Move Semantics, Rvalue References, and Perfect Forwarding

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C++0x Warning

Some examples show C++0x features unrelated to move semantics.

I'm sorry about that.

But not that sorry :-)

Abridgement Warning

A thorough treatment of this topic requires 3-4 hours.

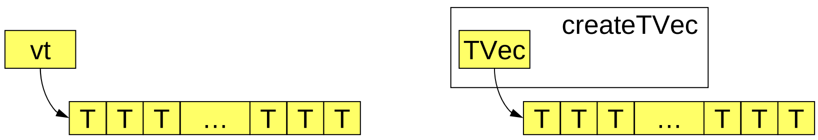
We have 90 minutes.

Some details have been sacrificed :-)

Move Support

C++ sometimes performs unnecessary copying:

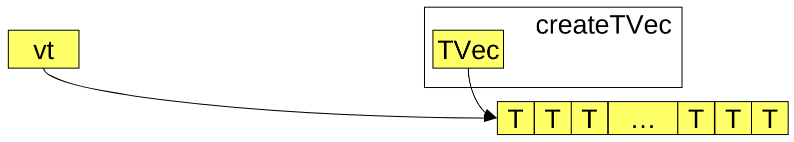
```
typedef std::vector<T> TVec;
TVec createTVec();          // factory function
TVec vt;
…
vt = createTVec();          // copy return value object to vt,
                            // then destroy return value object
```



Move Support

Moving values would be cheaper:

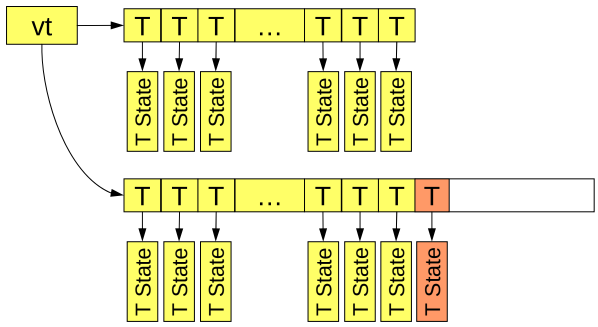
```
TVec vt;
…
vt = createTVec();          // move data in return value object
                            // to vt, then destroy return value
                            // object
```



Move Support

Appending to a full vector causes much copying before the append:

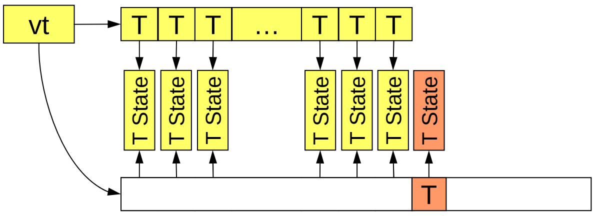
```
std::vector<T> vt;
...
vt.push_back(T object);          // assume vt lacks
                                 // unused capacity
```



Move Support

Again, moving would be more efficient:

```
std::vector<T> vt;
...
vt.push_back(T object);                 // assume vt lacks
                                        // unused capacity
```



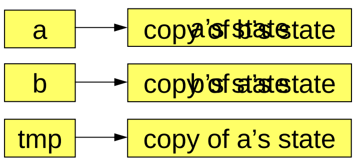
Other vector and deque operations could similarly benefit.

- insert, emplace, resize, erase, etc.

Move Support

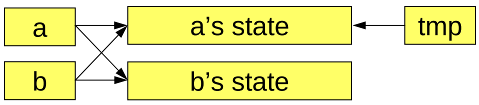
Still another example:

```
template<typename T>           // straightforward std::swap impl.
void swap(T& a, T& b)
{
  T tmp(a);                    // copy a to tmp (⇒ 2 copies of a)
  a = b;                       // copy b to a (⇒ 2 copies of b)
  b = tmp;                     // copy tmp to b (⇒ 2 copies of tmp)
}                              // destroy tmp
```



Move Support

```
template<typename T>             // straightforward std::swap impl.
void swap(T& a, T& b)
{
  T tmp(std::move(a));           // move a's data to tmp
  a = std::move(b);              // move b's data to a
  b = std::move(tmp);            // move tmp's data to b
}                                // destroy (eviscerated) tmp
```



Move Support

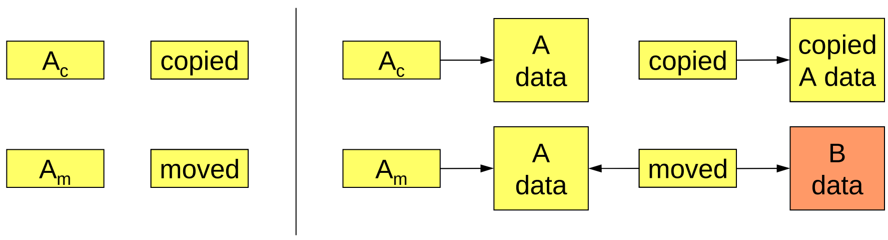
Moving most important when:

- Object has data in separate memory (e.g., on heap).
- Copying is deep.

