Modern C++ for Computer Vision and Image Processing

Lecture 09: Templates

Ignacio Vizzo and Cyrill Stachniss

UNIVERSITÄT BONN

Generic programming

What is Programming?

- "The craft of writing useful, maintainable, and extensible source code which can be interpreted or compiled by a computing system to perform a meaningful task." —Wikibooks

What is Meta-Programming?

- "The writing of computer programs that manipulate other programs (or themselves) as if they were data." —Anders Hejlsberg

Meaning of template

Dictionary Definitions:

- Something that serves as a model for others to copy
- A preset format for a document or file
- Something that is used as a pattern for producing other similar things

Meaning of template

C++ Definitions:

A template is a C++ entity that defines one of the following:

- A family of classes (class template), which may be nested classes.
- A family of functions (function template), which may be member functions.

Motivation: Generic functions

abs():

```
1 double abs(double x) { return (x >= 0) ? x : -x; }
2    int abs(int x)    { return (x >= 0) ? x : -x; }
```

And then also for:

- long
- int
- float
- complex types?
- Maybe char types?
- Maybe short?
- Where does this end?

Motivation: Generic functions

C-style, C99 Standard:

- `abs (int)`
- `labs (long)`
- `llabs (long long)`
- `imaxabs (intmax_t)`
- `fabsf (float)`
- `fabs (double)`
- `fabsl (long double)`
- `cabsf (_Complex float)`
- `cabs (_Complex double)`
- `cabsl (_Complex long double)`

Function Templates

abs<T>():

```
1 template <typename T>
2 T abs(T x) {
3   return (x >= 0) ? x : -x;
4 }
```

- Function templates are not functions.
  - **They are templates for making functions**
- Don’t pay for what you don’t use:
  - **If nobody calls abs<int>, it won’t be instantiated by the compiler at all.**

Template functions

- Use keyword `template`

```
1 template <typename T, typename S>
2 T awesome_function(const T& var_t, const S& var_s) {
3   // some dummy implementation
4   T result = var_t;
5   return result;
6 }
```

- `T` and `S` can be any type.
- A **function template** defines a **family** of functions.

Using Function Templates

```
1  template <typename T>
2  T abs(T x) {
3    return (x >= 0) ? x : -x;
4  }
5
6  int main() {
7    const double x = 5.5;
8    const    int y = -5;
9
10   auto abs_x = abs<double>(x);
11   int  abs_y = abs<int>(y);
12
13   double abs_x_2 = abs(x);  // type-deduction
14   auto   abs_y_2 = abs(y);  // type-deduction
15 }
```

Template classes

```
1 template <class T>
2 class MyClass {
3  public:
4   MyClass(T x) : x_(x) {}
5
6  private:
7   T x_;
8 };
```

- Classes templates are not classes.
  - **They are templates for making classes**
- Don’t pay for what you don’t use:
  - **If nobody calls MyClass<int>, it won’t be instantiated by the compiler at all.**

Template classes usage

```
1  template <class T>
2  class MyClass {
3   public:
4    MyClass(T x) : x_(x) {}
5
6   private:
7    T x_;
8  };
9
10 int main() {
11   MyClass<int> my_float_object(10);
12   MyClass<double> my_double_object(10.0);
13   return 0;
14 }
```

Template Parameters

```
1 template <typename T, size_t N = 10>
2 T AccumulateVector(const T& val) {
3   std::vector<T> vec(val, N);
4   return std::accumulate(vec.begin(), vec.end(), 0);
5 }
```

- Every `template` is parameterized by one or more `template parameters`:
  `template < parameter-list > declaration`
- Think the `template parameters` the same way as any `function arguemnents`, but at **compile-time**.

