> {
    // …
};

Range<int> r1(1,5,10);                      // ok
Range< complex<double> > r2(1,5,10);        // constraint error: no < or <=
```

Templates: Constraints

- How can we check template parameter constraints?
  - The compiler always checks
    - late and gives poor error messages
  - The programmer can specify a check
    - Checking arbitrary constraints
      - Not just subtype/subclass relationships
      - Correspondence between several types
      - Specific properties of types
    - Readable compile-time error messages
    - No spurious code generated when constraints are met

Managing Resources

- Examples of resources
  - Memory, file handle, thread handle, socket
- General structure ("resource acquisition is initialization")
  - Acquire resources at initialization
  - Control access to resources
  - Release resources when destroyed
- Key to exception safety
  - No object is created without the resources needed to function
  - Resources implicitly released when an exception is thrown

Managing Resources

// unsafe, naïve use:

```
void f(const char* p)
{
    FILE* f = fopen(p,"r");      // acquire
    // use f
    fclose(f);                   // release
}
```

Managing Resources

// naïve fix:

```
void f(const char* p)
{
    FILE* f = 0;
    try {
      f = fopen(p,”r”);
      // use f
    }
    catch (…) {          // handle every exception
      // …
    }
    if (f) fclose(f);
 }
```

Managing Resources

// use an object to represent a resource ("resource acquisition in initialization")

```
class File_handle {      // belongs in some support library
        FILE* p;
public:
        File_handle(const char* pp, const char* r) { p = fopen(pp,r); }
        File_handle(const string& s, const char* r) { p = fopen(s.c_str(),r); }
        ~File_handle() { if (p) fclose(p); }  // destructor
        // copy operations
        // access functions
};

void f(string s)
{
        File_handle f(s,"r");
        // use f
}
```

Generic Programming

- First aim: Standard Containers
  - Type safe
    - without the need for run-time checking
  - Efficient
    - Without excuses
  - Interchangeable
    - Where reasonable
- Consequential aim: Standard Algorithms
  - Applicable to many/all containers
- General aim: The most general, most efficient, most flexible representation of concepts
  - Represent separate concepts separately in code
  - Combine concepts freely wherever meaningful

Read and sort example

```
int n;
while (cin>>n) vi.push_back(n);        // read integers
sort(vi.begin(), vi.end());            // sort integers

string s;
while (cin>>s) vs.push_back(s);        // read strings
sort(vs.begin(),vs.end());             // sort strings


template<class T> void read_and_sort(vector<T>& v)   // use < for comparison
{
    T t;
    while (cin>>t) v.push_back(t);
    sort(v.begin(),v.end());
}
```

Read and sort example

```
template<class T, class Cmp>
void read_and_sort(vector<T>& v, Cmp c = less<T>())
{
    T t;
    while (cin>>t) v.push_back(t);
    sort(v.begin(), v.end(), c);
}

vector<double> vd;
read_and_sort(vd);              // sort using the default <

vector<string> vs;
read_and_sort(vs,No_case());  // sort case insensitive
```

Generality/flexibility is affordable

- Read and sort floating-point numbers
  - C: read using stdio; **qsort(buf,n,sizeof(double),compare)**
  - C++: read using iostream; **sort(v.begin(),v.end());**

#elements	C++	C	C/C++ ratio
500,000	2.5	5.1	2.04
5,000,000	27.4	126.6	4.62

- How?
  - clean algorithm
  - inlining

(Details: May'99 issue of C/C++ Journal; http://www.research.att.com/~bs/papers.html)

Matrix optimization example

```
struct MV {        // object representing the need to multiply
    Matrix* m;
    Vector* v;
    MV(Matrix& mm, Vector& vv) : m(&mm), v(&vv) { }
};

