The Essence of C++

with examples in C++84, C++98, C++11, and C++14

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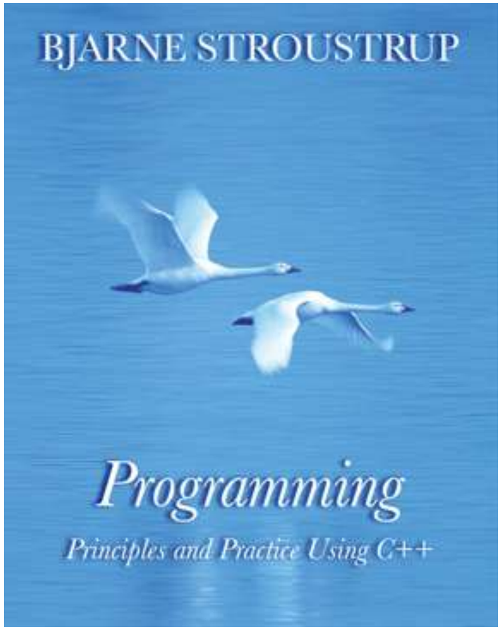
Overview

- Aims and constraints
- C++ in four slides
- Resource management
- OOP: Classes and Hierarchies
  - (very briefly)
- GP: Templates
  - Requirements checking
- Challenges

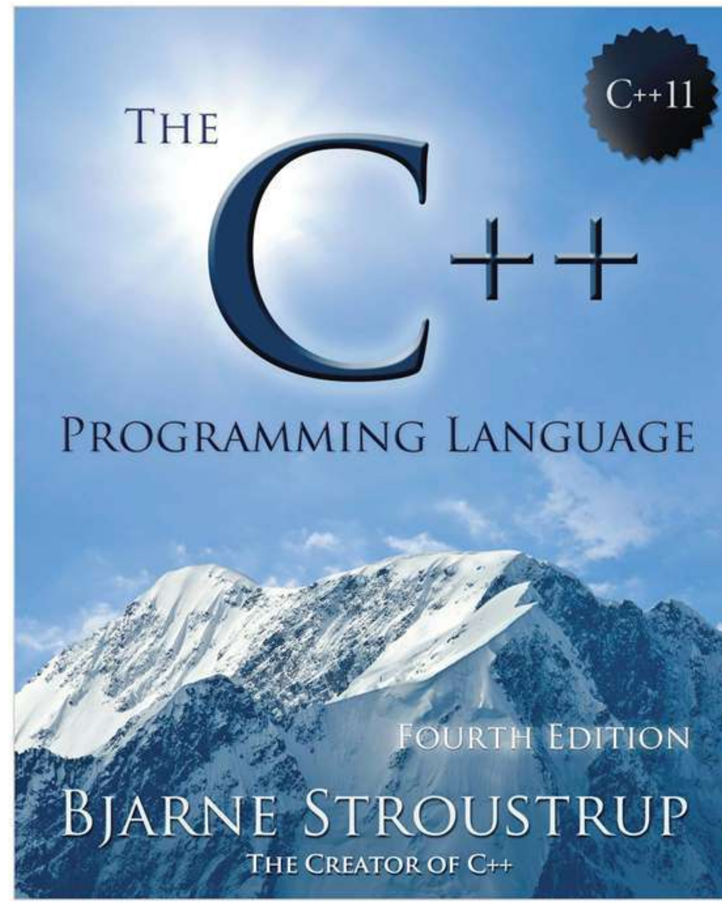
What did/do I want?



- Type safety
  - Encapsulate necessary unsafe operations
- Resource safety
  - It's not all memory
- Performance
  - For some parts of almost all systems, it's important
- Predictability
  - For hard and soft real time
- Teachability
  - Complexity of code should be proportional to the complexity of the task
- Readability
  - People and machines ("analyzability")

Who did/do I want it for?

- Primary concerns
  - Systems programming
  - Embedded systems
  - Resource constrained systems
  - Large systems
- Experts
  - “C++ is expert friendly”
- Novices
  - C++ Is not ***just*** expert friendly



What is C++?

Template
meta-programming!

Class hierarchies

A hybrid language

Buffer
overflows

A multi-paradigm
programming language

It's C!

Classes

Embedded systems
programming language

Too big!

Low level!

