Algorithm Library Design: Crash Course in Modern C++

Based on the

Algorithm Library Design Course 2003

http://www.mpi-sb.mpg.de/~kettner/courses/lib_design_03/

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Algorithm and Data Structure Libraries

- LEDA – Library of Efficient Datatypes and Algorithms
  - C++, uses templates for container, static graphs, …
- STL – Standard Template Library
  - C++ standard library, almost exclusively template code
- BOOST – collection of various C++ libraries
  - BGL – Boost Graph Library
- CGAL – Computational Geometry Algorithms Library
  - C++, almost exclusively template code, follows STL design
- EXACUS – Efficient and Exact Alg. for Curves and Surfaces
  - C++, almost exclusively template code, follows CGAL design

Contents

- C++ Templates
- Generic Programming

Function Template

```
template <class T>
void swap( T& a, T& b) {
    T tmp = a; a = b; b = tmp;
}

int main() {
    int i = 5; int j = 7;
    swap( i, j); // uses "int" for T.
}
```

Class Template

```
template <class T>
struct vector {
    void push_back( const T& t); // append t to vector.
};



int main() {
    vector<int> vs; // uses "int" for T.
    vs.push_back(5);
}
```

Class Template

```
template <class T>
struct vector {
    void push_back( const T& t); // append t to vector.
};

template <class T>
void vector<T>::push_back( const T& t) { ... }

int main() {
    vector<int> vs; // uses "int" for T.
    vs.push_back(5);
}
```

Advantages of Templates

- Static polymorphism
  - flexibility (but at compile time)

- Strong type checking
  - compile-time instantiation allows for type checking not possible with the conventional runtime polymorphism of object orientation or function pointers

```
void qsort( void  *base,  size_t  nel,  size_t  width,
                    int (*compare)( const void *, const void *));
```

- Efficient inlining and static optimizations

```
template <class Compare>
void qsort( void  *base,  size_t  nel,  size_t  width,   Compare cmp);
```

Pattern Matching in Function Templates

```
template <class T>
void foo( vector<T>& vs);
```

Default Template Arguments

```
template <class T, class Alloc = std::allocator<T> >
struct vector { ... };
```

Integral Builtin Types as Template Arguments

```
template <int dim>
struct Point {
    double coordinates[dim]; // coordinate array
    // ...
};

int main() {
    Point<3> // a point in 3d space
}
```

Member Templates

```
template <class T1, class T2>
struct pair {
    T1 first;
    T2 second;
    pair() {} // explicit default constructor
    template <class U1, class U2>  // template constructor
    pair( const pair<U1,U2>& p);
};
```

Member Templates

```
template <class T1, class T2>
struct pair {
    T1 first;
    T2 second;
    pair() {} // explicit default constructor
    template <class U1, class U2>  // template constructor
    pair( const pair<U1,U2>& p);
};
template <class T1, class T2>
template <class U1, class U2>
pair<T1,T2>::pair( const pair<U1,U2>& p)
    : first( p.first), second( p.second) {}
```

Template Full Specialization

```
template <class T>
struct vector;

template <>
struct vector<bool> {
    // specialized implementation
};
```

Template Partial Specialization

```
template <class T, class Alloc = std::allocator>
struct vector;

template <class Alloc>
struct vector<bool, Alloc> {
    // specialized implementation
};
```

Member Types

```
template <class T>
struct vector {
    typedef T value_type;
};

int main() {
    list<int> ls;
    list<int>::value_type i; // is of type int
}
```

Member Types

```
template <class T>
struct vector {
   typedef T value_type;
};

template <class Container>
struct X {
   typedef Container::value_type value_type; // not correct
   // ...
};
```

Member Types: typename keyword

```
template <class T>
struct vector {
    typedef T value_type;
};

template <class Container>
struct X {
    typedef typename Container::value_type value_type;
    // ...
};
```

Templates are Turing-computable

- Enums as integers
- Partial template specialization for if’s
  - ```
    template <int condition, class ThenType, class ElseType>
    struct MetaIf {
        typedef ThenType Result;
    };
    template <class ThenType, class ElseType>
    struct MetaIf<0,ThenType,ElseType> {
        typedef ElseType Result;
    };
    ```
- Recursive and partial template instantiations for recursion
    ```

