C++11 Style – A Touch of Class

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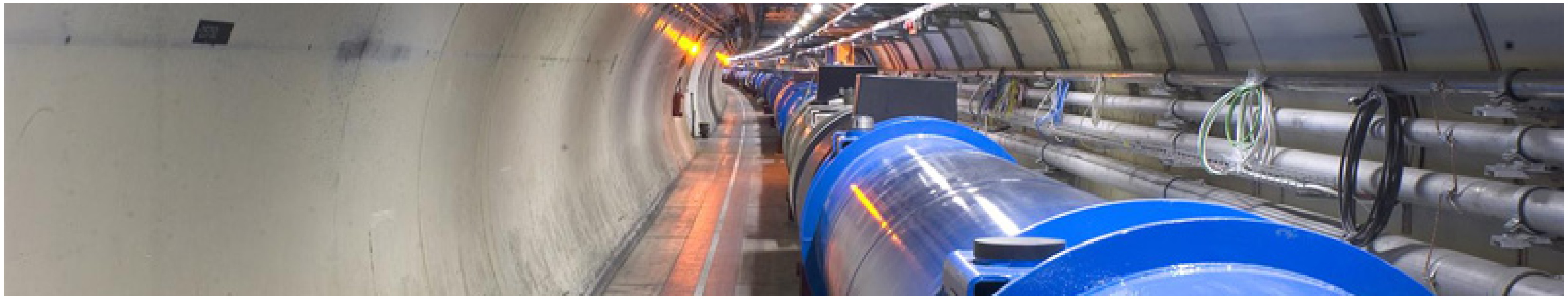


What is C++?

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

No one size fits all

- Different projects have different constraints
  - Hardware resources
  - Reliability constraints
  - Efficiency constraints
    - Time
    - Power
  - Time to completion
  - Developer skills

- Extremes
  - All that matters is to get to the market first!
  - If the program fails, people die
  - A 50% overhead implies the need for another $50M server farm

What we want

- A synthesis
  - And integrated set of features
  - C++11 is a significant improvement in that direction
- Articulated guidelines for use
  - What I call “style”

“Multi-paradigm” is not good enough

The styles/”paradigms” were never meant to be disjoint:

- C style
  - functions and structures
  - Typically lots of macros, void*, and casts
- C++85 style (aka “C with Classes”)
  - classes, class hierarchies, and virtual functions
- “True OO” style
  - Just class hierarchies
  - Often lots of casts and macros
- Generic C++
  - Everything is a template

What we want

- Easy to understand
  - For humans and tools
  - correctness, maintainability
- Modularity
  - Well-specified interfaces
  - Well-defined error-handling strategy
- Effective Resource management
  - Memory, locks, files, …
- Thread safety
- Efficient
  - Compact data structures
  - Obvious algorithmic structure
- Portable
  - Unless specifically not

Overview

- Ghastly style
  - qsort() example
- Type-rich Programming
  - Interfaces
  - SI example
- Resources and errors
  - RAII
  - Resource handles and pointers
  - Move semantics
- Compact data structures
  - List vs. vector
  - Vector of point
- Simplify control structure
  - Algorithms, lambdas
- Low-level != efficient
- Type-safe concurrency
  - Threads, async(), and futures

B. Stroustrup: *Software Development for Infrastructure*. IEEE Computer, January 2012,

ISO C++11

- This is a talk about how to use C++ well
  – In particular, C++11
  – The C++ features ***as a whole*** support programming style
- This is ***not*** a talk about the new features in ISO C++11
  – I use those where appropriate
  – My C++11 FAQ lists the new features
- Most of the C++11 features are already shipping
  – E.g. Clang, GCC, and Microsoft C++ (the order is alphabetical ☺)
- The C++11 standard library is shipping
  – E.g. Boost, Clang, GCC, Microsoft C++

Ghastly Style

Memory to be sorted

Number of bytes in an element

```
void qsort(void *base, size_t nmemb, size_t size, int(*compar)(const void *, const void *));
```

Number of elements in memory

Element comparison function

```
void f(char* arr[], int m, double* darr, int n)
{
        qsort(arr, m, sizeof(char *), cmpstringp);
        qsort(darr, n, sizeof(double), compare_double);
}
```

"It" doesn't know how to compare doubles?

"It" doesn't know the size of a double?

"It" doesn't know the number of elements?

Ghastly Style

```
void qsort(void *base, size_t nmemb, size_t size, int(*compar)(const void *, const void *));

static int cmpstringp(const void *p1, const void *p2)
{           /* The actual arguments to this function are "pointers to pointers to char */
            return strcmp(* (char * const *) p1, * (char * const *) p2);
}

static int compare_double(const void *p1, const void *p2)
{
            double p0 = *(double*)p;
            double q0 = *(double*)q;
            if (p0 > q0) return 1;
            if (p0 < q0) return -1;
            return 0;
}
```

Uses inefficient indirect function call

Prevents inlining

Throw away useful type information

Ghastly Style

- **qsort()** implementation details
  - Note: I looked for implementations of qsort() on the web, most of what I found were "educational fakes"