Generic programming

An object-oriented
programming language

A random collection
of features

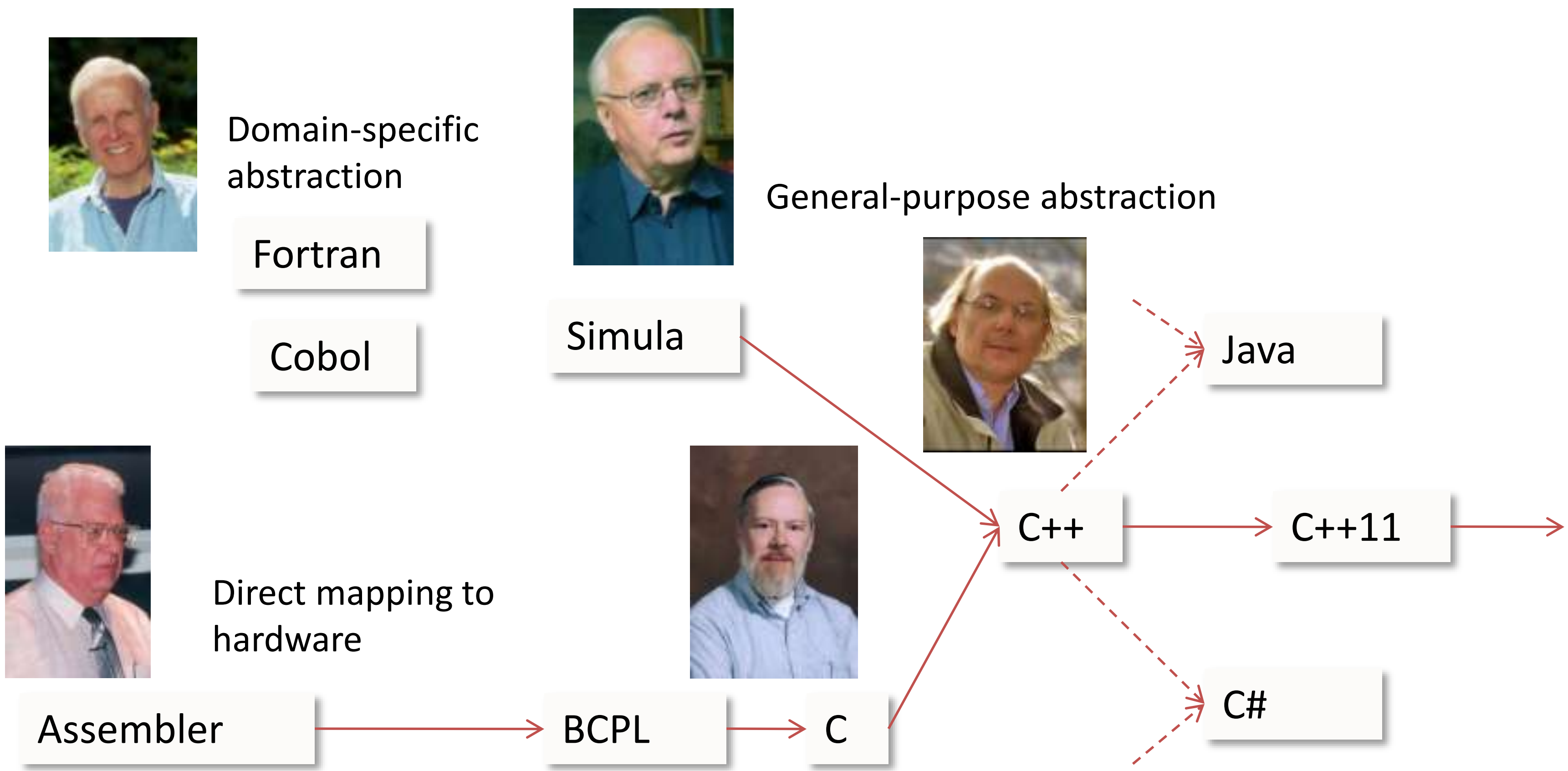
C++

A light-weight abstraction programming language

Key strengths:

- software infrastructure
- resource-constrained applications

Programming Languages

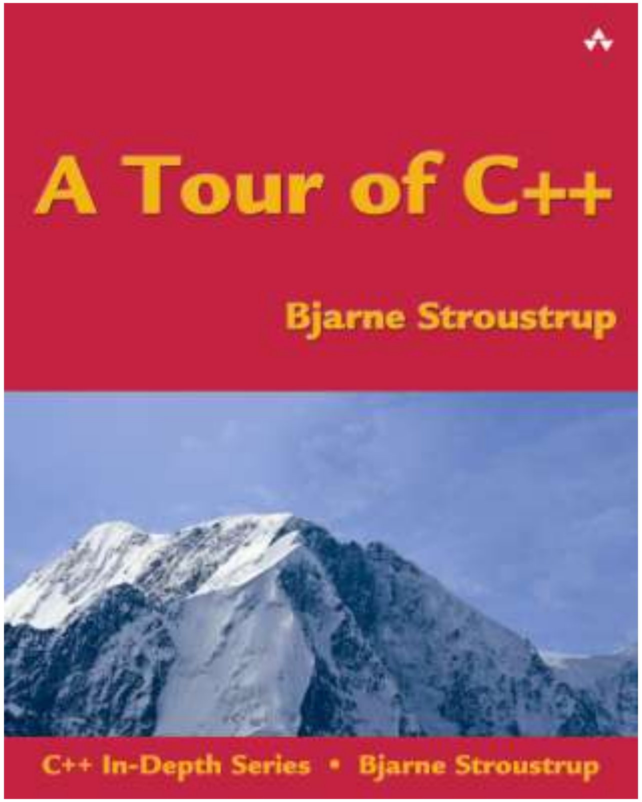


What does C++ offer?

- Not perfection
  - Of course
- Not everything for everybody
  - Of course
- A solid fundamental model
  - Yes, really
- 30+ years of real-world “refinement”
  - It works
- Performance
  - A match for anything
- The best is buried in “compatibility stuff’’
  - long-term stability is a feature

What does C++ offer?

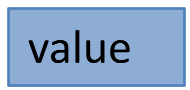
- C++ in Four slides
  – Map to hardware
  – Classes
  – Inheritance
  – Parameterized types



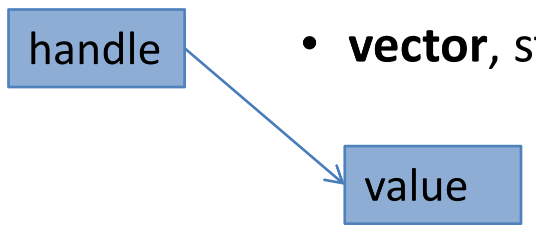
- If you understand **int** and **vector**, you understand C++
  – The rest is "details" (1,300+ pages of details)