Moving copies only object memory.

- Copying copies object memory **+ separate memory**.

Consider copying/moving A to B:



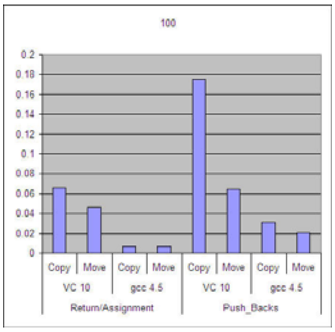
Moving never slower than copying, and often faster.

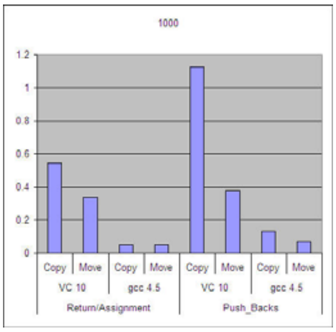
Performance Data

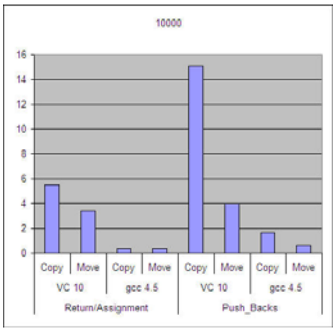
Consider these use cases again:

```
vt = createTVec();              // return/assignment
vt.push_back(T object);         // push_back
```

Copy-vs-move performance differences notable:







Move Support

Lets C++ recognize move opportunities and take advantage of them.

- How recognize them?
- How take advantage of them?

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Lvalues and Rvalues

Lvalues are generally things you can take the address of:

- Named objects.
- Lvalue references.
  - More on this term in a moment.

Rvalues are generally things you can't take the address of.

- Typically unnamed temporary objects.

Examples:

```
int x, *pInt;                     // x, pInt, *pInt are lvalues
std::size_t f(std::string str);   // str is lvalue, f's return is rvalue
f("Hello");                       // temp string created for call
                                  // is rvalue
std::vector<int> vi;              // vi is lvalue
…
vi[5] = 0;                        // vi[5] is lvalue
```

- Recall that vector<T>::operator[] returns T&.

Moving and Lvalues

Value movement generally not safe when the source is an lvalue.

- The lvalue object continues to exist, may be referred to later:

```
TVec vt1;
…
TVec vt2(vt1);      // author expects vt1 to be
                    // copied to vt2, not moved!
…use vt1…           // value of vt1 here should be
                    // same as above
```

Moving and Rvalues

Value movement is safe when the source is an rvalue.

- Temporaries go away at statement's end.
  - ➡ No way to tell if their value has been modified.

```
TVec vt1;
vt1 = createTVec();                   // rvalue source: move okay
auto vt2 { createTVec() };            // rvalue source: move okay
vt1 = vt2;                            // lvalue source: copy needed
auto vt3(vt2);                        // lvalue source: copy needed

std::size_t f(std::string str);       // as before
f("Hello");                           // rvalue (temp) source: move okay
std::string s("C++0x");
f(s);                                 // lvalue source: copy needed
```


Rvalue References

C++0x introduces **rvalue references**.

- Syntax: T&&
- "Normal" references now known as **lvalue references**.

Rvalue references behave similarly to lvalue references.

- Must be initialized, can't be rebound, etc.

Rvalue references identify objects that may be moved from.

Reference Binding Rules

Important for overloading resolution.

As always:

- Lvalues may bind to lvalue references.
- Rvalues may bind to lvalue references to const.

In addition:

- Rvalues may bind to rvalue references to non-const.
- Lvalues may *not* bind to rvalue references.
  - ➡ Otherwise lvalues could be accidentally modified.

