B2B: C++ Templates

Part 1

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fertig

adjective /ˈfɛrtɪç/

finished
ready
complete
completed

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What is generic programming

- Generic programming is a method to implement algorithms and data structures in the most general sensible way.
- Algorithms are written in terms of types to-be-specified-later.
- The term *generic programming* was originally coined by David Musser and Alexander Stepanov [1].
- Generic programming helps us to reduce redundancy and programming effort, while it increases reusability and flexibility.

Templates

- Templates are a kind of pattern for the compiler.
- We can *instantiate* templates with different types or values.
  - Each instantiation for a new type or value results in additional code, the fill-in template is generated with the given template argument.
- Templates reduce a lot of writers' work. We do not have to implement functions multiple times just because it's a slightly different type.
- There are different types of templates:
  - Function-templates
  - Class-templates
  - Variable-templates (seit C++14).
- Templates are always initiated by the keyword `template`.

The different kinds of template parameters

- There are three different types of template parameters:

  Type parameter whenever we use a concrete type, e.g., `int`, `char`, or even a class. Type parameters are the most common type.

  none-type parameter typically values like 3. Excluded are floating-point numbers and strings (C-arrays). Since C++20, they work as well, with minor limitations.

  template-template parameter is required if we pass a template as a parameter to a template.

The template parts applied

Here is a piece of code which declares and uses a template.

```
A The template-head
template<typename T,    B A type parameter
         size_t N>      C A NTTP
constexpr auto
Size(const T (&)[N])    D Expect an array of type T and size N as parameter
{
  return N;   E Use a NTTP
}

void Main()
{
  char buffer[16]{};

  // Prefer a range-based for-loop!
  for(int i = 0; i < Size(buffer); ++i) {
    // do something with buffer
  }
}
```

Function templates

- With a function template, we can implement uniform functionality for different types once and let the compiler do the filling.
- The parameters are types and values (with restrictions):
  - Types are initiated by `typename` or `class`.
  - The name of the template parameter then follows `typename`.
  - The name usually has `T` for the first parameter and `U` for the second parameter.
  - Within the function, we use this name instead of a specific type.

```cpp
template<typename T>
T min(const T& a, const T& b)
{
  return (a < b) ? a : b;
}

void Main()
{
  const int a = 2;
  const int b = 1;

  printf("%d\n", min(a, b));
}
```


Function templates: Instantiation

- *instantiation* is when the compiler replaces a template, with the concrete arguments.
  - C ++ Insights helps to visualize the result.
  - The example is the output of C ++ Insights.
- The compiler instantiates the function template automatically:
  - because of the arguments
  - if he can derive these.
- If the compiler can not determine the arguments itself, they must be specified explicitly.

```cpp
template<typename T>
T min(const T& a, const T& b)
{
  return (a < b) ? a : b;
}

/* First instantiated from: insights.cpp:13 */
#ifdef INSIGHTS_USE_TEMPLATE
template<>
int min<int>(const int& a, const int& b)
{
  return (a < b) ? a : b;
}
#endif

void Main()
{
  const int a = 2;
  const int b = 1;
  printf("%d\n", min(a, b));
}
```

Function templates: Specialization

- *specialization* is the procedure that provides a concrete implementation for an argument combination of a function template.

```
template<typename T>
bool equal(const T& a, const T& b)
{
  return a == b;
}

template<>
bool equal(const double& a, const double& b)
{
  return std::abs(a - b) < 0.00001;
}

void Main()
{
  int a = 2;
  int b = 1;

  printf("%d\n", equal(a, b));

  double d = 3.0;
  double f = 4.0;

  printf("%d\n", equal(d, f));
}
```


Class templates

- As with a function template, a class template is introduced by the keyword `template`.
  - Most rules of function templates also apply to class templates.
  - Methods can be implemented inside the class or outside.
  - Methods implemented outside the class require the template-head before the method as in the class.
  - Each instantiation of a class creates a new type.
- (A) represents a *type parameter*.
- (B) represents a *non-type template parameter (NTTP)*.

```
template<typename T,        (A) A type parameter
         size_t SIZE>       (B) A NTTP
struct Array
{
  T*       data();
  const T* data() const
  {
    return std::addressof(mData[0]);
  }
  constexpr size_t size() const { return SIZE; }
  T*               begin() { return data(); }
  T*               end() { return data() + size(); }
  T& operator[](size_t idx) { return mData[idx]; }

  T mData[SIZE];
};

template<typename T, size_t SIZE>
T* Array<T, SIZE>::data()
{
  return std::addressof(mData[0]);
}

void Main()
{
  Array<int, 2>    ai{3, 5};
  Array<double, 2> ad{2.0};
}
```

Class templates: Instantiation

- Again, analogous to the function template with one important exception:
  - A class template can not automatically derive its arguments.
  - Each template argument *must* be specified explicitly.
  - Exception: C++17. Here we have *class template argument deduction*.

