Design Patterns in C++
Template metaprogramming

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Outline

1. C++ Template meta-programming
2. Techniques
3. Detecting inheritance relationship
4. Lists of types
A template is a way to generate code. The following program generates three functions

```cpp
template<typename T>
void swap(T& a, T&b) {
    T t = a;
    a = b;
    b = t;
}

int main() {
    char z = 1, w = 2;
    int x = 3, y = 4;
    double r = 5, s = 6;

    swap(z, w);
    swap(z, y);
    swap(r, s);
}
```
A template is a way to generate code. The following program generates three functions:

```cpp
template<typename T>
void swap(T& a, T&b) {
    T t = a;
    a = b;
    b = t;
}

int main() {
    char z = 1, w = 2;
    int x = 3, y = 4;
    double r = 5, s = 6;

    swap(z, w);
    swap(z, y);
    swap(r, s);
}

void swap(char &a, char &b) {
    char t = a;
    a = b;
    b = t;
}

void swap(int &a, int &b) {
    int t = a;
    a = b;
    b = t;
}

void swap(double &a, double &b) {
    double t = a;
    a = b;
    b = t;
}
```
Template members

- It is also possible to make one member function a template

```cpp
class MyClass {
    ...

public:
    template<class V>
    void accept(V &v) {
        v.visit(*this);
    }
};
```

- The member function is not compiled if it is not used
- Important restriction: cannot make template virtual methods
Incomplete instantiation

- Remember that template classes are not generated if not used.
- This is also valid for members of template classes

```cpp
template <class T>
class MyClass {
    T *obj;
public:
    MyClass(T *p) : obj(p) {}

    void call_fun() {
        obj->fun();
    }

    T* getPtr() { return ptr; }
};

MyClass<int> my(new int(6));
cout << my.getPtr() << endl;
```

- In the code above, function `call_fun()` is never called, so the code is correct (it would give error on an `int` type!)
It is possible to require a parameter to be a template:

```cpp
template <template <class Created> <class CreationPolicy>
class WidgetManager : public CreationPolicy<Widget> {
    ...

public:
    void fun() {
        Widget *w = create();
    }
};

template <class T>
class DynamicCreation {
public:
    T* create() { return new T; }
};
```
**template parameter** Created can be entirely omitted

```cpp
template <template <class> class CreationPolicy>
class WidgetManager : public CreationPolicy<Widget> {

    ...  

public:
    void fun() {
        Widget *w = create();
    }
};
```
Another important feature is template specialization. Given a template with one or more parameters:

- we can provide special versions of the template where some of the parameter is assigned specific types

```cpp
// general version
template<class T> class MyClass {
    ...
};

// special version with T = int
template<> class MyClass<int> {
};

MyClass<double> m;
// uses the general version

MyClass<int> n;
// uses the special version
```
When we have more than one type parameter, we can specialize a subset of the types

```cpp
// general version
template<typename T, typename U> class A { ... };

// specialization on T
template<typename U> class A<int, U> { ... };

// specialization on both
template<> class A<int, int> { ... };

A<double, double> a; // uses general version
A<int, double> b; // uses first specialization
A<int, int> a; // uses second specialization
```
Be careful with partial template specialization

```cpp
// general version
template< typename T, typename U > class A { ... };

// specialization on T
template< typename U > class A<int, U> { ... };

// specialization on U
template< typename T > class A<T, int> { ... };

A<int, int> a; // Error! ambiguous
```
Partial template specialization does not apply to functions

```cpp
template <class T, class U> T fun(U obj) {...}

// the following is illegal
template <class U> void fun<void, U>(U obj) {...}

// the following is legal (overloading)
template <class T> T fun(Window obj) {...}
```
Integral template parameters

- The parameters of a template can be constant numbers instead of types
  - By constant I mean that they are known at compile time

```
template <unsigned n>
struct Num {
    static const unsigned num = n;
};

Num<5> x;
Num<8> y;

cout << x.num << endl;
cout << y.num << endl;
cout << "sizeof(Num<5>) = " << sizeof(x) << endl;
```

- **Note 1**: the output of last instruction is 1
The parameters of a template can be constant numbers instead of types