Swaps bytes (POD only)

```
/* Byte-wise swap two items of size SIZE. */
#define SWAP(a, b, size) do { register size_t __size = (size); register char *__a = (a), *__b = (b); do { char __tmp = *__a; *__a++ = *__b; *__b++ = __tmp; } while (--__size > 0); } while (0)
/* … */
char *mid = lo + size * ((hi - lo) / size >> 1);
if ((*cmp) ((void *) mid, (void *) lo) < 0) SWAP (mid, lo, size);
if ((*cmp) ((void *) hi, (void *) mid) < 0) SWAP (mid, hi, size); else goto jump_over;
if ((*cmp) ((void *) mid, (void *) lo) < 0) SWAP (mid, lo, size);
jump_over:;
```

Lots of byte address manipulation

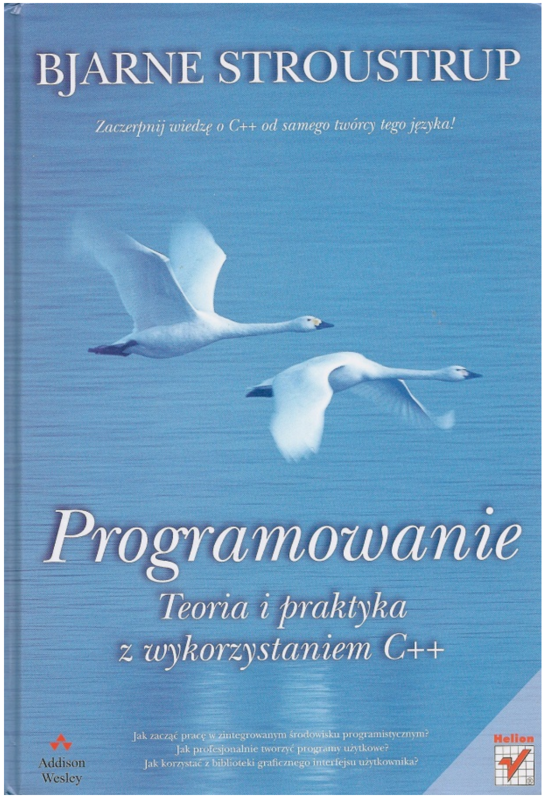
Lots of indirect function calls

Unfair? No!

- I didn't make up that example
  - it is repeatedly offered as an example of good code (for decades)
  - qsort() is a popular ISO C standard-library function
  - That qsort() code is readable compared to most low-level C/C++ code
- The style is not uncommon in production code
  - Teaching and academic versions often simplify to protect the innocent (fraud?)
- I see much worse on bulletin boards
  - Have a look, and cry
- Many students aim for that level of code
  - "for efficiency"
  - because it is cool (their idols does/did it!)
- It's not just a C/C++ problem/style
  - Though I see C and C-style teaching as the source of the problem

Does it matter? Yes!

- Bad style is the #1 problem in real-world C++ code
  - Makes progress relatively easy
  - Only relatively easy: bad code breeds more bad code
- Lack of focus on style is the #1 problem in C++ teaching
  - A “hack” is usually the quickest short-term solution
    - Faster than thinking about “design”
  - Many teach poor style
  - Many are self-taught
    - Take advice from
      - Decades old books
      - Other novices
    - Imitate
      - Other languages
      - Bad old code



So what do I want?

- Simple interfaces

```
void sort(Container&);          // for any container (e.g. vector, list, array)
                                // I can't quite get this is in C++ (but close)
```

- Simple calls

```
vector<string> vs;
// …
sort(vs);      // this, I can do
```

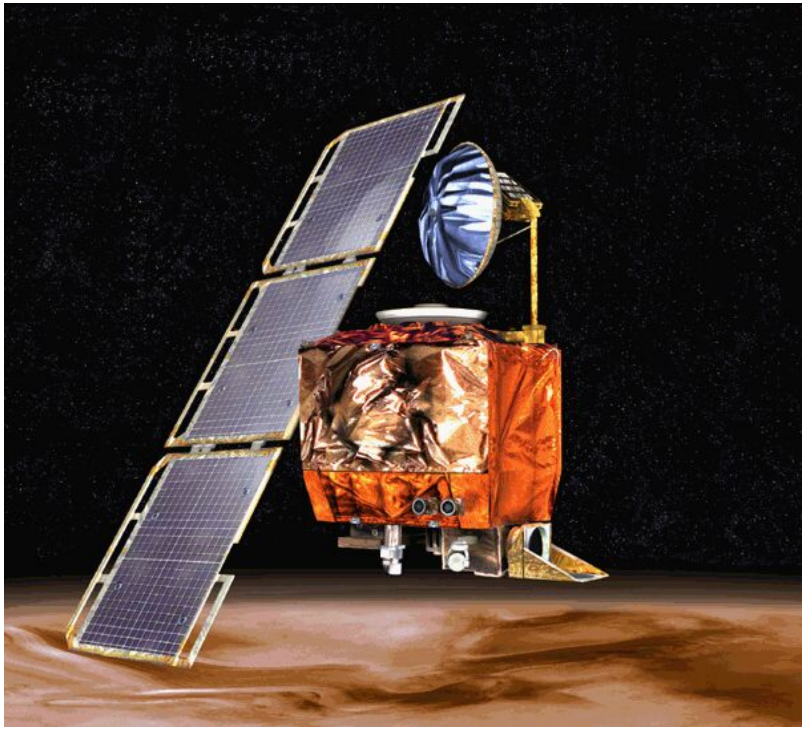
- Uncompromising performance
  - Done: **std::sort()** beats **qsort()** by large factors (not just a few percent)
- No static type violations
  - Done
- No resource leaks
  - Done (without a garbage collector)

