Optimization in C & C++: good practices, pitfalls

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Outline

- Constructors and destructors
- Temporaries
- Cost of virtual functions
- Cost of exceptions
- If and when to inline functions
- Standard library containers
- Templates

Common vocabulary - goal

- C/C++ performance has many aspects
  - execution speed
  - code size
  - data size
  - memory footprint at run-time
  - time and space consumed by the edit/compile/link cycle
- C++ is a **large** language with many features, idioms and constructs
  - constructors/destructors, exceptions, templates, late-binding, overloading, RAII, ...
  - knowing (or having a rough idea of) the cost of these features is important for building a (re)usable efficient application
  - model of time and space overheads of various C++ language features

Classes and inheritance

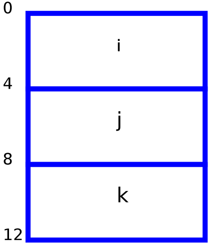
`C++` supports object-oriented programming

- involves (possibly deep) inheritance hierarchies of classes
- operations performed on classes and class hierarchies
- space and time overheads of using classes instead of structs ?

Representation overhead

- C++ class with no virtual function
  - no space overhead **wrt** a good old C struct
  - WYSIWYG
  - non-virtual functions do **NOT** take any space in an object
  - ditto for static data
  - ditto for static function

```
struct C
{
  int i;
  int j;
  int k;
};
```

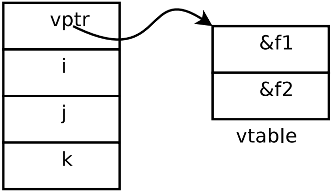



```
class Cxx
{ public:
  int i;
  int j;
  int k;
};
```

Representation overhead

- a polymorphic class (with at least one virtual function)
  - per-object overhead of 1 pointer (`vptr`)
  - per-class overhead of a `virtual function table`
    - 1 or 2 words per virtual function
  - per-class overhead of a `type information object` (RTTI)
    - `O(10)` bytes
    - name string (identifying the class)
    - couple of words of more infos
    - couple of words for each base class

```
class Polymorphic
{ virtual void f1();
  virtual void f2();
  int i;
  int j;
  int k;
};
```



Basic classes operations

- cost of calling non-virtual, non-static, non-inline member function
- compared to calling a freestanding function with one extra pointer

lr basic fct call	timings
non-virtual	
`px->f(1)`	0.016
`g(ps,1)`	0.016
non-virtual	
`x.g(1)`	0.016
`g(\&s,1)`	0.016
static fct mbr	
`X::h(1)`	0.013
`h(1)`	0.013

Virtual function

- calling a virtual function
- calling a function through a pointer stored in an array

virtual fct call	timings
virtual	
`px->f(1)`	0.019
`x.f(1)`	0.016
ptr-to-fct	
`p[1](ps,1)`	0.016
`p[1](\&s,1)`	0.018

Virtual functions of class templates

- new C++ support structures (`vtbl`) for **each** specialization
- pure replication of code at the instruction level
- workarounds
  - use non-template helper functions
  - factor out non-parametric functionalities into a non-templated base class

```
void foo_helper_fct(...);
template<class T> class Foo
{...};

class Base { void dostuff(); };
template<class T> class Derived : public Base
{...};
```

Inlining

- calling a function has a cost
- for simple functions, it may be pure overhead
- inlining: directly copy callee's body at call site

	timings
non-inline	
`px->g(1)`	0.016
`x.g(1)`	0.016
inline	
`px->k(1)`	0.006
`x.k(1)`	0.005
macro	
`K(ps,1)`	0.005
`K(\&s,1)`	0.005