```
// Program by Erwin Unruh, adapted to C++ standard.
// Compile with: g++ -ftemplate-depth-50 -c prime.C | & grep conversion
```

```
template <int i, int prim> struct D {};     // "output" at compile time (error messages)
template <int i> struct D<i,0> { D(int);};

template <int p, int i> struct is_prime {                    // compute prime condition
   enum { prim = ((p%i) && is_prime< (i>2 ? p : 0), i-1>::prim) };
};
template<> struct is_prime<0,1> { enum { prim = 1}; };
template<> struct is_prime<0,0> { enum { prim = 1}; };

template <int i> struct Prime_print {                 // iterate through all values: 2..i
   Prime_print<i-1> a;
   enum { prim = is_prime<i,i-1>::prim };
   void f() { a.f(); D<i,prim> d = prim; }
};
template<> struct Prime_print<2> {
   enum { prim = 1};
   void f() { D<2,prim> d = prim; }
};

void foo() {    Prime_print<17> a;    a.f();  }
```

Standard Template Library STL

- Part of the ISO/OSI C++ Standard Library
- Provides basic data types, such as list, vector, set, map, …
- and basic algorithms, such as find, sort, …
- Good online reference manuals http://www.sgi.com/tech/stl/
- Good introduction in M.H. Austern. *Generic Programming and the STL: Using and Extending the C++ Standard Template Library*. Addison-Wesley, 1998.
- Prime example of the generic programming paradigm

Generic Programming Paradigm

[Jazaeri98]:

- *Generic programming is a sub-discipline of computer science that deals with finding abstract representations of efficient algorithms, data structures, and other software concepts, and with their systematic organization. The goal of generic programming is to express algorithms and data structures in a broadly adaptable, interoperable form that allows their direct use in software construction.*

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Key ideas include:

- *Expressing algorithms with minimal assumptions about data abstractions, and vice versa, thus making them as interoperable as possible.*

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Key ideas include:

- *Lifting of a concrete algorithm to as general a level as possible without losing efficiency; i.e., the most abstract form such that when specialized back to the concrete case the result is just as efficient as the original algorithm.*

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Key ideas include:

- *When the result of lifting is not general enough to cover all uses of an algorithm, additionally providing a more general form, but ensuring that the most efficient specialized form is automatically chosen when applicable.*

Generic Programming Paradigm

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Key ideas include:

- *Providing more than one generic algorithm for the same purpose and at the same level of abstraction, when none dominates the others in efficiency for all inputs. This introduces the necessity to provide sufficiently precise characterizations of the domain for which each algorithm is the most efficient.*

Generic Programming Paradigm

Summary:

- Focus on algorithms
- Focus on efficiency
- Focus on abstraction of assumptions about data

Example: remove_if_divides

A short program in [Stepanov&Lee 95] makes us if this negator. The program copies all integers from cin to cout that cannot be divided by the integer parameter given to the program.

```
int main( int argc, char** argv) {
    if ( argc != 2)
        throw( "usage: remove_if_divides integer\n");
    remove_copy_if( istream_iterator<int>(cin), istream_iterator<int>(),
                    ostream_iterator<int>(cout, "\n"),
                    not1( bind2nd( modulus<int>(), atoi( argv[1]))));
    return 0;
}
```

Concept and Model

