C++ Template Meta Programming

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Outline

Reference: K. Czarnecki, U. W. Eisenecker, "Generative Programming: Methods, Tools, and Applications", Chapter 10

What Is Template Metaprogramming?

- At this moment is quite difficult to give a definition. First define two terms:
  - Template
  - Metaprogramming

What Are Templates?

- Templates are a C++ technique to create Generic Code
- Some templates are in C++ Standard and can be found in STL
- The first version of STL architecture was made by Alexander Stepanov
- Some examples of templates in STL are: `std::vector`, `std::map` and `std::list`

C++ Templates Example: Very Simple Array

```
template <typename T, unsigned int L>
class VerySimpleArray{
    T a[L];
  public:
    VerySimpleArray(){
       for(int i=0; i < L; ++i) a[i] = T();
    }
    T& Get(unsigned int i){return a[i];}
    void Set(unsigned int i, T& v){a[i] = v;}
};

VerySimpleArray<float, 42> vsa;
vsa.Set(3, 6.0);
```

C++ Templates Example: Template specialization


```
template<typename _Tp, typename _Alloc=allocator<_Tp> >
  class vector : protected _Vector_base<_Tp, _Alloc>
  {
    __glibcpp_class_requires(_Tp, _SGIAssignableConcept)

    typedef _Vector_base<_Tp, _Alloc>               _Base;
...
template <typename _Alloc>
  class vector<bool,_Alloc>: public _Bvector_base<_Alloc>
  {
  public:
    typedef bool value_type;
...
```

/usr/include/c++/3.3.2/bits/std_vector.h
/usr/include/c++/3.3.2/bits/std_bvector.h

What Is Metaprogramming?

- Metaprogramming means writing programs that can modify other programs or themselves
- The modification can happen at run time or at compile time
- Compilers are an example of metaprograming: they take a program in an input language (C, Java...) and produce another program (with same semantic) in an output language (machine code, bytecode...)
- Metaprograms have three advantages:
  - Produce code quickly
  - Lift abstraction
  - Produce correct code (if the metaprogram is correct)

What Is Template Metaprogramming?

- Now it is time for the replay, Template Metaprograming is...
- Producing metaprograms in C++ using templates
- But... wait a second... why do I need Template Metaprogramming?

The Need For Speed

```
int Fact(int x){
  int acc = 1;
  for(;x>0;--x) acc*=x;
  return acc;
}

int a, b;
a = read_int_from_stdin();
b = Fact(a); //we compute at run time
...
b = Fact(5); //we can compute at compile
             //time but we do not
```

We pay the time to compute something that is a constant!

Naive Solution

```
...

b = 120; //b = Fact(5);
```

The solution is not elegant. We need to place a lot Magic Numbers in the code. And the magic number does not keep its meaning ($5! = 120$ or $42 + 78 = 120$ ...).
We can use a `#define` but it is not better: we must provide a define for all possible value of the input of `Fact`.

```
...
#define FACT_4  (24)
#define FACT_5  (120)
...

b = FACT_5;
```

Template Metaprogramming Solution

- The general idea is to use the compiler to do some computation at compile time.
- To do this we need a only a C++ compiler that provides Templates
- This can be done because the compiler, when compiles Templates, produces code
- If we produce the right code (e.g. the sum of constant terms), the compiler optimize and do constant folding
- But we can do more...

First Step


```
template< int i>
struct C {
  enum { RES = i };
};

cout << C<2>::RES;
```

`C<2>::RES` is substituted by the compiler with 2: it is a cost ant and we can optimize.

Back To Factorial


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

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

int b = Fact<5>::RET; // == 120
```

To do computation we must unroll templates: a kind of recursion

Where is The Trick?

```
enum { RET = 5 * Fact<4>::RET };
enum { RET = 5 * 4 * Fact<3>::RET };
enum { RET = 5 * 4 * 3 * Fact<2>::RET };
enum { RET = 5 * 4 * 3 * 2  * Fact<1>::RET };
enum { RET = 5 * 4 * 3 * 2  * 1 };
enum { RET = 120 };

b = 120; //Fact<5>::RET;
```

C++ Template Metaprogramming Operators


```
template <bool C, class T, class E>
struct IF {
  typedef T RET;
};

template <class T, class E>
struct IF<false, T, E> {
  typedef E RET;
};
```

C++ Template Metaprogramming Operators

```
class CopyingGC {
public:
  void Collect()  /*...*/
};

class MarkAndSweepGC {
public:
  void Collect()  /*...*/
};

IF<GC == COPY, CopyingGC, MarkAndSweepGC>::RET gc;
gc.Collect();
```

C++ Template Metaprogramming Functions

```
Template<int n1, int n2>
struct Max {
  enum { RET = (n1 > n2) ? n1 : n2 };
};

cout <≤ Max<42, 6>::RET; //prints 42
```

C++ Template Metaprogramming Code Generation

```
inline int Power(const int x, int n){
  int p = 1;
  for(;n>0; --n) p *= x;
  return p;
}
```

We can specialize Power code for particular cases:

```
inline int Power3(const int x){
  int p = 1;
  p *= x;
  p *= x;
  p *= x;
  return p;
}
```

C++ Template Metaprogramming Code Generation

```
template<int n>
inline int Power(const int x){
   return Power<n-1>(x) * x;
}

template<>
inline int Power<1>(const int x){
   return 1;
}

template<>
inline int Power<0>(const int x){
   return 1;
}

cout << Power<4>(m);
```

C++ Template Metaprogramming Code Generation

```
cout <≤ Power<4>(m);

cout <≤ Power<3>(m) * m;

cout <≤ Power<2>(m) * m * m;

cout <≤ Power<2>(m) * m * m * m;

cout <≤ Power<1>(m) * m * m * m * m;

cout <≤ 1 * m * m * m * m;

cout <≤ m * m * m * m;
```

C++ Template Metaprogramming Loop Unrolling(1)