Multiple inheritance

- more complicated binary layout of instances
- for each call, need to **adjust** the `this` pointer to get the right substructure
  - caller applies an offset to `this` from the `vtbl`
  - or use a `thunk`: man-in-the-middle fragment of code

	timings
SI, non-virtual `px->g(1)`	0.016
Base1, non-virtual `pc->g(1)`	0.016
Base2, non-virtual `pc->gg(1)`	0.017
SI, virtual `px->f(1)`	0.019
Base1, virtual `pa->f(1)`	0.019
Base2, virtual `pa->ff(1)`	0.024

Virtual base classes

- additional overhead **wrt** simple multiple inheritance
  - position of base class subobject not known at compile time
  - needs one additional indirection

	timings
SI, non-virtual `px->g(1)`	0.016
VBC, non-virtual `pd->gg(1)`	0.021
SI, virtual `px->f(1)`	0.019
VBC, virtual `pa->f(1)`	0.025

Exception handling

- systematic and robust way to cope with errors
- traditional alternatives
  - returning error codes
  - setting error states indicators (`errno`)
  - calling error handling functions
  - escaping into error handling code using `longjmp`
  - passing along a pointer to a state object w/ each call

```
double f1(int a) { return 1.0 / a; }
double f2(int a) { return 2.0 / a; }
double f3(int a) { return 3.0 / a; }

// no error handling
double g(int x, int y, int z)
{ return f1(x) + f2(y) + f3(z); }
```

Exception handling

- with error handling

```
int error_state = 0;
double f1(int a) {
  if (a <= 0) {
    error_state = 42;
    return 0;
  }
  return 1.0 / a;
}
double g(...) {
  double xx = f1(x);
  if (error_state) {...}
  ...
  return xx+yy+zz;
}
```

- with EH

```
struct Err {...};
double f1(int a) {
  if (a <= 0)
    throw Err(42);
  return 1.0 / a;
}

double g(...) {
  try {
    return f1(x)+f2(y)
          +f3(z);
  } catch (Err& err) {...}
}
```

Exception handling

- 3 sources of overhead
  - data and code associated with `try` blocks
  - data and code associated with the normal execution of additional fcts
  - data and code associated with `throw` expressions
- implementation issues
  - context setup of `try` blocks for associated `catch` clauses
  - `catch` clause needs some kind of type identification
  - clean-up of handled exceptions (memory mgt)
  - ctors/dtors of non-trivial objects
  - ...
- 2 main implementation techniques
  - the 'code' approach
  - the 'table' approach
- both need some kind of RTTI (thus code/data increase)

Exception handling

- the 'code' approach
  - dynamically maintain auxiliary data structures
    - to manage execution contexts
    - to track the list of objects to be unwound (in case an exception occured)
  - associated stack and run-time costs can be significant
  - even when no exception is thrown, bookkeeping is performed
- the 'table' approach (g++)
  - read-only tables are generated
    - to determine the current execution context
    - to locate catch clauses
    - to track the list of objects to be unwound
  - all bookkeeping is pre-computed
  - no run-time cost if no exception is thrown (zero cost overhead for normal execution path)

Templates

- template overheads
  - for each new specialization, generation of a new instantiation of code
  - **can** lead to unexpectedly large amount of code and data
    - EH, vtbl, ...
  - canonical experiment:
    - instantiate 100 `std::list<T*>` for some fixed `T` type
    - instantiate 1 `std::list<T*>` for 100 `T` different types
    - measure programs' size
  - optimization:
    - recognize that all different specializations project onto the same generated machine code
    - can be done by the compiler
    - or by a clever STL implementation
    - ie: implement (under the hood) all `std::list<T*>` in terms of `void*`
  - compilation time

Templates vs inheritance

- templates are usually more runtime efficiency friendly
- deep inheritance trees incur overhead:
  - ctors/dtors
  - pointer indirection / virtual functions

Programmer directed optimizations

usual disclaimer:

—

- don't do it:
  - early (performance) optimization is the root of all evil
  - spend that time on unit tests (make sure the code is right), documentation and new features
- think twice before applying performance any optimization tips
- make it thrice

—

in the following:

- a few rules of thumb
- cover usual gotchas

Constructors & Destructors

- C++ creates instances of classes with ctors
  - allocate memory
  - initialize fields
- ... and cleans-up/relinquishes resources with dtors

```c
{ /* in good old C */
  struct S s;
  S_init(&s);
  /* compute s... */
  S_cleanup(&s);
}
```

```cpp
{ // in C++
  S s;
  // compute s...
}
```

in an **ideal** world: **no overhead** introduced by ctor/dtor

- in **practice**:
  - overhead because of inheritance
  - overhead because of composition
- overhead: perform computations which may be rarely needed

Object construction

- in ctors prefer to use initializers
  - no need to do the work twice

```
UsuallyOk::UsuallyOk(...) : m_1(42), m_2(str) {...}
UsuallyBad::UsuallyBad(...) { m_1 = ...; m_2 = str; }
```

- define variables as close to use-site than possible
- define variables when ready to initialize (no ctor+assign)

```
X x1 = 42;      X x2; x2 = 42;
```

- passing arguments to a function by value is. . .
  - **cheap** for built-ins
  - potentially **expensive** for class types
  - prefer passing by const-ref or address

```
void f(const std::string&);
void g(const T*);
```

Implicit conversions & temporaries

- Calling a function with the ‘wrong’ arg.’s type implies type conversion
- may require work at run-time

```
void f1(double);
f1(7.0);  // no conversion but copy
f1(7);    // conversion: f1(double(7));

void f2(const double&);
f2(7.0); // no conversion
f2(7);   // const double tmp =7; f2(tmp);

void f3(std::string);  std::string s = "foo";
f3(s);      // no conversion but copy
f3("bar"); // f3(std::string("bar"))

void f4(const std::string&);
f4(s);      // no conversion, no copy
f4("f");    // const std::string tmp("f"); f4(tmp);
```

Explicit constructors

consider the class definition:

```
class Rational
{
  friend Rational operator+(const Rational&,
                            const Rational&);
public:
  Rational(int a=0, int b=1) : num(a), den(b) {}
private:
  int num; // Numerator
  int den; // Denominator
};
```

Explicit constructors

and the following snippet:

```
Rational r;
// ...
r = 100;
```

- no assignment operator with `int` so the above will be "translated" to:

```
Rational tmp(100);
r.operator=(tmp);
tmp.~Rational();
```

- usually a good idea to define ctors which can be called with one argument, as **explicit**:

```
explicit Rational(int a=0, int b=1) : num(a), den(b) {}
```

- also good to overload `operator=(T)`

Default constructors

```
class X
{
  A a;
  B b;
  virtual void fct();
};

class Y : public X
{
  C c;
  D d;
};
```

```
class Z : public Y
{
  E e;
  F f;
 public:
  Z() {}
};

Z z;
```

- compiler-generated default constructors are inline
- substantial (!) amount of machine code can be inserted each time a Z is constructed. . .

Temporary objects

- probably the most acute problem wrt performance and efficiency.
- preventing creation of temporaries benefits
  - run-time speed
    - creating temporaries takes CPU cycles
    - destroying them, too !
  - memory footprint
- understand how and when compilers generate temporary objects
  - initializing objects
  - passing parameters to functions
  - returning values from functions

Temporaries & initialization

quick example:

```
{ std::string s1 = "Hello";
  std::string s2 = "World";
  std::string s3;
  s3 = s1 + s2; // s3 is now: "HelloWorld"
}
```

where the last statement is equivalent to:

```
{ std::string _temp;
  operator+(_temp, s1, s2);           // pass _temp by reference
  s3.std::string::operator=(_temp); // assign _temp to s3
  _temp.std::string::~string();      // destroy _temp
}
```

on top of that, the string concatenation function may itself create temporaries.

