Template Metaprogramming

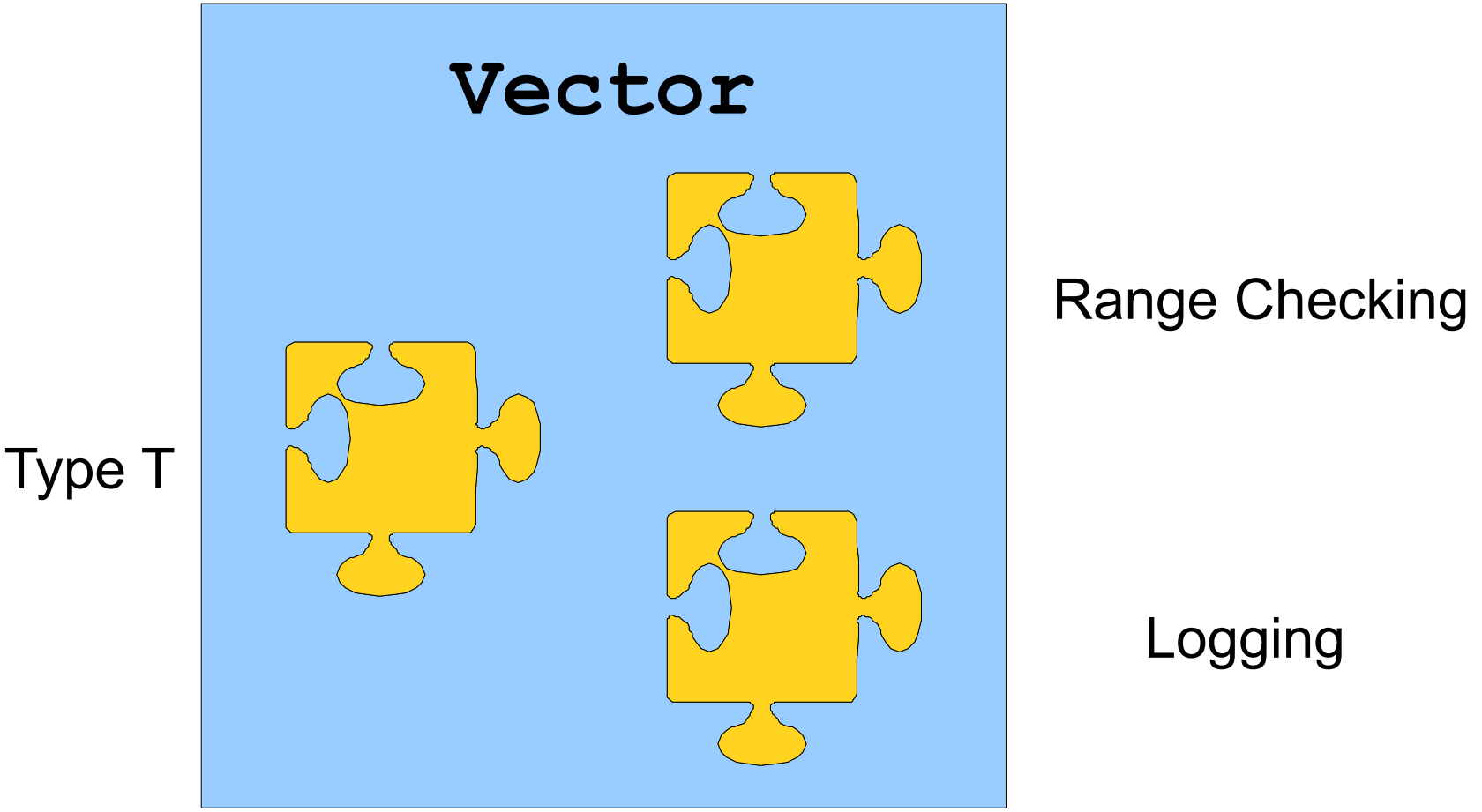
A **metaprogram** is a program that produces or manipulates constructs of a target language.