Type-rich Programming

- Interfaces
- SI-units

Focus on interfaces

- Underspecified / overly general:
  - **void increase_speed(double);**
  - **Object obj; … obj.draw();**
  - **Rectangle(int,int,int,int);**



- Better:
  - **void increase_speed(Speed);**
  - **Shape& s; … s.draw();**
  - **Rectangle(Point top_left, Point bottom_right);**
  - **Rectangle(Point top_left, Box_hw b);**

SI Units

- Units are effective and simple:

```
Speed sp1 = 100m/9.8s;            // very fast for a human
Speed sp2 = 100m/9.8s2;           // error (m/s2 is acceleration)
Speed sp3 = 100/9.8s;             // error (speed is m/s and 100 has no unit)
Acceleration acc = sp1/0.5s;      // too fast for a human
```

- They are also almost never used in programs
  - General-purpose languages generally don’t directly support units
  - Run-time checking is far too costly

SI Units

- We can define Units to be handled at compile time:

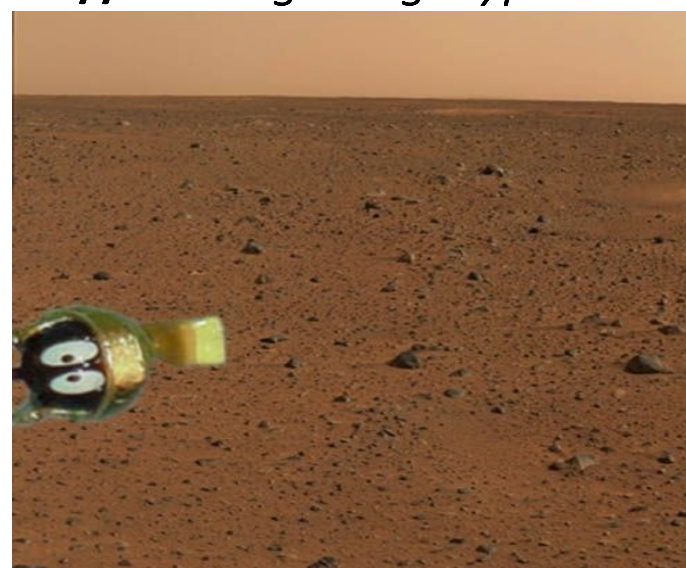
```
template<int M, int K, int S> struct Unit {        // a unit in the MKS system
      enum { m=M, kg=K, s=S };
};

template<typename Unit>     // a magnitude with a unit
struct Value {
      double val;                                 // the magnitude
      explicit Value(double d) : val(d) {}  // construct a Value from a double
};

using Speed = Value<Unit<1,0,-1>>;            // meters/second type
using Acceleration = Value<Unit<1,0,-2>>; // meters/second/second type
```

SI Units

- We have had libraries like that for a decade
  - but people never used them:

```
Speed sp1 = Value<1,0,0> (100)/ Value<0,0,1> (9.8);  // very explicit
Speed sp1 = Value<M> (100)/ Value<S> (9.8);       // use a shorthand notation
Speed sp1 = Meters(100)/Seconds(9.8);             // abbreviate further still
Speed sp1 = M(100)/S(9.8);                        // this is getting cryptic
```

- Notation matters.



SI Units

- So, improve notation using user-defined literals:

```
using Second = Unit<0,0,1>;      // unit: sec
using Second2 = Unit<0,0,2>;    // unit: second*second

constexpr Value<Second> operator"" s(long double d)
        // a f-p literal suffixed by 's'
{
        return Value<Second> (d);
}

constexpr Value<Second2> operator"" s2(long double d)
        // a f-p literal  suffixed by 's2'
{
        return Value<Second2> (d);
}
```

SI Units

- Units are effective and simple:

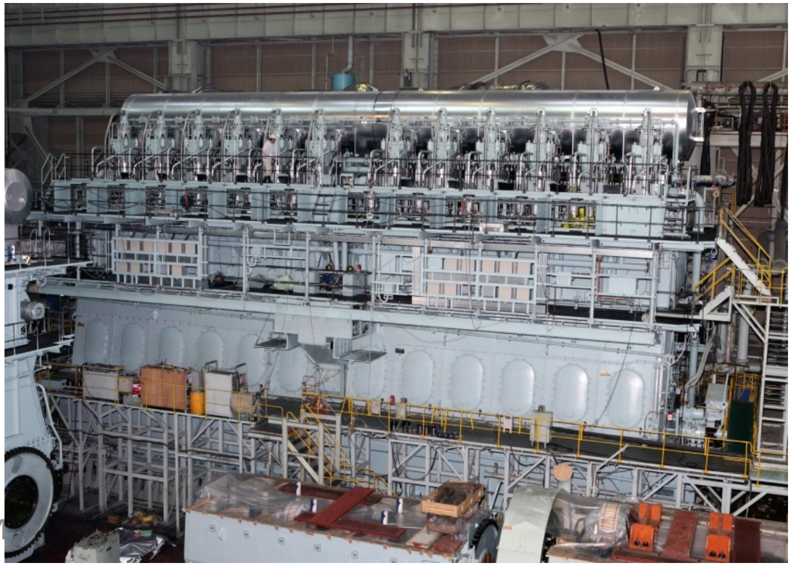
```
Speed sp1 = 100m/9.8s;             // very fast for a human
Speed sp2 = 100m/9.8s2;            // error (m/s2 is acceleration)
Speed sp3 = 100/9.8s;              // error (speed is m/s and 100 has no unit)
Acceleration acc = sp1/0.5s;       // too fast for a human
```