Class templates: Method templates

- Methods of a class template can themselves be a template of their own. This is called a method template.
  - A method template can be defined inside or outside a class.
  - The copy constructor and destructor can not be templates.

```cpp
template<typename T>
class Foo
{
public:
  Foo(const T& x)
  : mX{x}
  {
  }

  template<typename U>
  Foo<T>& operator=(const U& u)
  {
    mX = static_cast<T>(u);
    return *this;
  }

private:
  T mX;
};

void Main()
{
  Foo<int> fi{3};
  fi = 2.5;
}
```

Class templates: Inheritance

- Class templates or classes can inherit from each other in any combination.
- When deriving a class template, there is a restriction:
  - In the derived class, methods and attributes of the base class are not automatically available.
- There are three possible solutions:
  - To qualify the method call by the `this` pointer.
  - Make the name known by `using Base<T>::func`.
  - Call the method of the base class directly.

```
template<typename T>
class Foo
{
public:
  void Func() {}
};

template<typename T>
class Bar : public Foo<T>
{
public:
  void BarFunc()
  {
    // Func();
    this->Func();
    Foo<T>::Func();
  }
};

void Main()
{
  Bar<int> b{};
  b.BarFunc();
}
```


Alias templates

- Alias templates allow you to create synonyms for templates.
  - This allows a partial specialization of templates.
  - Alias templates themselves can not be further specialized.

```
#include <array>

template<size_t N>
using CharArray = std::array<char, N>;

void Main()
{
  CharArray<24> ar;
}
```

Alias templates

- Alias templates allow you to create synonyms for templates.
  - This allows a partial specialization of templates.
  - Alias templates themselves can not be further specialized.
  - Can help to abstract small type differences for different products.

```cpp
#include <array>

template<size_t N>
using CharArray =
#ifdef PRODUCT_A
  Array<char, N>;
#else
  std::array<char, N>;
#endif

void Main()
{
  CharArray<24> ar;
}
```


Guidelines for efficient use of templates

- Templates generate code for us.
  - It is as if we copy and paste our implementation and changes types or values.
  - Depending on the compiler and optimizer, this can result in a larger binary.
  - Sometimes we overlook this, and people then refer to it as *code bloat*.
- This is in our control!

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Guidelines for efficient use of templates - An example

- The pattern of passing value and length is:
  - Typical C API.
  - Error-prone.
  - More to write & read.

```cpp
bool Send(const char* data, size_t size)
{
  if(!data) { return false; }

  return write(data, size);
}

void Read(char* data, size_t size)
{
  if(!data) { return; }

  // fill buffer with data
}

void Main()
{
  char buffer[1'024]{};

  Read(buffer, sizeof(buffer));
  Send(buffer, sizeof(buffer));

  char buffer2[2'048]{};

  Read(buffer, sizeof(buffer2));
  Send(buffer, sizeof(buffer2));
}
```


Guidelines for efficient use of templates - An example

- The pattern of passing value and length is:
  - Typical C API.
  - Error-prone.
  - More to write & read.
- It is better with `std::array`:
  - Disadvantage here: The size must always be the same.

```cpp
bool Send(const std::array<char, 1'024>& data)
{
  return write(data.data(), data.size());
}

void Read(std::array<char, 1'024>& data)
{
  // fill buffer with data
}

void Main()
{
  std::array<char, 1'024> buffer{};

  Read(buffer);
  Send(buffer);

  std::array<char, 2'048> buffer2{};

  //  Read(buffer2);
  //  Send(buffer2);
}
```


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- It is better with `std::array`:
  - Disadvantage here: The size must always be the same.
  - Alternative: Make Read / Send a template with a NTTP for the size.

```cpp
template<size_t N>
bool Send(const std::array<char, N>& data)
{
  return write(data.data(), data.size());
}

template<size_t N>
void Read(std::array<char, N>& data)
{
  // fill buffer with data
}

void Main()
{
  std::array<char, 1'024> buffer{};

  Read(buffer);
  Send(buffer);

  std::array<char, 2'048> buffer2{};

  Read(buffer2);
  Send(buffer2);
}
```