MV operator*(const Matrix& m, const Vector& v)
    { return MV(m,v); }

MVV operator+(const MV& mv, const Vector& v)
    { return MVV(mv.m,mv.v,v); }

v = m*v2+v3;  // operator*(m,v2) -> MV(m,v2)
              // operator+(MV(m,v2),v3) -> MVV(m,v2,v3)
              // operator=(v,MVV(m,v2,v3)) -> mul_add_and_assign(v,m,v2,v3);
```

Function Objects

- Function objects
  - Essential for flexibility
  - Efficient
    - in practice, more so than inline functions
    - important: **sort()** vs. **qsort()**
  - Some find them tedious to write
    - Standard function objects
      - e.g., **less**, **plus**, **mem_fun**
    - Can be automatically written/generated
      - **Vector v2 = m*v+k;** // matrix and vector libraries
      - **find_if(b,e, 0<x && x<=max);** // lambda libraries

Object-oriented Programming

- Hide details of many variants of a concepts behind a common interface

```
void draw_all(vector<Shape*>& vs)
{
   typedef vector<Shape*>::iterator VI;
   for (VI p = vs.begin(); p!=vs.end(), ++p) p->draw();
}
```

- Provide implementations of these variants as derived classes

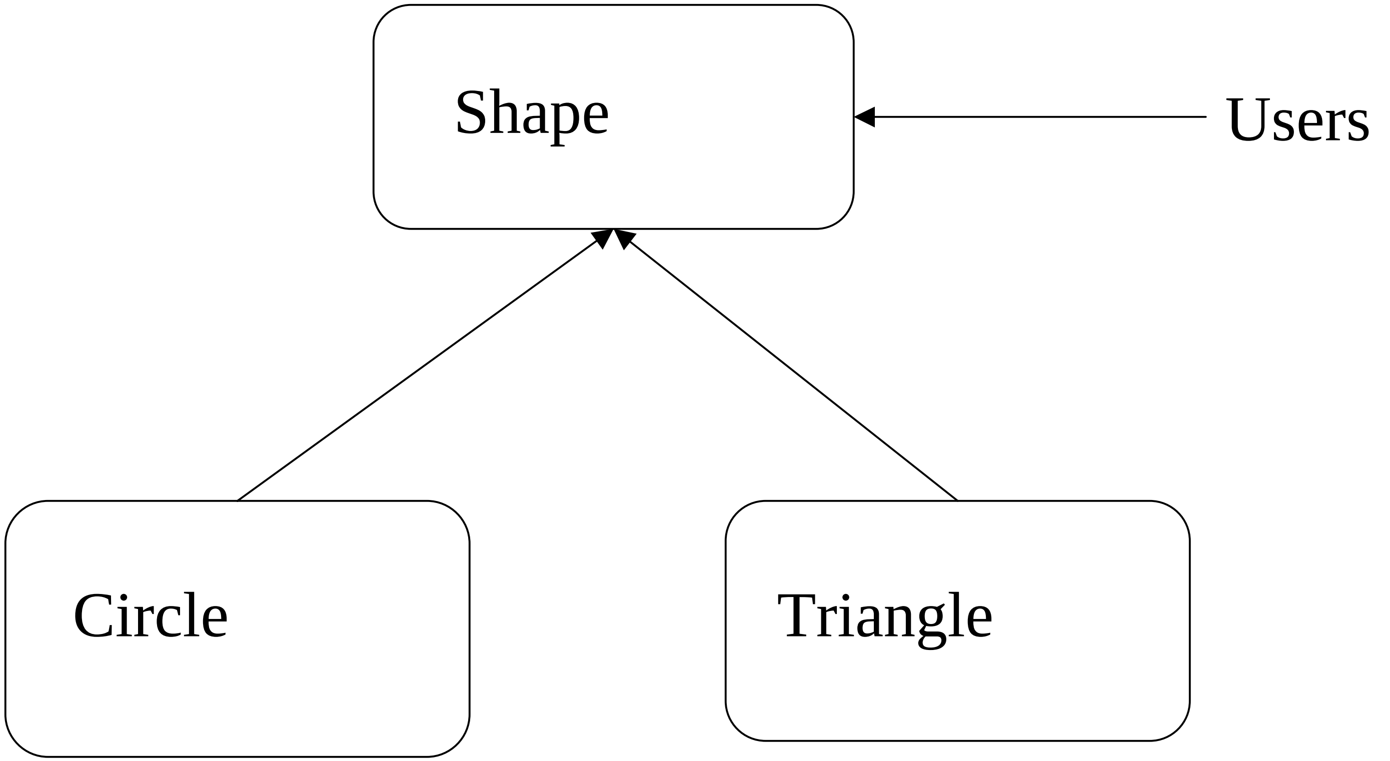
Class Hierarchies

- One way (often flawed):