Map to Hardware

- Primitive operations => instructions
  - +, %, ->, [], (), …

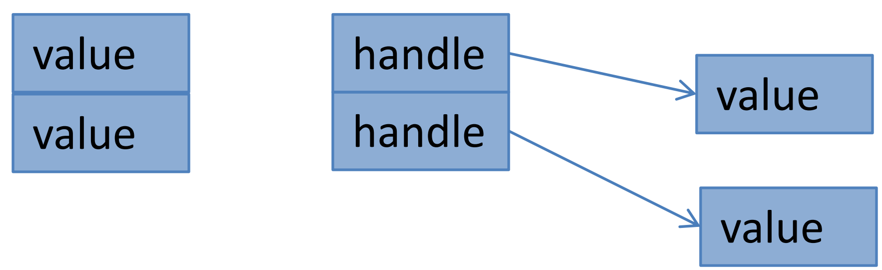


- **int**, double, complex<double>, Date, …



- **vector**, string, thread, Matrix, …

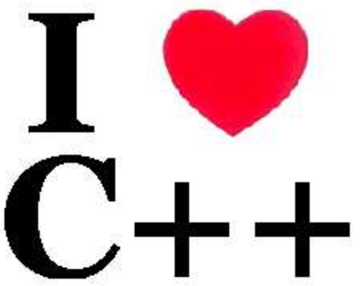
- Objects can be composed by simple concatenation:
  - Arrays
  - Classes/structs



Classes: Construction/Destruction

- From the first week of “C with Classes” (1979)

```
class X {                  // user-defined type
public:          // interface
      X(Something);      // constructor from Something
      ~X();              // destructor
      // …
private:         // implementation
      // …
};
```



“A constructor establishes the environment for the members to run in; the destructor reverses its actions.”

Abstract Classes and Inheritance

- Insulate the user from the implementation

```
struct Device {                                   // abstract class
        virtual int put(const char*) = 0;         // pure virtual function
        virtual int get(const char*) = 0;
};
```

- No data members, all data in derived classes
  - "not brittle"
- Manipulate through pointer or reference
  - Typically allocated on the free store ("dynamic memory")
  - Typically requires some form of lifetime management (use resource handles)
- Is the root of a hierarchy of derived classes

Parameterized Types and Classes

- Templates
  - Essential: Support for generic programming
  - Secondary: Support for compile-time computation

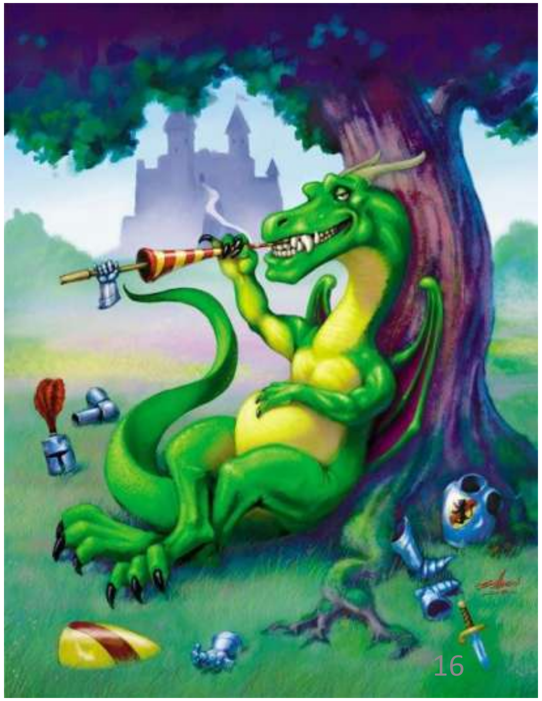
```
template<typename T>
class vector { /* … */ };                    // a generic type

vector<double> constants = {3.14159265359, 2.54, 1, 6.62606957E-34, }; // a use


template<typename C>
void sort (Cont& c) { /* … */ }         // a generic function

sort(constants);                              // a use
```

Not C++ (fundamental)

- No crucial dependence on a garbage collector
  - GC is a last and imperfect resort
- No guaranteed type safety
  - Not for all constructs
  - C compatibility, history, pointers/arrays, unions, casts, …
- No virtual machine
  - For many reasons, we often want to run on the real machine
  - You can run on a virtual machine (or in a sandbox) if you want to

Not C++ (market realities)

- No huge “standard” library
  - No owner
    - To produce “free” libraries to ensure market share
  - No central authority
    - To approve, reject, and help integration of libraries
- No standard
  - Graphics/GUI
    - Competing frameworks
  - XML support
  - Web support
  - …

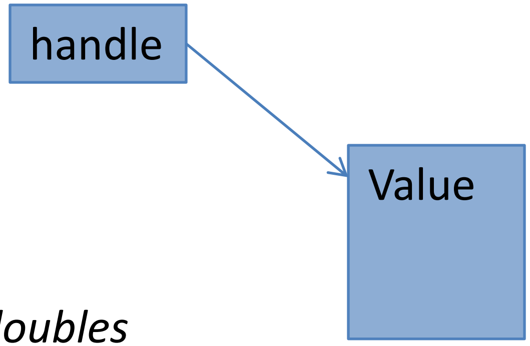


Resource Management

Resource management

- A resource should be owned by a "handle"
  - A "handle" should present a well-defined and useful abstraction
    - E.g. a vector, string, file, thread
- Use constructors and a destructor

```
class Vector {                                   // vector of doubles
        Vector(initializer_list<double>);  // acquire memory; initialize elements
        ~Vector();                               // destroy elements; release memory
        // …
private:
        double* elem;          // pointer to elements
        int sz;                // number of elements
};

void fct()
{
        Vector v {1, 1.618, 3.14, 2.99e8};          // vector of doubles
        // …
}
```



