Template Metaprogramming in C++

CS242, Fall 2009
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Preliminaries

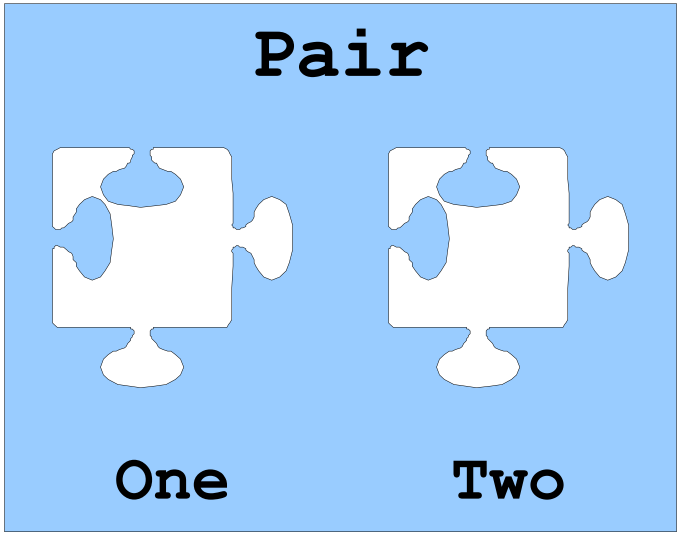
A **C++ template** is a type or function parameterized over a set of types, functions, or constants.

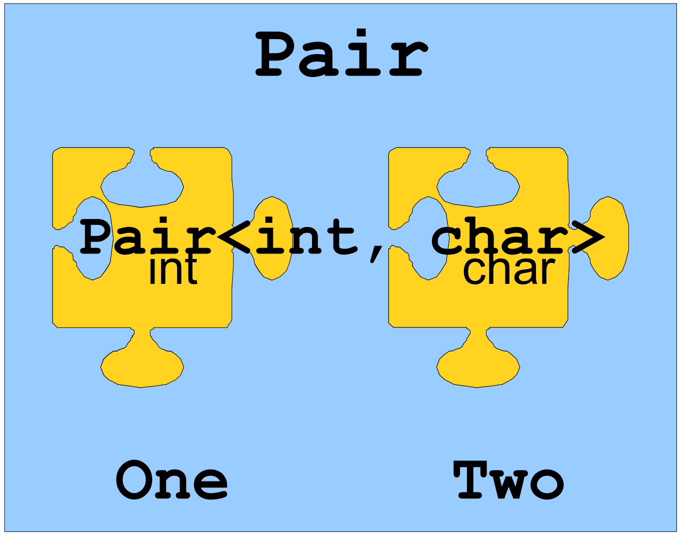
```
template <typename One, typename Two>
struct Pair
{
   One first;
   Two second;
};
```

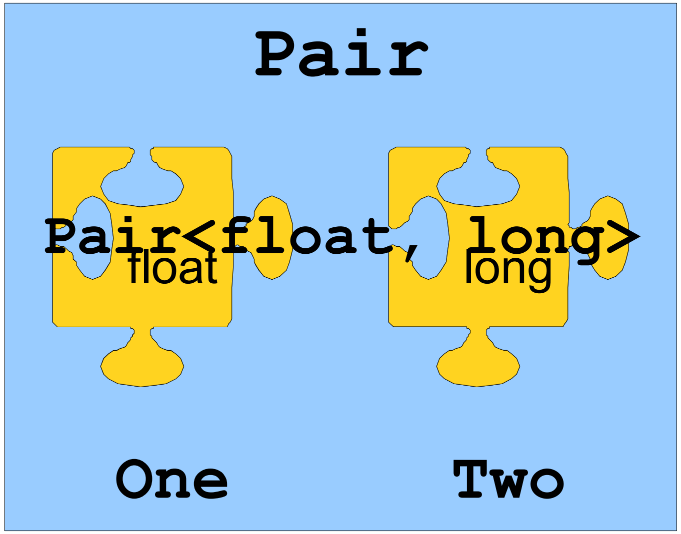
```
template <typename One, typename Two>
struct Pair
{
    One first;
    Two second;
};
```

```
template <typename One, typename Two>
struct Pair
{
   One first;
   Two second;
};
```

Providing arguments to a template **instantiates** the template with those arguments. Instantiation occurs at **compile-time**.


Pair
One
Two


Pair
Pair<int, char>
int
char
One
Two


Pair
Pair<float, long>
float
long
One
Two

Template Specialization

- A version of a template to use when a specific pattern of arguments are supplied.
- Structure independent of primary template.
  - Can add/remove functions from interface, etc.
- *Full specialization* used when all arguments are specified.
- *Partial specialization* used when arguments have a particular structure.

```
/* Primary template */
template <typename T> class Set
{
   // Use a binary tree
};
```

