

The Essence of C++

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

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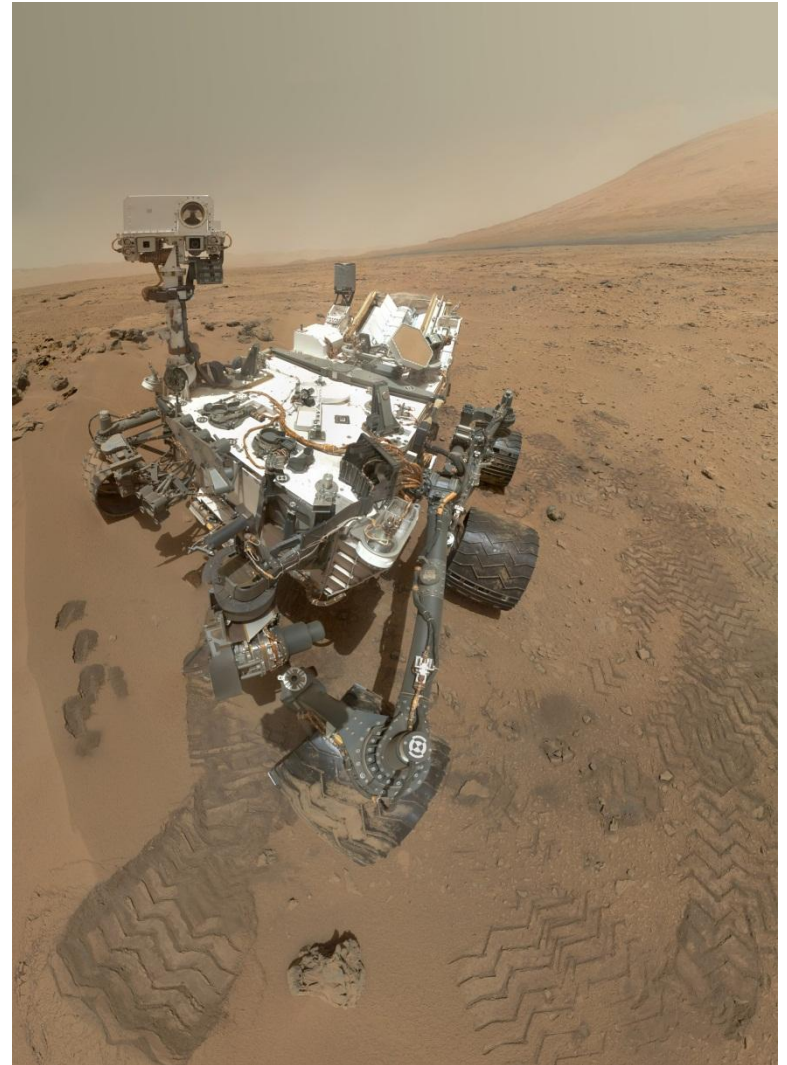


Abstract

- C++11 is being deployed and the shape of C++14 is becoming clear. This talk examines the foundations of C++. What is essential? What sets C++ apart from other languages? How do new and old features support (or distract from) design and programming relying on this essence.
- I focus on the abstraction mechanisms (as opposed to the mapping to the machine): Classes and templates. Fundamentally, if you understand vector, you understand C++.
- Type safety and resource safety are key design aims for a program. These aims must be met without limiting the range of applications and without imposing significant run-time or space overheads. I address issues of resource management (garbage collection is not an ideal answer and pointers should not be used as resource handles), generic programming (we must make it simpler and safer), compile-time computation (how and when?), and type safety (casts belong in the lowest-level hardware interface). I will touch upon move semantics, exceptions, concepts, type aliases, and more. My aim is not so much to present novel features and technique, but to explore how C++'s feature set supports a new and more effective design and programming style.
- Primary audience
 - Experienced programmers with weak C++ understanding
 - Academics/Teachers/Mentors
 - Architects (?)