```
template <class T>
void swap( T& a, T& b) { T tmp = a; a = b; b = tmp;}
```

- T requires a default constructor and assignment
- Collections of requirements are called **concepts**
  - Syntactic requirements, e.g., existence of operators and functions
  - Semantic requirements, e.g., behavior or runtime complexity
- Concepts are used to document template parameters, e.g.,
  T requires the **Assignable** concept.
- If an actual type fulfills the requirements of a concept, it is a called a **model** for this concept, e.g.,
  int is a model of the **Assignable** concept.

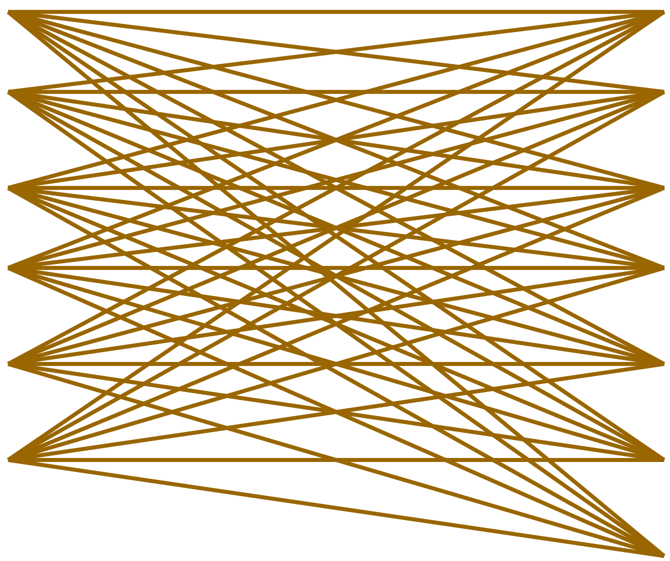
Common Basic Concepts

Concept	Syntactic requirements
Assignable	copy constructor assignment operator
Default Constructible	default constructor
Equality Comparable	equality and inequality operator
LessThan Comparable	order comparison with operators <, <=, >=, and >

Data Structures and Algorithms

Data Structures

- vector
- list
- deque
- map
- set
- …



Algorithms

- copy
- find
- transform
- sort
- generate
- nth_element
- …

$O(n^2)$-combinations

Generic Algorithms Based on Iterators

Data Structures

- vector
- list
- deque
- map
- set
- …

Iterators

Algorithms

- copy
- find
- transform
- sort
- generate
- nth_element
- …

O(n)-combinations

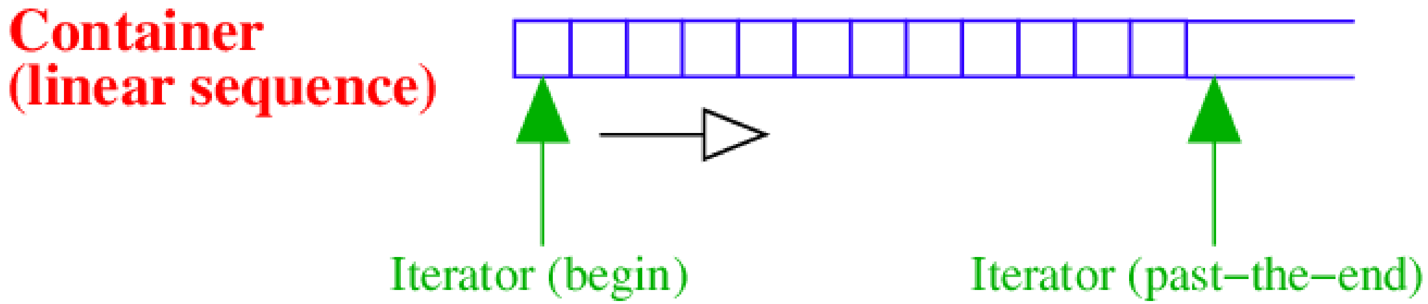
Iterator Concept Refinement Hierarchy

Concept	Refinement of	Syntactic requirements
Trivial Iterator	Assignable, Equality Comparable	operator*() operator->()
Input Iterator	Trivial Iterator	operator++(), ...
Output Iterator	Assignable	operator*(), operator++() ...
Forward Iterator	Input Iterator, Output Iterator, Default Constructible	...
Bidirectional Iterator	Forward Iterator	operator--(), ...
Random Access Iterator	Bidirectional Iterator, LessThan Comparable	operator+(), operator+=(), operator-(), operator[](), ...

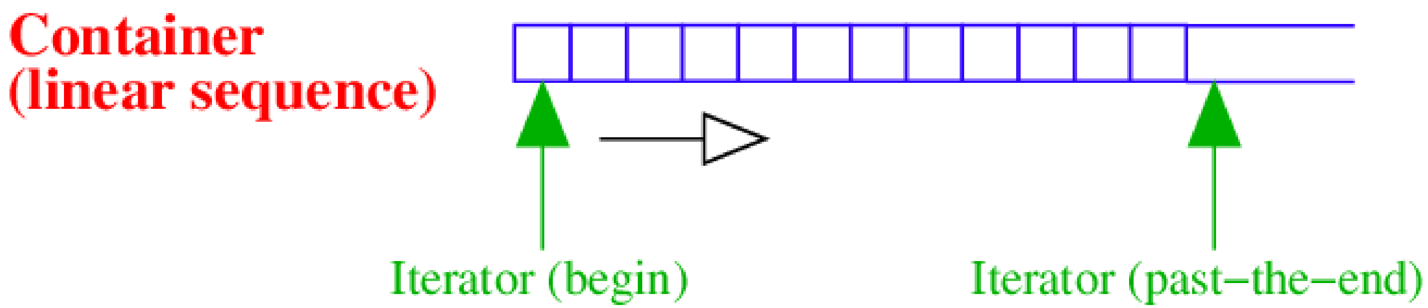
Models of Iterators

- C pointers into C arrays are models of iterators.
- Classes can be programmed to fulfill all iterator requirements, e.g., with operator overloading, so a pointer to a linked list can be encapsulated in a class to behave like an iterator.

Iterator Ranges



Container Provide Iterators