- and essentially free (in C++11)
  - Compile-time only
  - No run-time overheads

Style

- Keep interfaces strongly typed
  - Avoid very general types in interfaces, e.g.,
    - **int**, **double, …**
    - **Object, …**

Because such types can represent just about anything
  - Checking of trivial types finds only trivial errors
  - Use precisely specified interfaces



Resources and errors

- Resources
- RAII
- Move

Resources and Errors

```
//     unsafe, naïve use:

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

Resources and Errors

```
//     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);
      throw;
    }
    if (f) fclose(f);
 }
```

RAII (Resource Acquisition Is Initialization)

```
// use an object to represent a resource
class File_handle {        // belongs in some support library
        FILE* p;
public:
        File_handle(const char* pp, const char* r)
                { p = fopen(pp,r); if (p==0) throw File_error(pp,r); }
        File_handle(const string& s, const char* r)
                { p = fopen(s.c_str(),r); if (p==0) throw File_error(s,r); }
        ~File_handle() { fclose(p); }          // destructor
        // copy operations
        // access functions
};

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

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**), …

```
mutex m;        // a resource
int sh;         // shared data

void f()
{
    // …
    unique_lock<mutex> lck {m};     // grab (acquire) the mutex
    sh+=1;                          // manipulate shared data
}                                   // implicitly release the mutex
```

Resource Handles and Pointers

- 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::run_time_error{"Weird!"};     // leak
    if (x<200) return;                                  // leak
    // …
    delete p;                       // and I want my garbage collector! ☹
}
```

  - No "Naked New"!
  - But, why use a 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::run_time_error{"Weird!"};        // no leak
        if (x<200) return;                                     // no leak
        // …
}
```

  – But why use a **shared_ptr**?
  – I'm not sharing anything.

Resource Handles and Pointers

- A **std::unique_ptr** releases its object at when the **unique_ptr** is destroyed

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

  - But why use ***any*** kind of pointer ?
  - I'm not passing anything around.

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::run_time_error{“Weird!”};       // no leak
        if (x<200) return;                                      // no leak
        // …
}
```

Resource Management Style

- Prefer classes where the resource management is part of their fundamental semantics
  - E.g., **std::vector**, **std::ostream**, **std::thread**, …
- Use “smart pointers” to address the problems of premature destruction and leaks
  - **std::unique_ptr** for (unique) ownership
    - Zero cost (time and space)
  - **std::shared_ptr** for shared ownership
    - Maintains a use count
  - But they are still pointers
    - “any pointer is a potential race condition – even in a single threaded program”

How to move a resource

- Common problem:
  - How to get a lot of data cheaply out of a function
- Idea #1:
  - Return a pointer to a **new**'d object

```
Matrix* operator+(const Matrix&, const Matrix&);
Matrix& res = *(a+b);            // ugly! (unacceptable)
```

- Who does the **delete**?
  - there is no good general answer

How to move a resource

- Common problem:
  - How to get a lot of data cheaply out of a function
- Idea #2
  - Return a reference to a **new**'d object

```
Matrix& operator+(const Matrix&, const Matrix&);
Matrix res = a+b;        // looks right, but …
```

- Who does the **delete**?
  - What **delete**? I don't see any pointers.
  - there is no good general answer

How to move a resource

- Common problem:
  - How to get a lot of data cheaply out of a function
- Idea #3
  - Pass an reference to a result object

```
void operator+(const Matrix&, const Matrix&, Matrix& result);
Matrix res = a+b;              // Oops, doesn't work for operators
Matrix res2;
operator+(a,b,res2);           // Ugly!
```

- We are regressing towards assembly code

How to move a resource

- Common problem:
  - How to get a lot of data cheaply out of a function
- Idea #4
  - Return a **Matrix**

```
Matrix operator+(const Matrix&, const Matrix&);
Matrix res = a+b;
```

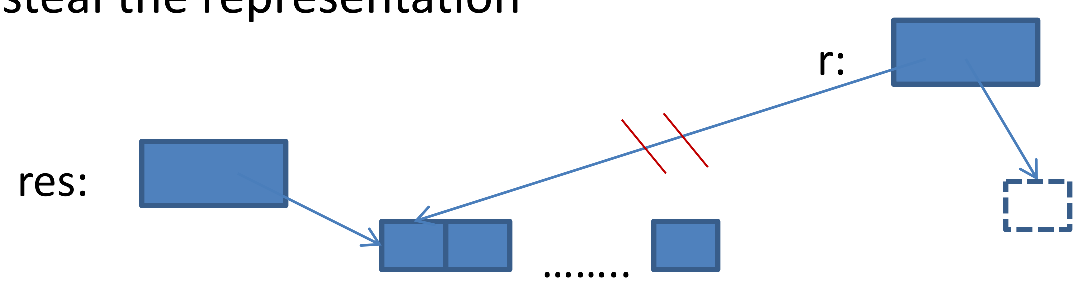
- Copy?
  - expensive
- Use some pre-allocated “result stack” of **Matrix**es
  - A brittle hack
- Move the **Matrix** out
  - don’t copy; “steal the representation”
  - Directly supported in C++11 through move constructors

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;
```