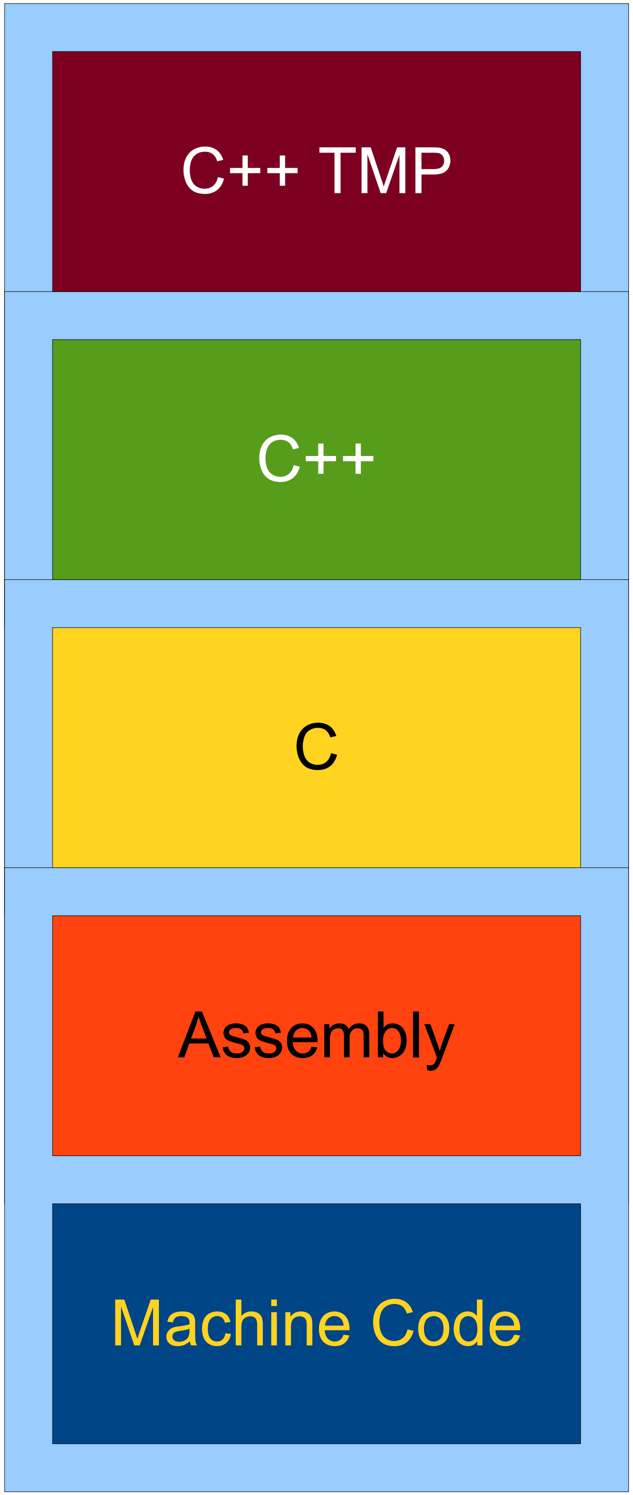
```
/* Primary template */
template <typename T> class Set
{
   // Use a binary tree
};

/* Full specialization */
template <> class Set<char>
{
   // Use a bit vector
};
```

```
/* Primary template */
template <typename T> class Set
{
   // Use a binary tree
};

/* Full specialization */
template <> class Set<char>
{
   // Use a bit vector
};

/* Partial specialzation */
template <typename T> class Set<T*>
{
   // Use a hash table
};
```

A **metaprogram** is a program that produces or manipulates constructs of a target language.

A **template metaprogram** is a C++ program that uses templates to generate customized C++ code at compile-time.

Why would you ever want to do this?



