Templates in ANSI C++

Advanced Template Programming

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Agenda - Class Templates

- **Run-time vs. compile-time polymorphism**
- Template parameters and arguments
- Static members
- Template specialization
- Nested typedefs, `typename` , and traits

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A Means of Generalization

```
class Stack {
private:   int* v; int* p; int sz;
public:
 Stack(int s) { v = p = new int[sz=s]; }
 ~Stack() { delete[] v; }
 void push(int i) { *p++ = i; }
 int pop() { return *--p; }
 int size() const { return p-v; }
};
```


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A Means of Generalization

```
template <class T>
class Stack {
private:   T* v; T* p; int sz;
public:
 Stack(T s) { v = p = new T[sz=s]; }
 ~Stack() { delete[] v; }
 void push(T i) { *p++ = i; }
 T pop() { return *--p; }
 int size() const { return p-v; }
};
```


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Run-Time Polymorphism

```
class Rotatable {
public:
  virtual void rotate(int) = 0;
};

class Ellipse : public Rotatable {
public:
  Ellipse(int x, int y)
  : Xradius(x), Yradius(y) { }
  virtual void rotate(int);
private:  int Xradius,Yradius;
};
```


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Run-Time Polymorphism

```
void vertical_flip(Rotatable& d)
{ d.rotate(180); }


Ellipse ellipse(100,600);
vertical_flip(ellipse);

Rectangle rectangle(999,500);
vertical_flip(rectangle);
```


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Compile-Time Polymorphism

```
class Ellipse{
public: Ellipse(int x, int y)
        : Xradius(x), Yradius(y) { }
        void rotate(int);
private:  int Xradius,Yradius;
};
class Rectangle {
public: Rectangle(int x, int y)
        : Xedge(x), Yedge(y)  { }
        void rotate(int);
private:  int Xedge, Yedge;
};
```


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Compile-Time Polymorphism

```
template <class Rotatable>
void vertical_flip(Rotatable& d)
{ d.rotate(180); }


Ellipse ellipse(100,600);
vertical_flip(ellipse);

Rectangle rectangle(999,500);
vertical_flip(rectangle);
```


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Run-Time vs. Compile-Time Dispatch

Inheritance-based polymorphism (OOP) can be replaced by templates (GP = generic programming).

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Evaluation OOP vs. GP

Overhead:

- GP: code bloat & compile-time overhead
- OOP: run-time overhead

Conformance to an interface:

- GP: common names
- OOP: a common base class

Integration of built-in types:

- GP: overloaded operators <=> native operators
function objects <=> function pointers
- OOP: not possible

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Defining a Class Template

```
template <class C> class String {
public:    String();
           String(const C*);
           String(const String&);
           C read(int i) const;
private:   struct Srep;
           Srep* rep;
};
```

C is the *template parameter* and stands for a type name.

String is a *class template*.

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Using a Class Template

```
String<char> cs;
String<unsigned char> us;
String<wchar_t> ws;

class Jchar { /* Japanese character */ };
String<Jchar> js;
```

String<char> is the name of a class.

A class generated from a template is called a *template class*.

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Template Instantiation

Generating a class from a class template is called *template instantiation*.

```
void f()
{ String<char> cs;
  cs = "Hello World!"
}
```

generates declaration of:

- classes `String<char>` and `String<char>::Srep`,
- `constructor`, `destructor`, and
- `assignment operator`.

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Template Parameter

Template parameters can be:

- type parameters
- non-type parameters
- template parameters

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Type and Non-Type Parameters

```
template <class T, int s>
class Buffer {
public:  Buffer() : sz(s) {}
private: T v[s];
         int sz;
};

Buffer<char,127> cbuf;
Buffer<Record,8> rbuf;
```


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Non-Type Parameters

A non-type template parameter can be:

- an integral or enumeration type,
- the pointer or reference to an object or function with external linkage, or
- a pointer to member.

A non-type template parameter must not be:

- type `void`, or
- a floating type.