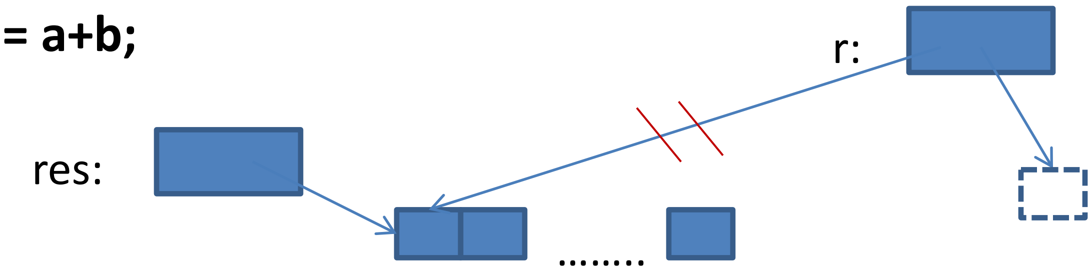
- Define move a constructor for **Matrix**
  - don't copy; "steal the representation"



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;
```



Move semantics

- All the standard-library containers have move constructors and move assignments
  - **vector**
  - **list**
  - **forward_list** (singly-linked list)
  - **map**
  - **unordered_map** (hash table)
  - **set**
  - …
  - **string**
- Not **std::array**

Style

- No naked pointers
  - Keep them inside functions and classes
  - Keep arrays out of interfaces (prefer containers)
  - Pointers are implementation-level artifacts
  - A pointer in a function should not represent ownership
  - Always consider **std::unique_ptr** and sometimes **std::shared_ptr**
- No naked **new** or **delete**
  - They belong in implementations and as arguments to resource handles
- Return objects "by-value" (using move rather than copy)
  - Don't fiddle with pointer, references, or reference arguments for return values

Use compact data

- Vector vs. list
- Object layout

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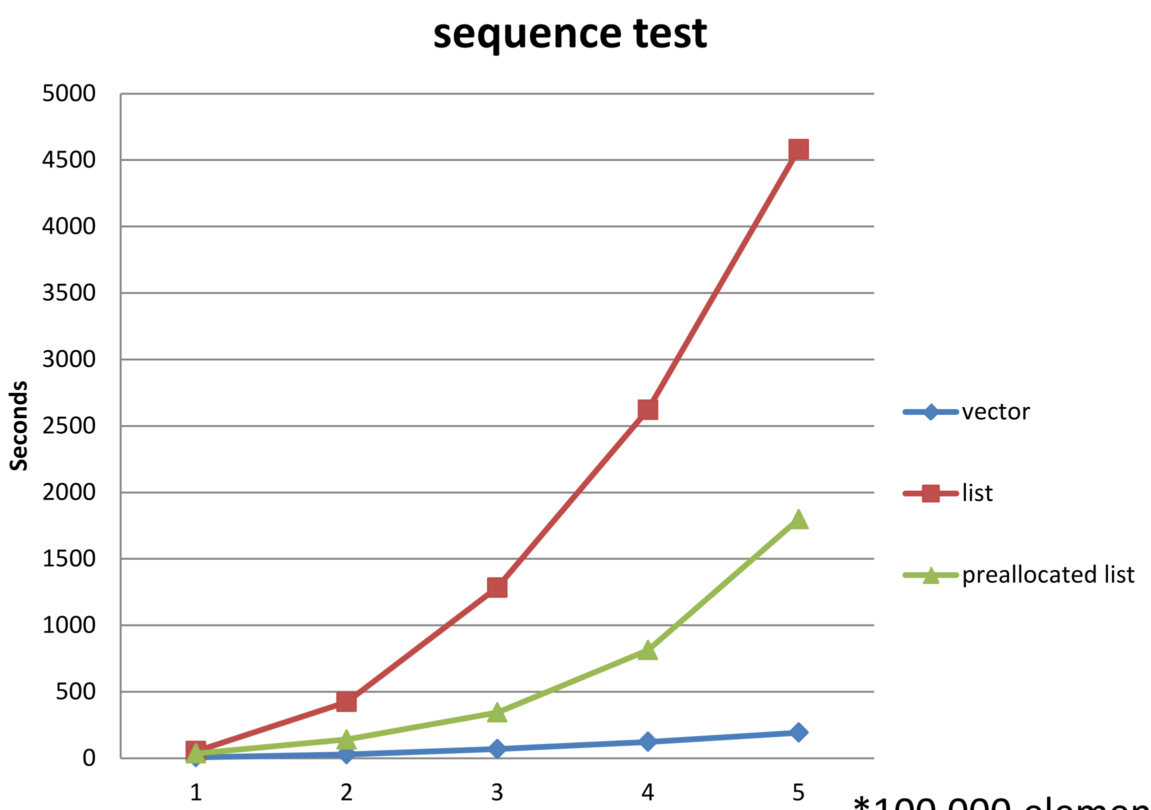
Vector vs. List

- Generate N random integers and insert them into a sequence so that each is inserted in its proper position in the numerical order. **5 1 4 2** gives:
  - **5**
  - **1 5**
  - **1 4 5**
  - **1 2 4 5**
- Remove elements one at a time by picking a random position in the sequence and removing the element there. Positions **1 2 0 0** gives
  - **1 2 4 5**
  - **1 4 5**
  - **1 4**
  - **4**
- For which N is it better to use a linked list than a vector (or an array) to represent the sequence?

Vector vs. List



*100,000 elements

- Vector beats list massively for insertion and deletion
  - For small elements and relatively small numbers (up to 500,000 on my machine)
  - Your mileage ***will*** vary

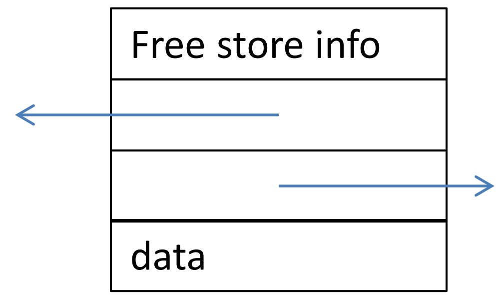
Vector vs. List

- Find the insertion point
  - Linear search