- By constant I mean that they are known at compile time

```cpp
template <unsigned n>
struct Num {
    static const unsigned num = n;
};

Num<5> x;
Num<8> y;

cout << x.num << endl;
cout << y.num << endl;
cout << sizeof(Num<5>) = " << sizeof(x) << endl;
```

**Note 1:** the output of last instruction is 1

**Note 2:** we can also make calculation with n, but of course they must be solved at run-time
We can also specialize on certain numbers

```cpp
template <unsigned n>
struct VarNum {
    void p() { cout << "Number is " << n << endl; }
};

template <>
struct VarNum<0> {
    void p() { cout << "N is zero!!" << endl; }
};
```
The “code generation engine” that is embedded in the C++ compiler can actually make some simple calculation, using recursion.

The key trick is combine specialization with integral parameters.

This is calculation made by the compiler, not at run-time!

Here is how to compute the factorial:

```cpp
template <int n>
struct Fact {
    enum { value = n * Fact<n-1>::value };
};

template <>
struct Fact<1> {
    enum { value = 1 };
};

cout << Fact<5>::value << endl;
```

See the code.
Very simple types

- C++ does not require much for defining a type
- The following ones are all different types

```cpp
struct Simple {};  
struct AnotherSimple {};  
struct YetAnotherSimple {};  
```

- Of course, you cannot do much with such types, except telling the compiler that a certain type exist
- at run time there is no code associated with it
- `sizeof(Simple)` returns 1
Look at this code

```cpp
template<
typename T>
struct Cont {
    typedef T MyType;
};

Cont<int>::MyType anInteger = 2;
Cont<double>::MyType aDouble = 0.5;
```

- Cont does not contain anything, only the definition of another type, which is only used by the compiler, but not at run-time
- Cont<int> is not different from Simple
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It is sometimes necessary generate new types from integers. Here is how to do it:

```cpp
template<int v>
struct Int2Type
{
    enum {value = v};
};
```

This template generates a new type for each integral number it is passed.

- we will use this in the following to do a “compile-time dispatch”
  - You want to select one of several functions to be called, and you want to do this selection at compile time, depending on a compile-time constant
Run-time dispatching is something that depends on the values of certain variables that are only known at run-time.

- It can be performed by using \texttt{if-then-else} or \texttt{switch-case} statements.
- It can also be performed using virtual functions and dynamic binding.
- The cost of doing this is often negligible.

Of course, you can also do run-time dispatching based on compile-time constants.

- However, this is not always possible.
Selection example

Suppose you are designing a container

```cpp
template<class T> MyContainer { ... };
```

You want to provide the ability to copy objects of type `MyContainer` by copying all contained objects to duplicated contained objects, you can call the copy constructor, but this may not be always available

- Suppose instead that class `T` provides a virtual `clone()` method

you would like your container to be generic, i.e. a container that can be used both for objects with copy constructors (non-polymorphic), and objects with clone (polymorphic)

- therefore, the choice of calling one of the two functions is based on a compile-time boolean constant `isPolymorphic`
The following code does not work:

```cpp
template <class T, bool isPolymorphic>
class MyContainer {
    ...
    void function() {
        T *p = ...;
        if (isPolymorphic) {
            T *p2 = p->clone();
            ...
        } else {
            T *p2 = new T(*p);
            ...
        }
    }
};
```

why?
Solution:

```cpp
template<class T, bool isPolymorphic>
class MyContainer {
private:
    void function(T* p, Int2Type<true>) {
        T *p2 = p->clone();
        ...
    }
    void function(T *p, Int2Type<false>) {
        T *p2 = new T(*p);
        ...
    }
public:
    void function(T *p) {
        function(p, Int2Type<isPolymorphic>());
    }
};
```

The basic trick is that only one between the two private function will be compiled, the right one!
Unfortunately, it is not possible to apply partial template specialization to functions

- You can simulate this with overload

**Example:**

```cpp
// creates a class by invoking the constructor, // which takes one argument
template<class T, class U>
T *create(const U &arg) {
    return new T(arg);
}
```

Now, suppose you want to specialize it by using the same function on objects of class Widget, whose constructor takes two arguments, the second one must always be -1
Wrong:

```cpp
template<class T, class U>
T *create(const U &arg) {
    return new T(arg);
}

template<class U>
Widget *create<Widget, U>(const U &arg) {
    return new Widget(arg, -1);
}
```
Special version