C++ TMP

C++

C

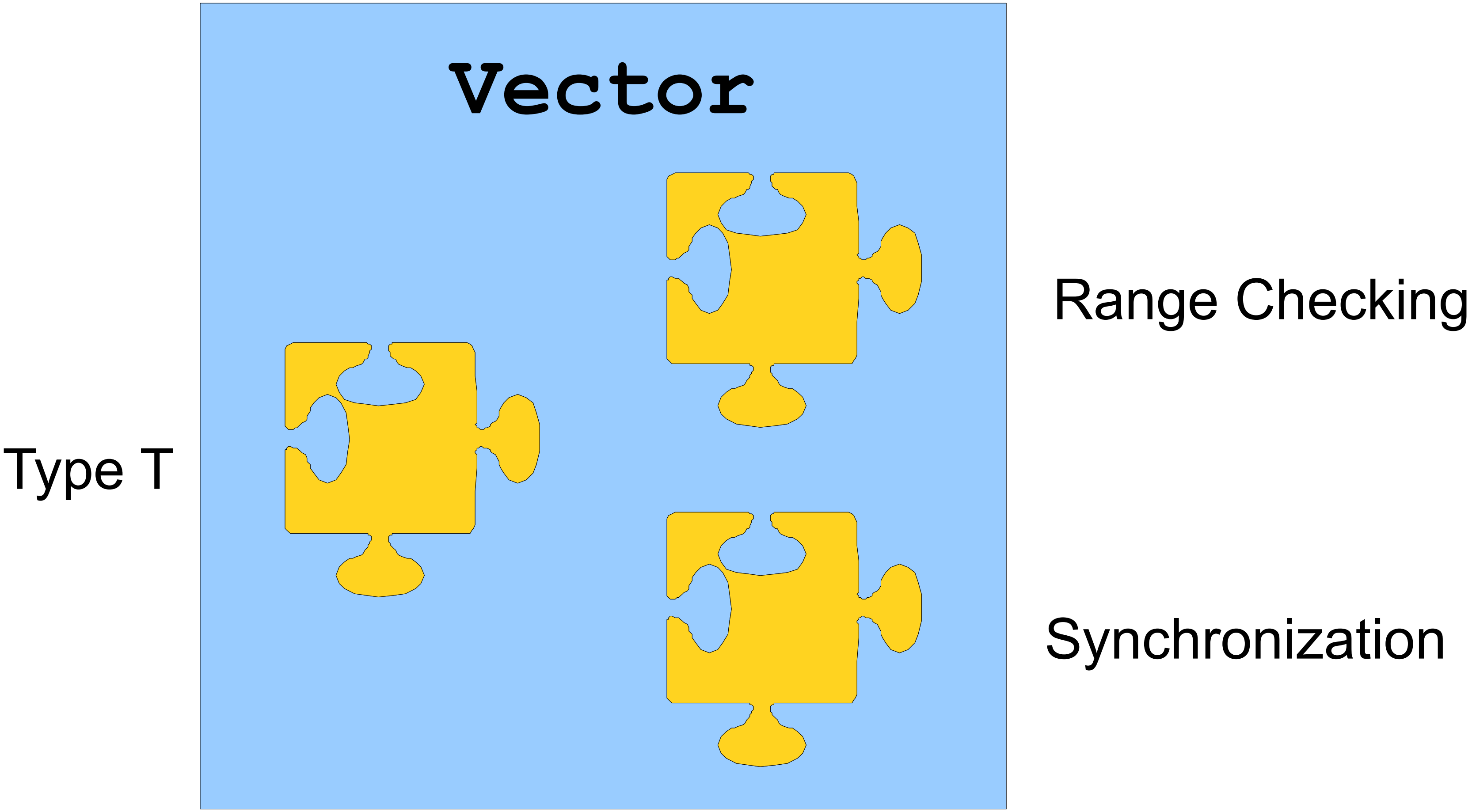
Assembly

Machine Code

Template Metaprogramming In Action

Part One: Policy Classes

```
template <typename T> class Vector
{
public:
   /* ... ctors, dtor, etc. */
         T& operator[] (size_t);
   const T& operator[] (size_t) const;

   void insert(iterator where,
               const T& what);

   /* ... etc. ... */
};
```



Vector

Type T

Range Checking

Synchronization

Templates are parameterized over **types**, not **behaviors**.

A **policy class** is a type that implements a particular behavior.

```
template <typename T>
class Vector

{
public:
   /* ... ctors, dtor, etc. */
         T& operator[] (size_t);
   const T& operator[] (size_t) const;

   void insert(iterator where,
               const T& what);

   /* ... etc. ... */
};
```

```
template <typename T,
          typename RangePolicy,
          typename LockingPolicy>
class Vector

{
public:
   /* ... ctors, dtor, etc. */
         T& operator[] (size_t);
   const T& operator[] (size_t) const;

   void insert(iterator where,
               const T& what);

   /* ... etc. ... */
};
```

```
template <typename T,
          typename RangePolicy,
          typename LockingPolicy>
class Vector: public RangePolicy,
              public LockingPolicy
{
public:
   /* ... ctors, dtor, etc. */
         T& operator[] (size_t);
   const T& operator[] (size_t) const;

   void insert(iterator where,
               const T& what);

   /* ... etc. ... */
};
```

Sample Range Policy

```
class ThrowingErrorPolicy
{
protected:
   ~ThrowingErrorPolicy() {}

   static void CheckRange(size_t pos,
                          size_t numElems)
   {
      if(pos >= numElems)
          throw std::out_of_bounds("Bad!");
   }
};
```

Another Sample Range Policy

```
class LoggingErrorPolicy
{
public:
   void setLogFile(const std::string&);
protected:
   ~LoggingErrorPolicy();
   void CheckRange(size_t pos,
                   size_t numElems)
   {
      if(pos >= numElems && output != 0)
          *log << "Error!" << std::endl;
   }
private:
   std::ofstream* log;
};
```

Another Sample Range Policy

```
class LoggingErrorPolicy
{
public:
   void setLogFile(const std::string&);
protected:
   ~LoggingErrorPolicy();
   void CheckRange(size_t pos,
                   size_t numElems)
   {
      if(pos >= numElems && output != 0)
          *log << "Error!" << std::endl;
   }
private:
   std::ofstream* log;
};
```

Implementer Code

```
template <typename T,
          typename RangePolicy,
          typename LockingPolicy>
T& Vector<T, RangePolicy, LockingPolicy>::
      operator[] (size_t position)
{




   return this->elems[position];
}
```

Implementer Code

```
template <typename T,
          typename RangePolicy,
          typename LockingPolicy>
T& Vector<T, RangePolicy, LockingPolicy>::
      operator[] (size_t position)
{
   LockingPolicy::Lock lock;


   return this->elems[position];
}
```