```
template<int n, class B>
struct FOR {
   static void loop(int m) {
      for (int i = 0; i < m/n; i++) {
         UNROLL<n, B>::iteration(i * n);
      }
      for (int i = 0; i < m%n; i++) {
         B::body(n * m/n + i);
      }
   }
};
```

C++ Template Metaprogramming Loop Unrolling(2)


```
template <int n, class B>
struct UNROLL{
   static void iteration(int i) {
      B::body(i);
      UNROLL<n-1, B>::iteration(i + 1);
   }
};

template <class B>
struct UNROLL<0, B> {
   static void iteration(int i){ }
};
```

C++ Template Metaprogramming Code Generation

- We can generate code for multiple purposes:
  - Vector operations
  - Math functions
  - ...
- Exercise: try to write some C++ Template Metaprograming functions and control structures (`WHILE`)

C++ Template Metaprogramming Data Structures

- Lisp lovers know very well this code:
  `(cons 1 (cons 2 (cons 3 (cons 4 (cons nil)))))`
- The previous code represents the list:
  `(1 2 3 4)`
- C++ Template Metaprogrammers have this too...

C++ Template Metaprogramming Data Structures

```
template <int n, class T>
struct Cons {
  enum { item = n };
  typedef T next;
};
struct Nil { };

typedef Cons<1, Cons<2, Nil()> > V;
//V::item == 1;
//V::next::item == 2;
//V::next::next == Nil;
```

Exercise: try to create a `Tree`

Total Loop Unroll

- We want to copy all elements of an `int` array into another
- We want to do it fast
- We can use an approach similar to `FOR` template metastructure

Total Loop Unroll (C++ Code 1)


```
template<int N>
inline void Copy(int n, int* from, int* to){
  for (int i = 0; i < n/N; ++i) {
    TMP_COPY_UNROLL<N>::iteration(i * N, from, to);
  }
  for (int i = 0; i < n%N; ++i) {
    *to++ = *from++;
  }
}
```

Total Loop Unroll (C++ Code 2)

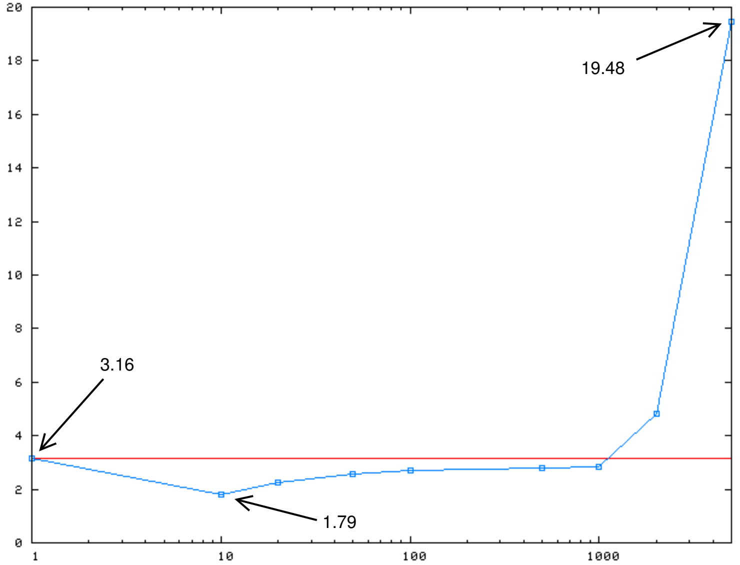
```
template <int N>
struct TMP_COPY_UNROLL {
  static void iteration(int i, int *f, int* t){
      *t++ = *f++;
      TMP_COPY_UNROLL<N-1>::iteration(i + 1, f, t);
  }
};

template <>
struct TMP_COPY_UNROLL<1> {
  static void iteration(int i, int* f, int* t){
     *t++ = *f++;
  }
};
```

Performance Results

- We measure the "Execution Time" of various values of unroll and...
- ...surprise

# Loop Unroll	Execution Time
1	3.16
10	1.79
50	2.23
100	2.70
500	2.81
1000	2.84
2000	4.83
5000	19.48

Performance Results (Chart)



Performance Results (An Explanation)

- Why?
- Loop unroll produce very big executable files
- Big executable files cannot be kept in the code cache
- We have a lot of cache misses

Boost.MPL

- Meta Programming Library is part of Boost library
- Boost is a portable C++ library that provides a big number utilities:
  - Threads
  - Containers
  - Math
  - I/O
  - Much more (circa 70 sub libraries)...
- "The Boost.MPL library is a general-purpose, high-level C++ template metaprogramming framework of compile-time algorithms, sequences and metafunctions"

Boost.MPL (Example)


```
typedef list_c<int,0,1,2,3,4,5,6,7,8,9>::type numbers;
typedef list_c<int,0,1,2,3,4>::type answer;
typedef copy_if<numbers,
               vector_c<int>,
               push_back<_1,_2>,
               less<_1,int_<5> >
>::type result;

BOOST_STATIC_ASSERT(size<result>::value == 5);
BOOST_STATIC_ASSERT((equal<result,answer>::type::value));
```

Conclusions

- C++ template metaprogramming is a powerful method to do computational tasks at compile time
- First approach is not very easy
- Some lib is present (general, matrix/math...)
- Must be careful on compile errors (the templates tree is unrolled!)