  - Vector could use binary search, but I did not
- Insert
  - List re-links
  - Vector moves on average n/2 elements
- Find the deletion point
  - Linear search
  - Vector could use direct access, but I did not
- delete
  - List re-links
  - Vector moves on average n/2 elements
- Allocation
  - List does N allocations and N deallocations
  - The optimized/preallocated list do no allocations or dealloations
  - Vector does approximately log2(N) allocations and log2(N) deallocations
  - The optimized list does 1 allocation and 1 deallocation

This completely dominates

Vector vs. List

- The amount of memory used differ dramatically
  - List uses 4+ words per element
    - it will be worse for 64-bit architectures
    - 100,000 list elements take up 6.4MB or more (but I have Gigabytes!?)
  - Vector uses 1 word per element
    - 100,000 list elements take up 1.6MB or more



- Memory access is relatively slow
  - Caches, pipelines, etc.
  - 200 to 500 instructions per memory access
  - Unpredictable memory access gives many more cache misses
- Implications:
  - Don’t store data unnecessarily.
  - Keep data compact.
  - Access memory in a predictable manner.

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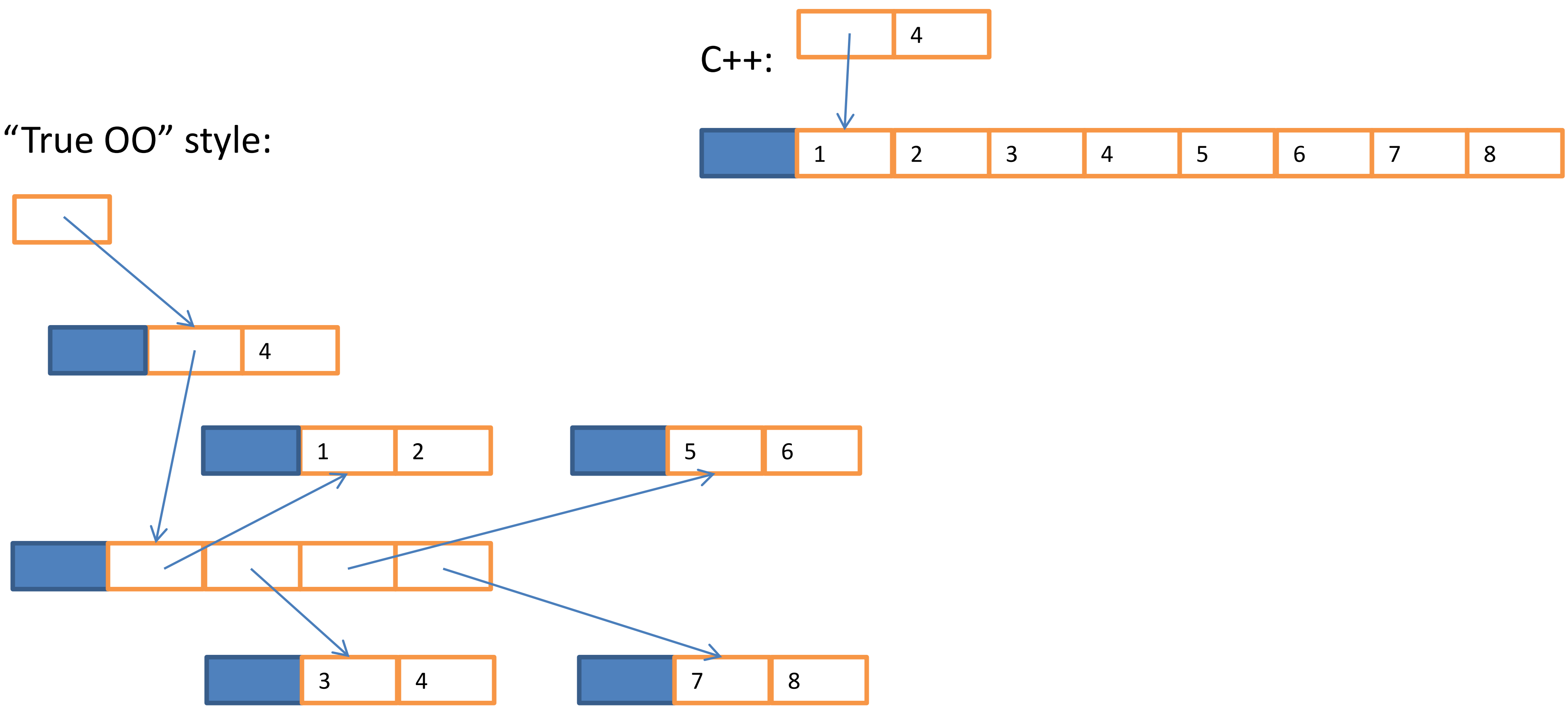
Use compact layout

- **vector<Point> vp = { Point{1,2}, Point{3,4}, Point{5,6}, Point{7,8} };**



Simplify control structure

- Prefer algorithms to unstructured code

Algorithms vs. "Code"

- Problem: drag item to an insertion point
- Original solution (after cleanup and simplification):
  - 25 lines of code
    - one loop
    - three tests
    - 14 function calls
- Messy code
  - Is it correct?
    - who knows? try lots of testing
  - Is it maintainable?
    - Probably not, since it is hard to understand
  - Is it usable elsewhere?
    - No, it's completely hand-crafted to the details of the problem
- The author requested a review
  - Professionalism!

Algorithms vs. "Code"

- Surprise!
  - it was a simple **find_if** followed by moving the item

