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# Reflective Metaprogramming in C++

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## Topics/Overview

- Generalities
  - What is *reflective metaprogramming*?
- C++ Template Metaprogramming
  - Principles
  - Pros and cons
- The Metacode Extension
  - Principles
  - Constructs
  - Implementation notes

# Part I

Generalities

## What is “Metaprogramming”?

- **Meta**? *The New Shorter OED*:
  - “Denoting a nature of a higher order”
  - “Denoting change, alteration, or effect generally”
  - …
- Programming = creating/modifying a program
- Metaprogramming =

**Creating a program that creates or modifies another program**

## What is “Reflection”?

**A program’s ability to observe itself**

- At a sufficiently high level
  - Inspecting bytes is not the spirit
- At run time or at translation time
- Partial (e.g., just types) or complete (including executable code)

## Applications

- “Middleware”
  - Distribution
  - Persistence
  - …
- ABI bridging
- API transitions/usability
- Component-specific optimization
- All kinds of instrumentation

# Part II

C++ Template Metaprogramming

## C++ Template Metaprogramming Basics

- Use the template instantiation process as a computational engine
- Use parameterized types and constants to record state
- Use explicit or partial specialization to implement conditions

➧ Computationally Complete

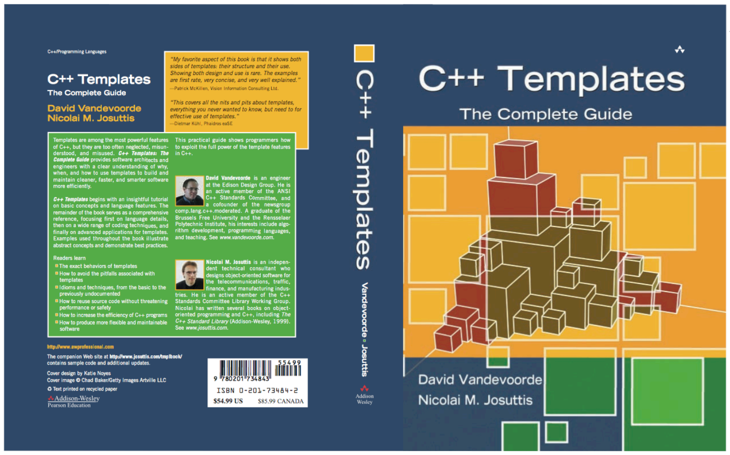
# C++ Template Metaprogramming Example A

```
template<int B, int N> struct Pow {
  enum { value = B*Pow<B, N-1>::value };
};

template<int B> struct Pow<B, 0> {
  enum { value = 1 };
};

int bitset[Pow<2, 13>::value];
```

# C++ Template Metaprogramming Example B

```
typedef char One; typedef char (&Two)[2];

template<typename T> One f(typename T::X*);
template<typename T> Two f(...); // Ellipsis parameter

template<typename T> struct HasMemberTypeX {
  enum { yes = (sizeof(f<T>(0)) == sizeof(One)) };
};

struct S1 { typedef int X; };
struct S2 {};

int a1[HasMemberTypeX<S1>::yes]; // OK
int a2[HasMemberTypeX<S2>::yes]; // Error
```

## Plug Plug Plug




## C++ Template Metaprogramming Strengths

- Serendipitous
- Widely used
  - Perhaps the only truly successful form of compile-time reflective metaprogramming

## C++ Template Metaprogramming Weaknesses

- Verbose
- Indirect/Opaque
- Expensive
- Poor tools/diagnostics
- Limited scope
- Limited reflection

## C++ Template Metaprogramming Cost

- Speed
  - Requires complete C++ semantic checking
- Storage
  - HasMemberTypeX<T>: 3.5 KB/instance
  - Pow<B, N>: Nx2.2 KB/instance

(EDG 3.0, Strict ANSI, minimal configuration)

# Part III

The Metacode Extension

## C++ Native Metalanguage Challenges

- Already a very complex language
  - Arcane properties and restrictions
  - Exposing compiler internals not practical
- Metalanguage must be portable and neutral

```
#include <iostream>
typedef int Int;
void f(Int);
int main() {
  std::cout << typeid(f).name() << std::endl;
}
```