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Arguments to Non-Type Parameters

A non-type template argument can be:

- a constant expression,
- the address of an object or function with external linkage, or
- a non-overloaded pointer to member.

A non-type template argument must not be:

- a string literal.

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Arguments to Non-Type Parameters

```
template <int* p> class X;
int global_i;
X<&global_i>; // ok: external linkage

int a[10];
X<&a[2]> x; // error: address of array element

struct S {int m; static int n;} s;
X<&s.m> x; // error: addr of non-static member
X<&S::n> x; // ok: address of static member
```


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Arguments to Non-Type Parameters

```
enum M {min=-10,max=100000};
template <M m> class X;
X<max> x;      // ok

template <double& d> class X;
X<3.1415> x;   // error, not an l-value
double d;
X<d> x;        // ok
```


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Arguments to Non-Type Parameters

```
template <class Tt, char* p> class X;

X<int,"BMW"> x;     // error: string literal

char p[] = "Mercedes";
X<int,p> x;         // ok
```


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Template Template Parameters

```
template < class K, class V
         , template<class T> class C >
class Map {
  C<K> key;
  C<V> value;
};

template <class T> class myArray { .... };

Map<int,string,myArray> phone_numbers;
Map<string,long,vector> prices;
```


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Template Typedefs

- If your compiler does not support template template parameters, use a *template typedef*.
- Require of the container that is allows *rebinding*:

```
template < class T> class Container {
public:
  template <class U> struct rebind
  { typedef Container<U> other; };
  ...
};
```


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Template Typedefs

Instead of template template parameter:

```
template < class K, class V
         , template<class T> class C >
class Map {
  C<K> key;
  C<V> value;
};
```

use template typedef:

```
template < class K, class V, class C >
class Map {
  C<K> key;
  typename C::rebind<V>::other value;
};
```


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Member Templates

A class can have type members.

```
class ios_base {
public:
  class failure;
  ...
};
```

A class template can have type members that are themselves templates.

```
template <class T> class X {
public:
  template <class U> class Y;
};
```


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Template Typedefs

An example from the standard library:

```
template <class T> class allocator {
public:
  template <class U> struct rebind
  { typedef allocator<U> other; };
};
```

i.e. **`allocator::rebind<aType>::other`**

is a typedef for

`allocator<aType>`

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Template Typedefs

```
template <class T, class Allocator>
class List {
private:
  class Node;
  typedef typename A::rebind<Node>::other
     NodeAllocator; // alias for Allocator<Node>
  ...
};
```


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Parameterization vs. Type

Objects of the same type are distinguished by their object state's value.

If you add a property you can:

- add it to the object state, or
- add new types.

Example: a *Command* class

New properties: *redoable* and *undoable*

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Object Parameterization

Extend the object state by adding flags for *redoable* and *undoable*.

```
class Command {
private: bool redoable, undoable;
public:  Command(..., bool redo, bool undo);
         void redo() { if(redoable) // ...
                       else // do nothing }
         void undo() { if(undoable) // ...
                       else // do nothing }
};
```


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Object Parameterization

Advantage:

— easy, no deep thought required

Drawback:

— "fat" classes with questionable semantics

— hard to maintain

— number of combinations cannot be mastered; consistency checks for flag combinations needed

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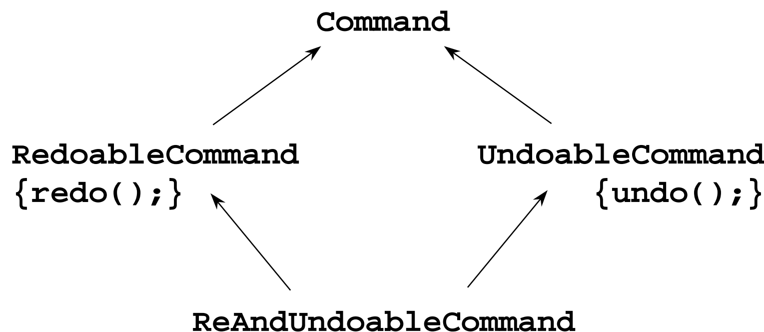
Expressing Properties as Types

Add new types *redoableCommand* and *undoableCommand.*



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Lab: Time Values with Precision

Implement a class representing time values that have a precision, such as years, days, or seconds.