Template Parameters

```
1  template <typename T, size_t N = 10>
2  T AccumulateVector(const T& val) {
3    std::vector<T> vec(val, N);
4    return std::accumulate(vec.begin(), vec.end(), 0);
5  }
6
7  using namespace std;
8  int main() {
9    cout << AccumulateVector(1) << endl;
10   cout << AccumulateVector<float>(2) << endl;
11   cout << AccumulateVector<float, 5>(2.0) << endl;
12   return 0;
13 }
```

Type Deduction

Type deduction for function templates:

```
1  #include <cstdio>
2
3  template <typename T>
4  void foo(T x) {
5    puts(__PRETTY_FUNCTION__);
6  }
7
8  int main() {
9    foo(4);          // void foo(T) [T = int]
10   foo(4.2);        // void foo(T) [T = double]
11   foo("hello");    // void foo(T) [T = const char *]
12 }
```

Type Deduction Rules (short)

- Each function parameter may contribute (or not) to the deduction of each template parameter (or not).
- At the end of this process, the compiler checks to make sure that each template parameter has been deduced at least once (otherwise: `couldn't infer template argument T`) and that all deductions agree with each other (otherwise:`deduced conflicting types for parameter T`) .

Type Deduction

Type deduction for function templates:

```
1  template <typename T, typename U>
2  void f(T x, U y) {
3    // ..
4  }
5  template <typename T>
6  void g(T x, T y)
7  // ..
8  }
9
10 int main() {
11   f(1, 2);  // void f(T, U) [T = int, U = int]
12   f(1, 2u); // void f(T, U) [T = int, U = unsigned int]
13   g(1, 2);  // void g(T, T) [T = int]
14   g(1, 2u); // error: no matching function for call
15             // to g(int, unsigned int)
16 }
```

Type Deduction

Type deduction for class templates:

```
1  template <typename T>
2  struct Foo {
3   public:
4    Foo(T x) : x_(x) {}
5    T x_;
6  };
7
8  int main() {
9    auto obj = Foo<int>(10).x_;
10   auto same_obj = Foo(10).x_;
11   auto vec = std::vector<int>{10, 50};
12   auto same_vec = std::vector{10, 50};
13 }
```

Note: New in C++17

Type Deduction Puzzle

```
1  template <typename T, typename U>
2  void foo(std::array<T, sizeof(U)> x,
3           std::array<U, sizeof(T)> y) {
4    puts(__PRETTY_FUNCTION__);
5  }
6
7  int main() {
8    foo(std::array<int, 8>{}, std::array<double, 4>{});
9    foo(std::array<int, 9>{}, std::array<double, 4>{});
10 }
```

Template Full Specialization

```
1  template <typename T>
2  bool is_void() {
3    return false;
4  }
5
6  template <>
7  bool is_void<void>() {
8    return true;
9  }
10
11 int main() {
12   std::cout << std::boolalpha
13             << is_void<int>() << std::endl
14             << is_void<void>() << std::endl;
15 }
```

Template Full Specialization

- Prefix the definition with `template<>`
- Then write the function **definition**.
- Usually means you don't need to write any more angle brackets at all.
- Unless `T` **can't** be deduced:

```
1 template <typename T>
2 int my_sizeof() {
3   return sizeof(T);
4 }
5
6 template <>
7 int my_sizeof<void>() {
8   return 1;
9 }
```

Template Full Specialization

- Prefix the definition with `template<>`
- Then write the function **definition**.
- Usually means you don't need to write any more angle brackets at all.
- Unless `T` can't be deduced/**defaulted**:

```
1 template <typename T = void>
2 int my_sizeof() {
3   return sizeof(T);
4 }
5
6 template <>
7 int my_sizeof() {
8   return 1;
9 }
```

Template Partial Specialization

```
1  template <typename T>
2  constexpr bool is_array = false;
3
4  template <typename Tp>
5  constexpr bool is_array<Tp[]> = true;
6
7  int main() {
8    std::cout << std::boolalpha;
9    std::cout << is_array<int>   << std::endl   // false
10             << is_array<int[]> << std::endl;  // true
11 }
```

A partial specialization is any specialization that is, itself, a template. It still requires further “customization” by the user before it can be used.

