The Essence of C++

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

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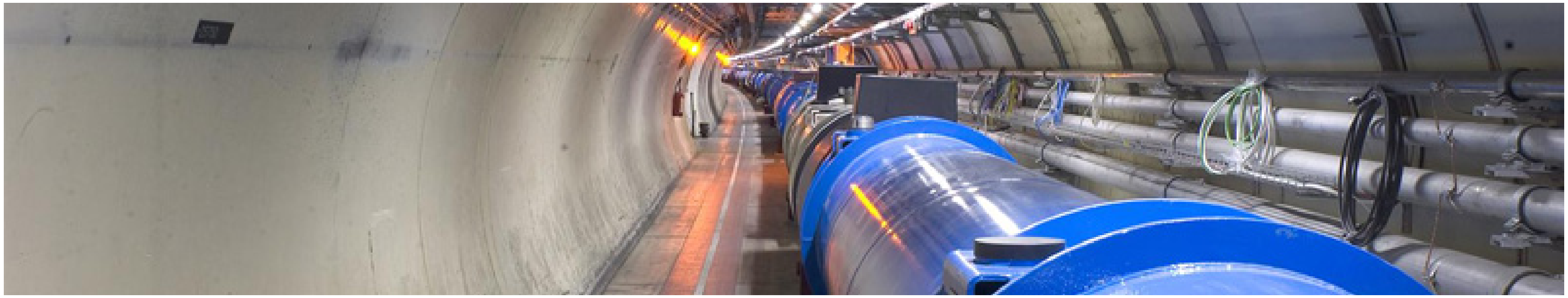
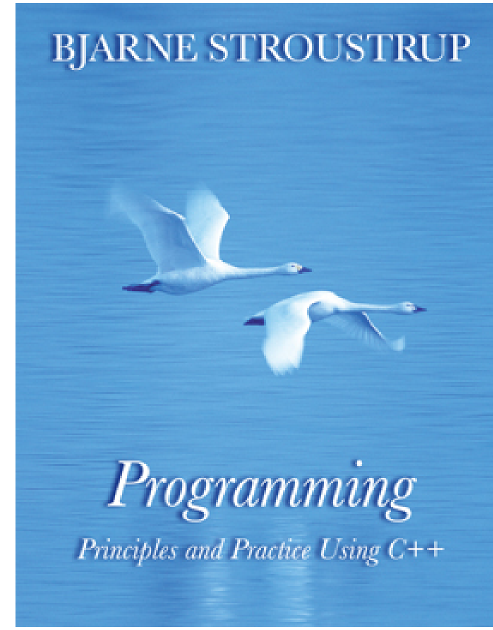


Overview

- Aims and constraints
- C++ in four slides
- Resource management
  - RAII
  - Move semantics
- Generic Programming
  - Templates
  - Requirements checking

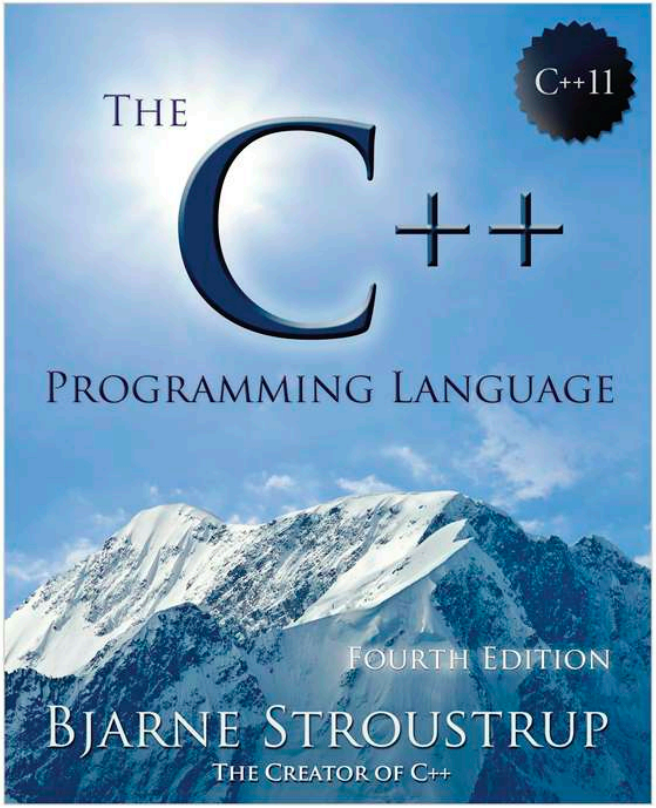
What did/do I want?