Provide means for calculation the difference between time values.

```
Ptime now;
Ptime Xmas(/* ctor args */);
cout << "It's still " << diff(Xmas,now) <<
"days 'til Xmas!\n";
```


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Lab: Time Values with Precision

1st Idea: Add precision to the object state.

```
Ptime now(seconds);
Ptime Xmas(/* ctor args */,days);
cout << diff(Xmas,now);
```

What is the difference between a time value in seconds and one in days?

Problems with operations that take two or more time values with different precision.

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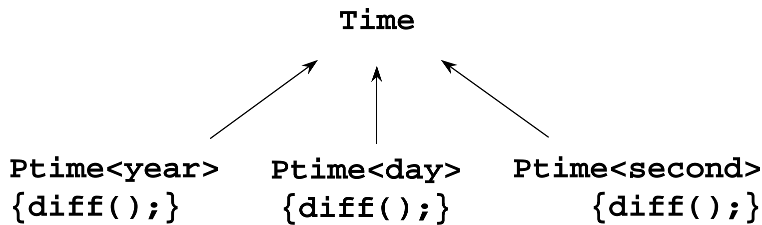
The Derived Classes

Express different precision in terms of different types.



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The `Time` Base Class

```
class Time {
public:
 Time() : _t(time(NULL)) {}
 Time(long sec) : _t(sec) {}

protected:
 const time_t _t;
};
```


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The `Time` Base Class

```
class Time {
public:
 ...
 int getSeconds()
 { return localtime(&_t)->tm_sec; }

 /* and in the same way:  int getMinutes(); etc. */

 string toString()
 { return string(asctime(localtime(&_t))); }
};
```


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The Derived Class Template

```
template<long p>
class PTime : public Time {
public:
     typedef long TUnit;

     PTime<p>() {}
     PTime<p>(long sec) : Time(sec) {}

     TUnit diff(const PTime<p>& rhs)
     { return ((_t/p) - (rhs._t/p)); }
};
```


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For convenience ...

```
const long second = 1;
const long minute = 60 * second;
//  ... and so on ...

void main() {
 PTime<minute> pt1;
 PTime<minute> pt2(time(NULL) - 2*hour);

 cout << pt1.toString();
 cout << pt2.toString();

 cout << "diff is: " << pt1.diff(pt2) << endl;
}
```


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Class Template Specialization

- *general class template:*
```
template<class Key, class Value>
class directory;
```
- *partially specialized class template:*
```
template<class Value>
class directory<long,Value>;
```
- *fully specialized class template:*
```
template<>
class directory<long,string>;
```


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Code Bloat Reduction

```
template <class T>
class Vector {  // general vector type
 T * v;
 int sz;
public:
 Vector();
 Vector(int);

 T& elem(int i) { return v[i]; }
 T& operator[](int i);

 void swap(Vector&);
 // …
};
```


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Code Bloat Reduction

Instantiations of the `Vector` template:

```
Vector<int>    vi;
Vector<Shape*> vps;
Vector<string> vs;
Vector<char*>  vpc;
Vector<Node*>  vpn;
```

For each instantiation the code of the member functions is replicated (=> code bloat).

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Code Bloat Reduction

Many instantiations are for pointer types (to preserve run-time polymorphic behavior).

Specialization can be used for reducing the code bloat: vectors of pointers can share a single implementation.

=> Provide a version of the `Vector` template for pointer types, i.e. a specialization.