Temporaries, loops and type mismatch

- what's wrong with that code (short of being midly useful) ?

```
Complex operator+(const Complex& rhs,
        const Complex& lhs);

Complex a, b;
for (int i=0; i<100; ++i) a = i*b + 1.0;
```

- temporary generated to represent the complex `1+0j`
- lift the constant expression out of the loop

```
Complex one(1.0);
for (int i=0; i<100; ++i) a = i*b + one;
```

- a clever optimizer **might** do it for you (YMMV)

Eliminate temporaries with [some-op]=()

the following snippet generates 3 temporaries:

```
std::string s1,s2,s3,s4;
std::string s5 = s1 + s2 + s3 + s4;
```

the following does not:

```
std::string s5 = s1;
s5 += s2;
s5 += s3;
s5 += s4;
```

Pass by value

avoid writing APIs which use this pattern :

```
void f(T t) { /* do something with t*/ }

{
  T t;
  f(t);
}
// is equivalent to:
{
  T t;
  T _temp;
  _temp.T::T(t);  // copy construct _temp from t
  f(_temp);       // pass _temp by reference
  _temp.T::~T();  // destroy _temp
}
```

Return by value

another source of temporaries is function return value:

```
std::string fct()
{
  std::string s;
  ... // compute 's'
  return s;
}

// the following snippet:
{
  std::string p;
  // ...
  p = fct();
}
```

```
// is equivalent to: (pseudo-code)
{
  std::string p;
  // ...
  std::string _temp;
  // pass _temp by reference
  fct(_temp);

  // assign _temp to p
  p.std::string::operator=(_temp);

  // destroy _temp
  _temp.std::string::~string();
}
```

Return value - corollary

- so we don't like (performance-wise) functions which return objects

```
class T
{
 public:
  T operator++(int i); // foo++
  T operator++();      // ++foo
  ...
};
```

- prefer prefix over postfix increment operator

```
for (std::vector<T>::iterator
      it = vec.begin(),
  end= vec.end();
     it != end; ++it) { // <-- and NOT: it++
   //...
}
```

Return value optimization (RVO)

- one way to side-step inefficiency of return by value: write 'C-like' APIs:

```
T fct();
T t;
//...
t = fct();

void compute_t(T& t);
T t;
compute_t(t);
```

- another way is to enable the compiler to apply RVO...

RVO

```
class Complex {
 public:
  Complex(double re=0., double im=0.);
  double re, im;
};

Complex operator+(const Complex& a, const Complex& b) {
  Complex res;
  res.re = a.re + b.re;
  res.im = a.im + b.im;
  return res;
}

Complex c1,c2,c3;
c3 = c1 + c2;
```

RVO

- without any optimization, the emitted (pseudo)code would look like:

```
Complex _tmp;
_add_complex(_tmp, c1, c2);
c3.operator=(_tmp);
_tmp.~Complex();

void _add_complex(Complex &_tmp,
                  const Complex &a, const Complex &b) {
  Complex ret;
  //... as previously
  _tmp.operator=(ret);
  ret.~Complex();
  return;
}
```

- how to remove all these temporaries and their associated c/dtors ?

RVO

- rewrite the add function to remove the local named temporary
- use an unnamed temporary to help the compiler:

```
Complex operator+(const Complex &a, const Complex &b) {
 double re = a.re + b.re;
 double im = a.im + b.im;
 return Complex(re, im);
}
```

- note that complicated functions with multiple return statements are harder to elect for RVO
- RVO is **not mandatory**
  - done at the discretion of the compiler
  - inspection of generated code + trial & error

Inlining basics

- replaces a function call with a verbatim copy of the function at call-site
    - kind of like a C-macro
- works around the overhead of calling functions.
- 2 ways to express **intent** of inlining a function

```
class FourMom {
 float m_px, m_py, m_pz, m_ene;
public:
 // implicit inlining:
 // definition provided w/ declaration
 float px() const { return m_px; }
 void set_px(float px);
};

// use inline keyword
inline void FourMom::set_px(float px) { m_px = px; }
```