```
class Shape {      // define interface and common state
    Color c;
    Point center;
    // …
public:
    virtual void draw();
    virtual void rotate(double);
    // …
};

class Circle : public Shape { /* … */ void rotate(double) { } /* … */ };
class Triangle : public Shape { / * … */ void rotate(double); /* … */ };
```

Class Hierarchies



Class Hierarchies

- Fundamental advantage: you can manipulate derived classes through the interface provided by a base:

```
void f(Shape* p)
{
        p->rotate(90);
        p->draw();
}
```

- You can add new **Shape**s to a program without changing or recompiling code such as **f()**

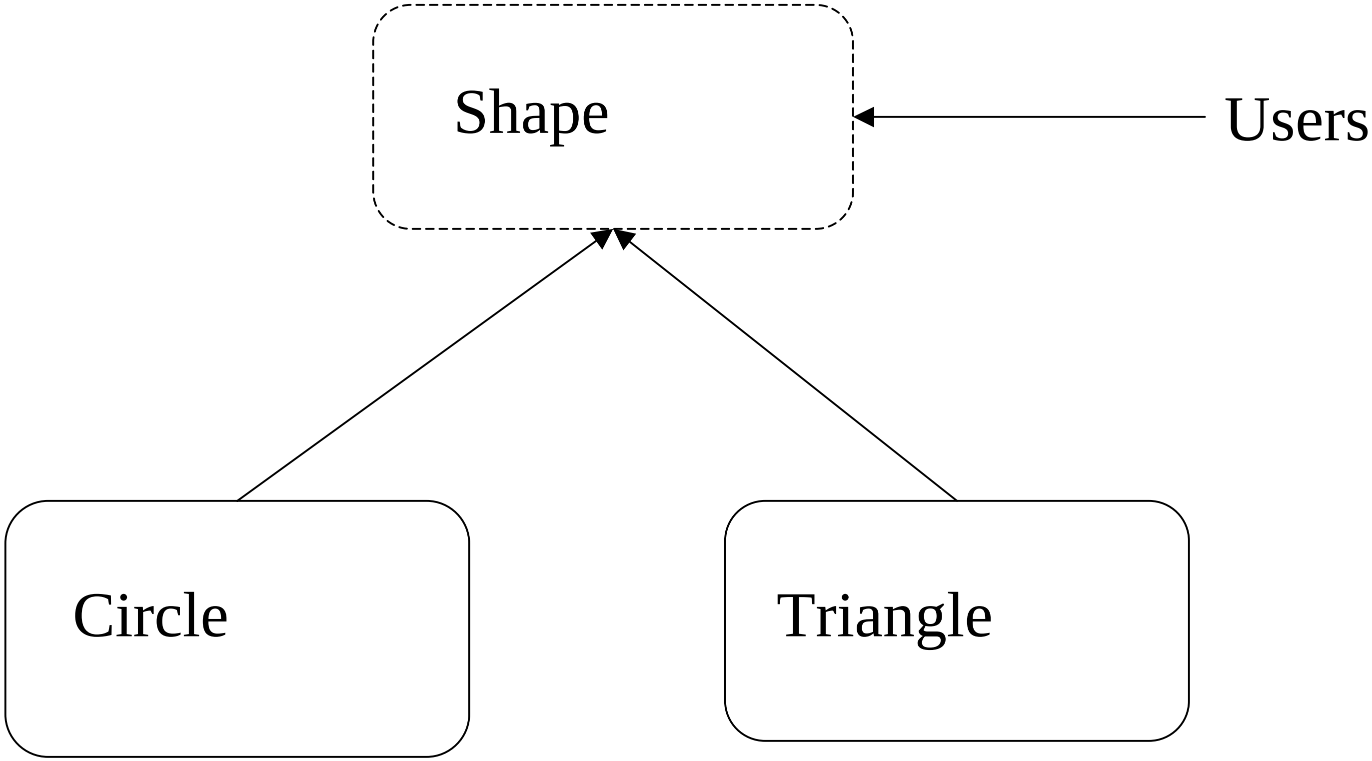
Class Hierarchies

- Another way (usually better):