Resource management

- A handle usually is scoped
  - Handles lifetime (initialization, cleanup), and more

```
Vector::Vector(initializer_list<double> lst)
    :elem {new double[lst.size()]}, sz{lst.size()};      // acquire memory
{
    uninitialized_copy(lst.begin(),lst.end(),elem);      // initialize elements
}

Vector::~Vector()
{
    delete[] elem;      // destroy elements; release memory
};
```

Resource management

- What about errors?
  - A resource is something you acquire and release
  - A resource should have an owner
  - Ultimately “root” a resource in a (scoped) handle
  - “Resource Acquisition Is Initialization” (RAII)
    - Acquire during construction
    - Release in destructor
  - Throw exception in case of failure
    - Can be simulated, but not conveniently
  - Never throw while holding a resource ***not*** owned by a handle
- In general
  - Leave established invariants intact when leaving a scope

“Resource Acquisition is Initialization” (RAII)

- For all resources
  - Memory (done by **std::string**, **std::vector**, **std::map**, …)
  - Locks (e.g. **std::unique_lock**), files (e.g. **std::fstream**), sockets, threads (e.g. **std::thread**), …

```
std::mutex mtx;              // a resource
int sh;                      // shared data

void f()
{
    std::lock_guard lck {mtx}; // grab (acquire) the mutex
    sh+=1;                     // manipulate shared data
}                              // implicitly release the mutex
```

Pointer Misuse

- Many (most?) uses of pointers in local scope are not exception safe

```
void f(int n, int x)
{
        Gadget* p = new Gadget{n};          // look I'm a java programmer! ☺
        // …
        if (x<100) throw std::runtime_error{"Weird!"};        // leak
        if (x<200) return;                                     // leak
        // …
        delete p;          // and I want my garbage collector! ☹
}
```

  – But, garbage collection would not release non-memory resources anyway
  – But, why use a "naked" pointer?

Resource Handles and Pointers

- A **std::shared_ptr** releases its object at when the last **shared_ptr** to it is destroyed

```
void f(int n, int x)
{
	shared_ptr<Gadget> p {new Gadget{n}};	// manage that pointer!
	// …
	if (x<100) throw std::runtime_error{"Weird!"};		// no leak
	if (x<200) return;				// no leak
	// …
}
```

  – **shared_ptr** provides a form of garbage collection
  – But I'm not sharing anything
    - use a **unique_ptr**

Resource Handles and Pointers

- But why use a pointer at all?
- If you can, just use a scoped variable

```
void f(int n, int x)
{
	Gadget g {n};
	// …
	if (x<100) throw std::runtime_error{"Weird!"};	// no leak
	if (x<200) return;				// no leak
	// …
}
```

Why do we use pointers?

- And references, iterators, etc.

- To represent ownership
  - Don't! Instead, use handles
- To reference resources
  - from within a handle
- To represent positions
  - Be careful
- To pass large amounts of data (into a function)
  - E.g. pass by **const** reference
- To return large amount of data (out of a function)
  - Don't! Instead use move operations

How to get a lot of data cheaply out of a function?

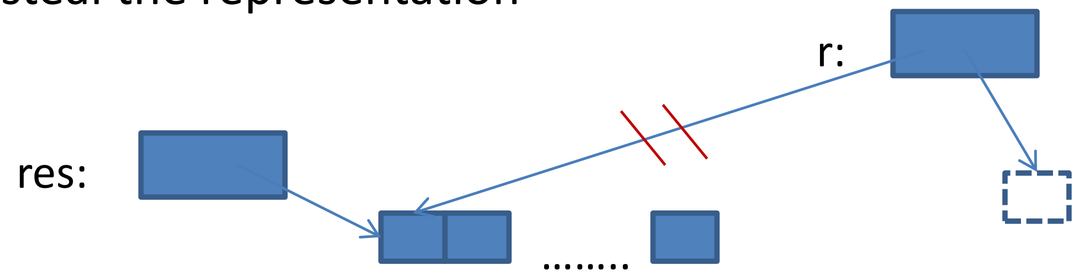
- Ideas
  – Return a pointer to a **new**'d object
    - Who does the **delete**?
  - Return a reference to a **new**'d object
    - Who does the **delete**?
    - Delete what?
  - Pass a target object
    - We are regressing towards assembly code
  - Return an object
    - Copies are expensive
    - Tricks to avoid copying are brittle
    - Tricks to avoid copying are not general
  - Return a handle
    - Simple and cheap

Move semantics

- Return a **Matrix**

```
Matrix operator+(const Matrix& a, const Matrix& b)
{
        Matrix r;
        // copy a[i]+b[i] into r[i] for each i
        return r;
}
Matrix res = a+b;
```

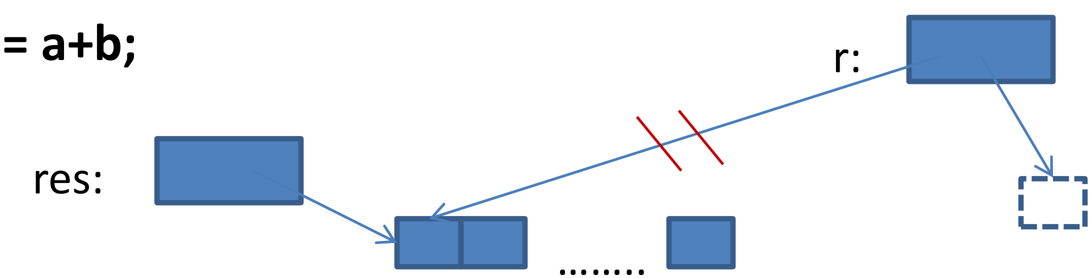
- Define move a constructor for **Matrix**
  - don't copy; "steal the representation"