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  - Typical C API.
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- It is better with `std::array`:
  - Disadvantage here: The size must always be the same.
  - Alternative: Make Read / Send a template with a NTTP for the size.
  - **Disadvantage:** Code-bloat danger!

```cpp
template&lt;size_t N&gt;
bool Send(const std::array<char, N>& data)
{
  return write(data.data(), data.size());
}

template&lt;size_t N&gt;
void Read(std::array<char, N>& data)
{
  // fill buffer with data
}

void Main()
{
  std::array<char, 1'024> buffer{};

  Read(buffer);
  Send(buffer);

  std::array<char, 2'048> buffer2{};

  Read(buffer2);
  Send(buffer2);
}
```


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Guidelines for efficient use of templates - An example

- The pattern of passing value and length is:
  - Typical C API.
  - Error-prone.
  - More to write & read.
- It is better with `std::array`:
  - Disadvantage here: The size must always be the same.
  - Alternative: Make Read / Send a template with a NTTP for the size.
  - **Disadvantage:** Code-bloat danger!
- Better: Abstract the size away.
- For example span
  - Can hold both C-Array and `std::array`.
  - Of course, range-based forready.
  - Cleaned up the code safely and with little overhead.

```cpp
bool Send(const span<char>& data)
{
  return write(data.data(), data.size());
}

void Read(span<char> data)
{
  int i = 1;
  // fill buffer with data
  for(auto& c : data) {
    c = i;
    ++i;
  }
}

void Main()
{
  std::array<char, 1'024> buffer{};

  Read(buffer);
  Send(buffer);

  char buffer2[2'048]{};

  Read(buffer2);
  Send(buffer2);
}
```


Guidelines for efficient use of templates - An example

- The pattern of passing value and length is:
  - Typical C API.
  - Error-prone.
  - More to write & read.
- It is better with `std::array`:
  - Disadvantage here: The size must always be the same.
  - Alternative: Make Read / Send a template with a NTTP for the size.
  - **Disadvantage:** Code-bloat danger!
- Better: Abstract the size away.
- For example span
  - Can hold both C-Array and `std::array`.
  - Of course, range-based forready.
  - Cleaned up the code safely and with little overhead.
  - C++20 Single Header Version of span: [2].

```cpp
template<typename T>
class span {
public:
  constexpr span() = default;
  constexpr span(T* start, const size_t len)
  : data_{start}, length{len} { }

  template<size_t N>
  constexpr span(T (&arr)[N])
  : span(arr, N) { }

  template<size_t N>
  constexpr span(const T (&arr)[N])
  : span(arr, N) { }

  template<size_t N, class AT = std::remove_const_t<T>>
  constexpr span(std::array<AT, N>& arr)
  : span(arr.data(), arr.size()) { }

  constexpr size_t size() const { return length; }
  T*               data() const { return data_; }
  bool empty() const { return nullptr != data_; }

  T* begin() const { return data_; }
  T* end() const   { return data_ + length; }

private:
  T*     data_;
  size_t length;
};
```


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Guidelines for efficient use of templates

- Guidelines for class templates:
  - Move code, which stays the same for all instantiations into a base class.
  - Weight, if storing an additional type/value, is better than passing it as a template parameter.
- Guidelines for function templates:
  - Check if you can use them as API only but forward the actual work to a non-template function.
    - With that, you get the safety and simplicity for your users and only internally use the unsafe version.

Thinking in types

- We usually think in values as they are computed during run-time.
- Types are known at compile-time.
  - We can do checks and modifications to types at compile-time.

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Thinking in types

- We usually think in values as they are computed during run-time.
- Types are known at compile-time.
  - We can do checks and modifications to types at compile-time.
- Let's limit `Array` not to be a pointer.
  - There is a type trait `is_pointer`, which does the job.
  - The code presented is a simplification of what is in `type_traits`.

```
A Helper to store a value at compile-time
template<class T, T v>
struct integral_constant
{
  static constexpr T value = v;
};

B Aliases for clean TMP
using true_type  = integral_constant<bool, true>;
using false_type = integral_constant<bool, false>;

C Base is_pointer template
template<class T>
struct is_pointer : false_type
{
};

D is_pointer specialization for T*
template<class T>
struct is_pointer<T*> : true_type
{
};

E Test it
static_assert(is_pointer<int*>::value);
static_assert(not is_pointer<int>::value);
```


Thinking in types

- We usually think in values as they are computed during run-time.
- Types are known at compile-time.
  - We can do checks and modifications to types at compile-time.
- Let's limit `Array` not to be a pointer.
  - There is a type trait `is_pointer`, which does the job.
  - The code presented is a simplification of what is in `type_traits`.

```
template<typename T, size_t SIZE>
struct Array
{
  A Added a check that T is not a pointer
  static_assert(not std::is_pointer<T>::value);

  T*       data() { return std::addressof(mData[0]); }
  const T* data() const
  {
    return std::addressof(mData[0]);
  }
  constexpr size_t size() const { return SIZE; }
  T*               begin() { return data(); }
  T*               end() { return data() + size(); }
  T& operator[](size_t idx) { return mData[idx]; }

  T mData[SIZE];
};

void Main()
{
  int x{22};

  // Array<int*, 2> invalid{&x}; B This will not compile
  Array<int, 2> valid{x};
}
```