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

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
Logging

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 LoggingPolicy>
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 LoggingPolicy>
class Vector: public RangePolicy,
              public LoggingPolicy
{
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 LoggingPolicy>
T& Vector<T, RangePolicy, LoggingPolicy>::
      operator[] (size_t position)
{



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

Implementer Code

```
template <typename T,
          typename RangePolicy,
          typename LoggingPolicy>
T& Vector<T, RangePolicy, LoggingPolicy>::
      operator[] (size_t position)
{
   LoggingPolicy::Log("Element lookup");


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

Implementer Code

```
template <typename T,
          typename RangePolicy,
          typename LoggingPolicy>
T& Vector<T, RangePolicy, LoggingPolicy>::
      operator[] (size_t position)
{
   LoggingPolicy::Log("Element lookup");
   RangePolicy::CheckRange(position,
                           this->size);
   return this->elems[position];
}
```

Client Code

```
int main()
{
   Vector<int, ThrowingErrorPolicy,
             NoLoggingPolicy> 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 Specialization

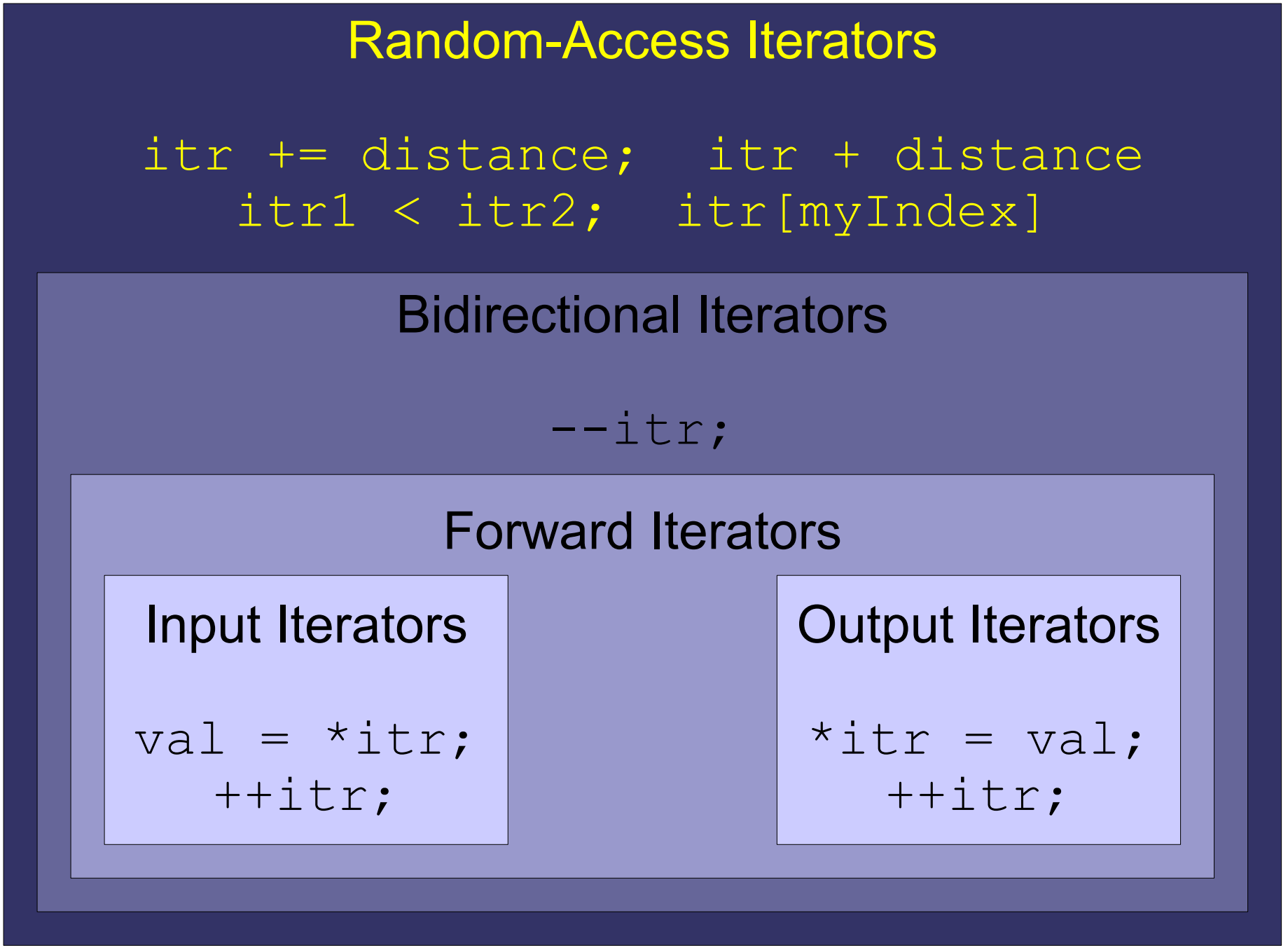
- A version of a template to use when a specific pattern of arguments is supplied.
- Structure independent of primary template.
  - Can add/remove functions from interface, etc.
- *Full specialization* used when all arguments are specified.
- *Partial specialization* used when arguments have a particular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