```
void drag_item_to(Vector& v, Vector::iterator source, Coordinate p)
{
        Vector::iterator dest = find_if(v.begin(), v.end(), contains(p));
        if (source < dest)
                rotate(source, source+1, dest); // from before insertion point
        else
                rotate(dest, source, source+1); // from after insertion point
}
```

- It's comprehensible (maintainable), but still special purpose
  - **Vector** and **Coordinate** are application specific

Algorithms vs. “Code”

- Why move only one item?
  - Some user interfaces allow you to select many

```
template < typename Iter, typename Predicate>
pair<Iter, Iter> gather(Iter first, Iter last, Iter p, Predicate pred)
        // move elements for which pred() is true to the insertion point p
{
        return make_pair(
                stable_partition(first, p, !bind(pred, _1)),    // before insertion point
                stable_partition(p, last, bind(pred, _1))       // after insertion point
        );
}
```

- Shorter, simpler, faster, general (usable in many contexts)
  - No loops and no tests

Style

- Focus on algorithms
  - Consider generality and re-use
- Consider large functions suspect
- Consider complicated control structures suspect

Stay high level

- When you can; most of the time

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Low-level != efficient

- Language features + compiler + optimizer deliver performance
  - You can afford to use libraries of algorithms and types
  - **for_each()**+lambda vs. for-loop
    - Examples like these give identical performance on several compilers:

```
sum = 0;
for(vector<int>::size_type i=0; i<v.size(); ++i)     // conventional loop
    sum += v[i];

sum = 0;
for_each(v.begin(),v.end(),                          // algorithm + lambda
    [&sum](int x) {sum += x; });
```

Low-level != efficient

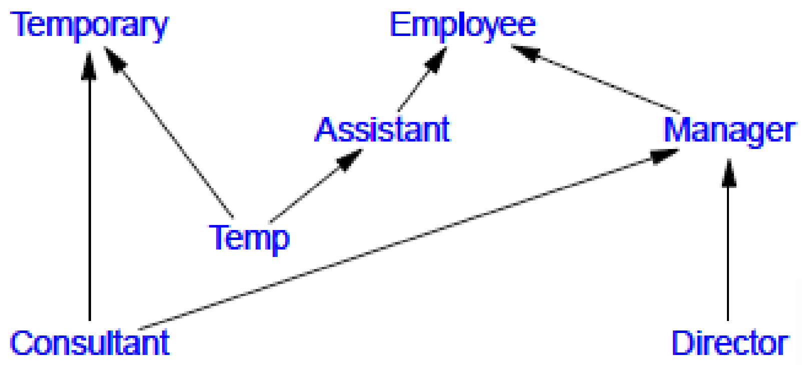
- Language features + compiler + optimizer deliver performance
  - **sort()** vs. **qsort()**
  - Roughly : C is 2.5 times slower than C++
    - Your mileage ***will*** wary
- Reasons:
  - Type safety
    - Transmits more information to the optimizer
    - also improves optimization, e.g. type-bases anti-aliasing
  - Inlining
- Observations
  - Performance of traditional C-style and OO code is roughly equal
  - Results vary based on compilers and library implementations
    - But sort() is typical

Low-level != efficient

- Don't lower your level of abstraction without good reason
- Low-level implies
  - More code
  - More bugs
  - Higher maintenance costs

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"

Concurrency

- There are many kinds
- Stay high-level
- Stay type-rich

Type-Safe Concurrency

- Programming concurrent systems is hard
  - We need all the help we can get
  - C++11 offers type-safe programming at the threads-and-locks level
  - Type safety is hugely important
- threads-and-locks
  - is an unfortunately low level of abstraction
  - is necessary for current systems programming
    - That's what the operating systems offer
  - presents an abstraction of the hardware to the programmer
  - can be the basis of other concurrency abstractions

Threads