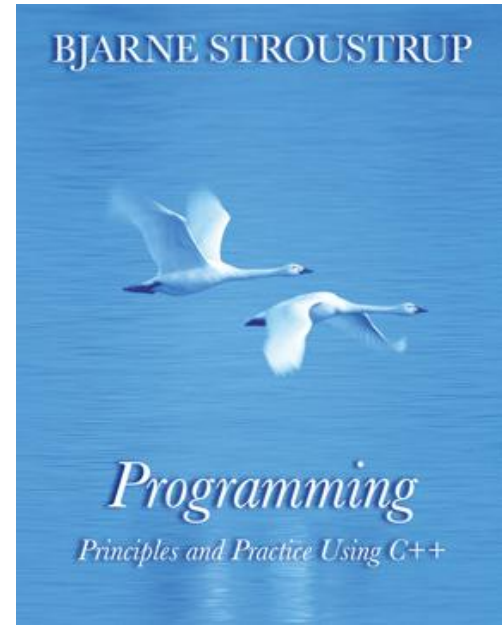
Overview

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



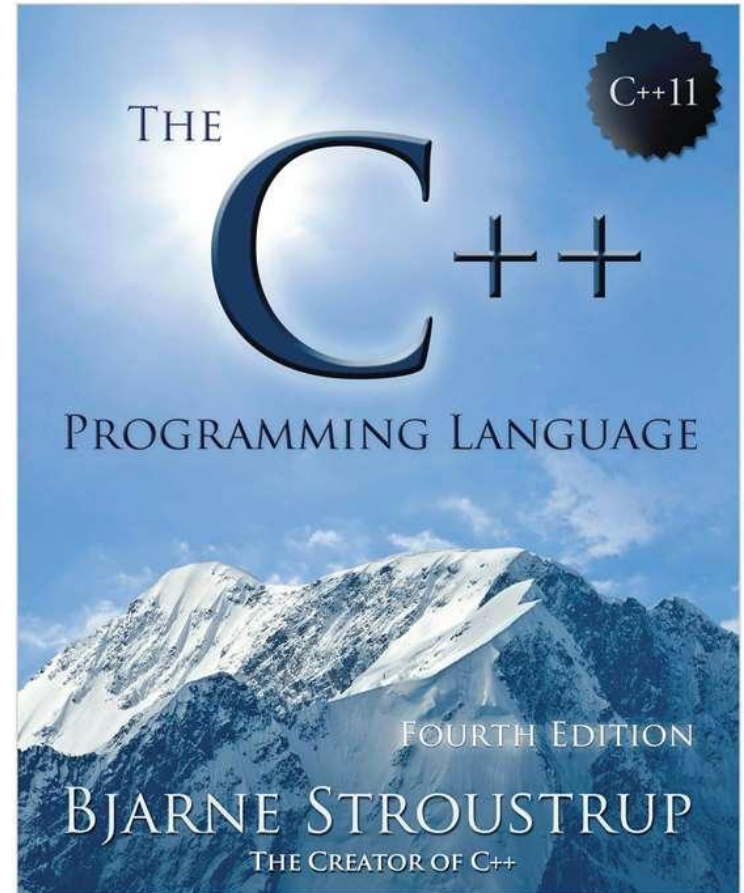
What did/do I want?

- 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

A multi-paradigm
programming language

Buffer
overflows

It's C!

Classes

Embedded systems
programming language

Too big!



Low level!