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

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

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


Random-Access Iterators
itr += distance; itr + distance
itr1 < itr2; itr[myIndex]
Bidirectional Iterators
--itr;
Forward Iterators
Input Iterators
val = *itr;
++itr;
Output Iterators
*itr = val;
++itr;

```
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

```
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 :
   public input_iterator_tag,
   public output_iterator_tag {};

struct bidirectional_iterator_tag :
   public forward_iterator_tag {};

struct random_access_iterator_tag :
   public bidirectional_iterator_tag {};
```

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

Tag dispatching is function overloading on tag classes.

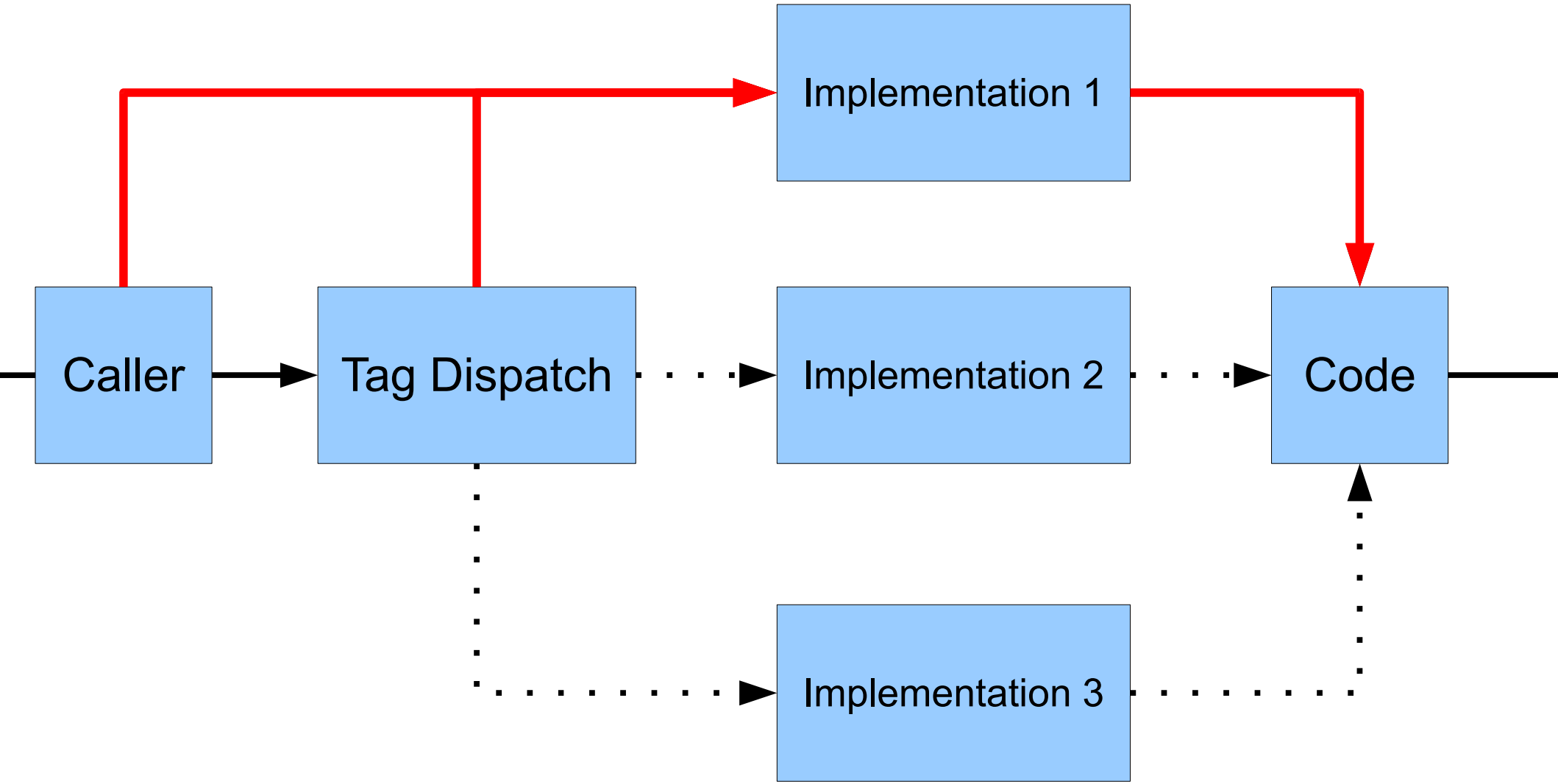
```
template <...>
   template <typename Iter>
void Vector<...>::insert(iterator where,
                         Iter start,
                         Iter stop)
{
 doInsert(where, start, stop,
   typename std::iterator_traits<Iter>::iterator_category());
}
```