Move semantics

- Direct support in C++11: Move constructor

```
class Matrix {
        Representation rep;
        // …
        Matrix(Matrix&& a)          // move constructor
        {
                rep = a.rep;        // *this gets a's elements
                a.rep = {};         // a becomes the empty Matrix
        }
};

Matrix res = a+b;
```



No garbage collection needed

- For general, simple, implicit, and efficient resource management
- Apply these techniques in order:
  1. Store data in containers
     - The semantics of the fundamental abstraction is reflected in the interface
     - Including lifetime
  2. Manage ***all*** resources with resource handles
     - RAII
     - Not just memory: ***all*** resources
  3. Use “smart pointers”
     - They are still pointers
  4. Plug in a garbage collector
     - For “litter collection”
     - C++11 specifies an interface
     - Can still leak non-memory resources

Range-**for**, **auto**, and move

- As ever, what matters is how features work in combination

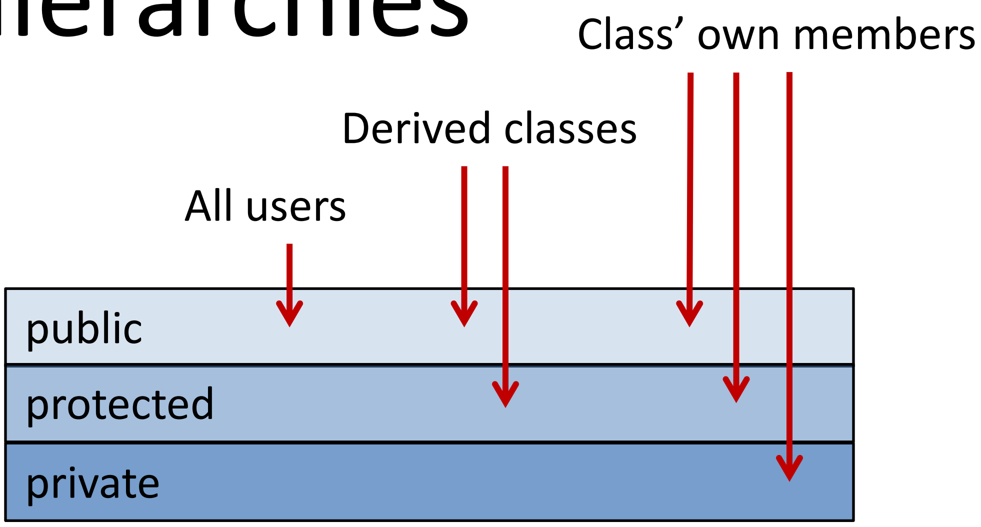
```
template<typename C, typename V>
vector<Value_type<C>*> find_all(C& c, V v)  // find all occurrences of v in c
{
        vector<Value_type<C>*> res;
        for (auto& x : c)
                if (x==v)
                        res.push_back(&x);
        return res;
}

string m {"Mary had a little lamb"};
for (const auto p : find_all(m,'a'))   // p is a char*
        if (*p!='a')
                cerr << "string bug!\n";
```

RAII and Move Semantics

- All the standard-library containers provide it
  - **vector**
  - **list, forward_list** (singly-linked list), …
  - **map, unordered_map** (hash table),…
  - **set, multi_set, …**
  - …
  - **string**
- So do other standard resources
  - **thread, lock_guard, …**
  - **istream, fstream, …**
  - **unique_ptr, shared_ptr**
  - …

OOP

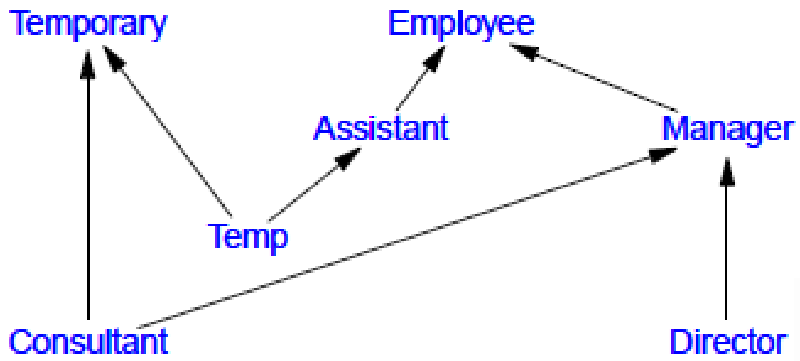
Class hierarchies



- Protection model
- No universal base class
  - an unnecessary implementation-oriented artifact
  - imposes avoidable space and time overheads.
  - encourages underspecified (overly general) interfaces
- Multiple inheritance
  - Separately consider interface and implementation
  - Abstract classes provide the most stable interfaces
- Minimal run-time type identification
  - **dynamic_cast<D*>(pb)**
  - **typeid(p)**

Inheritance

- Use it
  - When the domain concepts are hierarchical
  - When there is a need for run-time selection among hierarchically ordered alternatives



- Warning:
  - Inheritance has been seriously and systematically overused and misused
    - "When your only tool is a hammer everything looks like a nail"

GP

Generic Programming: Templates

- 1980: Use macros to express generic types and functions
- 1987 (and current) aims:
  - Extremely general/flexible
    - "must be able to do much more than I can imagine"
  - Zero-overhead
    - vector/Matrix/… to compete with C arrays
  - Well-specified interfaces
    - Implying overloading, good error messages, and maybe separate compilation

- "two out of three ain't bad"
  - But it isn't really good either
  - it has kept me concerned/working for 20+ years

Templates

- Compile-time duck typing
  - Leading to template metaprogramming
- A massive success in C++98, better in C++11, better still in C++14
  - STL containers
    - **template<typename T> class vector { /* *…* */ };**
  - STL algorithms
    - **sort(v.begin(),v.end());**
  - And much more
- Better support for compile-time programming
  - C++11: **constexpr** (improved in C++14)