```
template <class T>
class list {
   void push_back( const T& t); // append t to list.
   typedef UnknownInternalType iterator;
   iterator begin();
   iterator end();
};
```

Generic Algorithms on Iterator Ranges

```
template <class InputIterator, class T>
bool contains( InputIterator first, InputIterator beyond,
                    const T& value) {
    while ((first != beyond) && (*first != value))
        ++first;
    return (first != beyond);
}
```

Returns true iff the value is contained in the values of the range [first,beyond).

Generic Algorithm on C Pointer

```
template <class InputIterator, class T>
bool contains( InputIterator first, InputIterator beyond,
                  const T& value) {
   while ((first != beyond) && (*first != value))
      ++first;
   return (first != beyond);
}

int a[100];
// ... initialize elements of a.
bool found = contains( a, a+100, 42);
```

Generic Algorithm on C Pointer

```
template <class InputIterator, class T>
bool contains( InputIterator first, InputIterator beyond,
                    const T& value) {
    while ((first != beyond) && (*first != value))
        ++first;
    return (first != beyond);
}

int a[100];
// ... initialize elements of a.
bool found = contains( a, a+100, 42);
bool in_first_half = contains( a, a+50, 42);
```

Generic Algorithm on Container Class

```
template <class InputIterator, class T>
bool contains( InputIterator first, InputIterator beyond,
                     const T& value) {
    while ((first != beyond) && (*first != value))
        ++first;
    return (first != beyond);
}

list<int> ls;
// ... insert some elements into ls.
bool found = contains( ls.begin(), ls.end(), 42);
```

Generic Copy Function

```
template <class InputIterator, class OutputIterator>
OutputIterator
copy( InputIterator first, InputIterator beyond,
        OutputIterator result)
{
   while (first != beyond)
      *result++ = *first++;
   return result;
}
```

Copy Elements in int-Arrays

```
int a1[100];
int a2[100];
// ... initialize elements of a1.
copy( a1, a1+100, a2);
```

Copy Elements in Lists

```
list<int> ls1;
list<int> ls2;
// ... initialize elements of ls1.
copy( ls1.begin(), ls1.end(), ls2.begin());
```

Copy Elements in Lists

list<int> ls1;

list<int> ls2;

// ... initialize elements of ls1.

~~copy(ls1.begin(), ls1.end(), ls2.begin());~~

// … writes into non-existing memory of empty list ls2!!!

Copy Elements in Lists

list<int> ls1;

list<int> ls2;

// ... initialize elements of ls1.

~~copy(ls1.begin(), ls1.end(), ls2.begin());~~

// … writes into non-existing memory of empty list ls2!!!

// … use a small adaptor class to convert iterator calls

// … write operations to push_back calls on container

copy(ls1.begin(), ls1.end(), back_inserter(ls2));

Adaptors to Convert Between Concepts

