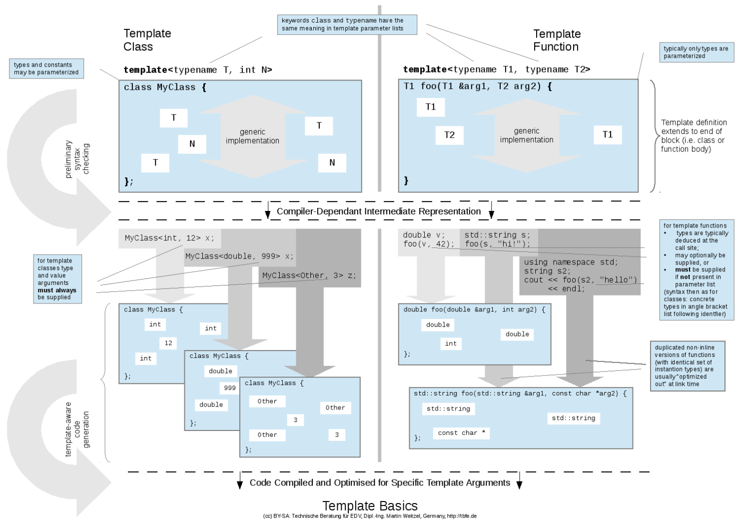
Advanced Use of Templates

Templates selbst schreiben

- Template-Klassen
- Template-Funktionen



Template-Klassen

Template-Klassen sind im Hinblick auf Datentypen und/oder andere Compilezeit-Konstanten parametrisierte Klassen.

Man spricht in diesem Zusammenhang auch von generischen Klassen.

Bei der Verwendung von Template-Klassen sind die entsprechenden Typ- und Wertargumente stets anzugeben.

Template-Funktionen

Template-Funktionen sind in der Regel im Hinblick auf Datentypen* parametrisierte Funktionen

Bei der Verwendung von Template-Funktionen ergeben sich die tatsächlich zu verwendenden Typen oft direkt oder indirekt aus den Typen der Aufrufargumente.

*: Die Parametrisierung im Hinblick auf Compilezeit-Konstanten ist bei Funktionen ebenfalls möglich, tritt in der Praxis aber sehr selten auf.

Optimierung von Templates

- Ursache für "Code-Bloat"

- Über einen Zwischenschritt ...
- ... zur optimierten Template

Ursache für "Code-Bloat"

"Unnötig erzeugter" Maschinencode ergibt sich oft aus einer ungeschickten Strukturierung von Templates.

Problematisch ist eine erhebliche Vermischung von

- Abschnitten, welche abhängig von den Instanziierungs-Parametern stets **unterschiedlichen** Maschinencode erzeugen, und
- Abschnitten, die stets **ein und denselben** Maschinencode erzeugen.

Vorbereitender Zwischenschritt

Die Vorbereitung für die Reduzierung von Code-Bloat sieht wie folgt aus:

In einer Template-Klasse oder -Funktion sind möglichst große, zusammenhängende Abschnitte zu schaffen,

- die Maschinencode erzeugen, der tatsächlich von den Instanziierungs-Parametern abhängt, und
- diese damit zu trennen von anderen, immer auf ein und denselben Maschinencode hinauslaufenden.

Optimierte Template

Abschnitte einer Template, die auf ein und denselben Maschinencode hinauslaufen, können ausgelagert werden, und zwar

- für eine Template-Klasse in eine **Nicht-Template** Basisklasse, und
- für eine Template-Funktion in eine **Nicht-Template** Hilfsfunktionen.

Templates als Compilezeit-Funktionen

Eine weitere Sicht auf Templates ist es, sie als zur Compilezeit ausgeführte Funktionen zu verstehen.

Der wesentliche Schlüssel dazu ist, das folgende zu verstehen:

- Jeglicher "Input" besteht aus Datentypen.*
- Jeglicher "Output" besteht aus Datentypen.

Anders ausgedrückt:
Templates sind (auch) Typ-Transformationen zur Compilezeit.

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*: Mit einem kleinen Kunstgriff fallen darunter auch sämtliche zur Compilezeit konstanten Werte von Grundtypen, sowie daraus berechenbaren Werte.

Wiederholung und Verzweigung

Allerdings gibt es kein Konstrukt für zur Compilezeit ausgeführte

- Schleifen (analog `while` zur Laufzeit) und
- Verzweigungen (analog `if` zur Laufzeit).

> Verwendbar sind dagegen die entsprechenden Alternativen der *Funktionalen Programmierung* (FP).