Rvalue References

Examples:

```
void f1(const TVec&);          // takes const lvalue ref

TVec vt;

f1(vt);                        // fine (as always)
f1(createTVec());              // fine (as always)

void f2(const TVec&);          // #1: takes const lvalue ref
void f2(TVec&&);               // #2: takes non-const rvalue ref

f2(vt);                        // lvalue ⇒ #1
f2(createTVec());              // both viable, non-const rvalue ⇒ #2

void f3(const TVec&&);         // #1: takes const rvalue ref
void f3(TVec&&);               // #2: takes non-const rvalue ref

f3(vt);                        // error!  lvalue
f3(createTVec());              // both viable, non-const rvalue ⇒ #2
```

Distinguishing Copying from Moving

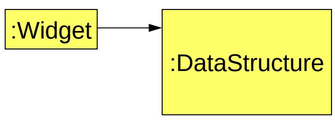
Overloading exposes move-instead-of-copy opportunities:

```
class Widget {
public:
  Widget(const Widget&);                  // copy constructor
  Widget(Widget&&);                       // move constuctor

  Widget& operator=(const Widget&);       // copy assignment op
  Widget& operator=(Widget&&);            // move assignment op
  …
};

Widget createWidget();                    // factory function

Widget w1;

Widget w2 = w1;                           // lvalue src ⇒ copy req'd

w2 = createWidget();                      // rvalue src ⇒ move okay

w1 = w2;                                  // lvalue src ⇒ copy req'd
```


Implementing Move Semantics

Move operations take source's value, but leave source in valid state:

```
class Widget {
public:
  Widget(Widget&& rhs)
  : pds(rhs.pds)                    // take source's value
  { rhs.pds = nullptr; }            // leave source in valid state

  Widget& operator=(Widget&& rhs)
  {
    delete pds;                     // get rid of current value
    pds = rhs.pds;                  // take source's value
    rhs.pds = nullptr;              // leave source in valid state
    return *this;
  }
  …
private:
  struct DataStructure;
  DataStructure *pds;
};
```



Easy for built-in types (e.g., pointers). Trickier for UDTs…

Implementing Move Semantics

Part of C++0x's string type:

```
string::string(const string&);          // copy constructor
string::string(string&&);               // move constructor
```

An incorrect move constructor:

```
class Widget {
private:
  std::string s;

public:
  Widget(Widget&& rhs)                  // move constructor
  : s(rhs.s)                            // compiles, but copies!
  { … }
  …
};
```

- rhs.s an **lvalue**, because it has a name.
  - Lvalueness/rvalueness orthogonal to type!
    - ints can be lvalues or rvalues, and rvalue references can, too.
  - s initialized by string's *copy* constructor.

Implementing Move Semantics

Another example:

```
class WidgetBase {
public:
  WidgetBase(const WidgetBase&);        // copy ctor
  WidgetBase(WidgetBase&&);             // move ctor
  …
};

class Widget: public WidgetBase {
public:
  Widget(Widget&& rhs)                  // move ctor
  : WidgetBase(rhs)                     // copies!
  { … }
  …
};
```

- rhs is an **lvalue**, because it has a name.
  - Its declaration as Widget&& not relevant!

Explicit Move Requests

To request a move on an lvalue, use std::move:

```
class WidgetBase { … };
class Widget: public WidgetBase {
public:
  Widget(Widget&& rhs)                          // move constructor
  : WidgetBase(std::move(rhs)),                 // request move
    s(std::move(rhs.s))                         // request move
  { … }
  Widget& operator=(Widget&& rhs)               // move assignment
  {
    WidgetBase::operator=(std::move(rhs));      // request move
    s = std::move(rhs.s);                       // request move
    return *this;
  }
  …
};
```

std::move turns lvalues into rvalues.

- The overloading rules do the rest.

Why move Rather Than Cast?

std::move uses implicit type deduction. Consider:

```
template<typename It>
void someAlgorithm(It begin, It end)
{
  // permit move from *begin to temp, static_cast version
  auto temp1 =
    static_cast<typename std::iterator_traits<It>::value_type&&>(*begin);
  // same thing, C-style cast version
  auto temp2 = (typename std::iterator_traits<It>::value_type&&)*begin;
  // same thing, std::move version
  auto temp3 = std::move(*begin);
  ...
}
```

What would you rather type?

Implementing std::move

std::move is simple – in concept:

```
template<typename T>
T&&                                   // return as an rvalue whatever
move(MagicReferenceType obj)          // is passed in; must work with
{                                     // both lvalue/rvalues
  return obj;
}
```

Between concept and implementation lie arcane language rules.

- Fundamentally, std::move simply casts to a T&&.