- 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!

Generic programming

An object-oriented programming language

A random collection of features

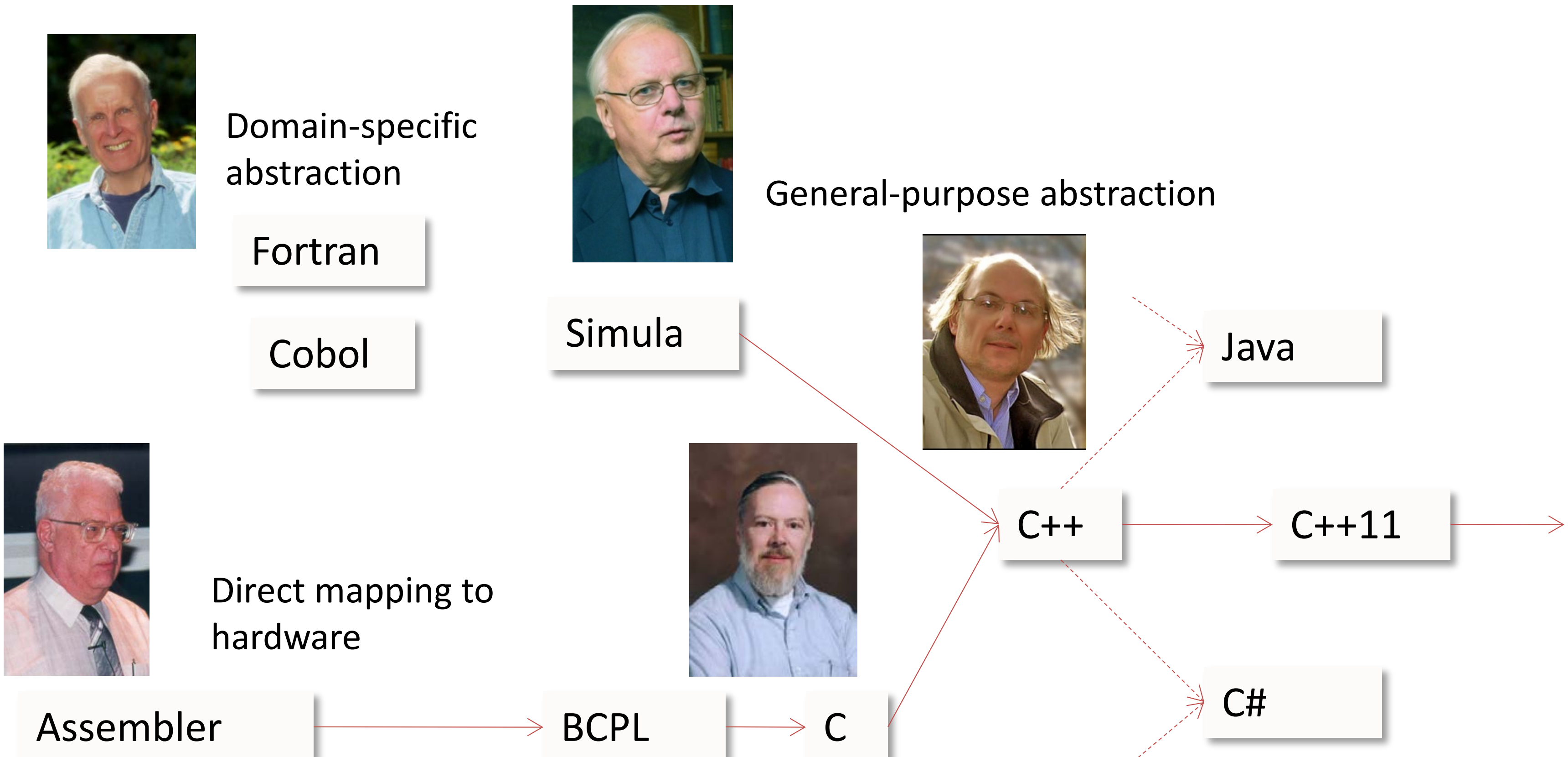
C++

A light-weight abstraction programming language

Key strengths:

- software infrastructure
- resource-constrained applications

Programming Languages

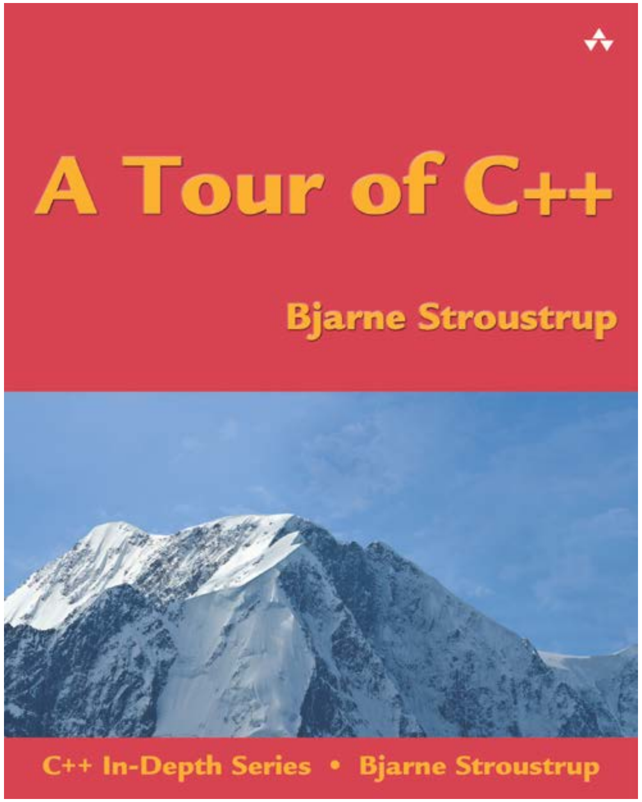


What does C++ offer?

- 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?

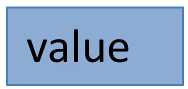
- C++ in Four slides
  - Map to hardware
  - Classes
  - Inheritance
  - Parameterized types



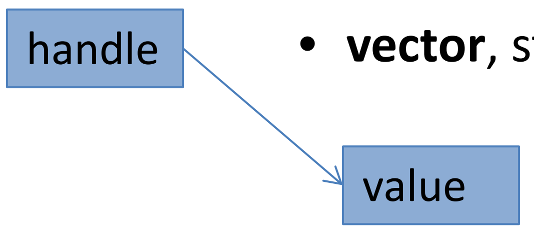
- If you understand **int** and **vector**, you understand C++
  - The rest is “details” (1,300+ pages of details)