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Code Bloat Reduction

Define a specialization for `void*` pointers:

```
template<> class Vector<void*> {
 void** p;
 // ...
 void*& operator[](int I);
};
```

Complete specialization; used for

```
Vector<void*> vpv;
```


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Code Bloat Reduction

Implement a specialization for pointers types:

```
template<class T> class Vector<T*>
: private Vector<void*> {
public:
 typedef Vector<void*> Base;

 Vector() : Base() {}
 explicit Vector(int i) : Base(i) {}

 // ...
};
```


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Code Bloat Reduction

```
template<class T> class Vector<T*>
: private Vector<void*> {
public:
 T*& elem(int i)
 { return static_cast<T*&>(Base::elem(i)); }
 T*& operator[](int i)
 { return
  static_cast<T*&>(Base::operator[](i)); }
 // ...
};
```


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Code Bloat Reduction

Partial specialization; used for

```
Vector<Shape*> vps;  // T is Shape
Vector<int**> vppi;  // T is int*
```

`Vector<T*>` is an *interface* to `Vector<void*>`.

No overhead due to inline expansion.

General technique: Minimize code bloat by maximizing the amount of shared code.

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Retrieving Template Arguments

```
template<class T, int s> class Buffer {
public:
 T& operator[](int i)  { return buf[i];}
};

Buffer<int,11> b; // range [-5,+5]
 for (int i = -5; i<= 5; i++)  b[i+5] = i;

Ranged<Buffer<int,11> > rb(-5,5);
 for (int i = -5; i<= 5; i++)  rb[i] = i;
```


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Retrieving Template Arguments

```
template<class T, int s> class Buffer {
public:
 T& operator[](int i)  { return buf[i];}
};

template<class Cont> class Ranged {
public:
 value_type& operator[](int i)
 { return c[i-lb]; }
};
```

What is the return type of operator[] ???

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Retrieving Template Arguments

We might try this:

```
template<class T, class Cont>
class Ranged
{ public:  T& operator[](int i); };
```

// redundant:

```
Ranged<int, Buffer<int,11> > rb(-5,5);
```

// error-prone:

```
Ranged<string, Buffer<int,11> > rb(-5,5);
```


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Retrieving Template Arguments

There is a relationship between a template class and its template arguments.

It can be expressed by defining:

- nested typedefs for type arguments and
- static constants for non-type arguments.

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Nested Typedefs and Static Constants

```
template<class T, int s> class Buffer {
public:
 typedef T val_t;
 static const int siz = s;

 Buffer() {};

 val_t& operator[](int i)
 { return buf[i];}
private:
  val_t buf[siz];
};
```


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Nested Typedefs and Static Constants

```
template<class Cont> class Ranged {
public:
 class Error {};
 Ranged(int low, int high)
 {if (high-low+1 > Cont::siz) throw Error;
  else                        lb=low;
 }
 typename Cont::val_t& operator[](int i);

private:
 int lb; // lower bound
 Cont c;
};
```


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Nested Typedefs and Static Constants

```
template<class Cont> class Ranged {
public:
 typedef Cont cont_t;
 typedef typename Cont::val_t val_t;
 static const int siz = Cont::siz;
 // ...
};
```


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Typename

Type arguments can have members that are either data members, function members, or nested types.

```
class X {
 static int d;                // data member
 int f(int);                  // function member
 typedef int siz_t;           // type member
};
```


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Typename

```
template <class T> class Adaptor {
 int f(T t)
 { s = T::siz_t(0); // is siz_t a function?
   i = T::f(0);
   x = T::d;
 }
};
```

Unless otherwise stated, an identifer is assumed to refer to something that is *not* a type.