```
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 Head, typename Tail>
  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)
```

List Recursion with Templates

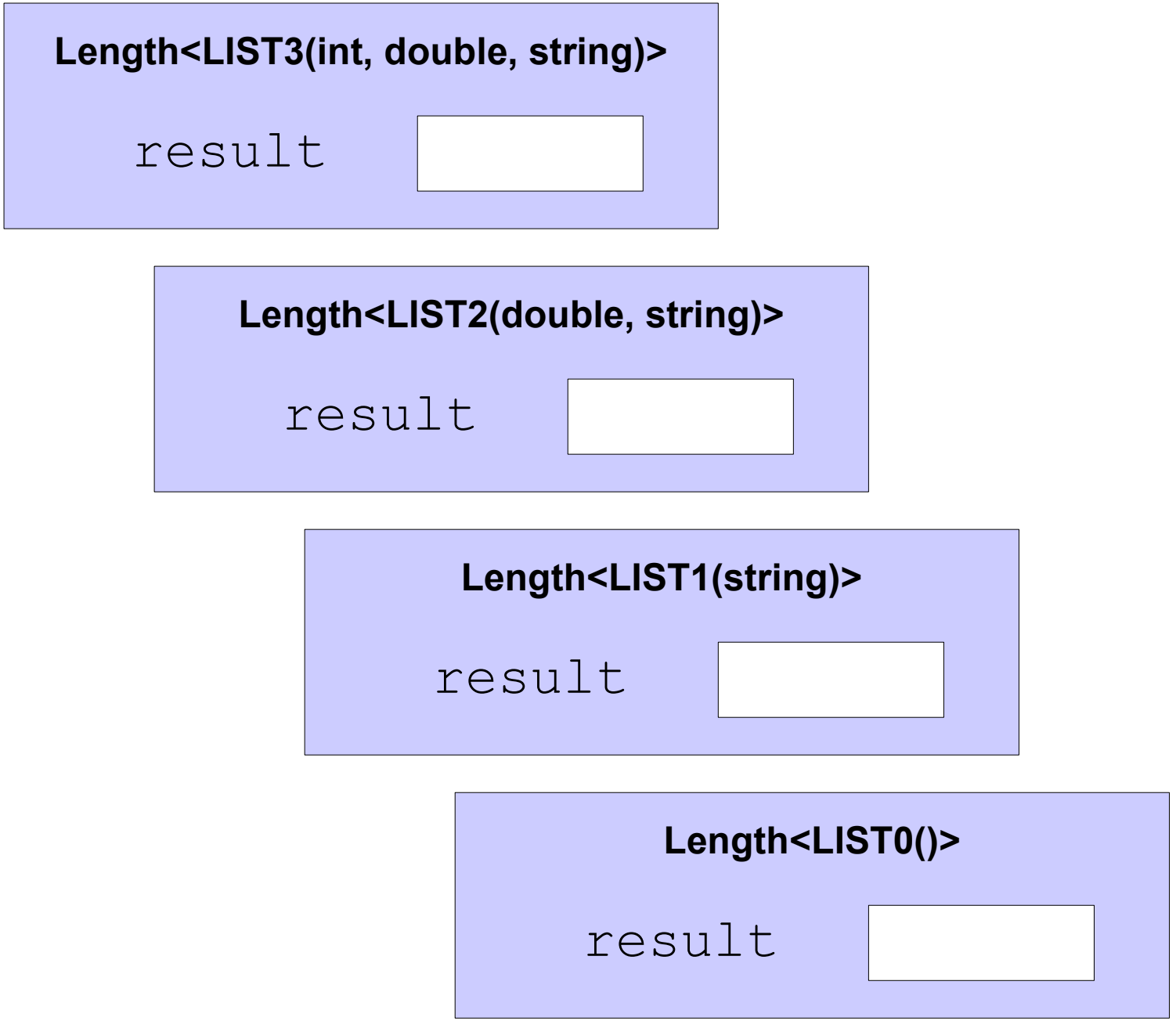
```
template <typename> struct Length;
```

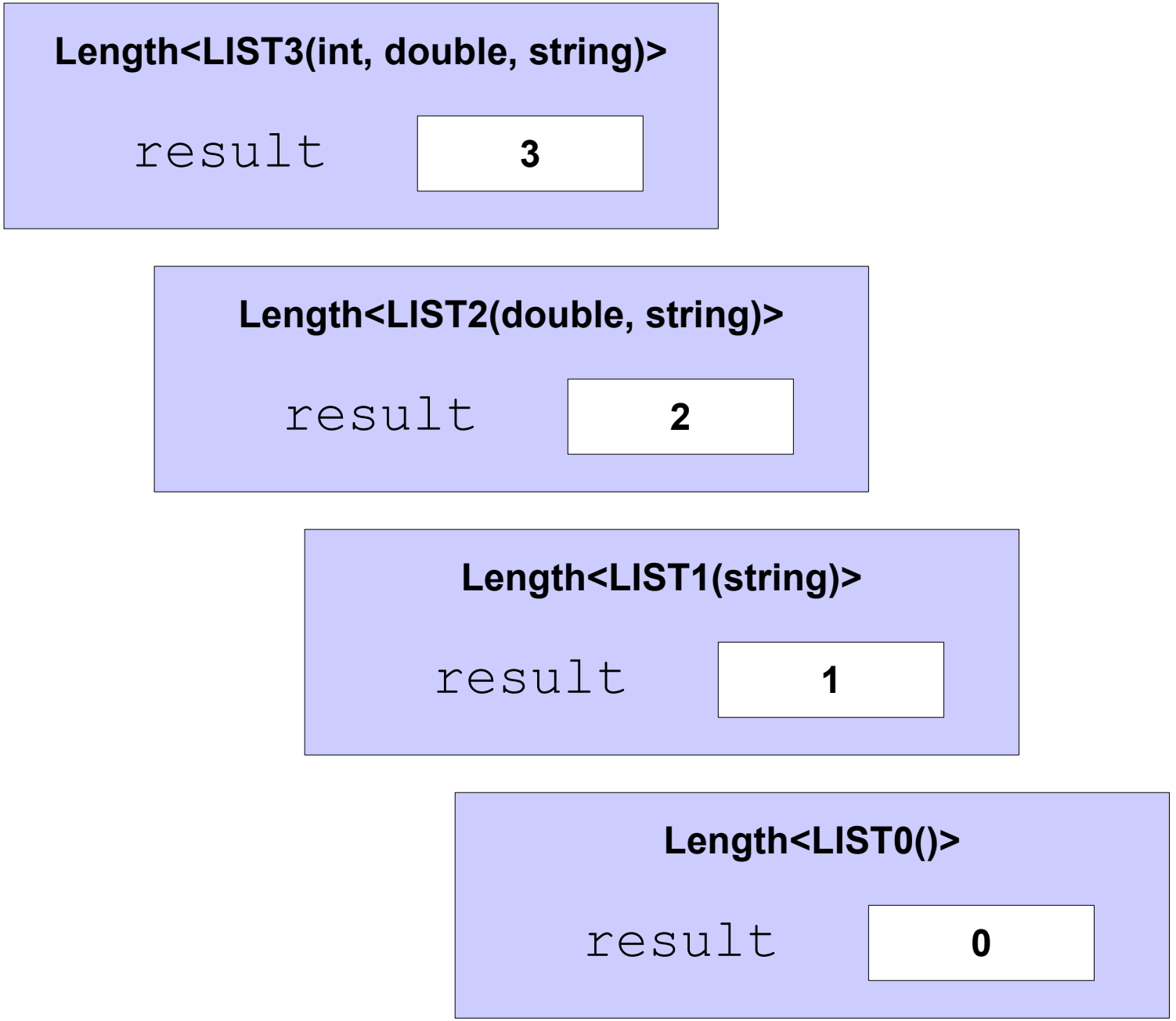
List Recursion with Templates