Template headers/source

- Concrete templates are instantiated at compile time.
- Linker does not know about implementation
- There are three options for template classes:
  1. Declare and define in header files
  2. Declare in `NAME.hpp` file, implement in `NAME_impl.hpp` file, add `#include <NAME_impl.hpp>` in the end of `NAME.hpp`
  3. Declare in `*.hpp` file, implement in `*.cpp` file, in the end of the `*.cpp` add explicit instantiation for types you expect to use
- Read more about it:

http://www.drdobbs.com/moving-templates-out-of-header-files/184403420

Static code generatrion with `constexpr`

```
1  #include <iostream>
2  constexpr int factorial(int n) {
3    // Compute this at compile time
4    return n <= 1 ? 1 : (n * factorial(n - 1));
5  }
6
7  int main() {
8    // Guaranteed to be computed at compile time
9    return factorial(10);
10 }
```

- `constexpr` specifies that the value of a variable or function can appear in constant expressions

It only works if the variable of function can be defined at **compile-time**:

```
1  #include <array>
2  #include <vector>
3
4  int main() {
5    std::vector<int> vec;
6    constexpr size_t size = vec.size();  // error
7
8    std::array<int, 10> arr;
9    constexpr size_t size = arr.size();  // works!
10 }
```

error: constexpr variable 'size' must be initialized by a constant expression

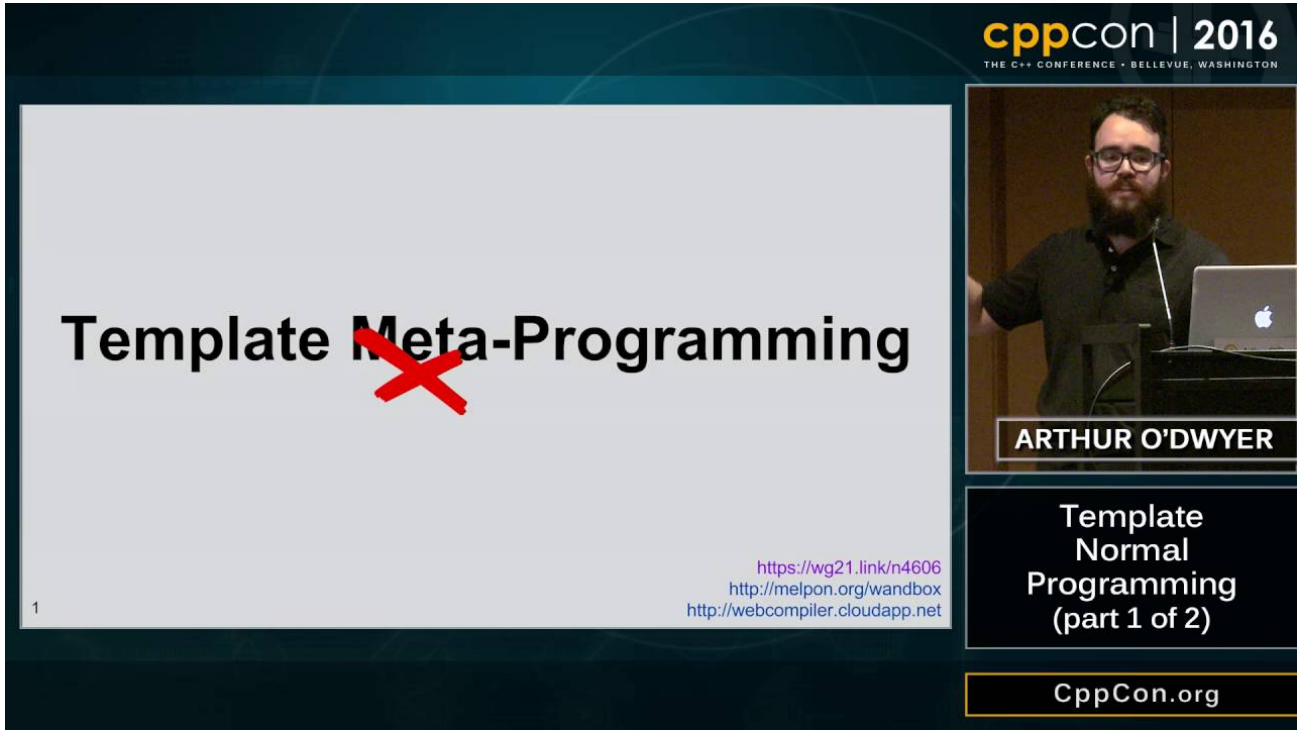
It only works if the variable of function can be defined at **compile-time**:

```
1  #include <array>
2  #include <vector>
3
4  int main() {
5    std::vector<int> vec;
6    constexpr size_t size = vec.size();  // error
7
8    std::array<int, 10> arr;
9    constexpr size_t size = arr.size();  // works!
10 }
```