```
copy( istream_iterator<int>(cin), istream_iterator<int>(),
      ostream_iterator<int>( cout, "\n"));
```

The concepts in the STL and the adaptors form an extremely flexible toolkit. Most adaptors are small classes and function. Own adaptors for other concepts are easy to add. The whole is more than the sum of its parts.

Iterator Traits

- Assume an algorithm needs the value type of an iterator

```
template <class Iterator>
void sort( Iterator first, Iterator last) {
   TYPE pivot = *first;   // …… TYPE becomes Iterator::value_type
```

- We could provide the type as member type of iterators

```
struct iterator_over_ints {
   typedef int value_type;
   // ...
};
```

- Doesn’t work with C pointers as iterators.
- We could specialize the algorithm to work with pointers:

```
template <class T>
void sort( T* first, T* last) { // ……
```

- Needs to be done for each algorithm ➔ factor this into own class.

Iterator Traits

- Get value type from intermediate iterator traits class

```
template <class Iterator>
void sort( Iterator first, Iterator last) {
   typename iterator_traits<Iterator>::value_type pivot = *first;  // ……
```

- In general, iterator traits get the value type from the iterator

```
template <class Iterator>
struct iterator_traits {
   typedef typename Iterator::value_type value_type;
}
```

- Now we can specialize the iterator traits instead of the algorithm to handle the special case of pointers (and const pointers):

```
template <class T>
struct iterator_traits<T*> {
   typedef T value_type;
}
```

Function Objects

(a.k.a. Functors)

A function object basically is an instance of a class with the operator() member function implemented, such that a call to this member function of the object looks like a function call.

```
template <class T>
struct equals {
   bool operator()( const T& a, const T& b) { return a == b; }
};
```

Function Objects

```
template <class T>
struct equals {
    bool operator()( const T& a, const T& b) { return a == b; }
};
```

Using a function object:

```
equals<int> int_equal;
if ( int_equal( 42, 42)) { … }
```

Function Objects

```
template <class T>
struct equals {
    bool operator()( const T& a, const T& b) { return a == b; }
};
```

Using a function object:

```
equals<int> int_equal;
if ( int_equal(42, 42)) { … }
```

… or functor instantiation and functor call in one step:

```
if ( equals<int>()(42, 42)) { … }
```

Generic Contains Function Revisited

```
template <class InputIterator, class T, class Equal>
bool contains( InputIterator first, InputIterator beyond,
                    const T& value, Equal eq = equals<T>()) {
   while ((first != beyond) && ( ! eq(*first,value)))
      ++first;
   return (first != beyond);
}
```

Generic Contains Function Revisited

```
template <class InputIterator, class T, class Equal>
bool contains( InputIterator first, InputIterator beyond,
                 const T& value, Equal eq = equals<T>()) {
   while ((first != beyond) && ( ! eq(*first,value)))
      ++first;
   return (first != beyond);
}

int a[100];
// ... initialize elements of a.
bool found = contains( a, a+100, 42, equals<int>());
```

Generic Contains Function Revisited

```
template <class InputIterator, class T, class Equal>
bool contains( InputIterator first, InputIterator beyond,
                    const T& value, Equal eq = equals<T>()) {
   while ((first != beyond) && ( ! eq(*first,value)))
      ++first;
   return (first != beyond);
}
```

Use a plain C function as parameter instead

```
bool equality( int a, int b) { return a == b; }

bool found = contains( a, a+100, 42, equality);
```

Benefits of Functors vs. Function Pointers

- Faster, because compile-time instantiation allows inlining etc.
- Can have state, e.g., see this epsilon neighborhood comparison:

```
template <class T>
struct eps_equals {
   T epsilon;
   eps_equals( const T& eps) : epsilon(eps) {}
   bool operator()( const T& a, const T& b) {
      return (a-b <= epsilon) && (b-a <= epsilon);
   }
};
bool found = contains( a, a+100, 42, eps_equals<int>(1));
```

Adaptable Function Objects

- Adaptable function objects require in addition to regular function objects some local types that describe the result type and the argument types.
- A function pointer can be a valid model for a function object, but it cannot be a valid model of an adaptable function object.