- Wrong:

  ```cpp
  template<class T, class U>
  T * create(const U &arg) {
    return new T(arg);
  }
  
  template<class U>
  Widget * create<Widget, U>(const U &arg) {
    return new Widget(arg, -1);
  }
  ```

- Correct:

  ```cpp
  template<class T, class U>
  T * create(const U &arg, T) {
    return new T(arg);
  }
  
  template<class U>
  Widget * create(const U &arg, Widget) {
    return new Widget(arg, -1);
  }
  ```
To eliminate the overhead of creating a dummy parameter to pass by value, we can use the following "trick":

```cpp
template<typename T>
struct Type2Type {
    typedef T OriginalType;
};

template<class T, class U>
T *create(const U &arg, Type2Type<T>) {
    return new T(arg);
}

template<class U>
Widget *create(const U &arg, Type2Type<Widget>) {
    return new Widget(arg, -1);
}

string *ps = create("Hello", Type2Type<string>());
Widget *pw = create("Hello", Type2Type<Widget>());
```
Suppose that in MyContainer we want to store objects if the type is non-polymorphic, and pointers to objects if the type is polymorphic.

For simplicity, suppose that internally we use a vector.

What type should we give to the vector? T or T*?

We can make use of a “select” structure.

```cpp
template <bool flag, typename T, typename U>
struct Select {
    typedef T Result;
};

template<
    typename T, typename U>
struct Select<false, T, U> {
    typedef U Result;
};
```
template <typename T, bool isPolymorphic>
class MyContainer {
    typedef typename Select<isPolymorphic, T*, T>::Result ValueType;
    ...
    std::vector<ValueType> objects;
    ...
};
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How to detect type relationship

- Sometimes it is important to be able to understand if two generic types T and U are in a relationship of inheritance
  - for example, we would like to know if U derives from T
  - this may be useful sometimes when we have to check and enforce some properties on types in our generic algorithms at compile time
  - also, some algorithms may be optimized if an inheritance relationship exists

- inheritance is a special case of convertibility between pointers

- there are only three cases in which we can automatically convert U* to T*:
  - T and U are the same case
  - T is a public base class of U
  - T is void (because any pointer can be converted to void *)

- So, now the problem is how to detect if an automatic conversion exists at compile time
**Using sizeof**

- `sizeof()` is a compile time mechanism of C/C++ to compute the size of a type. Since it is done at compile time, its argument is not actually executed at run-time, but it is only evaluated.
  - For example, if the argument contains a function call, it does not actually invoke the function, but it only checks its type.

```c
int returnInt(); // not implemented
sizeof(returnInt()); // equivalent to sizeof(int)
```

- `sizeof()` returns an integer that we can use in comparisons, so let's define two types of different size.

```c
typedef char Small;
class Big { char dummy[2]; };
```
template <typename T, typename U>
class Conversion {
    typedef char Small;
    class Big { char dummy[2]; };
    static Small Test(U);
    static Big Test(...);
    static T MakeT();

public:
    enum { exists = sizeof(Test(MakeT())) == sizeof(Small) };
};

- We try pass an object of type \( T \) to a function that takes a \( U \) or anything else;
  - If the conversion exist, the first version is used which returns a Small
We can define (also in the previous code) an additional enum value `sameType` and provide the following specialization:

```cpp
template<typename T>
class Conversion {
public:
  enum { exists = true, sameType = true; }
};

#define SUPERSUBCLASS(T, U)  
  (Conversion<const U*, const T*>*::exists &&  
   !Conversion<const T*, void*>::sameType)

#define SUPERSUBCLASS_STRICT(T, U)  
  (SUPERSUBCLASS(T, U) &&  
   !Conversion<const U*, const T*>*::sameType)
```
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4 Lists of types
A type list is a simple list of any number of types (from 1 to any)
At compile time the user instantiates the typelist with the desired types
however, C++ does not support a variable number of template arguments
Therefore, we have to simulate it
the basic structure is very simple:

```cpp
struct NullType {};

template<typename H, typename T>
struct TypeList {
    typedef H Head;
    typedef T Tail;
};
```
Defining typelists