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Typename

```
template <class T> class Adaptor {
 int f(T t)
 { s = typename T::siz_t(0);
   i = T::f(0);
   x = T::d;
 }
};
```


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Typename

You can also use `typename` as an alternative to `class` in a template declaration:

```
template <typename T> class X;
```

instead of

```
template <class T> class X;
```


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Traits

```
char, wchar_t    // built-in character types

struct Jchar {  // Japanese characters
 wchar_t c;
 encoding e;
};
struct Achar {  // Arabic characters
 char c;
 orientation o;
};
```


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Traits

```
template <class Char>
class String {
public:
 // ctors, dtor, ...
 int length() const;
 int compare (const String&);
 // ...
private:
 Char* p;
};
```


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Traits

```
String::length { // for type char
  for (int i=0; p[i] != '\0'; i++);
  return i;
};

String::length { // for any character type
  for (int i=0;
       p[i] != end_of_string_char; i++);
  return i;
};
```


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Traits

```
String::compare(const String& s) {
  // ...
  if ( p[i] < s.p[i] ) // code comparison
                // e.g. 'Z' (0x5A) < 'a' (0x61) in ASCII
};
// in general:
String::compare(const String& s) {
  // ...
  if ( less_than(p[i],s.p[i]) )
};
```


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Traits

```
template <class Char>
struct charTraits {
 static const Char EOS;
 static bool less(Char, Char);
};

template <class Char, class Traits>
class String;
```


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Traits

```
template <class Char, class Traits>
String::length {
 for (int i=0;p[i] != Traits::EOS; i++);
 return i;
};
template <class Char, class Traits>
String::compare(const String& s) {
  // ...
  if ( Traits::less(p[i],s.p[i]) )
};
```


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Traits

```
struct Jchar {  // Japanese characters
 wchar_t c;
 encoding e;
 static const Jchar EOS;
 static bool less(Jchar j1, Jchar j2)
 { return (j1.c < j2.c); }
};
const Jchar::EOS = Jchar(0);
```


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Traits

```
template <class Char>
struct charTraits {
 static const Char EOS = Char::EOS;
 static bool less(Char c1, Char c2)
 { return Char::less(c1,c2); }
};

String<Jchar,charTraits<Jchar> > // OK
String<Achar,charTraits<Achar> > // OK
String<char,charTraits<char> >   // ???
```


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Traits

```
template <>
struct charTraits<char> {
 static const char EOS = '\0';
 static bool less(char c1, char c2)
 { return (c1 < c2); }
};
struct charTraits_Dictionary {
 static const char EOS = '\0';
 static bool less(char c1, char c2)
 { // order according to dictionary sorting rules }
};
```


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Default Template Arguments

```
template <class Char
 , class Traits = charTraits<Char> >
class String;

String<char> // is same as
String<char,charTraits<char> >

// non-default traits:
String<char,charTraits_Dictionary>
```


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Traits

... are a means to express the relationship between a template argument and associated static functionality or values.

character type <=> end-of-string character (value)

character type <=> comparison (functionality)

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Agenda - Function Templates

- **Function template arguments**
- Function template overloading
- Member templates

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Declaring and Using a Function Template

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

void f(vector<int>& vi, vector<string>& vs)
{ sort(vi);     // sort(vector<int>& v);
  sort(vs);     // sort(vector<string>& v);
}
```

sort is a *function template*.

Template arguments are deduced from the function arguments.

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Function Template Arguments

Type and non-type template arguments are deduced from a call, provided the function argument list uniquely identifies the set of template arguments.

```
template <class T, int i>
T lookup(Buffer<T,i>& b,const char* p);

class Record { ... };

int f(Buffer<Record,128>& buf, const char* p)
{ return lookup(buf,p); }
```

`T` is reduced to `Record` and `i` is `128`.

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Deducing Class Template Arguments

Use function template argument deduction for class template argument deduction:

```
template<class T> class X { ... };

template<class T>
inline X<T> make_X(const T& t)
{ return (X<T>(t)); }

make_X(5);          // creates X<int>
make_X("Mary");     // creates X<const char*>
```


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Class Template Arguments

Why is this useful?

