Department I - C Plus Plus

Modern and Lucid C++ Advanced for Professional Programmers

Week 6 – Advanced Templates

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Rapperswil, 04.04.2023
FS2023

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Agenda

- **Week 5 Recap**
- **Static vs. Dynamic Polymorphism**
- **Substitution Failure Is Not An Error (SFINAE)**
- **Type Constraints**

- **Participants should…**
  - … get a deeper understanding of why template code (static polymorphism) is faster than virtually dispatched code (dynamic polymorphism)
  - … have refreshed their general template knowledge
  - … can implement deduction guides for class template argument deduction
  - … are able to eliminate function template overloads by applying SFINAE
  - … define their own named type constraints and use them to restrict template parameters

Recap Week 5

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- **Simple function overload resolution determines which implementation to use**

```
template <typename InputIter, typename Distance>
auto advanceImpl(InputIter& i, Distance d, std::input_iterator_tag) -> void {
  while (d--) { i++; }
}

template <typename RandomAccessIter, typename Distance>
auto advanceImpl(RandomAccessIter& i, Distance d, std::random_access_iterator_tag) -> void {
  i += d;
}

template <typename InputIter, typename Distance>
auto advance(InputIter& i, Distance n) -> void {
  typename std::iterator_traits<InputIter>::difference_type d = n;
  advanceImpl(i, d, typename std::iterator_traits<InputIter>::iterator_category{});
}
```

```
::advance(iter, 15);
```

- **Using `boost/operators.hpp` shortens definition**

```
struct IntIteratorBoost
  : boost::input_iterator_helper<IntIteratorBoost, int> {

  explicit IntIteratorBoost(int start = 0)
    : value { start } {}

  auto operator==(IntIteratorBoost const& r) const -> bool {
    return value == r.value;
  }

  auto operator*() const -> value_type { return value; }

  auto operator ++() -> IntIteratorBoost& {
    ++value;
    return *this;
  }

private:
  value_type value;
};
```

Pass own type
CRTP = Curiously Recurring Template Parameter

Inherit to obtain types and operations (through CRTP)

Explicit Constructor

`operator==` required

Reuse predefined type

```
struct IntInputter {
  using iterator_category = std::input_iterator_tag;
  using value_type = int;
  /* Other Member Types Omitted */

  IntInputter();
  explicit IntInputter(std::istream & in)
    : input { in } {}
  auto operator*() -> value_type;
  auto operator++() -> IntInputter& {
    return *this;
  }
  auto operator++(int) -> IntInputter {
    IntInputter old{*this};
    ++(*this);
    return old;
  }
  auto operator==(IntInputter const & other) const -> bool;
  auto operator!=(IntInputter const & other) const -> bool {
    return !(*this == other);
  }
private:
  std::istream & input;
};
```

Default Constructor for EOF

++ does nothing

Equal only if both EOF

Caller must guarantee survival of object, otherwise "dangling" reference!

Static vs. Dynamic Polymorphism

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Pros of static polymorphism

- Happens at compile-time
- Faster execution time
  - No dynamic dispatch required
  - Easier to optimize (inline)
- Type checks at compile-time