An object-oriented
programming language

Generic programming

A random collection
of features

C++

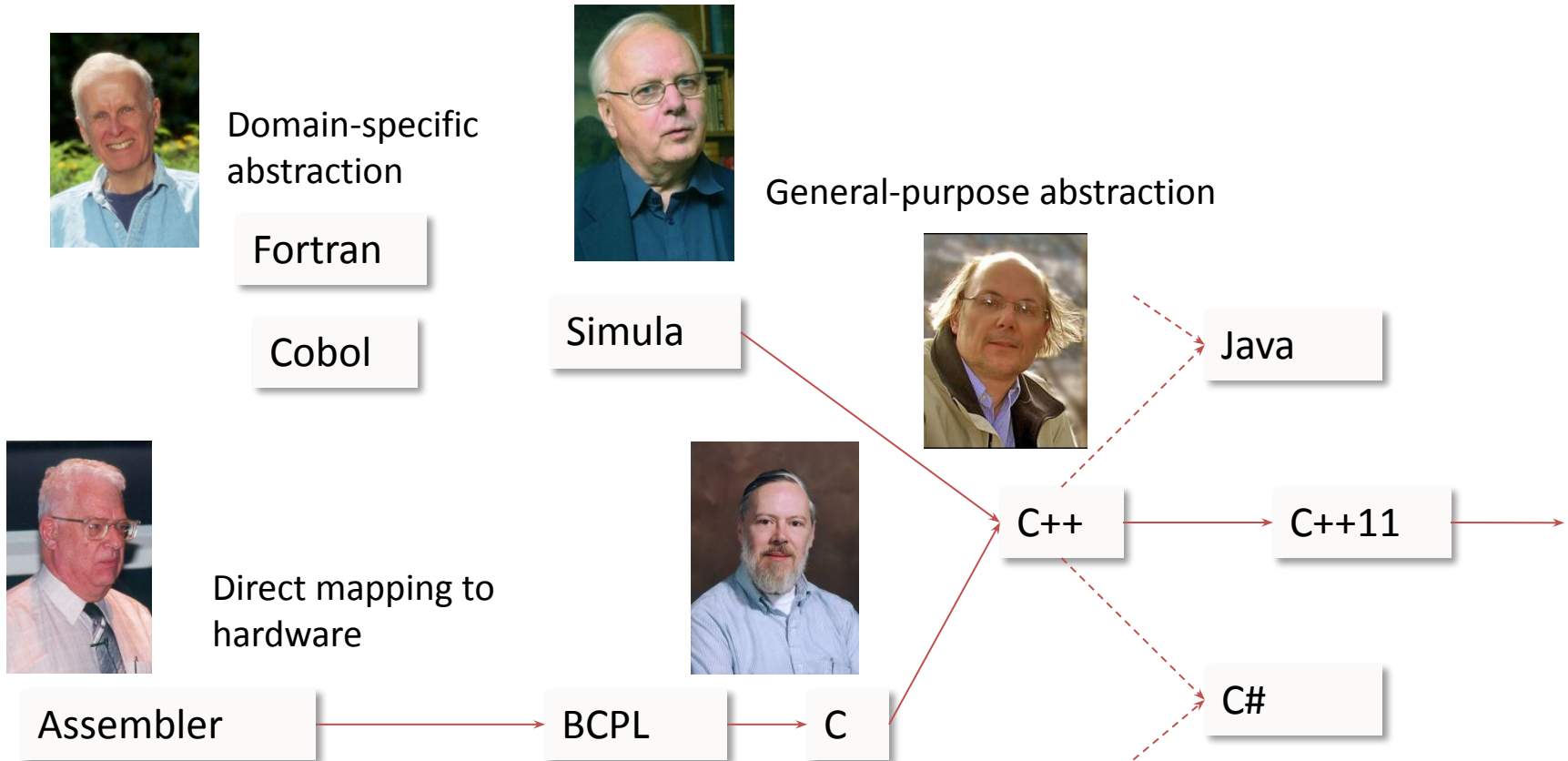
A light-weight abstraction programming language



Key strengths:

- software infrastructure
- resource-constrained applications

Programming Languages



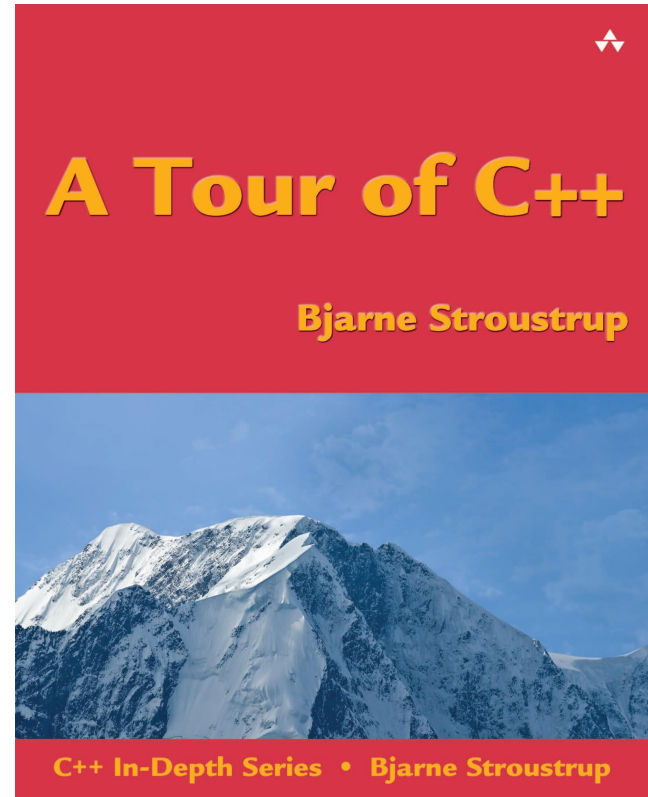
What does C++ offer?