Implementer Code

```
template <typename T,
          typename RangePolicy,
          typename LockingPolicy>
T& Vector<T, RangePolicy, LockingPolicy>::
      operator[] (size_t position)
{
   LockingPolicy::Lock lock;
   RangePolicy::CheckRange(position,
                           this->size);
   return this->elems[position];
}
```

Client Code

```
int main()
{
    Vector<int, ThrowingErrorPolicy,
                NoLockingPolicy> v;

    for(size_t k = 0; k < kNumElems; ++k)
        v.push_back(k);

    /* ... etc. ... */

    return 0;
}
```

```
template <
 typename T,
 typename RangePolicy = NoErrorPolicy,
 typename LockingPolicy = NoLockingPolicy>
class Vector: public RangePolicy,
              public LockingPolicy
{
public:
   /* ... ctors, dtor, etc. */
         T& operator[] (size_t);
   const T& operator[] (size_t) const;

   void insert(iterator where,
               const T& what);

   void erase(iterator where);

   /* ... etc. ... */
};
```

Updated Client Code

```
int main()
{
    Vector<int, ThrowingErrorPolicy> v;

    for(size_t k = 0; k < kNumElems; ++k)
        v.push_back(k);

    /* ... etc. ... */

    return 0;
}
```

Summary of Policy Classes

- Identify **mutually orthogonal** behaviors in a class.
- Specify an **implicit interface** for those behaviors.
- **Parameterize** a host class over each policy.
- Use **multiple inheritance** to import the policies into the host.

Template Metaprogramming In Action

Part Two: Traits Classes and Tag Dispatching

```
template </* ... */>
class Vector: /* ... */
{
public:
   void insert(iterator where,
               const T& what);

   template <typename IteratorType>
       void insert(iterator where,
                   IteratorType start,
                   IteratorType stop);

   /* ... */
};
```

```
template <...>
   template <typename Iter>
void Vector<...>::insert(iterator where,
                         Iter start,
                         Iter stop)
{
   /* Insert elements one at a time. */
   for(; start != stop; ++start, ++where)
       where = insert(where, start);
}
```

```
template <...>
   template <typename Iter>
void Vector<...>::insert(iterator where,
                         Iter start,
                         Iter stop)
{
   /* Insert elements one at a time. */
   for(; start != stop; ++start, ++where)
       where = insert(where, start);
}
```

```
template <typename Iter> struct iterator_traits
{
  typedef typename Iter::difference_type
     difference_type;
  typedef typename Iter::value_type value_type;
  typedef typename Iter::pointer pointer;
  typedef typename Iter::reference reference;
  typedef typename Iter::iterator_category
     iterator_category;
};

/* Specialization for raw pointers */
template <typename T> struct iterator_traits<T*>
{
  typedef ptrdiff_t difference_type;
  typedef T value_type;
  typedef T* pointer;
  typedef T& reference;
  typedef random_access_iterator_tag
     iterator_category;
};
```

A **traits class** is a template type that exports information about its parameters.

Schematic of Traits Classes

Language Construct

Traits Class

Metainformation

```
template <typename Iter> struct iterator_traits
{
  typedef typename Iter::difference_type
     difference_type;
  typedef typename Iter::value_type value_type;
  typedef typename Iter::pointer pointer;
  typedef typename Iter::reference reference;
  typedef typename Iter::iterator_category
     iterator_category;
};

/* Specialization for raw pointers */
template <typename T> struct iterator_traits<T*>
{
  typedef ptrdiff_t difference_type;
  typedef T value_type;
  typedef T* pointer;
  typedef T& reference;
  typedef random_access_iterator_tag
     iterator_category;
};
```

```
template <typename Iter> struct iterator_traits
{
  typedef typename Iter::difference_type
     difference_type;
  typedef typename Iter::value_type value_type;
  typedef typename Iter::pointer pointer;
  typedef typename Iter::reference reference;
  typedef typename Iter::iterator_category
     iterator_category;
};

/* Specialization for raw pointers */
template <typename T> struct iterator_traits<T*>
{
  typedef ptrdiff_t difference_type;
  typedef T value_type;
  typedef T* pointer;
  typedef T& reference;
  typedef random_access_iterator_tag
     iterator_category;
};
```

```
struct input_iterator_tag {};

struct output_iterator_tag {};

struct forward_iterator_tag :
   input_iterator_tag, output_iterator_tag {};

struct bidirectional_iterator_tag :
   forward_iterator_tag {};

struct random_access_iterator_tag :
   bidirectional_iterator_tag {};
```

A **tag class** is a (usually empty) type encoding semantic information.

Tag dispatching is function overloading on tag classes.