error: constexpr variable 'size' must be initialized by a constant expression

Suggested Video

Template Normal Programming



https://youtu.be/vwrXHznaYLA

References

- https://en.cppreference.com/w/cpp/language/templates
- https://en.cppreference.com/w/cpp/language/function_template
- https://en.cppreference.com/w/cpp/language/class_template
- https://en.cppreference.com/w/cpp/language/template_parameters
- https://en.cppreference.com/w/cpp/language/template_argument_deduction
- https://en.cppreference.com/w/cpp/language/template_specialization
- https://en.cppreference.com/w/cpp/language/partial_specialization

Tools

- GNU/Linux **[Tutorial]**
  - Filesystem
  - Terminal
  - standard input/output
- Text Editor
  - Configuring
  - Terminal
  - Compile
  - Debug
- Build systems
  - #include statements
  - headers/sources
  - Libraries
  - Compilation flags
  - CMake
  - 3rd party libraries
- Git **[Tutorial]**
- Homework submissions **[Tutorial]**
- Gdb **[Tutorial]**
- Web-based tools
  - Quick Bench
  - Compiler Explorer
  - Cpp insights
  - Cppreference.com
- Clang-tools **[Tutorial]**
  - Clang-format
  - Clang-tidy
  - Clangd
  - Cppcheck
- Google test **[tutorial]**
- OpenCV **[tutorial]**

Core C++

- C++ basic syntax
- Variables
- Operators
- Scopes
- Built-in types
- Control structures (if, for, while)
- streams
- Input parameters

- C++ strings
- Functions
- Function overloading
- Pass by value / Pass by reference
- Namespaces

- Containers
- Iterators
- STL Algorithms

- Exceptions
- Utilities
- filesystem
- I/O Files
- Classes introduction

Modern C++

- enum classes
- Operator overloading
- Const correctness
- typedef/using
- static variables /methods
- Move Semantics
- Special Functions

- Inheritance
- Function Overriding
- Abstract classes
- Interfaces
- Strategy Pattern
- Singleton Pattern
- Polymorphism
- Typecasting

- Memory management
- Stack vs Heap
- Pointers
- new/delete
- **this** pointer
- Memory issues
- RAII
- Smart pointers

- Generic programming
- Template functions
- Template classes
- Template argument deduction
- Template partial specialization
- Template parameters
- constexpr
- Static code generation

Where to go from now on?

#	Date	Topics	Homework	Recommended Deadline	Official Deadline
Part I: C++ tools					
–	6-Apr	[[No Lectures]]	–	–	**–**
0	13-Apr	Course Introduction, Organization, Hello world	–	–	–
1	20-Apr	C++ Tools	Homework 1	1-May	**8-May**
Part II: The C++ core language					
2	27-Apr	C++ Basic syntax	Homework 2	8-May	**15-May**
3	4-May	C++ Functions	Homework 3	15-May	**22-May**
4	11-May	C++ STL	Homework 4	22-May	**29-May**
5	18-May	Filesystem + BoW Introduction	Homework 5	29-May	**5-Jun**
Part III: Modern C++					
6	25-May	Classes	Homework 6	5-Jun	**12-Jun**
7	1-Jun	OOP	Homework 7	12-Jun	**19-Jun**
8	8-Jun	Memory Managment	Homework 8	19-Jun	**26-Jun**
9	15-Jun	Generics Programing	Homework 9	26-Jun	**3-Jul**
Part IV: Final Project "Place recognition using Bag of Visual Words in C++"					
10	22-Jun	Bag of Visual Words			
11	29-Jun	[[No Lectures]]	Final Project	**31 of July**	
12	6-Jul				
13	13-Jul				