Algorithms

- Messy code is a major source of errors and inefficiencies
- We must use more explicit, well-designed, and tested algorithms
- The C++ standard-library algorithms are expressed in terms of half-open sequences [**first**:**last**)
  - For generality and efficiency

```
void f(vector<int>& v, list<string>& lst)
{
    sort(v.begin(),v.end());                      // sort the vector using <

    auto p = find(lst.begin(),lst.end(),"Aarhus");  // find "Aarhus" in the list

      // …
}
```

- We parameterize over element type and container type

Algorithms

- Simple, efficient, and general implementation
  - For any forward iterator
  - For any (matching) value type

```
template<typename Iter, typename Value>
Iter find(Iter first, Iter last, Value val) // find first p in [first:last) so that *p==val
{
    while (first!=last && *first!=val)
        ++first;
    return first;
}
```

Algorithms and Function Objects

- Parameterization with criteria, actions, and algorithms
  - Essential for flexibility and performance

```
void g(vector< string>& vs)
{
	auto p = find_if(vs.begin(), vs.end(), Less_than{"Griffin"});

	// …
}
```

Algorithms and Function Objects

- The implementation is still trivial

```
template<typename Iter, typename Predicate>
Iter find_if(Iter first, Iter last, Predicate pred)  // find first p in [first:last) so that pred(*p)
{
    while (first!=last && !pred(*first))
        ++first;
    return first;
}
```

Function Objects and Lambdas

- General function object
  - Can carry state
  - Easily inlined (i.e., close to optimally efficient)

```
struct Less_than {
    String s;
    Less_than(const string& ss) :s{ss} {}  // store the value to compare against
    bool operator()(const string& v) const { return v<s; } // the comparison
};
```

Lambda notation

- We can let the compiler write the function object for us

```
auto p = std::find_if(vs.begin(),vs.end(),
                      [](const string& v) { return v<"Griffin"; } );
```

Container algorithms

- The C++ standard-library algorithms are expressed in terms of half-open sequences [first:last)
  - For generality and efficiency
  - If you find that verbose, define container algorithms

```
namespace Extended_STL {
        // …
        template<typename C, typename Predicate>
        Iterator<C> find_if(C& c, Predicate pred)
        {
                return std::find_if(c.begin(),c.end(),pred);
        }
        // …
}

auto p = find_if(v, [](int x) { return x%2; } );        // assuming v is a vector<int>
```

Duck Typing is Insufficient

- There are no proper interfaces
- Leaves error detection far too late
  - Compile- and link-time in C++
- Encourages a focus on implementation details
  - Entangles users with implementation
- Leads to over-general interfaces and data structures
  - As programmers rely on exposed implementation "details"
- Does not integrate well with other parts of the language
  - Teaching and maintenance problems
- We must think of generic code in ways similar to other code
  - Relying on well-specified interfaces (like OO, etc.)

Generic Programming is just Programming

- *Traditional code*

```
double sqrt(double d);       // C++84: accept any d that is a double
double d = 7;
double d2 = sqrt(d);         // fine: d is a double
double d3 = sqrt(&d);        // error: &d is not a double
```

- Generic code

```
void sort(Container& c);     // C++14: accept any c that is a Container
vector<string> vs { "Hello", "new", "World" };
sort(vs);                    // fine: vs is a Container
sort(&vs);                   // error: &vs is not a Container
```

C++14: Constraints aka "Concepts lite"

- How do we specify requirements on template arguments?
  - state intent
    - Explicitly states requirements on argument types
  - provide point-of-use checking
    - No checking of template definitions
  - use constexpr functions
- Voted as C++14 Technical Report
- Design by B. Stroustrup, G. Dos Reis, and A. Sutton
- Implemented by Andrew Sutton in GCC
- There are no C++0x concept complexities
  - No concept maps
  - No new syntax for defining concepts
  - No new scope and lookup issues

What is a Concept?

- Concepts are fundamental
  - They represent fundamental concepts of an application area
  - Concepts are come in "clusters" describing an application area
- A concept has semantics (meaning)
  - Not just syntax
  - "**Subtractable**" is not a concept
- We have always had concepts
  - C++: Integral, arithmetic
  - STL: forward iterator, predicate
  - Informally: Container, Sequence
  - Algebra: Group, Ring, …

What is a Concept?

- Don’t expect to find a new fundamental concept every year
- A concept is ***not*** the minimal requirements for an implementation
  – An implementation does not define the requirements
  – Requirements should be stable
- Concepts support interoperability
  – There are relatively few concepts
  – We can remember a concept

C++14 Concepts (Constraints)

- A concept is a predicate on one or more arguments
  - E.g. **Sequence<T>()** **//** *is T a Sequence?*

- Template declaration

```
template <typename S, typename T>
  requires Sequence<S>()
           && Equality_comparable<Value_type<S>, T>()
Iterator_of<S> find(S& seq, const T& value);
```

- Template use

```
void use(vector<string>& vs)
{
  auto p = find(vs,"Jabberwocky");
  // …
}
```

C++14 Concepts: Error handling

- Error handling is simple (and fast)

```
template<Sortable Cont>
        void sort(Cont& container);

vector<double> vec {1.2, 4.5, 0.5, -1.2};
list<int> lst {1, 3, 5, 4, 6, 8,2};

sort(vec);      // OK: a vector is Sortable
sort(lst);      // Error at (this) point of use: Sortable requires random access
```

- Actual error message

  error: ‘list<int>’ does not satisfy the constraint ‘Sortable’

C++14 Concepts: “Shorthand Notation”

- Shorthand notation

```
template <Sequence S, Equality_comparable<Value_type<S>> T>
        Iterator_of<C> find(S& seq, const T& value);
```