```
template <typename> struct Length;

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

List 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 Engine { /* ... */ };

class CarEngine: public Engine { /* ... */ };

class DeLoreanEngine: public Engine { /* ... */ };

class JetEngine: public Engine { /* ... */ };

class GoldPlatedJetEngine: public JetEngine { /* ... */ };
```

```
class Brakes { /* ... */ };

class CarBrakes: public Brakes { /* ... */ };

class DeLoreanBrakes: public CarBrakes { /* ... */ };

class JetBrakes: public Brakes { /* ... */ };

class GoldPlatedJetBrakes: public JetBrakes { /* ... */ };
```

```
class Chassis { /* ... */ };

class CarChassis: public Chassis { /* ... */ };

class DeLoreanChassis: public Chassis { /* ... */ };

class JetChassis: public Chassis { /* ... */ };

class GoldPlatedJetChassis: public JetChassis { /* ... */ };
```

```
class VehicleFactory
{
public:
    virtual ~VehicleFactory() {}
    virtual Engine*  createEngine() = 0;
    virtual Brakes*  createBrakes() = 0;
    virtual Chassis* createChassis() = 0;
};
```

```
class VehicleFactory
{
public:
    virtual ~VehicleFactory() {}
    virtual Engine*  createEngine() = 0;
    virtual Brakes*  createBrakes() = 0;
    virtual Chassis* createChassis() = 0;
};

class CarFactory: public VehicleFactory
{
public:
    virtual CarEngine*  createEngine()
    { return new CarEngine; }
    virtual CarBrakes*  createBrakes()
    { return new CarBrakes; }
    virtual CarChassis* createChassis() = 0;
    { return new CarChassis; }
};
```