Inlining basics

- at source-code level, inlined functions are used like any other function:

```
int main(int, char**)
{
 FourMom mom;
 mom.set_px(20.*GeV);
 std::cout << "px: " << mom.px()
           << std::endl;
 return 0;
}
```

- code expanded inline at call site:
  - call site must know the definition of the function
  - compilation coupling
  - potential compilation time increase

cross-call optimizations

```
int main(int, char**)
{
 FourMom mom;
 mom.set_px(20.*GeV);
 std::cout << "px: " << mom.px()
           << std::endl;
 return 0;
}
```

- inlining is most nutritious with cross-call optimizations

cross-call optimizations

```
int main(int, char**)
{
 FourMom mom;
 mom.m_px = 20.*GeV;
 std::cout << "px: " << mom.m_px
           << std::endl;
 return 0;
}
```

- inlining is most nutritious with cross-call optimizations

cross-call optimizations

```
int main(int, char**)
{
 FourMom mom;
 mom.m_px = 20.*GeV;
 std::cout << "px: " << mom.m_px
           << std::endl;
 return 0;
}
```

- inlining is most nutritious with cross-call optimizations

```
int main(int, char**)
{
 std::cout << "px: " << 20.
           << std::endl;
 return 0;
}
```

why not inline

- code expansion
  - disk space
  - memory size
  - cache size, increase cache fault
  - code size
- compilation coupling
- recursive methods

Logical data structures

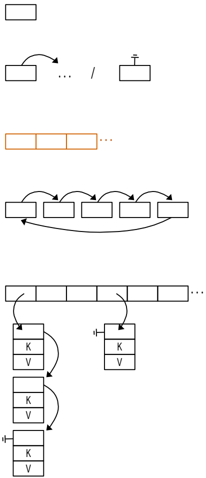
Scalar

Pointer

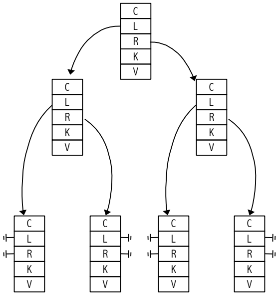
Structure / Array

Linked list

Hash



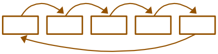
Balanced Binary Tree, e.g. Red-Black



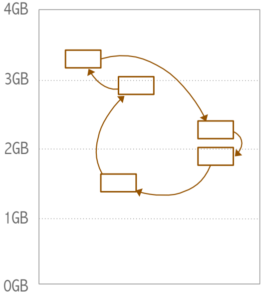
K = key, V = value, C = color, L = left, R = right
= by far the most efficient

Logical vs Real data structures

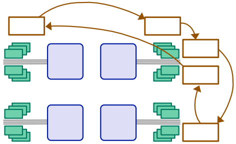
This logical linked list…



Could be scattered in virtual address space like this…



And in physical memory like this…

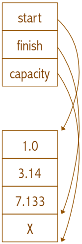


Standard Template Library (STL)

- a powerful combination of containers and generic algorithms
- performance guarantees of the asymptotic complexity of containers and algorithms:
  - an approximation of algorithm performance - big-O notation
  - `O(N), O(N*N),...`
- choosing the right container is based on the type of frequent and critical operations applied on it
  - various trade-offs
  - no one true best container
  - only best compromise for task at hand
- containers manage storage space for their elements
- provide methods to access elements, directly or through iterators

std::vector

```cpp
std::vector<double> v;
v.reserve(4);
v.push_back(1.0);
v.push_back(3.14);
v.push_back(7.133);
```



A good and efficient data structure in general.