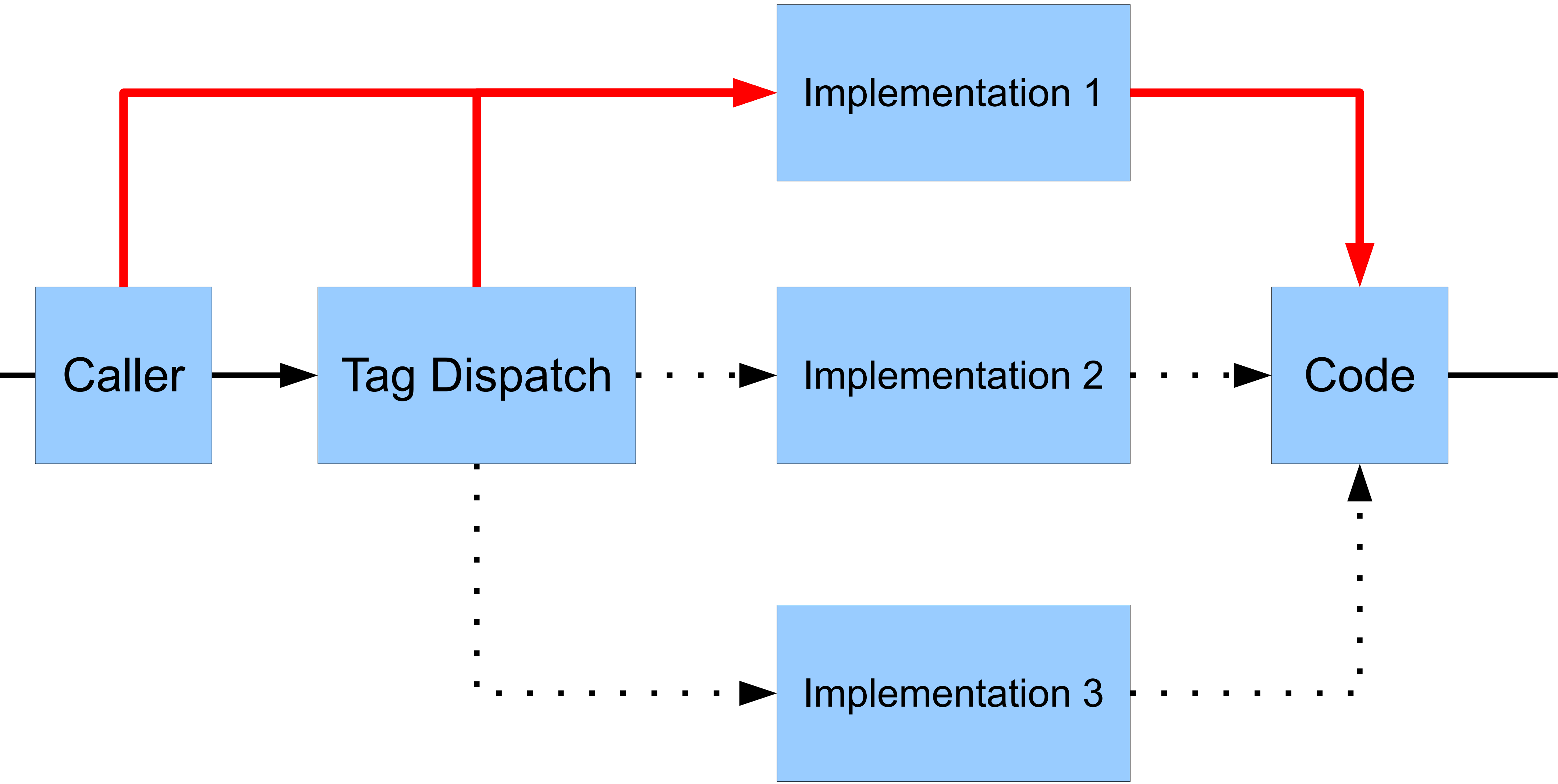
```
template <...>
   template <typename Iter>
void Vector<...>::insert(iterator where,
                         Iter start,
                         Iter stop)
{
 doInsert(where, start, stop,
   typename std::iterator_traits<Iter>::iterator_category());
}
```

```
template <...>
   template <typename Iter>
void Vector<...>::insert(iterator where,
                         Iter start,
                         Iter stop)
{
 doInsert(where, start, stop,
   typename std::iterator_traits<Iter>::iterator_category());
}
```

```
template <...>
   template <typename Iter>
void Vector<...>::doInsert(iterator where,
                           Iter start, Iter stop,
                           std::input_iterator_tag)
{
   /* Insert elements one at a time. */
   for(; start != stop; ++start, ++where)
       where = insert(where, start);
}

template <...>
   template <typename Iter>
void Vector<...>::doInsert(iterator where,
                           Iter start, Iter stop,
                           std::forward_iterator_tag)
{
   /* ... more complex logic to shift everything
    * down at the same time...
    */
}
```

```
template <...>
   template <typename Iter>
void Vector<...>::doInsert(iterator where,
                           Iter start, Iter stop,
                           std::input_iterator_tag)
{
   /* Insert elements one at a time. */
   for(; start != stop; ++start, ++where)
       where = insert(where, start);
}

template <...>
   template <typename Iter>
void Vector<...>::doInsert(iterator where,
                           Iter start, Iter stop,
                           std::forward_iterator_tag)
{
   /* ... more complex logic to shift everything
    * down at the same time...
    */
}
```

Schematic of Tag Dispatching



Summary of Tag Dispatching

- Define a set of tag classes encoding **semantic information**.
- Provide a means for obtaining a tag from each relevant type (often using **traits classes**)
- **Overload the relevant function** by accepting different tag types as parameters.
- Call the overloaded function using the tag associated with each type.