Thinking in types

- We usually think in values as they are computed during run-time.
- Types are known at compile-time.
  - We can do checks and modifications to types at compile-time.
- Let's limit `Array` not to be a pointer.
  - There is a type trait `is_pointer`, which does the job.
  - The code presented is a simplification of what is in `type_traits`.
- With C++20's Concepts.

```
template<typename T, size_t SIZE>
A C++20 require T to not be a pointer
requires(not std::is_pointer_v<T>) struct Array
{
  T*       data() { return std::addressof(mData[0]); }
  const T* data() const
  {
    return std::addressof(mData[0]);
  }
  constexpr size_t size() const { return SIZE; }
  T*                begin() { return data(); }
  T*                end() { return data() + size(); }
  T& operator[](size_t idx) { return mData[idx]; }

  T mData[SIZE];
};

void Main()
{
  int x{22};

  // Array<int*, 2> invalid{&x};
  Array<int, 2> valid{x};
}
```


C++17

`constexpr if`

- An extension of `constexpr`.
  - This `if` and all branches are evaluated at compile time.
  - Only the branch which yields `true` is preserved.
- We can use it with `is_pointer` to dereference pointers and return their value and otherwise just return it.

```
template<typename T>
auto getValue(T t)
{
  A constexpr if for compile-time dispatching
  if constexpr(std::is_pointer_v<T>) {
    assert(nullptr != t);
    return *t;
  } else {
    return t;
  }
}

void Main()
{
  int  i  = 4;
  int* ip = &i;

  B All calls will result in plain int as type
  auto iv  = getValue(i);
  auto ipv = getValue(ip);
  auto itv = getValue(43);
}
```


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C++17

`constexpr if`

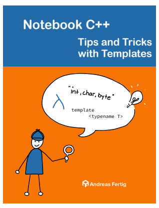
- An extension of `constexpr`.
  - This `if` and all branches are evaluated at compile time.
  - Only the branch which yields `true` is preserved.
- We can use it with `is_pointer` to dereference pointers and return their value and otherwise just return it.
- Or with `is_convertible_v` to convert everything into a `std::string`.

```cpp
template<typename T>
std::string str(T t)
{
  if constexpr(std::is_convertible_v<T, std::string>) {
    return t;
  } else {
    return std::to_string(t);
  }
}

void Main()
{
  auto s = str(std::string{"42"});
  auto i = str(42);
}
```


}

I am Fertig.



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Used Compilers & Typography

Used Compilers

- Compilers used to compile (most of) the examples.
  - g++ 10.2.0
  - clang version 10.0.0 (https://github.com/llvm/llvm-project.git d32170dbd5b0d54436537b6b75beaf44324e0c28)

Typography

- Main font:
  - Camingo Dos Pro by Jan Fromm (https://janfromm.de/)
- Code font:
  - CamingoCode by Jan Fromm licensed under Creative Commons CC BY-ND, Version 3.0 http://creativecommons.org/licenses/by-nd/3.0/

References

[1] Musser D. R. and Stepanov A. A., "Generic programming", in *Symbolic and Algebraic Computation*, Gianni P., Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 1989, pp. 13–25. http://stepanovpapers.com/genprog.pdf

[2] Moene M., "span lite - A single-file header-only version of a C++20-like span for C++98, C++11 and later". https://github.com/martinmoene/span-lite

Images:
33: Franziska Panter

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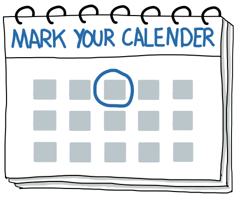
For my upcoming talks you can check https://andreasfertig.info/talks/.
For my training services you can check https://andreasfertig.info/training/.



About Andreas Fertig


Photo: Kristijan Matic www.kristijanmatic.de

Andreas Fertig is the CEO of Unique Code GmbH, which offers training and consulting for C++ specialized in embedded systems. He worked for Philips Medizin Systeme GmbH for ten years as a C++ software developer and architect focusing on embedded systems.
Andreas is involved in the C ++ standardization committee. He is a regular speaker at conferences internationally. Textbooks and articles by Andreas are available in German and English.
Andreas has a passion for teaching people how C++ works, which is why he created C++ Insights (cppinsights.io).

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