Es muss vielmehr

- Wiederholung durch **Rekursion** und
- Fallunterscheidung durch **Spezialisierung**

ausgedrückt werden.

Ein bisschen sollte man das vielleicht zunächst trainieren …[*]

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[*]: … was ganz gut mit einer Einführung in eine "echte" FP-Sprache wie etwa Haskell geht.

Fakultäts-Funktion als Beispiel

Der übliche Ansatz …

Die bekannte Funktion zur Fakultätsberechnung kann man in C++ mit einer Schleife so programmieren:

```
unsigned long long fakul(unsigned long long n) {
    auto result = 1uLL;
    while (n > 0)
        result *= n--;
    return result;
}
```

Oder auch – zur Laufzeit rekursiv – so:

```
unsigned long long fakul(unsigned long long n) {
    return (n == 0) ? 1 : n*fakul(n-1);
}
```

… und der im "Haskell-Stil"

```
unsigned long long fakul(unsigned long long n) {
    return n*fakul(n-1);
}
unsigned long long fakul(0uLL) {
    return 1;
}
```

Natürlich ist obiges **kein gültiges C++** … aber doch irgendwie verständlich, oder nicht?

> Die Idee ist, dass der Abbruch der gemäß der allgemeinen Funktion eigentlich endlosen Rekursion durch die Spezialisierung von `fakul` für den Argumentwert `0uLL` (0 im Typ `unsigned long long`) erfolgt.

Berechnung mit C++-Template

Das folgende aber **ist** gültiges C++ …

```
// the primary template (internally recursive) ...
template<unsigned long long n>
struct fakul {
    static const unsigned long long result = n*fakul<n-1>::result;
};

// ... and its specialisation (stops recursion)
template<>
struct fakul<0uLL> {
    static const unsigned long long result = 1;
};
```

… und doch auch irgendwie "verständlich", oder?

Der "Aufruf" in einem kleinen Testprogramm könnte dann so aussehen:

```
#include <iostream>
int main() {
    std::cout << fakul<5>::result << std::endl;
}
```

Beispiele für Typ-Transformationen

Eine Zeigerstufe hinzufügen

```
template<typename T> struct add_pointer { typedef T* result; };
```

Eine Zeigerstufe wegnehmen

```
template<typename T> struct remove_pointer;
template<typename T> struct remove_pointer<T*> { typedef T result; };
```

Alle Zeigerstufen wegnehmen

Denken Sie doch einfach mal selbst kurz nach ...*

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*: The solution – of course – is this:

```
// primary template
template<typename T> struct remove_all_ptr { typedef T result; };
// specialisation
template<typename T> struct remove_all_ptr<T*> { typedef remove_all_ptr<T> result; };
```

Type-Traits Library

With C++11 the Type-Traits originally developed as a Boost library became a part if the standard.

> **(i)** For more information on standard type traits see:
> http://www.cplusplus.com/reference/type_traits/
> http://en.cppreference.com/w/cpp/types/

C++14 simplified the use of the standardised type traits with a number of template aliases (instead of accessing `::type`` for traits returning types) and conventional conversion to`bool(as`constexpr`) is implemented for traits with a`static constexpr bool value`).

- For some type trait `xxx` accessed conventionally via `typename xxx<T>::type`, in C++14 just `xxx_t<T>` may be used.
- For some type trait `yyy` accessed conventionally via `yyy::value`, in C++14 just `yyy{}` may be used.

Using SFINAE with `std::enable_if`

Often, after doing type calculations, the final goal is to choose among several implementations of a given function.

If this is not the automatic effect from calculating a type that selects the appropriate overload, `std::enable_if` and SFINAE can be applied.

The basic idea is this:

- Create an overload set of (template) functions that is deliberately ambiguous.
- Make all but one instantiations of the functions in this set fail for a particular condition.

As compile time calculations must express every result as a type (last and finally), `std::enable_if` creates an illegal type as "substitution failure" and the particular instantiation is removed from the overload set.

Example for SFINAE with `std::enable_if` (C++11)

The following example selects between two implementations of foo, depending on whether the arguments `arg1` and `arg2` are objects related with each other as base and derived class:

```
template<typename T1, typename T2>
typename std::enable_if<
    std::is_base_of<T1, T2>::value
>::type foo(T1 arg1, T2 arg2) {
    … // code for T1 is base of T2
}

template<typename T1, typename T2>
typename std::enable_if<
    !std::is_base_of<T1, T2>::value
>::type foo(T1 arg1, T2 arg2) {
    … // code or T1 is NOT base of T2
}
```

Be sure to understand that without `std::enable_if` the above would create an ambiguity causing a compile error.