```
void f(vector<double>&);                // function

struct F {                              // function object
    vector<double>& v;
    F(vector<double>& vv) :v{vv} { }
    void operator()();
};

void code(vector<double>& vec1, vector<double>& vec2)
{
    std::thread t1 {f,vec1};            // run f(vec1) on a separate thread
    std::thread t2 {F{vec2}};           // run F{vec2}() on a separate thread
    t1.join();
    t2.join();
    // use vec1 and vec2
}
```

Thread – pass argument and result

```
double* f(const vector<double>& v);    // read from v return result
double* g(const vector<double>& v);    // read from v return result

void user(const vector<double>& some_vec)          // note: const
{
    double res1, res2;
    thread t1 {[&]{ res1 = f(some_vec); }};     // lambda: leave result in res1
    thread t2 {[&]{ res2 = g(some_vec); }};     // lambda: leave result in res2
    // …
    t1.join();
    t2.join();
    cout << res1 << ' ' << res2 << '\n';
}
```

async() – pass argument and return result

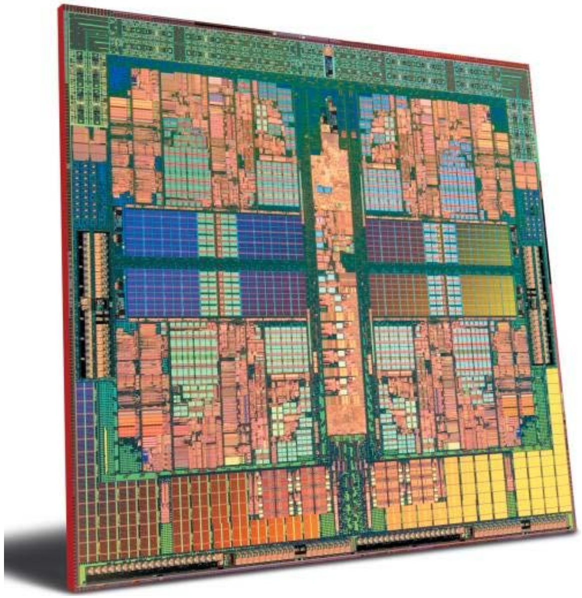
```
double* f(const vector<double>& v);    // read from v return result
double* g(const vector<double>& v);    // read from v return result

void user(const vector<double>& some_vec)          // note: const
{
    auto res1 = async(f,some_vec);
    auto res2 = async(g,some_vec);
    // …
    cout << *res1.get() << ' ' << *res2.get() << '\n';     // futures
}
```

- Much more elegant than the explicit thread version
  - And most often faster

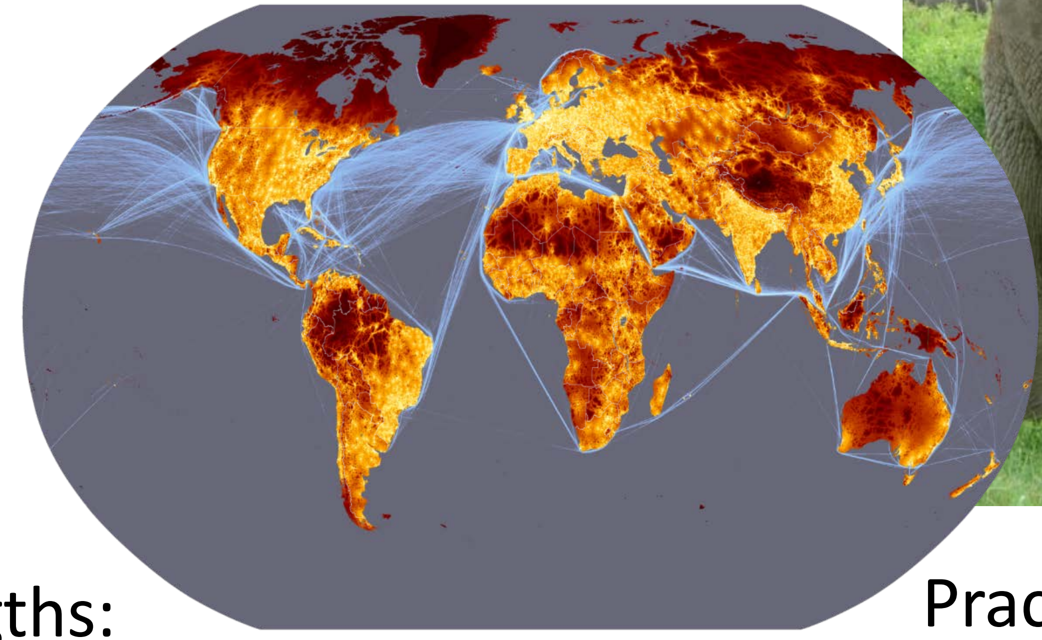
C++ Style

- Practice type-rich programming
  - Focus on interfaces
  - Simple classes are cheap – use lots of those
  - Avoid over-general interfaces
- Integrate Resource Management and Error Handling
  - By default, use exceptions and RAII
  - Prefer move to complicated pointer use
- Use compact data structures
  - By default, use **std::vector**
- Prefer algorithms to "random code"
- Build and use libraries
  - Rely on type-safe concurrency
  - By default, start with the ISO C++ standard library



Questions?

C++: A light-weight abstraction programming language



Key strengths:

- software infrastructure
- resource-constrained applications

Practice type-rich programming