Template Metaprogramming In Action

Part Three: Typelists

The Typelist

```
struct Nil {};
template <typename Car, typename Cdr>
  struct Cons {};
```

Sample Typelist

```
Cons<int,
   Cons<double,
      Cons<char,
         Cons<float,
            Cons<short,
               Cons<long, Nil>
                >
             >
          >
       >
    >
```

A Simplification

```
#define LIST0() Nil
#define LIST1(a) Cons<a, LIST0()>
#define LIST2(a, b) Cons<a, LIST1(b)>
#define LIST3(a, b, c) Cons<a, LIST2(b, c)>
#define LIST4(a, b, c, d) Cons<a, LIST3(b, c, d)>
/* ... etc. ... */


LIST6(int, double, float, char, short, long)
```

Car/Cdr Recursion with Templates

```
template <typename> struct Length;
```

Car/Cdr Recursion with Templates

```
template <typename> struct Length;

template <> struct Length<Nil>
{
    static const size_t result = 0;
};
```

Car/Cdr Recursion with Templates

```
template <typename> struct Length;

template <> struct Length<Nil>
{
    static const size_t result = 0;
};

template <typename Car, typename Cdr>
struct Length<Cons<Car, Cdr> >
{
    static const size_t result =
        1 + Length<Cdr>::result;
};
```

Length<LIST3(int, double, string)>

`result`

Length<LIST2(double, string)>

`result`

Length<LIST1(string)>

`result`

Length<LIST0()>

`result`

Length<LIST3(int, double, string)>

`result` 3

Length<LIST2(double, string)>

`result` 2

Length<LIST1(string)>

`result` 1

Length<LIST0()>

`result` 0

Typelists and template specialization allow us to write templates whose instantiation causes a **chain reaction** of further instantiations.

This lets us construct **arbitrarily complicated structures** at compile-time.

```
class ExprVisitor;

class ExprNode {
public:
   virtual void accept(ExprVisitor&);
};

class AddExpr: public ExprNode {
public:
   virtual void accept(ExprVisitor&);
};

class MulExpr: public ExprNode {
public:
   virtual void accept(ExprVisitor&);
};

class SubExpr: public ExprNode {
public:
   virtual void accept(ExprVisitor&);
};

class DivExpr: public ExprNode {
public:
   virtual void accept(ExprVisitor&);
};
```

```
class ExprVisitor
{
public:
    virtual void visit(ExprNode*) = 0;
    virtual void visit(AddExpr*) = 0;
    virtual void visit(MulExpr*) = 0;
    virtual void visit(SubExpr*) = 0;
    virtual void visit(DivExpr*) = 0;
}
```

```
void ExprNode::accept(ExprVisitor& v)
{
   v.visit(this); // Calls ExprVisitor::Visit(ExprNode*)
}

void AddExpr::accept(ExprVisitor& v)
{
   v.visit(this); // Calls ExprVisitor::Visit(AddExpr*)
}

void MulExpr::accept(ExprVisitor& v)
{
   v.visit(this); // Calls ExprVisitor::Visit(MulExpr*)
}

void DivExpr::accept(ExprVisitor& v)
{
   v.visit(this); // Calls ExprVisitor::Visit(DivExpr*)
}

void SubExpr::accept(ExprVisitor& v)
{
   v.visit(this); // Calls ExprVisitor::Visit(SubExpr*)
}
```

```
class FSVisitor;

class FileSystemEntity {
public:
    virtual void accept(FSVisitor&);
};

class File: public FileSystemEntity {
public:
    virtual void accept(FSVisitor&);
};

class Directory: public FileSystemEntity {
public:
    virtual void accept(FSVisitor&);
};

/* ... etc. ... */
```

```
class FSVisitor
{
public:
  virtual void visit(FileSystemEntity*) = 0;
  virtual void visit(File*) = 0;
  virtual void visit(Directory*) = 0;
  /* ... etc. ... */
}
```

Can we automatically generate a visitor for a type hierarchy?

Yes!

Idea: Create a type **parameterized over a typelist** that has one instance of `visit` for each type in the list.

```
template <typename List> class Visitor;
```

```
template <typename List> class Visitor;

template <typename T> class Visitor<LIST1(T) >
{
public:
    virtual ~Visitor() {}
    virtual void visit(T*) = 0;
};
```

```
template <typename List> class Visitor;

template <typename T> class Visitor<LIST1(T) >
{
public:
    virtual ~Visitor() {}
    virtual void visit(T*) = 0;
};

template <typename Car, typename Cdr>
class Visitor<Cons<Car, Cdr> > : public Visitor<Cdr>
{
public:
    virtual void visit(Car*) = 0;
    using Visitor<Cdr>::visit;
};
```

Visitor<LIST1(ExprNode)>

`virtual void visit(ExprNode*)`

Visitor<LIST2(DivExpr, ExprNode)>

`virtual void visit(DivExpr*)`

Visitor<LIST3(SubExpr, DivExpr, ExprNode)>

`virtual void visit(SubExpr*)`

Visitor<LIST4(MulExpr, SubExpr, DivExpr, ExprNode)>

`virtual void visit(MulExpr*)`

Visitor<LIST5(AddExpr, MulExpr, SubExpr, DivExpr, ExprNode)>

`virtual void visit(AddExpr*)`

Visitor<LIST5(AddExpr, MulExpr, SubExpr, DivExpr, ExprNode)>

```
virtual void visit(AddExpr*)
virtual void visit(MulExpr*)
virtual void visit(SubExpr*)
virtual void visit(DivExpr*)
virtual void visit(ExprNode*)
```

Summary of Typelists

- Construct types corresponding to **LISP-style lists** whose elements are types.
- Use **template specialization** to model car/cdr recursion.