Map to Hardware

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

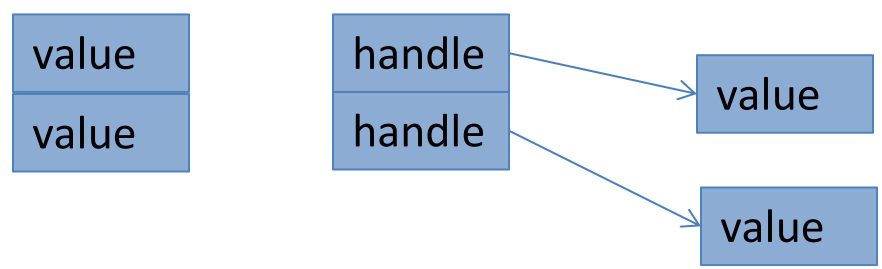


- **int**, double, complex<double>, Date, …



- **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

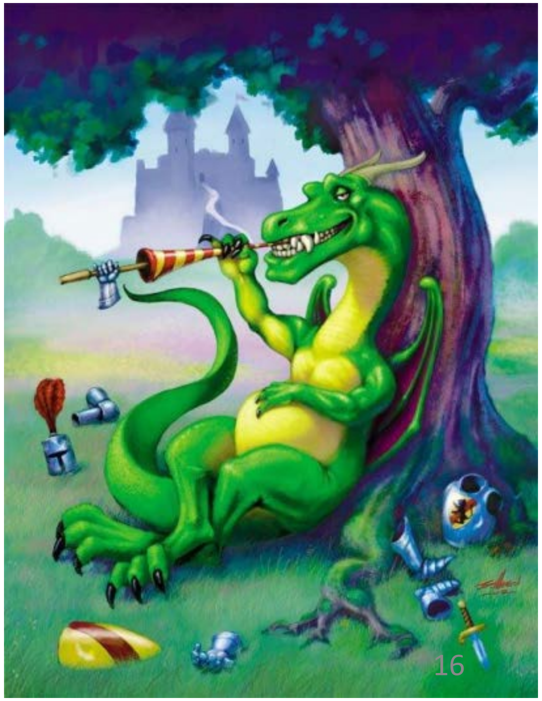
```
template<typename T>
class vector { /* … */ };                 // a generic type

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


template<typename C>
void sort (C& 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, but mot code can be type safe
  - C compatibility, history, pointers/arrays, unions, casts, …
- No virtual machine required
  - 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)

- Lots and lots of libraries
- 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
  - …

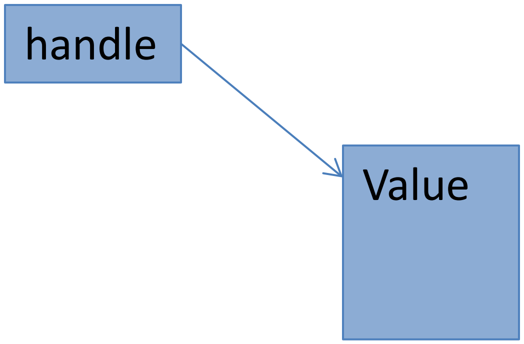


Resource Management

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?) direct 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?

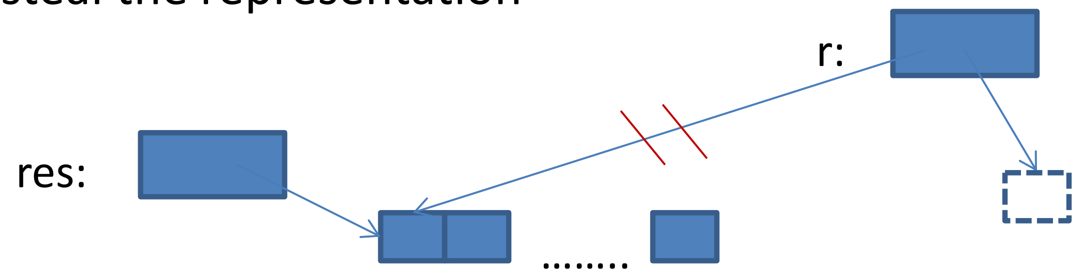
- Ideas
  – Return a pointer to a **new**'d object
    - Who does the **delete**?
  - Return a reference to a **new**'d object
    - Who does the **delete**?
    - Delete what?
  - Pass a target object
    - We are regressing towards assembly code
  - Return an object
    - Copies are expensive
    - 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;
```