- 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

- +, %, ->, [], (), ...

value

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

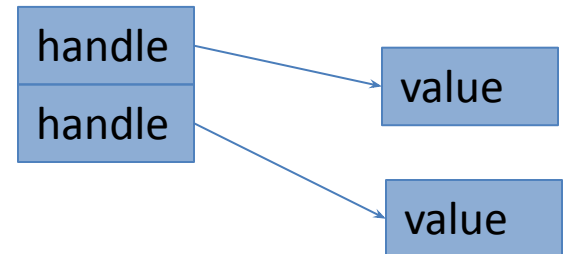
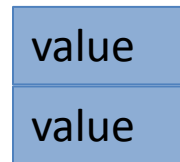
handle

- **vector**, string, thread, Matrix, ...

value

- Objects can be composed by simple concatenation:

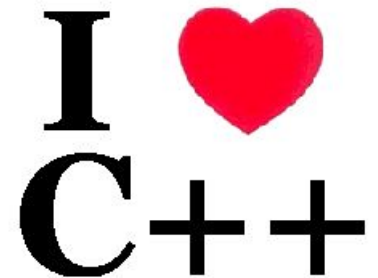
- Arrays
 - Classes/structs



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
```

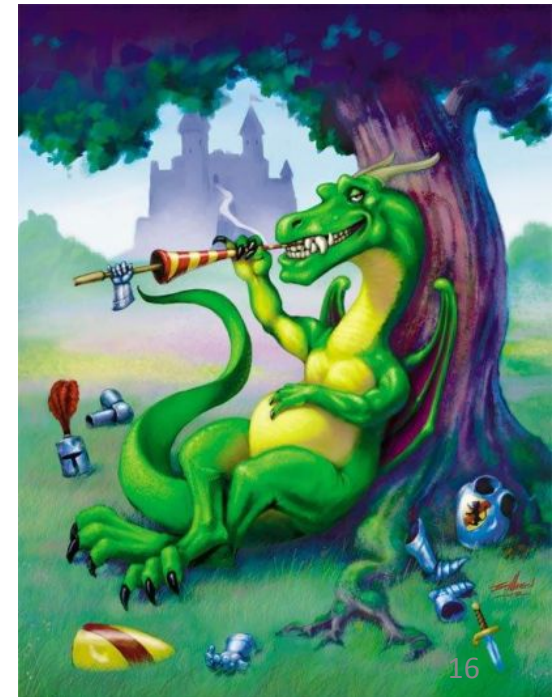
Not C++ (fundamental)

- 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
```

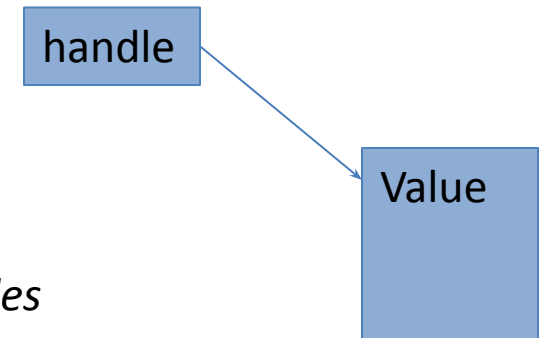
```
};
```

```
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
```

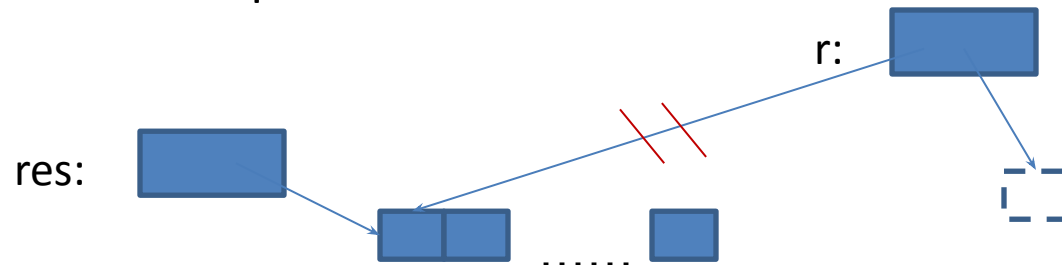
```
    return r;
```

```
}
```

```
Matrix res = a+b;
```