```
class CPU { /* ... */ };

class IntelCPU: public CPU { /* ... */ };

class AMDCPU: public CPU { /* ... */ };

class AtmelCPU: public CPU { /* ... */ };
```

```
class RAM { /* ... */ };

class DDRRAM: public RAM { /* ... */ };

class DDR2RAM: public RAM { /* ... */ };

class DDR3RAM: public RAM { /* ... */ };
```

```
class HardDrive { /* ... */ };

class SATADrive: public HardDrive { /* ... */ };

class SCSIDrive: public HardDrive { /* ... */ };

class RAIDDrive: public HardDrive { /* ... */ };
```

```
class ComputerFactory
{
public:
   virtual ~ComputerFactory() {}
   virtual CPU*       createCPU() = 0;
   virtual RAM*       createRAM() = 0;
   virtual HardDrive* createHardDrive() = 0;
};
```

Can we automatically generate abstract factories?

Yes!

Idea One: Rewrite Using Tag Dispatching

A Deceptively Simple Class

```
template <typename T> struct Box {};
```

```
class ComputerFactory
{
public:
   virtual ~ComputerFactory() {}
   virtual CPU*       createCPU() = 0;
   virtual RAM*       createRAM() = 0;
   virtual HardDrive* createHardDrive() = 0;
};
```

```
class ComputerFactory
{
public:
    virtual ~ComputerFactory() {}
    virtual CPU*       createImpl(Box<CPU>) = 0;
    virtual RAM*       createImpl(Box<RAM>) = 0;
    virtual HardDrive* createImpl(Box<HardDrive>) = 0;
};
```

```
class ComputerFactory
{
public:
    virtual ~ComputerFactory() {}
    virtual CPU*       createImpl(Box<CPU>) = 0;
    virtual RAM*       createImpl(Box<RAM>) = 0;
    virtual HardDrive* createImpl(Box<HardDrive>) = 0;
    template <typename T> T* create();
};

template <typename T> T* ComputerFactory::create()
{
     return createImpl(Box<T>());
}
```

```
class ComputerFactory
{
public:
    virtual ~ComputerFactory() {}
    virtual CPU*       createImpl(Box<CPU>) = 0;
    virtual RAM*       createImpl(Box<RAM>) = 0;
    virtual HardDrive* createImpl(Box<HardDrive>) = 0;
    template <typename T> T* create();
};

template <typename T> T* ComputerFactory::create()
{
     return createImpl(Box<T>());
}