The Limits of Template Metaprogramming

Queue Automaton

- A **queue automaton** is a finite-state machine equipped with a **queue**.
  - Contrast to PDA with a **stack**.
- Tuple $(Q, \Sigma, \Gamma, \$, q_0, \delta)$ where
  - Q is a set of states
  - Σ is the *input alphabet*
  - Γ is the *tape alphabet*
  - $\$ \in \Gamma - \Sigma$ is the *start symbol*
  - $q_0 \in Q$ is the *start state*
  - $\delta \in Q \times \Gamma \to Q \times \Gamma^*$ is the *transition function*

Source: http://en.wikipedia.org/wiki/Queue_machine

Queue Automaton Example

δ	**X**	**\$**
q_0	q_0, XX	q_1, ε
q_1	q_1, \$	q_1, ε

Queue Automaton Example

δ	**X**	**\$**
q_0	q_0, XX	q_1, ε
q_1	q_1, \$	q_1, ε

Input: XXX

Queue Automaton Example

δ	**X**	**$**
q_0	**q_0, XX**	**q_1, ε**
q_1	**q_1, $**	**q_1, ε**

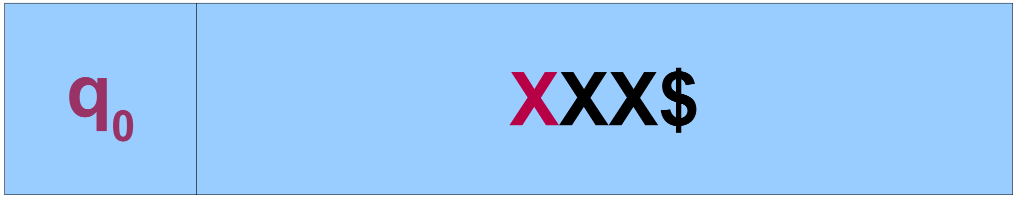
Input: XXX

q_0	**XXX$**

Queue Automaton Example

δ	**X**	**$**
q_0	**q_0, XX**	**q_1, ε**
q_1	**q_1, $**	**q_1, ε**

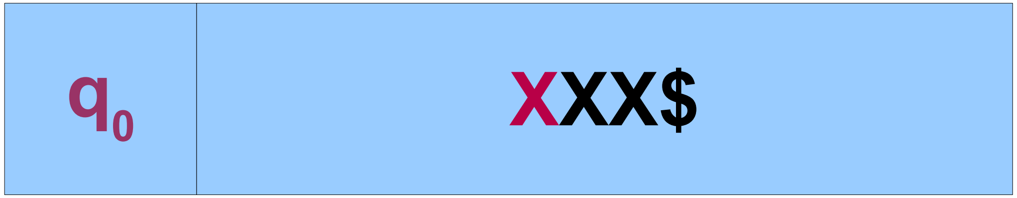
Input: XXX



Queue Automaton Example

δ	**X**	**$**
q_0	**q_0, XX**	**q_1, ε**
q_1	**q_1, $**	**q_1, ε**

Input: XXX



Queue Automaton Example

δ	X	$
q_0	q_0, XX	q_1, ε
q_1	q_1, $	q_1, ε

Input: XXX

q_0	XX$XX

Queue Automaton Example

δ	X	$
q_0	q_0, XX	q_1, ε
q_1	q_1, $	q_1, ε

Input: XXX

q_0	XX$XX

Queue Automaton Example

δ	**X**	**$**
q_0	**q_0, XX**	**q_1, ε**
q_1	**q_1, $**	**q_1, ε**

Input: XXX

q_0	**X$XXXX**

Queue Automaton Example

δ	X	$
q_0	q_0, XX	q_1, ε
q_1	q_1, $	q_1, ε

Input: XXX

q_0	$XXXXXX

Queue Automaton Example

δ	X	$
q_0	q_0, XX	q_1, ε
q_1	q_1, $	q_1, ε

Input: XXX

q_1	XXXXXX

Queue Automaton Example

δ	**X**	**$**
q_0	q_0, XX	q_1, ε
q_1	q_1, $	q_1, ε

Input: XXX

q_1	**XXXXX$**

Queue Automaton Example

δ	X	$
q_0	q_0, XX	q_1, ε
q_1	q_1, $	q_1, ε

Input: XXX

q_1	XXXX$$

Queue Automaton Example

δ	X	$
q_0	q_0, XX	q_1, ε
q_1	$q_1, \$$	q_1, ε

Input: XXX

q_1	**XXX$$$**

Queue Automaton Example

δ	**X**	$\$$
q_0	q_0, **XX**	q_1, ε
q_1	$q_1, \$$	q_1, ε

Input: XXX

q_1	**XX$\$\$\$\$$**

Queue Automaton Example

δ	X	$\$$
q_0	q_0, XX	q_1, ε
q_1	q_1, $\$$	q_1, ε

Input: XXX

q_1	$\mathrm{X}\$\$\$\$\$$

Queue Automaton Example

δ	X	$
q_0	q_0, XX	q_1, ε
q_1	q_1, $	q_1, ε

Input: XXX

q_1	$$$$$$

Queue Automaton Example

δ	X	$
q_0	q_0, XX	q_1, ε
q_1	$q_1, \$$	q_1, ε

Input: XXX

q_1	$$$$$

Queue Automaton Example

δ	**X**	**$\$$**
q_0	**q_0, XX**	**q_1, ε**
q_1	**$q_1, \$$**	**q_1, ε**

Input: XXX

q_1	**$\$\$\$\$$**

Queue Automaton Example

δ	**X**	**$\$$**
q_0	q_0, XX	q_1, ε
q_1	q_1, $\$$	q_1, ε

Input: XXX

q_1	$\$\$\$$

Queue Automaton Example

δ	**X**	**$**
q_0	q_0, XX	q_1, ε
q_1	q_1, $	q_1, ε

Input: XXX

q_1	$$