```
template<class T>
inline void foo(const X<T>& t);
// we can say:
foo(make_X("Mary"));
// instead of:
foo(X<const char*>("Mary"));
```

Typically used when unnamed objects are passed to a function (function objects, manipulators, pairs).

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Explicit Argument Specification

Function template arguments can be explicitly specified:

```
template<class T> class X { ... };

template<class T>
inline X<T> make_X(const T& t)
{ return (X<T>(t)); }

make_X<double>(5);          // creates X<double>
make_X<string>("Mary");     // creates X<string>
```


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Explicit Specification needed if ...

a template argument cannot be deduced; typically, if the template argument is part of the return type of a function template:

```
template <class T>
T* create(); // make a T and return a pointer to it

int* p create<int>();
```


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Argument Deduction Rules

A type argument T can be deduced if template parameter and argument have the following form:

- —T, const T, volatile T,
- —T*, T&,
- —T[const_expr],
- —class_template_name<T>,
- —type (*)(T), T (*)(args)

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Conversions on the parameter type

The top-level const- or volatile-qualifier of a template type parameter is ignored for type deduction.

```
template <class T> void foo(const T);
int i; foo(i); => T=int
```

If the parameter is a reference type, the type referred to is used for type deduction.

```
template <class T> void foo(T&);
int i; foo(i); => T=int
```


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Conversions on the argument type

If the argument is an array type, the pointer type (produced by array-to-pointer standard conversion) is used for type deduction.

```
template <class T> void foo(T*);
int a[5]; foo(a); => T=int
```

If the argument is a function type, the pointer type (produced by function-to-pointer standard conversion) is used for type deduction.

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Argument Deduction Rules

class_template_name<T>

```
template <class T> void foo(X<T>);
X<int> x; foo(x); => T=int
```

Note:

```
template <class T> void foo(X<T>::Y);
X<int>::Y y; foo(y); => T cannot be deduced
```


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Special Rule for Inheritance

If the type parameter is a reference or a pointer to class of the form class_template_name<arguments>, the argument can be a derived class.

```
template <class T> class B;
template <class T> class D1 : public B<T>;
class D2 : public B<T>;

template <class T> void foo(B<T>&);
D1<int> d1; foo(d1); => T=int, i.e. calls foo(B<int>&)
D2 d2; foo(d2); => T=int, i.e. calls foo(B<int>&)
```


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Not covered ...

- rules for non-type template arguments
- rules for template template arguments
- deduction from pointer-to-member
- special rules for references and pointers (qualification conversions)

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Scope of Template Parameters

The scope of a template parameter extends from its point of definition until the end of its template.

A template parameter can be used in the declaration of subsequent template parameters.

```
template <class T, T* P> class X {};
```

A template parameter can be used in the declaration of subsequent function parameters.

```
template <class T> void foo(T,T::V);
```

`Vector<int> v;  foo(v,5);` => T=Vector<int> and 5 must be convertible to Vector<int>::V

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Function Template Specialization

```
template <class T>
void sort(vector<T>&)
{// Shell sort (Knuth)
 const size_t n=v.size();
 for ( int gap=n/2; 0<gap; gap/=2 )
   for ( int i=gap; i<n; i++ )
     for ( int j=i-gap; 0<=j, j-=gap )
       if ( v[j+gap] < v[j] )
         swap(v[j], v[j+gap]);
}
```


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Function Template Specialization

sort<char*> does not sort a **Vector<char*>** correctly, because it compares the addresses of two strings, not the character sequences pointed to.

Replace *v[j+gap] < v[j]* by *less(v[j+gap], v[j])* and specialize **less()** for **char***:

```
template<> bool less<const char*>
 (const char* a, const char* b)
{ return (strcmp(a,b) < 0); }
```


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Function Template Specialization

... is useful for

- more efficient alternatives to a general algorithm for a certain template argument, e.g. swap(), and
- for "irregular types" that lead to undesired results, e.g. less(); often true for pointers and arrays.

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Function Overloading

```
void compare(string, string);
void compare(string, const char*);
void compare(string,date);

string s;
compare(s,"Xmas");
compare(s,date(12,24,98));
```


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Function Template Overloading