// Client use:
myFactory->create<CPU>();
```

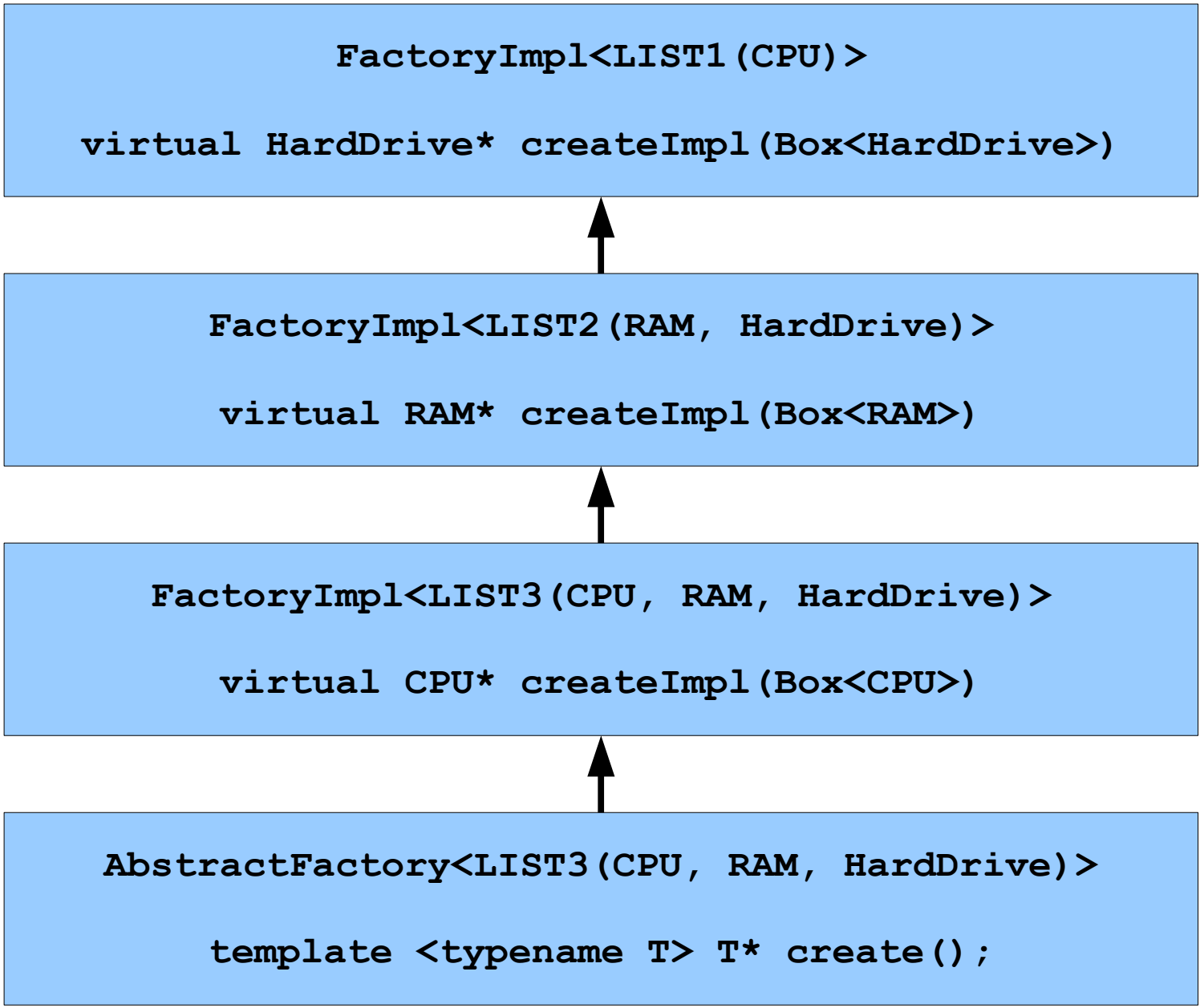
Idea Two: Parameterize the class over a **typelist** of the types to create.

```
template <typename> class FactoryImpl;
```

```
template <typename> class FactoryImpl;

template <typename T> class FactoryImpl<LIST1(T)>
{
public:
    virtual ~FactoryImpl() {};
    virtual T* createImpl(Box<T>) = 0;
}
```

```
template <typename> class FactoryImpl;

template <typename T> class FactoryImpl<LIST1(T)>
{
public:
    virtual ~FactoryImpl() {};
    virtual T* createImpl(Box<T>) = 0;
}

template <typename T, typename Tail>
class FactoryImpl<Cons<T, Tail> >: public FactoryImpl<Tail>
{
public:
    virtual T* createImpl(Box<T>) = 0;
    using FactoryImpl<Tail>::createImpl;
};
```

```
template <typename Types>
class AbstractFactory: public FactoryImpl<Types>
{
public:
    template <typename T> T* create()
    {
        return createImpl(Box<T>());
    }
};
```


FactoryImpl<LIST1(CPU)>
virtual HardDrive* createImpl(Box<HardDrive>)
FactoryImpl<LIST2(RAM, HardDrive)>
virtual RAM* createImpl(Box<RAM>)
FactoryImpl<LIST3(CPU, RAM, HardDrive)>
virtual CPU* createImpl(Box<CPU>)
AbstractFactory<LIST3(CPU, RAM, HardDrive)>
template <typename T> T* create();

```
AbstractFactory<LIST3(CPU,
        RAM, HardDrive)>

virtual CPU*       createImpl(Box<CPU>)
virtual RAM*       createImpl(Box<RAM>)
virtual HardDrive* createImpl(Box<HardDrive>)
template <typename T> T* create()
```

A word of warning...

The Limits of Template Metaprogramming

A Turing machine can simulate C++ templates.

C++ templates can simulate Turing machines.

C++ templates are Turing-complete.

In other words, C++ templates have 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?