Queue Automaton Example

δ	X	$
q_0	q_0, XX	q_1, ε
q_1	q_1, $	q_1, ε

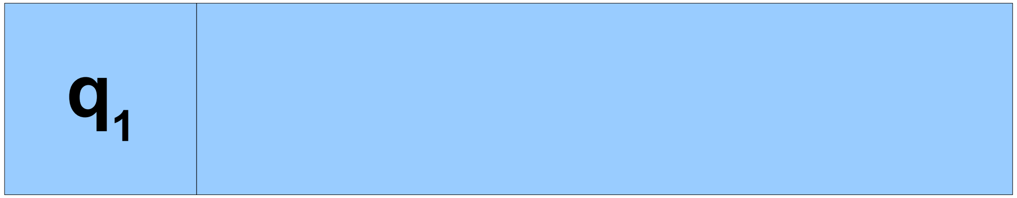
Input: XXX

q_1	$

Queue Automaton Example

δ	**X**	**$**
q_0	q_0, XX	q_1, ε
q_1	q_1, $	q_1, ε

Input: XXX



q_1

Queue Automaton Example

δ	**X**	**$**
q_0	q_0, XX	q_1, ε
q_1	q_1, $	q_1, ε

Input: XXX

q_1	

ACCEPT

Can we simulate a queue automaton with a template metaprogram?

Yes!

Concatenating Two Typelists

```
template <typename, typename> struct Concat;
template <typename T> struct Concat<Nil, T>
{
   typedef T result;
};
template <typename Car, typename Cdr, typename T>
struct Concat<Cons<Car, Cdr>, T>
{
   typedef Cons<Car, typename Concat<Cdr, T>::result>
      result;
};
```

Encoding $Q, \Sigma, \Gamma, \$, q_0$

```
/* Define a tag type for each state in Q */
struct State1 {};
struct State2 {};
     ...
struct StateN {};

/* Define a tag type for each symbol in Σ ∪ Γ */
struct Symbol1 {};
struct Symbol2 {};
     ...
struct SymbolN {};

/* Designate q0 and $. */
struct StartState {};
struct StartSymbol{};
```

Encoding the Transition Table δ

```
template <typename, typename> struct Delta;

/* Specialize Delta for each entry in δ */
template <> struct Delta<State1, Symbol1>
{
   typedef State2 nextState;
   typedef LIST2(Symbol1, Symbol1) nextSymbols;
};

template <> struct Delta<State1, Symbol2>
{
   typedef State1 nextState;
   typedef LIST0() nextSymbols;
};
            /* ... etc. ...*/
```

Running the Queue Automaton

```
template <typename State, typename Queue>
struct RunAutomaton;

template <typename State>
struct RunAutomaton<State, Nil>
{
  typedef void result;
};

template <typename Car, typename Cdr, typename State>
struct RunAutomaton<State, Cons<Car, Cdr> >
{
 typedef typename Delta<State, Car>::nextState newState;
 typedef typename Delta<State, Car>::nextSymbols newSym;
 typedef typename Concat<Cdr, newSym>::result newQueue;

 typedef
  typename RunAutomaton<newState, newQueue>::result result;
};
```

Starting the Queue Automaton

```
template <typename T>
struct SimulateQueueAutomaton
{
  typedef typename Concat<T, LIST1(StartSymbol)>::result
     initialQueue;

  typedef typename
    RunAutomaton<StartState, initialQueue>::result result;
};
```

A Turing machine can simulate C++ templates.

C++ templates can simulate queue automata.

Queue automata can simulate Turing machines.

C++ templates are Turing-complete.

In other words, the C++ type system has the **same computational capabilities** as C++.

Applications of TMP

- Compile-time dimensional analysis.
- Multiple dispatch.
- Optimized matrix operations.
- Domain-specific parsers.
- Compiler-enforced code annotations.
- Optimized FFT.

Questions?