```
class Shape {      // abstract class: interface only
    // no representation
public:
    virtual void draw() = 0;
    virtual void rotate(double) = 0;
    virtual Point center() = 0;
    // …
};

class Circle : public Shape { Point center; double radius; Color c; /* … */ };
class Triangle : public Shape {  Point a, b, c; Color c; / * … */ };
```

Class Hierarchies



Class Hierarchies

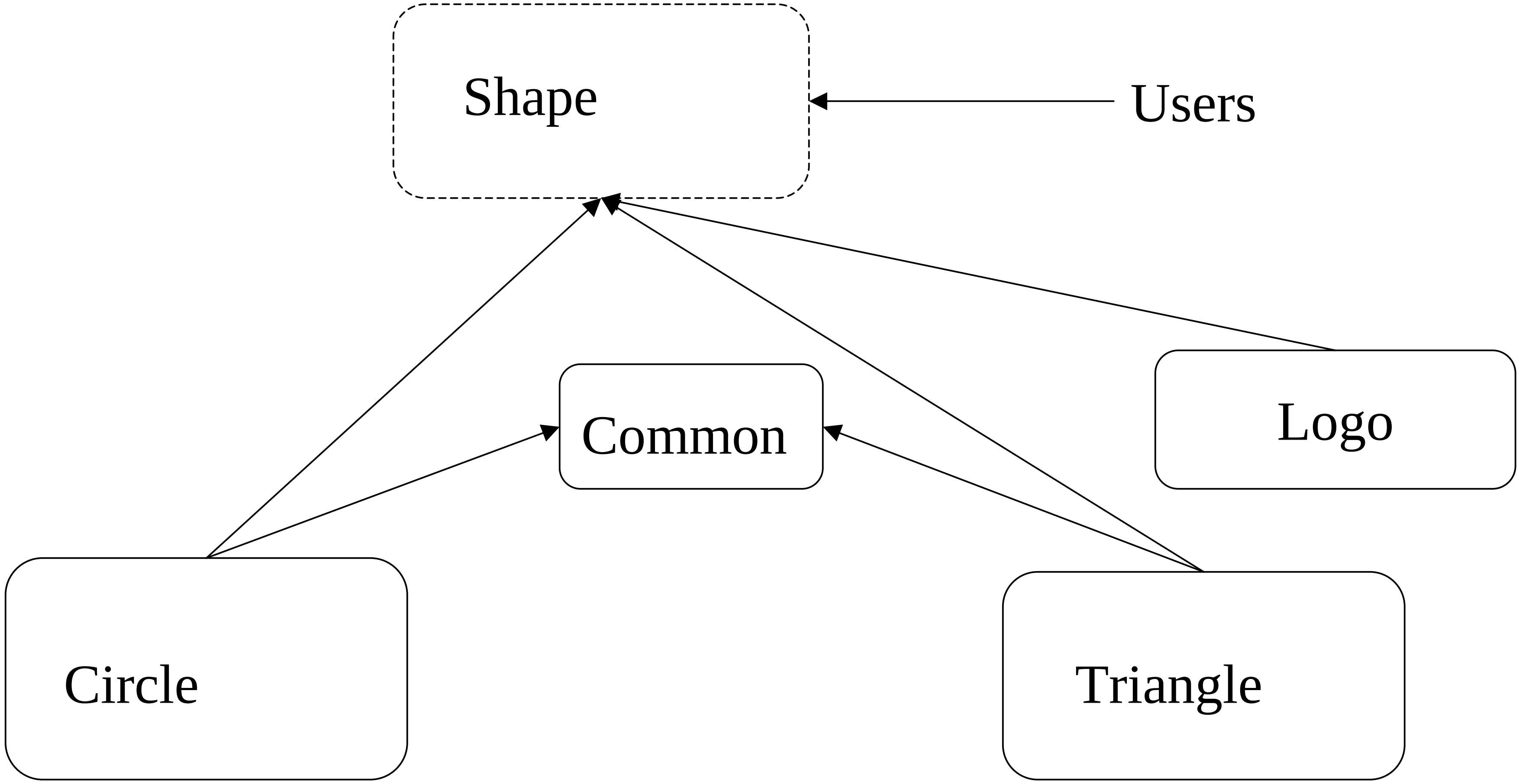
- One way to handle common state:

```
class Shape {       // abstract class: interface only
public:
    virtual void draw() = 0;
    virtual void rotate(double) = 0;
    virtual Point center() = 0;
    // …
};

class Common { Color c; /* … */ };          // common state for Shapes

class Circle : public Shape, protected Common{ /* … */ };
class Triangle : public Shape, protected Common { / * … */ };
class Logo: public Shape { /* … */ };        // Common not needed
```

Class Hierarchies



Multiparadigm Programming

- The most effective programs often involve combinations of techniques from different "paradigms"

- The real aims of good design
  - Represent ideas directly
  - Represent independent ideas independently in code

Algorithms on containers of polymorphic objects

```
void draw_all(vector<Shape*>& v)                    // for vectors
{
    for_each(v.begin(), v.end(), mem_fun(&Shape::draw));
}

template<class C> void draw_all(C& c)               // for all standard containers
{
    Contains<Shape*,C>();              // constraints check
    for_each(c.begin(), c.end(), mem_fun(&Shape::draw));
}

template<class For> void draw_all(For first, For last)     // for all sequences
{
    Points_to<Shape*,For>();           // constraints check
    for_each(first, last, mem_fun(&Shape::draw));
}
```

Implications for Larger Systems

- First build or buy extensive libraries
  - Without suitable libraries everything is difficult
  - With suitable libraries most things are easy
  - Where possible, build on the C++ standard library
- Focus design/implementation on
  - Abstract classes as interfaces
  - Templates for type safety and efficiency
  - Function objects for flexible parameterization
- Avoid large single-rooted hierarchies
  - More generally, avoid unnecessary dependencies/coupling

Summary

- Think of Standard C++ as a new language
  - not just C plus a bit
  - not just class hierarchies
- Experiment
  - Be adventurous: Many techniques that didn't work years ago now do
  - Be careful: Not every technique works for everybody, everywhere
- Prefer the C++ standard library style to C style
  - vector, list, string, etc. rather than array, pointers, and casts
  - Small free-standing classes are essential for flexibility
  - General algorithms should be free-standing (not members) for flexibility
- Use abstract classes to define major interfaces
  - Don't get caught with "brittle" base classes

More information

- Books
  - Stroustrup: The C++ Programming language (Special Edition)
    - New appendices: Standard-library Exception safety, Locales
  - Stroustrup: The Design and Evolution of C++
  - C++ In-Depth series
    - Koenig & Moo: Accelerated C++ (innovative C++ teaching approach)
    - Sutter: Exceptional C++ (exception handling techniques and examples)
  - Book reviews on ACCU site
- Papers
  - Stroustrup:
    - Learning Standard C++ as a New Language
    - Why C++ isn't just an Object-oriented Programming Language
  - Higley and Powell: Expression templates … (The C++ Report, May 2000)
- Links: http://www.research.att.com/~bs
  - FAQs libraries, the standard, free compilers, garbage collectors, papers, chapters, C++ sites, interviews
  - Open source C++ libraries: Boost.org, ACE, …