Example for SFINAE with `std::enable_if_t` (C++14)

With the additions C++14 made to the standard type traits, the previous example can be slightly simplified to:*

```
template<typename T1, typename T2>
std::enable_if_t<
    std::is_base_of<T1, T2>{}
> foo(T1 arg1, T2 arg2) { … } // called for T1 is base of T2

template<typename T1, typename T2>
typename std::enable_if_t<
    !std::is_base_of<T1, T2>{}
> foo(T1 arg1, T2 arg2) { … } // called for T1 is NOT base of T2
```

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*: Note that the support for this simplifications is close to trivial In `namespace std { … }`:

```
template<bool C, typename T = void> using enable_if_t = typename std::enable_if<C, T>::type;
```

And:

```
typename<T1, T2>
  struct is_base_of {
     /* as in C++11, set according to result */ static constexpr bool value = …;
     /* added in C++14 */ constexpr explicit operator bool() const { return value; }
  }
```

Variadic Templates

C++11 introduced [Parameter Packs] to allow templates to accept a variable number of arguments.

Such are used to

- defining variadic templates and to
- unpack parameter packs

Generally variable template argument lists help

- to avoid much repetitive systematic coding and
- at the same time removes arbitrary upper limits.

> **(i)** For more information see on variadic templates see:
> http://en.cppreference.com/w/cpp/language/parameter_pack

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*: The ellipsis was originally introduced with C to indicate variable length argument list.

Defining Variadic Templates

In the **definition** of template a symbolic name be introduced with three dots appended.

In this syntax the identifier right to the dots introduces kind of a list,*
actually representing

- either sequences of type names
- or values of a specified type.

This can be used with template classes or template functions.

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*: Before C++11, to implement templates with a variable number of arguments required repeated, similar code (though some libraries like Boost.Preprocessor provided means to generate such using the C/C++ preprocessor):

```
// defining a tuple class …
template<typename T1>
class tuple { T1 first; … };
template<typename T1, typename T2>
class tuple { T1 first; tuple<T2> rest; … };
template<typename T1, typename T2, typename T3>
class tuple { T1 first; tuple<T2, T3> rest; … };
template<typename T1, typename T2, typename T3, typename T4>
class tuple { T1 first; tuple<T2, T3, T4> rest; … };
… // etc. up to some upper limit
```

Example: Variadic Template Class

```
// Definition:
template<typename... Ts>
class MyClass {
    …
};
…
// Valid Uses:
… MyClass<int, double> …
… MyClass<const char *> …
… MyClass<std::string, bool> …
… MyClass<int, int, int, int> …
```

```
// Definition:
template<int... Ints>
class MyIntegers { … };
template<std::string... Words>
class MyStrings { … };
…
// Valid Uses:
… MyInts<2, 3, 5, 7, 11, 13> …
… MyStrings<> …
… MyStrings<
      std::string("hello"),
      std::string("world")> …
```

In a template class, if this mechanism is combined with other (fixed) template arguments, the variable part must come last:

```
template<typename T1, unsigned int N, typename T2, bool... Bs>
class Whatever { … };
…
… Whatever<std::string, 7u, int, true, false, true, true, false> …
… Whatever<const volatile unsigned long&, (~0u >> 12), void> …
```

Example: Variadic Template Function

The general syntax is similar to variadic template classes, but the type list usually also occurs as part of the argument list:

```
template<typename... Ts>
std::string concat(char, Ts...); // prototype only, so far
```

In signature of `concat` state that the function is to be called with a first (mandatory) argument of type `char` and any more arguments of arbitrary type, hence – in principle – all of the following calls were correct:

```
… concat(' ', "hello", 7, "world" '!') …
… concat('+', std::string("whatever"), 2/1.0, true, false) …
```

Implementing Variadic Templates

Implementing variable templates usually has two options:

- Internally forwarding to another variadic template.*
- Applying recursion at compile time.

For the latter the following has to be understood:

- Recursion is the (only) way to write "loops" at compile time, and
- there must be a "condition" to stop an otherwise endless recursion.

Furthermore:

Conditions at compile time are typically expressed

- as specialisation for some border case, or
- by selecting from an overload-set with SFINAE.

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*: Of course, this only shifts "the burden of implementation" to the callee ...

Unpacking Parameter Packs

The second use of the ellipsis is to unpack a parameter pack, by writing it after some "pattern" containing at least one name of a variadic template representing a parameter pack.