```
template <class T>
struct equals {
    typedef bool result_type;
    typedef T       first_argument_type;
    typedef T       second_argument_type;
    bool operator()( const T& a, const T& b) { return a == b; }
};
```

Adaptable Function Objects

Concept	**Refinement of**	**Syntactic requirem. model T**
Adaptable Generator	Generator	T::result_type
Adaptable Unary Function	Unary Function	T::result_type, T::argument_type
Adaptable Binary Function	Binary Function	T::result_type, T::first_argument_type, T::second_argument_type
Adaptable Predicate	Predicate, Adaptable Unary Function	
Adaptable Binary Predicate	Binary Predicate, Adaptable Binary Function	

Adaptable Function Objects

Simplify implementation with supporting base classes:

```
#include <functional>

template <class T>
struct equals : public std::binary_function<T,T,bool> {
   bool operator()( const T& a, const T& b) { return a == b; }
};
```

The definition of binary_function in the STL :

```
template <class Arg1, class Arg2, class Result>
struct binary_function {
   typedef Arg1 first_argument_type;
   typedef Arg2 second_argument_type;
   typedef Result result_type;
};
```

Predicate Adaptor: unary_negate

```
template <class Predicate>
class unary_negate : public unary_function<
                              typename Predicate::argument_type, bool> {
protected:
   Predicate pred;
public:
   explicit unary_negate( const Predicate& x) : pred(x) {}
   bool operator()(const typename Predicate::argument_type& x) const {
      return ! pred(x);
   }
};
```

Predicate Adaptor: unary_negate

A small helper function simplifies the use of the adaptor class:

```
template <class Predicate>
inline unary_negate< Predicate> not1( const Predicate& pred) {
    return unary_negate< Predicate>( pred);
}
```

Example: remove_if_divides

A short program in [Stepanov&Lee 95] makes us if this negator. The program copies all integers from cin to cout that cannot be divided by the integer parameter given to the program.

```
int main( int argc, char** argv) {
    if ( argc != 2)
        throw( "usage: remove_if_divides integer\n");
    remove_copy_if( istream_iterator<int>(cin), istream_iterator<int>(),
                    ostream_iterator<int>(cout, "\n"),
                    not1( bind2nd( modulus<int>(), atoi( argv[1]))));
    return 0;
}
```

Instead of the helper function one would have to write the type:

`unary_negate<binder2nd<modulus<int> > >(…)`

Implementation of bind2nd

bind2nd is a helper function to create an binder2nd object

```
template < class Operation, class Tp>
inline binder2nd< Operation>
bind2nd( const Operation& fn, const Tp& x) {
    typedef typename Operation::second_argument_type Arg2_type;
    return binder2nd< Operation>( fn, Arg2_type(x));
}
```

Implementation of binder2nd<Op>

binder2nd implements something similar to currying, i.e., it is a higher order function object

```
template <class Operation> struct binder2nd
  : public unary_function< typename Operation::first_argument_type,
                           typename Operation::result_type> {
    Operation op;
    typename Operation::second_argument_type value;

    binder2nd( const Operation& x,
               const typename Operation::second_argument_type& y)
      : op(x), value(y) {}
    typename Operation::result_type
    operator()(const typename Operation::first_argument_type& x) const {
        return op(x, value);
    }
};
```

Barton-Nackman Trick

We start with a simple class that, among other operations, provides an equality and an inequality comparison operator.

```
struct A {
   bool operator == (const A& a) const;
   bool operator != (const A& a) const { return ! (*this == a); }
};
```

Refactor generic inequality implementation into a base class.

Barton-Nackman Trick

Refactor generic inequality implementation into a base class.

Problem is that base class needs to know the derived class.

Let us provide it as template parameter.