- We can handle essentially all of the Palo Alto TR
  - (STL algorithms) and more
    - Except for the axiom parts
  - We see no problems checking template definitions in isolation
    - But proposing that would be premature (needs work, experience)
  - We don’t need explicit **requires** much (the shorthand is usually fine)

C++14 Concepts: Overloading

- Overloading is easy

```
template <Sequence S, Equality_comparable<Value_type<S>> T>
        Iterator_of<S> find(S& seq, const T& value);

template<Associative_container C>
        Iterator_type<C> find(C& assoc, const Key_type<C>& key);

vector<int> v { /* ... */ };
multiset<int> s { /* ... */ };
auto vi = find(v, 42);              // calls 1st overload:
                                    // a vector is a Sequence
auto si = find(s, 12-12-12);        // calls 2nd overload:
                                    // a multiset is an Associative_container
```

C++14 Concepts: Overloading

- Overloading based on predicates
  - specialization based on subset
  - Far easier than writing lots of tests

```
template<Input_iterator Iter>
        void advance(Iter& p, Difference_type<Iter> n) { while (n--) ++p; }

template<Bidirectional_iterator Iter>
      void advance(Iter& i, Difference_type<Iter> n)
      { if (n > 0) while (n--) ++p; if (n < 0) while (n++) --ip}

template<Random_access_iterator Iter>
        void advance(Iter& p, Difference_type<Iter> n) { p += n; }
```

- We don't say

```
        Input_iterator < Bidirectional_iterator < Random_access_iterator
```

we compute it

C++14 Concepts: Definition

- How do you write constraints?
  - Any **bool** expression
    - Including type traits and constexpr function
  - a **requires(expr)** expression
    - **requires()** is a compile time intrinsic function
    - **true** if **expr** is a valid expression
- To recognize a concept syntactically, we can declare it **concept**
  - Rather than just **constexpr**

C++14 Concepts: “Terse Notation”

- We can use a concept name as the name of a type than satisfy the concept

```
void sort(Container& c);                // terse notation
```

  – means

```
template<Container __Cont>              // shorthand notation
    void sort(__Cont& c);
```

  – means

```
template<typename __Cont>               // explicit use of predicate
    requires Container<__Cont>()
        void sort(__Cont)& c;
```

  – Accepts any type that is a Container

```
vector<string> vs;
sort(vs);
```

C++14 Concepts: “Terse Notation”

- We have reached the conventional notation
  - with the conventional meaning
- *Traditional code*

```
double sqrt(double d);       // C++84: accept any d that is a double
double d = 7;
double d2 = sqrt(d);         // fine: d is a double
double d3 = sqrt(&d);        // error: &d is not a double
```

- Generic code

```
void sort(Container& c);     // C++14: accept any c that is a Container
vector<string> vs { "Hello", "new", "World" };
sort(vs);                    // fine: vs is a Container
sort(&vs);                   // error: &vs is not a Container
```

C++14 Concepts: “Terse Notation”

- Consider **std::merge**
- Explicit use of predicates:

```
template<typename For,
                typename For2,
                typename Out>
    requires Forward_iterator<For>()
    && Forward_iterator<For2>()
    && Output_iterator<Out>()
    && Assignable<Value_type<For>,Value_type<Out>>()
    && Assignable<Value_type<For2,Value_type<Out>>()
    && Comparable<Value_type<For>,Value_type<For2>>()
void merge(For p, For  q, For2 p2, For2 q2, Out p);
```

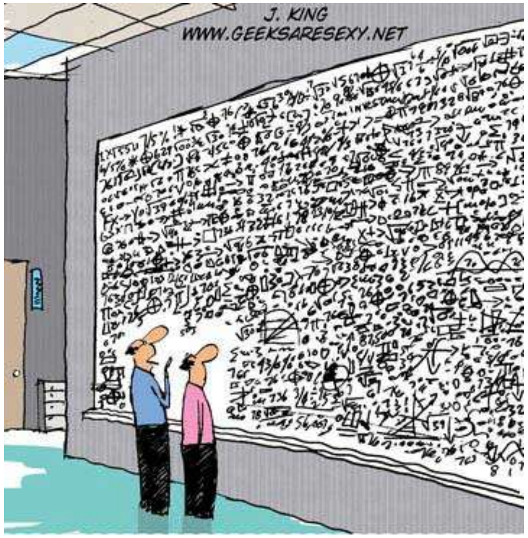
- Headache inducing, and **accumulate()** is worse

C++14 Concepts: “Terse Notation”

- Better, use the shorthand notation

```
template<Forward_iterator For,
         Forward_iterator For2,
         Output_iterator Out>
              requires Mergeable<For,For2,Out>()
void merge(For p, For  q, For2 p2, For2 q2, Out p);
```

- Quite readable



“...And that, in simple terms, is what’s wrong with your software design.”

C++14 Concepts: “Terse Notation”

- Better still, use the “terse notation”:

```
Mergeable{For,For2,Out}    // Mergeable is a concept requiring three types
void merge(For p, For  q, For2 p2, For2 q2, Out p);
```

- The

  concept-name { identifier-list }

  notation introduces constrained names

- Make simple things simple!