- Define move a constructor for **Matrix**

- don't copy; “steal the representation”

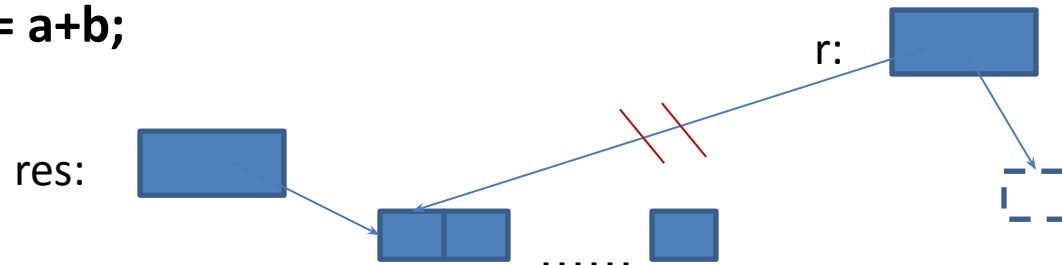


Move semantics

- 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, ostream, ...**
 - **unique_ptr, shared_ptr**
 - ...



OOP

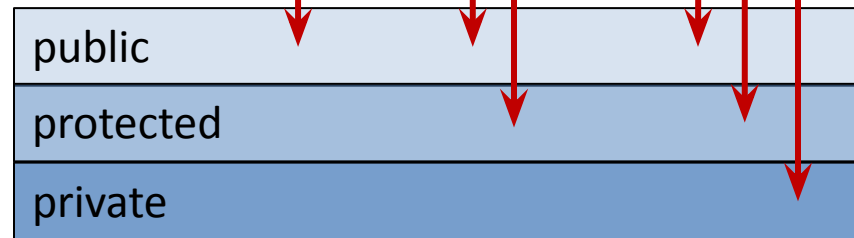


Class hierarchies

Class' own members

Derived classes

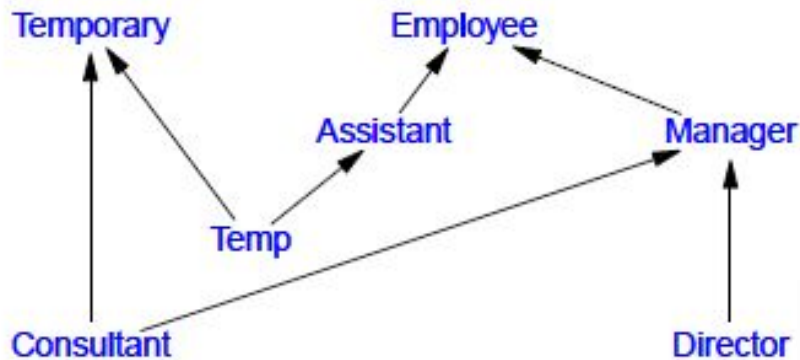
All users



- 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

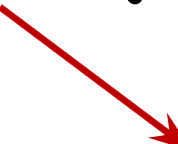
- The C++ standard-library algorithms are expressed in terms of half-open sequences [first:last)
 - For generality and efficiency
 - If you find that verbose, define container algorithms

```
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”

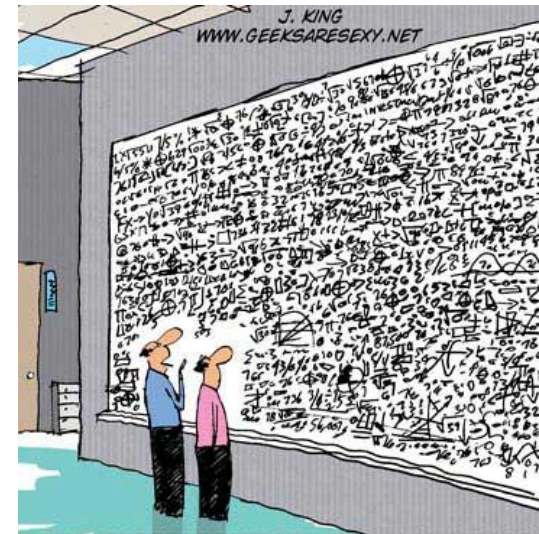
- Better, use the shorthand notation