```
template <class T>
struct Inequality {
    bool operator != (const T& t) const {
        return ! (static_cast<const T&>(*this) == t);
    }
};
struct A : public Inequality<A> {
    bool operator == (const A& a) const;
};
```

There is a pitfall with name-lookup rules; don't use equal member function names in the base class and in the derived class!

Solving Mutual Dependencies between Class Templates

```
struct Edge;

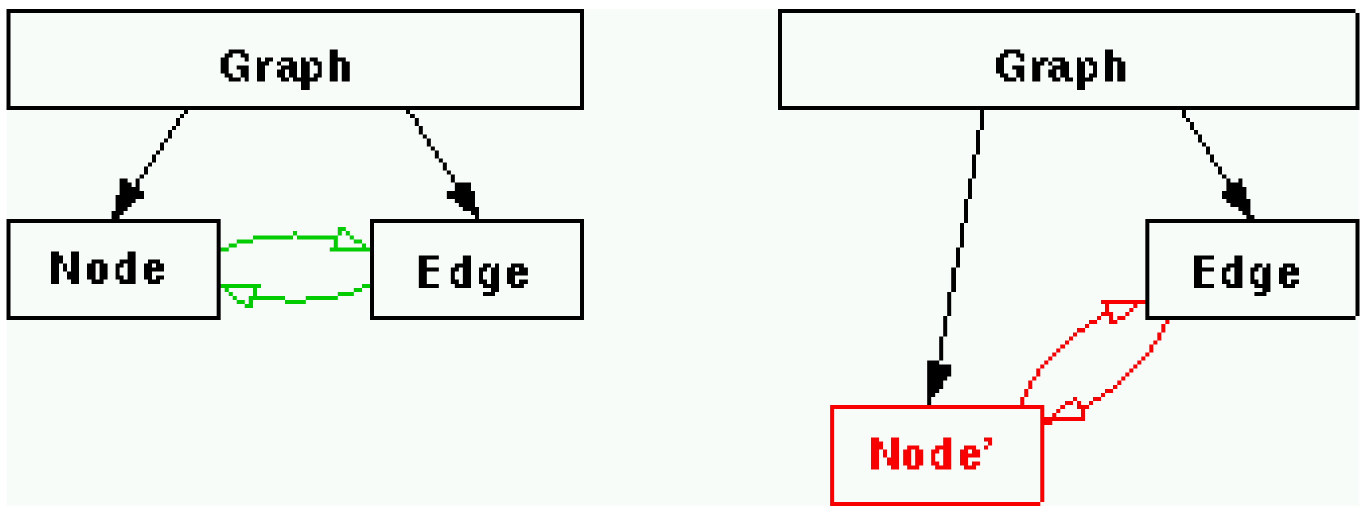
struct Node {
   Edge * edge;
   // .... maybe more than one edge ....
};

struct Edge {
   Node * source;
   Node * dest;
};
```

Solving Mutual Dependencies between Class Templates

For a templated solution one would like to exchange each of the participating types independently and let the user assemble the final structure.

For example, a **Node** will be replaced by a **Node’**.



Solving Mutual Dependencies between Class Templates

```
template <class G>                            template <class G>
struct Node {                                 struct Edge {
   typedef typename G::Edge Edge;                typedef typename G::Node Node;
   Edge* edge;                                   Node* node;
   // .... maybe some more edges ....         };
};
template < template <class G> class TNode, template <class G> class TEdge>
struct Graph {
   typedef Graph< TNode, TEdge>  Self;
   typedef TNode<Self>           Node;
   typedef TEdge<Self>           Edge;
};
int main() {
   typedef Graph< Node, Edge> G;
   G::Node node;    G::Edge edge;
   node.edge = &edge;   edge.node = &node;
}
```

Solving Mutual Dependencies between Class Templates

```
template <class Graph>
struct Colored_node : public Node<Graph> {
    int color;
};

int main() {
    typedef Graph< Colored_node, Edge> G;
    G::Node node;
    G::Edge edge;
    node.edge = &edge;
    edge.node = &node;
    node.color = 3;
}
```