- **A few examples:**

```cpp
// two types, int and double
TypeList
<
  int,
  TypeList<
double, NullType>
>
intDoubleVar;

// three types, int, double and char
TypeList
<
  int,
  TypeList<
double,
  TypeList<char, NullType>
>
>
intDoubleCharVar;
```
Obtaining types

- It is annoying to carry on a list in expanded form
- We can use defines to simplify the writing a little bit

```c
#define TYPELIST_1(t1) TypeList<t1, NullType>
#define TYPELIST_2(t1, t2) TypeList<t1, TYPELIST_1(t2)>
#define TYPELIST_3(t1, t2, t3) TypeList<t1, TYPELIST_2(t2, t3)>
...

TYPELIST_3(int, double, char) intDoubleCharVar;
```

- Remember: the size of variable `intDoubleCharVar` is ...
Obtaining types

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- We can use defines to simplify the writing a little bit

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#define TYPELIST_1(t1) TypeList<t1, NullType>
#define TYPELIST_2(t1, t2) TypeList<t1, TYPELIST_1(t2) >
#define TYPELIST_3(t1, t2, t3) TypeList<t1, TYPELIST_2(t2, t3) >
...

TYPELIST_3(int, double, char) intDoubleCharVar;
```

- Remember: the size of variable intDoubleCharVar is ... 1!!
- so, what is the purpose of this?
  - a typelist is not a “useful” class, because it does not contain code
  - it is only useful to help the compiler to generate code
  - it is a trick to pass “types” instead of “values”
How to use it

- A type list can be used to obtain the various types in the list

```cpp
typedef TYPELIST_3(int, double, char) ThreeTypes;

ThreeTypes::Head param1; // this will be an int
ThreeTypes::Tail::Head param2; // this will be a double
ThreeTypes::Tail::Tail::Head param3; // this will be a char
```

- It is quite ugly, but it works: I now defined three variables with the right type
- Almost there, we are missing a few steps
Example

- Suppose I need to write the code for a structure that must contain three data members
- however, I do not know “a-priori” the type of these members
- I would like to write generic, template code that instantiates the structure with the right types

```cpp
template <typename T>
struct MyStruct { 
    T::Head param1;
    T::Tail::Head param2;
    T::Tail::Tail::Head param3;
};

MyStruct< TYPELIST_3(int, double, char) > s;
s.param1 = 5;
s.param2 = 0.75;
s.param3 = 'a';
```
How to simplify type extraction

```cpp
template<typename H, typename T, unsigned index>
struct TypeAt {
    typedef typename TypeAt_<typename T::Head, typename T::Tail, index-1>::Result Result;
};

// specialization for index == 0
template <typename H, typename T>
struct TypeAt<H, T, 0> {
    typedef H Result;
};

// if it reaches the end of the list with index > 0...
template <typename H, unsigned index>
struct TypeAt<H, NullType, index> {
    typedef NullType Result;
};

// special case: the last element
template <typename H>
struct TypeAt<H, NullType, 0> {
    typedef H Result;
};

#define TYPEAT(L, i) typename TypeAt<typename L::Head, typename L::Tail, i>::Result
```

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How to use it

- Quite difficult to understand
  - However, once it works, it’s already there, you do not need to understand how it works every time
  - you only need to know how to use it

```cpp
template<typename L>
struct MyStruct {
    TYPEAT(L, 0) param1;
    TYPEAT(L, 1) param2;
    TYPEAT(L, 2) param3;
};

...
MyStruct< TYPELIST_3(int, double, char) > s;
s.param1 = 1;
s.param2 = 0.75;
s.param3 = 'c';
```
Count elements in the typelist

template<
typename H, typename T>
struct TypeListSize {
    enum { Result = TypeListSize<T::Head,
        T::Tail,
        index-1>::Result + 1 };
};

template<
typename H>
struct TypeListSize<H, NullType> {
    enum { Result = 1 };
};

template<
typename T>
struct TypeListSize<NullType, T> {
    enum { Result = 0 };
};

#define TYPELISTSIZE(L) TypeListSize<L::Head, L::Tail>::Result