Gratuitous Animal Photo

Leaf-Cutter Ants

Sources: http://seaviewwildlife.blogspot.com/2010/05/leaf-cutter-ants-due-to-arrive-at-park.html and http://en.wikipedia.org/wiki/Leafcutter_ant

Move is an Optimization of Copy

Move requests for copyable types w/o move support yield copies:

```
class Widget {                       // class w/o move support
public:
  Widget(const Widget&);             // copy ctor
};

class Gadget {                       // class with move support
public:
  Gadget(Gadget&& rhs)               // move ctor
  : w(std::move(rhs.w))              // request to move w's value
  { … }

private:
  Widget w;                          // lacks move support
};
```

rhs.w is *copied* to w:

- std::move(rhs.w) returns an rvalue of type Widget.
- That rvalue is passed to Widget's copy constructor.

Move is an Optimization of Copy

If Widget adds move support:

```
class Widget {
public:
  Widget(const Widget&);             // copy ctor
  Widget(Widget&&);                  // move ctor
};

class Gadget {                       // as before
public:
  Gadget(Gadget&& rhs)
  : w(std::move(rhs.w)) { … }        // as before

private:
  Widget w;
};
```

rhs.w is now *moved* to w:

- std::move(rhs.w) still returns an rvalue of type Widget.
- That rvalue now passed to Widget's move constructor.
  - ➡ Via normal overloading resolution.

Move is an Optimization of Copy

Implications:

- Giving classes move support can improve performance even for move-unaware code.
  - ➡ Copy requests for rvalues may silently become moves.
- Move requests safe for types w/o explicit move support.
  - ➡ Such types perform copies instead.
    - ◆ E.g., all built-in types.

In short:

- **Give classes move support.**
- **Use `std::move` for lvalues that may safely be moved from.**

Implicitly-Generated Move Operations

Move constructor and move `operator=` are "special: "

- Generated by compilers under appropriate conditions.

Conditions:

- All data members and base classes are movable.
  - ➡ Implicit move operations move everything.
  - ➡ Most types qualify:
    - ◆ All built-in types (move ≡ copy).
    - ◆ Most standard library types (e.g., all containers).
- Generated operations likely to maintain class invariants.
  - ➡ No user-declared copy or move operations.
    - ◆ Custom semantics for any ⇒ default semantics inappropriate.
    - ◆ Move is an optimization of copy.
  - ➡ No user-declared destructor.
    - ◆ Often indicates presence of implicit class invariant.

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Beyond Move Construction/Assignment

Move support useful for other functions, e.g., setters:

```
class Widget {
public:
  ...
  void setName(const std::string& newName)
  { name = newName; }                          // copy param
  void setName(std::string&& newName)
  { name = std::move(newName); }               // move param
  void setCoords(const std::vector<int>& newCoords)
  { coordinates = newCoords; }                 // copy param
  void setCoords(std::vector<int>&& newCoords)
  { coordinates = std::move(newCoords); }      // move param
  ...
private:
  std::string name;
  std::vector<int> coordinates;
};
```


Construction and Perfect Forwarding

Constructors often copy parameters to data members:

```
class Widget {
public:
  Widget(const std::string& n, const std::vector<int>& c)
  : name(n),                    // copy n to name
    coordinates(c)              // copy c to coordinates
  {}
  ...
private:
  std::string name;
  std::vector<int> coordinates;
};
```

Construction and Perfect Forwarding

Moves for rvalue arguments would be preferable:

```
std::string lookupName(int id);
int widgetID;
...
std::vector<int> tempVec;              // used only for Widget ctor
...
Widget w(lookupName(widgetID),         // rvalues args, but Widget
         std::move(tempVec));          // ctor copies to members
```

Overloading Widget ctor for lvalue/rvalue combos ⇒ 4 functions.

- Generally, n parameters requires 2^n overloads.
  - Impractical for large n.
  - Boring/repetitive/error-prone for smaller n.

Construction and Perfect Forwarding

Goal: one function that "does the right thing:"

- Copies lvalue args, moves rvalue args.

Solution is a **perfect forwarding** ctor:

- Templatized ctor forwarding T&& params to members:

```
class Widget {
public:
  template<typename T1, typename T2>
  Widget(T1&& n, T2&& c)
  : name(std::forward<T1>(n)),             // forward n to string ctor
    coordinates(std::forward<T2>(c))       // forward c to vector ctor
  {}
  ...
private:
  std::string name;
  std::vector<int> coordinates;
};
```

Construction and Perfect Forwarding

Once again:

- A *templatized ctor forwarding* T&& *params* to members:

```
class Widget {
public:
  template<typename T1, typename T2>
  Widget(T1&& n, T2&& c)
  : name(std::forward<T1>(n)),            // forward n to string ctor
    coordinates(std::forward<T2>(c))      // forward c to vector ctor
  {}
  ...
private:
  std::string name;
  std::vector<int> coordinates;
};
```

Effect:

- Lvalue arg passed to n ⇒ std::string ctor receives lvalue.
- Rvalue arg passed to n ⇒ std::string ctor receives rvalue.
- Similarly for for c and std::vector ctor.