```
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



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++

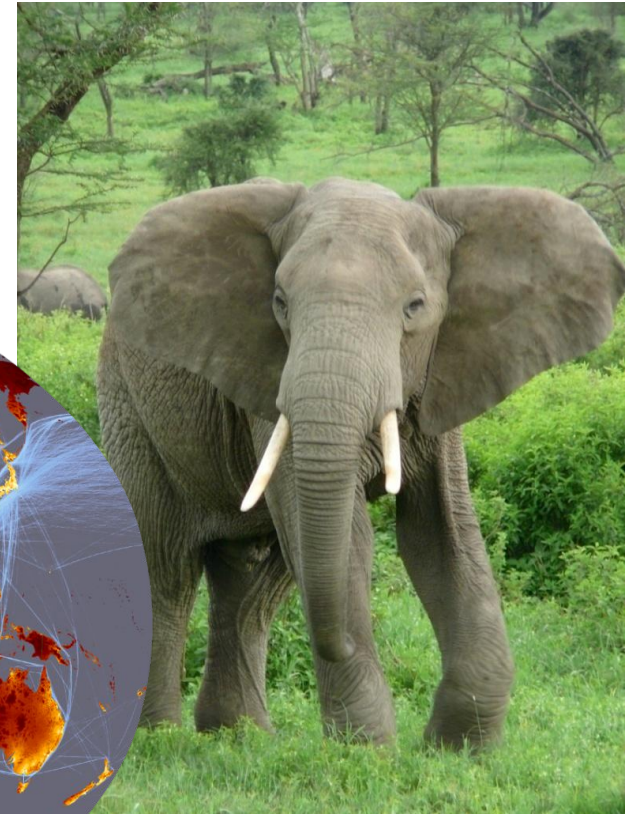
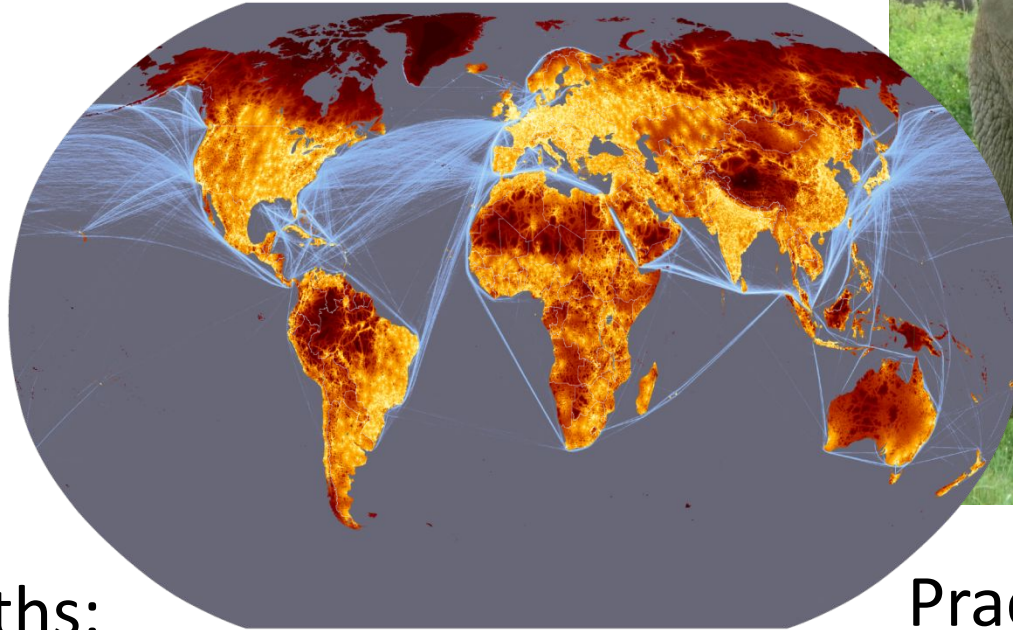
“Paradigms”

- 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