## The Metacode Extension: Principal Components

- Metacode functions
  - Compile-time function evaluation
- Code injection mechanisms
  - Code generation by metacode
- Standard Metacode Library
  - Lives in namespace `stdmeta`
  - E.g., `is_lvalue(`*`expr`*`)`
- Metacode blocks
  - Metacode in declarative contexts

## Metacode Functions: General Principles

- Introduced by new keyword `metacode`
  - But after template parameters
  - Function can be ctor, operator, … but not virtual
- Calls can be constant-expressions
  - Compile-time evaluation!
- Cannot call non-meta functions
- Arguments of meta-calls:
  - Implicit conversion not performed
  - “Value” of parameters only when constant argument
- Maybe: “`metacode ...`” parameter
  - Like regular ellipsis but always “best match”

## Metacode Functions: Example

```
template<typename T> metacode
T power(T b, unsigned n) {
  T r = 1;
  for (int k = 0; k<n; ++k) r *= b;
  return r;
}

float a1[power(2, 3)];  // OK: Same as a1[8]

int p = 3;
float a2[power(2, p)];
   // Error: Metacode routine attempts to
   // access value of nonconstant p
```

## Standard Metacode Library Metacode Types

- Many C++98 types OK
  - Distinct address spaces (pointers, references)
  - Implementation currently limited
- stdmeta::string_literal, stdmeta::id
  - To manipulate string literals and identifiers
- stdmeta::type
  - To manipulate C++ types
- stdmeta::array<T>, stdmeta::table<KT, VT>
  - Possibly the only dynamic meta-structures
  - E.g., type lists: array<type>

## Standard Metacode Library
## Built-in Metacode Functions

- Building blocks for user-defined metacode functions
- Often “magical”
  - is_accessible("C::x")
  - in_normal_function()
- May have compile-time side-effects
  - error("Too weird!")

## Metacode injection mechanisms

- `metacode->{ <code> }`
  - Injects <code> in enclosing class/namespace scope
- `metacode->::{ <code> }`
  - Injects <code> in global namespace
- `metacode-> N::M { <code> }`
  - Injects <code> in namespace N::M
- `return-> <expr> ;`
  - Injects non-constant expression
- Lookup rules:
  - Same as C++98
  - Variables from metacode accessible as simple, nondependent identifiers translate to appropriate tokens

## Metacode Injection: Example 1

```
metacode
double mypow(double b, int n) {
  using ::stdmeta::is_constant;
  if (is_constant(b) &&
      is_constant(n) &&
      n >= 0) {
    return power<>(b, (unsigned)n);
  } else {
    return-> ::std::pow(b, n);
  }
}
```

## Metacode Injection: Example 2

```
metacode define_fields(array<type>  types) {
  for (int k; k<types.length(); ++k) {
    type FieldT = types[k];
    id FieldName = id("field" +
                      string_literal(k));
    metacode-> {
      FieldT FieldName;  // Metacode identifiers
    }                    // translated according
  }                      // to their types.
}
```

## Metacode blocks:
### Metaprogramming in Declarative Contexts

- Allows for metacode to appear where no expressions are allowed
- In definitions of classes and functions

```
template<typename T> struct S {
  metacode {  // Start metacode block
    if (stdmeta::typevar<T>().is_reference()) {
      stdmeta::error("No reference, please.");
    }
  }
  // ...
};
```

## Problems This Solves/Helps

- Constrained genericity
- Move semantics
- Forwarding problem
- User-defined literals
- Efficient compile-time varargs
- …

## Implementation Notes (1)

- Partially implemented in an internal copy of the EDG front end
  - Also includes other useful extensions (e.g., `typeof`)
- Standard Metacode Library
  - Fairly straightforward
- Metacode functions
  - IL interpreter: Cumbersome
  - Otherwise, much like inline functions

## Implementation Notes (2)

- Metacode blocks
  - Not yet implemented
  - Like metacode functions, but larger impact on syntax
- Metacode injection
  - Not yet implemented
  - Expected to be relatively hard
  - Some similarities to template instantiation

## Open Issues/To Do

- Nonlocal metacode variables?
- User-defined metacode types?
- Exported metacode functions?
- Design of Standard Metacode Library?

- Complete EDG-based implementation
- Alternative implementation
- Metacode debugging tools
- Users needed

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