Perfect Forwarding Beyond Construction

Useful for more than just construction, e.g., for setters:

```
class Widget {                                          // revised
public:                                                 // example
  ...
  template<typename T>
  void setName(T&& newName)                             // forward
  { name = std::forward<T>(newName); }                  // newName

  template<typename T>
  void setCoords(T&& newCoords)                         // forward
  { coordinates = std::forward<T>(newCoords); }         // newCoords
  ...
private:
  std::string name;
  std::vector<int> coordinates;
};
```

Perfect Forwarding Beyond Construction

Despite T&& parameter, code fully type-safe:

- Type compatibility verified upon instantiation.
  - ➡ E.g., only std::string-compatible types valid in setName.

More flexible than a typed parameter.

- Accepts/forwards all compatible parameter types.
  - ➡ E.g., std::string, char*, const char* for setName.

Perfect Forwarding Beyond Construction

Flexibility can be removed via static_assert:

```
template<typename T>
void setName(T&& newName)
{
  static_assert(std::is_same< typename std::decay<T>::type,
                              std::string
                            >::value,
                "T must be a [const] std::string"
  );
  name = std::forward<T>(newName);
};
```

Perfect Forwarding

- Applicable only to function templates.
- Preserves arguments' lvalueness/rvalueness/constness when forwarding them to other functions.
- Implemented via std::forward.

Further Information

- "A Brief Introduction to Rvalue References," Howard E. Hinnant *et al.*, *The C++ Source*, 10 March 2008.
  - Details somewhat outdated per March 2009 rule changes.
- *C++ Rvalue References Explained*, Thomas Becker, June 2009, http://thbecker.net/articles/rvalue_references/section_01.html.
  - Good explanations of std::move/std::forward implementations.
- "Rvalue References: C++0x Features in VC10, Part 2," Stephan T. Lavavej, *Visual C++ Team Blog*, 3 February 2009.
- "GCC C++0x Features Exploration," Dean Michael Berris, *C++ Soup!*, 15 March 2009.
- "Howard's STL / Move Semantics Benchmark," Howard Hinnant, *C++Next*, 13 October 2010.
  - Move-based speedup for std::vector<std::set<int>> w/gcc 4.0.1.
  - Reader comments give data for newer gccs, other compilers.

Further Information

- "Making Your Next Move," Dave Abrahams, *C++Next*, 17 September 2009.
- "Your Next Assignment…," Dave Abrahams, *C++Next*, 28 September 2009.
  - ➡ Correctness and performance issues for move operator=s.
- "Exceptionally Moving!," Dave Abrahams, *C++Next*, 5 Oct. 2009.
  - ➡ Exception safety issues for move operations.
- "To move or not to move," Bjarne Stroustrup, *Document N3174 to the C++ Standardization Committee*, 17 October 2010, http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2010/n3174.pdf.
  - ➡ Describes rules governing implicit move operations.
- "Class invariants and implicit move constructors (C++0x)," comp.lang.c++, thread initiated 14 August 2010.

Further Information

- "Move Constructors," Andrei Alexandrescu, *CUJ Online*, February 2003.
  - ➡ Popularized the idea of move semantics.
- "Onward, Forward!," Dave Abrahams, *C++Next*, 7 Dec. 2009.
  - ➡ Discusses perfect forwarding.
- "Perfect Forwarding Failure Cases," comp.std.c++ discussion initiated 16 January 2010, http://tinyurl.com/ygvm8kc.
  - ➡ Arguments that can't be perfectly forwarded.

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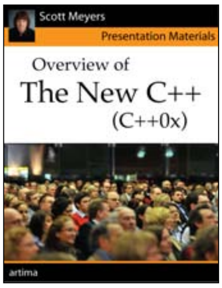

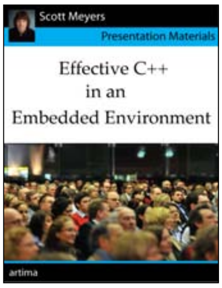

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