- If the name represents a type list, it may be used wherever type lists are acceptable, e.g. to instantiate some (other) variadic template.
- If the name represents a value list, it may be used to expand to parameter lists of a variadic function (template or classic) or as initialiser for data structures or be used as an `std::initializer_list`.
- If the name is the formal argument name representing an unpacked formal parameter list, the pattern will be expanded once for each parameter.
- Finally, several packs may be unpacked simultaneously.

Some practical examples (following) should help to clarify the above.

Example: Compile Time Recursive Data Structure

The following class shows an approach how something like `std::tuple` might be implemented with a variadic template:*

```
template<typename T,
         typename... Ts>
struct MyTuple {
    T first;
    MyTuple<Ts...> rest;
    MyTuple(T f, Ts... r)
        : first(f), rest(r)
    {}
};
```

The general case (left) …

… and its specialisation for the empty border case, required to stop endless recursion (below):

```
template<>
struct MyTuple<> {
};
```

With this, `MyTuple` objects could be created as follows:

```
MyTuple<int, double, const char *> x(1, 0.5, "one by three");
MyTuple<std::string, const char *> y("one", "two");
MyTuple<> z;
```

*: Note that this example is stripped down to its bare bones deliberately omits the finer points that were important for useful and performant tuple class.

Example: Compile Time Recursive Functions

The function `concat` was already introduced as example for a variadic template function.*

```
// FIRST(!) the basic form that stops recursion:
std::string concat(char) {
    return {};
}

// THEN the recursive form (to unfold at compile time):
template<typename T, typename... Ts>
std::string concat(char sep, T, arg, Ts... args) {
   return arg.append(&sep, 1) + concat(sep, args...);
};
```

> **[!]** The definition of the basic version (stopping recursion) and the recursive version must not be reversed – or the program will not compile any more.

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*: This example too is stripped down to its bare bones and deliberately omits the finer points that would make sense for useful and performant implementation.

Example: Stopping Recursion with SFINAE

Stopping recursion by using SFINAE is demonstrated in the following implementation of a `get<N>` member function of class `MyTuple`:*

```
template<typename T, typename... Ts>
class MyTuple {
    …
    … // as shown on a previous page
    …
    template<std::size_t N>
    typename std::enable_if<N == 0, T>::type
    get() { return first; }

    template<std::size_t N>
    using Rtype = decltype(rest.template get<N-1>());

    template<std::size_t N>
    typename std::enable_if<N != 0, Rtype<N>>::type
    get() { return rest.template get<N-1>(); }
};
```

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*: Note that implementing `get<N>` as a member is like Boost.Tuple provides member access, while `std::tuple` uses a non-member overload.

Simultaneous Unpacking of Parameter Packs

Two (or more) parameter packs may also be unpacked simultaneous, as shown in the following example. It demonstrates how `std::make_unique` (missing from C++11[*]) may be implemented:

```
template<typename T, typename... Args>
std::unique_ptr<T> make_unique(Args&&... args)
{
    return std::unique_ptr<T>{new T(std::forward<Args>(args)...)};
           //                                  /^^^^  ^^^^\
           // simultaneously unpack argument types and names
}
```

The interesting part with respect to simultaneous unpacking is marked in the comment.

> The example also demonstrates how perfect forwarding can be applied to whole argument lists with ease in a single statement

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[*]: Though a factory function for `std::unique_ptr` similar to `std::make_shared` for `std::shared_ptr` makes sense, it was not defined in C++11, but only added in C++14.

C++14 `std::integer_sequence` Template

As code implementing variadic templates needs to "unfold" at compile time, C++14 provides the following compile time integer sequences:

- A template `std::integer_sequence` holding a sequence of arbitrary values of a given integral type.
- A template `std::index_sequence` as special form of the above where the integral type is `std::size_t`.
- A helper template `std::make_index_sequence` to generate a given number of consecutive values, starting from zero.
- A helper template `std::index_sequence_for` to generates an index sequence with the length of a given parameter pack.

(i) For more information on the above including examples see: http://en.cppreference.com/w/cpp/utility/integer_sequence

MPL (Meta Programming Library)

From the Boost Documentation:

> The Boost.MPL Library is a general-purpose, high-level C++ template meta-programming framework of compile-time algorithms, sequences and meta-functions. It provides a conceptual foundation and an extensive set of powerful and coherent tools that make doing explict meta-programming in C++ as easy and enjoyable as possible within the current language.