- Good locality usually, guaranteed contiguous allocation.
- Avoid **small vectors** because of the **overhead**
- **Beware** creating vectors incrementally without `reserve()`. Grows exponentially and copies old contents on every growth step if there isn't enough space!
- **Beware** making a copy, the dynamically allocated part is copied!
- **Beware** using `erase()`, it also causes incremental copying.

std::vector<std::vector<std::vector<int> > >

```
typedef std::vector<int> VI; typedef std::vector<VI> VVI;
std::vector<VVI> vvvi;
for (int i = 0, j, k; i < 10; ++i)
  for (vvvi.push_back(VVI()), j = 0; j < 10; ++j)
    for (vvvi.back().push_back(VI()), k = 0; k < 10; ++k)
      vvvi.back().back().push_back(k);
```

A very common mistake. C++ vectors of vectors are expensive, and not contiguous matrices.

- Naively: 111 allocations, 5'320 bytes
- Reality: 980 allocs, total 30'402 bytes alloc'd, 5'632 at end, 9'508 peak.
- +780% # allocs, +460% bytes alloc'd, 79% working and 6% residual overhead!
- Versus 1 allocation, 4'440 bytes and some pointer setup had we used a real matrix.

std::vector<std::vector<std::vector<int> > >

```
std::vector<VVI> vvvi, vvvi2;
for (/*...*/) {/*...*/}
vvvi2 = vvvi;
```

Why you should avoid making container copies by value...

- +111 allocations, +5'320 bytes
- an allocation storm is inevitable if you copy nested containers by value. Evil bonus: memory churn. Because of the alloc/free pattern, by-value copies are an effective way to scatter the memory blocks all over the heap
- 'a nested container' does not have to be a standard library container. It can refer to any object type which makes an expensive deep copy (e.g. any normal type with `std::string`, `std::vector`,... data members, or objects which "clone" pointed-to objects on copy.)
- a simple "=" line may also generate lots of code

std::vector<uint16_t>

Typical std::vector<uint16_t> overhead is 40 bytes (64-bit system.)

- 3 pointers × 8 bytes for vector itself, plus average 2 words × 8 bytes malloc() overhead for dynamically allocated array data chunk.
- so, if x always has N <= 20 elements, it'd better to just use a uint16_t x[N].
- more generally, if 95+\% of uses of x have only N elements for some small N, it may be better to have an uint16_t x[N] for the common case, and a separate dynamically allocated "overflow" buffer for the rare N large case. (measure to see!)
- even more generally, this applies to any small object allocated from heap.

std::list

- a sequence container
- doubly linked list
- efficient insertion and removal anywhere in the container: `O(1)`
- efficient at moving (blocks of) elements within the container or between containers (`O(1)`)

associative containers

- std::map<K,V,Cmp,Alloc>
  - unique key-values
  - elements follow a strict weak ordering (at all time)
  - efficient access of elements by key (logarithmic complexity)
  - logarithmic complexity for insertion
- std::tr1::unordered_map<K,V,Hash,Pred,Alloc> (hash_map)
  - unique key-values
  - constant time insertion/access
- Beware of temporaries in x["foo"] = abc(); x["foo"].call();
- Beware code growth when using maps inside loops:
  for (...) { std::map<K,V> mymap; ...}

better than STL ?

- STL is generic
- if you know something about the problem's domain, you can squeeze some perfs wrt STL.

e.g. compare strings of a known format `"aaaa1"` and `"aaaa2"`

—

- the STL is an uncommon combination of abstraction, flexibility and efficiency (curtosy of generic programming)
- depending on your application, some containers are more efficient than others for a particular usage pattern
- unless you know something about the problem domain that STL doesn't, it is unlikely you will beat STL by a wide enough margin
- outperforming STL is still possible in some specific scenarios

C++ - Concluding remarks

- C++ is a wide and powerful language, difficult to really master entirely
- be wary of using fancy constructs and features
  - when in doubt, choose simplicity
- pay attention to compiler warnings
- strive for warning-free builds
- innocently looking C++ code can be treacheous
- profile before sprinkling your code with optimizations
- remember the code the C++ compiler automatically generates for you
- remember the trade-offs of inlining

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Remember, with great power, comes great responsibility

Ack.

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