C++14 Concepts: “Terse Notation”

- Now we just need to define **Mergeable**:

```
template<typename For, typename For2, typename Out>
concept bool Mergeable()
{
        return Forward_iterator<For>()
          && Forward_iterator<For2>()
          && Output_iterator<Out>()
          && Assignable<Value_type<For>,Value_type<Out>>()
          && Assignable<Value_type<For2,Value_type<Out>>()
          && Comparable<Value_type<For>,Value_type<For2>>();
}
```

- It’s just a predicate

Challenges

C++ Challenges

- Obviously, C++ is not perfect
  - How can we make programmers prefer modern styles over low-level code
    - which is far more error-prone and harder to maintain, yet no more efficient?
  - How can we make C++ a better language given the Draconian constraints of C and C++ compatibility?
  - How can we improve and complete the techniques and models (incompletely and imperfectly) embodied in C++?
- Solutions that eliminate major C++ strengths are not acceptable
  - Compatibility
    - link, source code
  - Performance
    - uncompromising
  - Portability
  - Range of application areas
    - Preferably increasing the range

Long-term C++ Challenges

- Close more type loopholes
  - in particular, find a way to prevent misuses of **delete** without spoiling RAII
- Simplify concurrent programming
  - in particular, provide some higher-level concurrency models as libraries
- Simplify generic programming
  - in particular, introduce simple and effective concepts
- Simplify programming using class hierarchies
  - in particular, eliminate use of the visitor pattern
- Better support for combinations of object-oriented and generic programming
- Make exceptions usable for hard-real-time projects
  - that will most likely be a tool rather than a language change
- Find a good way of using multiple address spaces
  - as needed for distributed computing
  - would probably involve defining a more general module mechanism that would also address dynamic linking, and more.
- Provide many more domain-specific libraries
- Develop a more precise and formal specification of C++

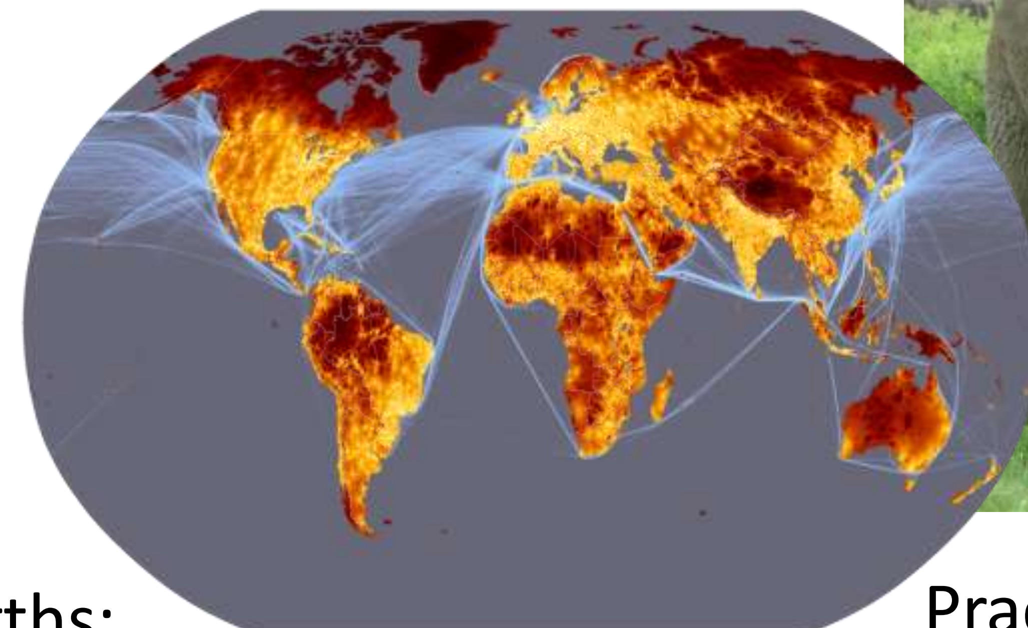
“Paradigms”

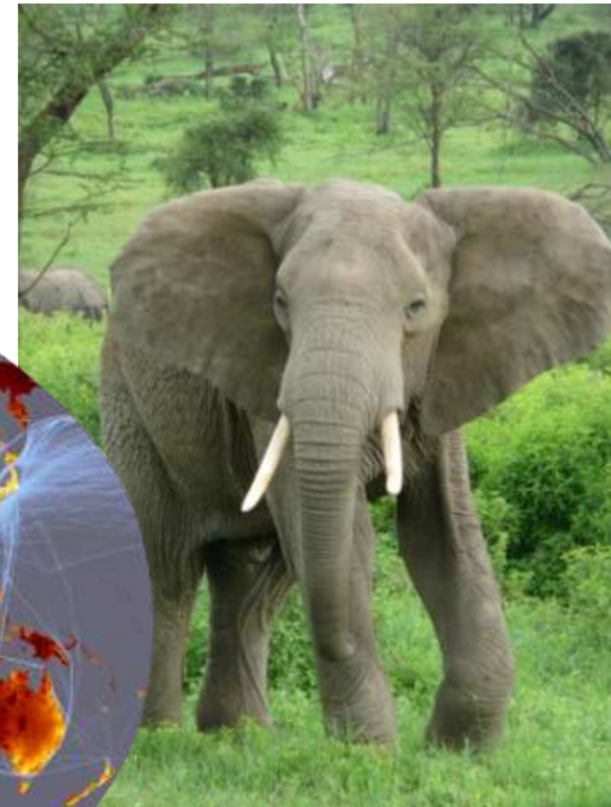
- Much of the distinction between object-oriented programming, generic programming, and “conventional programming” is an illusion
  - based on a focus on language features
  - incomplete support for a synthesis of techniques
  - The distinction does harm
    - by limiting programmers, forcing workarounds

```
void draw_all(Container& c)     // is this OOP, GP, or conventional?
        requires Same_type<Value_type<Container>,Shape*>
{
    for_each(c, [](Shape* p) { p->draw(); } );
}
```

Questions?

C++: A light-weight abstraction programming language





Key strengths:

- software infrastructure
- resource-constrained applications

Practice type-rich programming