```
template<class T> T sqrt(T);
template<class T>
complex<T> sqrt(complex<T>);
double sqrt(double);

void f(complex<double> z)
{ sqrt(2);      // sqrt<int>(int)
  sqrt(2.0);    // sqrt(double)
  sqrt(z);      // sqrt<complex<double>>(complex<double>)
}
```


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Function Template Overload Resolution

For each function template find the specialization that is best for the set of function arguments.

Then apply usual function overload resolution rules to these specializations and all ordinary functions.

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Member Templates

```
class IntStore {
public:
  // ...
 void add(const int* s, int n)
 { for (int i=0; i<n; i++)
       a[cur++] = s[i];
 }
private:
 int a[10];
 int cur;
};
```

```
IntStore buf;
short sarr[] = {10,20};
buf.add(sarr,2);  // error:
// cannot convert array of shorts to pointer to int
```


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Member Templates

A class can have members that are templates.

```
class IntStore {
public:
 template <class T>
 void add(const T* s, int n)
 { for (int i=0; i<n; i++)
      a[cur++] = s[i]; // assign T to int
 }
};
```

```
IntStore buf;
short sarr[] = {10,20};
buf.add(sarr,2);  // IntStore::add<short>
```


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Member Templates

A class template can have members that are themselves templates.

```
template <class Int>
class Store {
public:
 template <class Cont>
 void add(const Cont& s, int n=s.len())
 { for (int i=0; i<n; i++)
     a[cur++] = s[i];// assign containter element to Int
 }
};
```


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Member Templates

```
Store<long> buf;

long arr[];
buf.add(arr,3);  // Store<long>::add<long*>

Store<int> buf2;
buf.add(buf2);   // Store<long>::add<Store<int> >
```


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Member Templates

Member templates cannot be virtual.

```
class Shape {
 template<class T>
 virtual bool intersect(const T&)
  const = 0; // error: virtual template
};
```

The linker would have to add a new entry to the virtual function table each time `intersect()` is called with a new argument type.

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Generic Conversions

```
template <class Scalar>
class complex {
 Scalar re, im;
public:
 template <class T>
 complex(const complex<T>& c)
 : re(c.re), im (c.im) {}
 // ...
};       // requirement: a Scalar can be initialized by a T
```


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Generic Conversions

```
complex<float> cf(0,0);
complex<double> cd = cf;  // ok: converts float
                          // to double

class Quad {  // no conversion to int
};
complex<Quad> cq;
complex<int> ci = cq;  // error: cannot convert
                       // Quad to int
```


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Generic Conversions

Constructor templates allow "generic conversions":
We can create a complex<X> from a complex<Y>, if data members of X can be created from data members of Y.

Note:

Constructor templates are never used for generating a copy constructor. You must explicitly define it if you need one.

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Templates and Inheritance

```
class Shape { /*...*/ };
class Circle : public Shape { /*...*/ };
class Triangle : public Shape { /*...*/ };

void f(Vector<Shape*>& v)
{ ... v[i]->draw(); ... }
Vector<Circle*> v;
f(v);// error: type mismatch
     // Vector<Circle*> cannot be converted to Vector<Shape*>
```


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Template Conversions

```
template <class T>
class Ptr {  // smart pointer
 T* _p;
public:
 Ptr(T*);
 template <class U>
 operator Ptr<U> ();  // convert Ptr<T> to Ptr<U>
 // ...
};
```


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Template Conversions

```
Ptr<Circle> pc;
Ptr<Shape> ps = pc;  // should work,
  because Circle is derived from Shape
Ptr<Circle> pc2 = ps;  // should give error

Ptr<int> pi;
Ptr<void> pv = pi;  // should  work,
  because all pointer types can be converted to
  void*
```


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Template Conversions

```
template <class T> class Ptr {
private: T* _p;
public:  Ptr(T* p) : _p(p) {}
         template <class U>
         operator Ptr<U> ()
         { return Ptr<U>(_p); }
};
```

The return statement will only compile if `_p` (which is of type `T*`) can be an argument to the constructor of `Ptr<U>`.

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