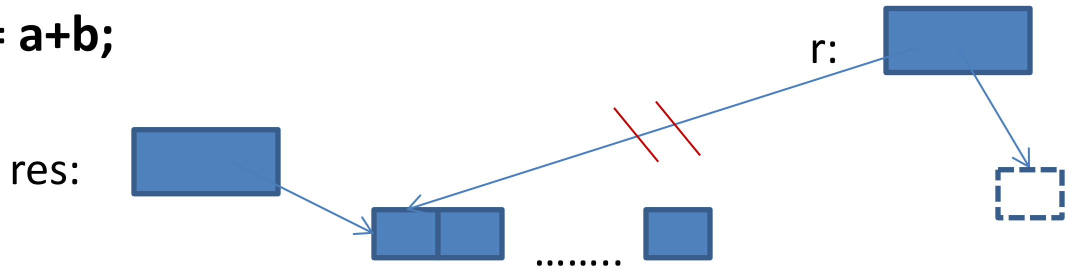
- Define move a constructor for **Matrix**
  - don’t copy; “steal the representation”



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**
  - …

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 great 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)

Containers and 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.)

Using Constraints: Concept

- We must specify what we expect of template arguments
- Concept:
  - A set of requirements on one or more template arguments
  - A compile-time predicate on a set of types and values
  - For example
    - **Sequence<T>** is T a sequence type
    - **Container<T>** is T a container type
    - **Forward_iterator<T>** is T a forward iterator
    - **Integer<T>** is T and integer type
    - **Function<T,A>** can a T be called with an argument of type A
  - Use
    - **template<typename C> requires Container<C>() void sort(C& c);**
    - **template<Container C> void sort(C& c);** **//** *shorthand notation*
    - **void sort(Container& c);** **//** *terse notation*

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 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: 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

- 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
```

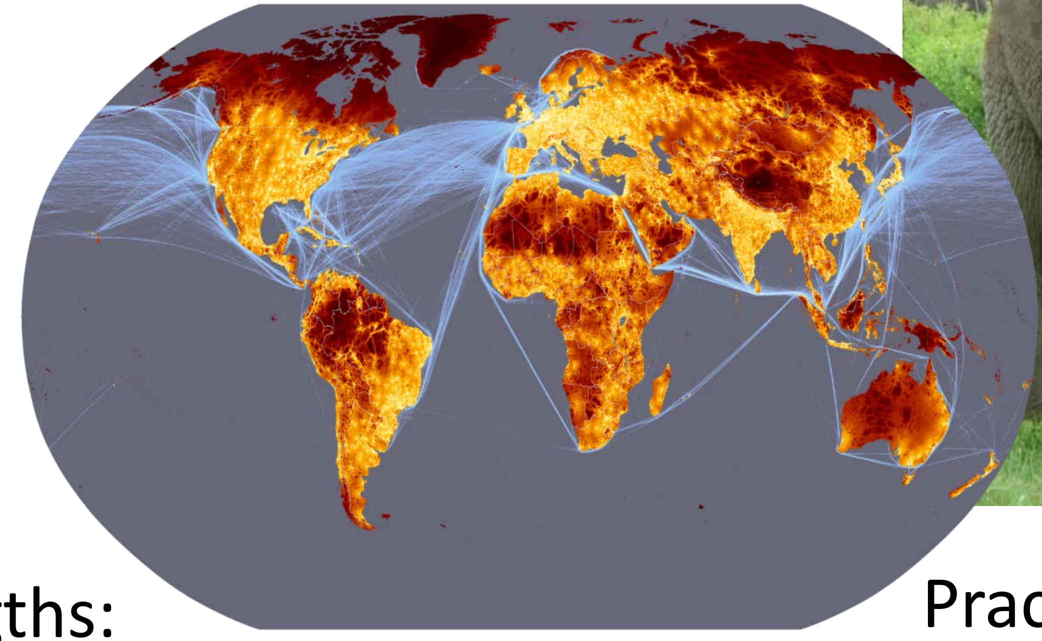
“Paradigms”

- 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