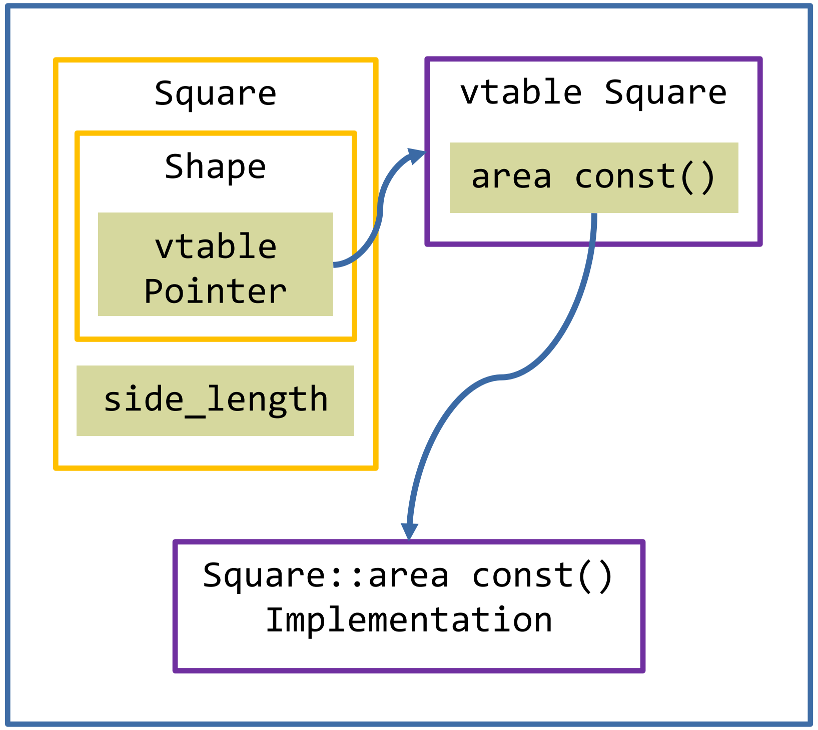
Cons of static polymorphism

- Longer compile-times
- Template code has to be known when used
- Larger binary size
  - Copy of the used parts for each (template) instance

- **A polymorphic call of a virtual function requires lookup of the target function**

```
struct Shape {
  virtual unsigned area() const = 0;
  virtual ~Shape();
};

struct Square : Shape {
  Square(unsigned side_length)
    : side_length{side_length} {}
  unsigned area() const {
    return side_length * side_length;
  }
  unsigned side_length;
};
```




```
decltype(auto) amountOfSeeds(Shape const & shape) {
  auto area = shape.area();
  return area * seedsPerSquareMeter;
};
```

- **Article on this topic:** http://eli.thegreenplace.net/2013/12/05/the-cost-of-dynamic-virtual-calls-vs-static-crtp-dispatch-in-c

Overhead of Dynamic Dispatching (2/2)

- **Non-virtual calls directly call the target function**

Argument Type

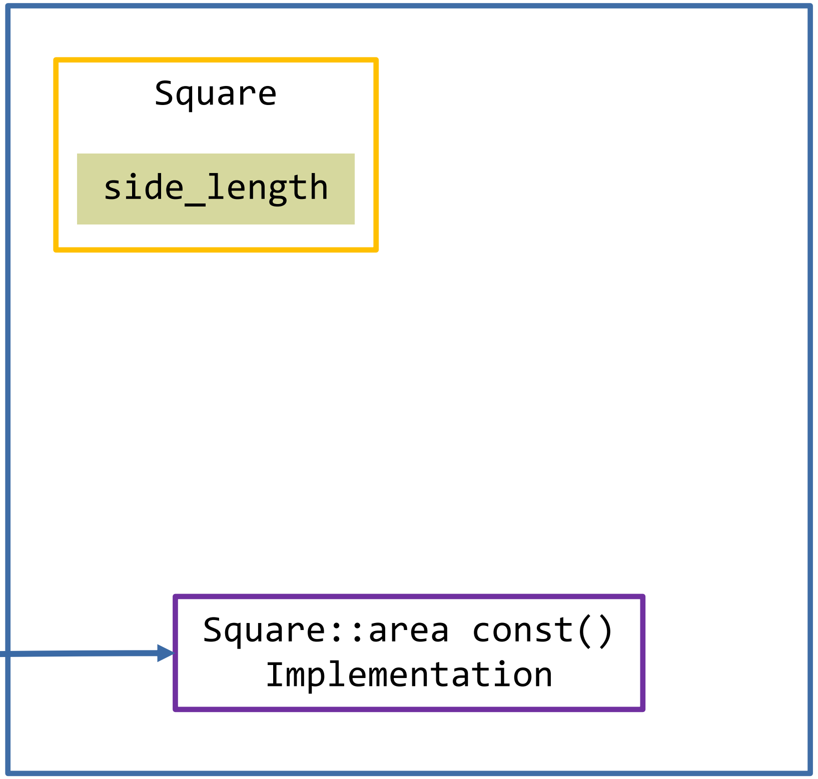
```
struct Square {
  Square(unsigned side_length)
    : side_length{side_length} {}
  unsigned area() const {
    return side_length * side_length;
  }
  unsigned side_length;
};
```

Template

```
template<typename ShapeType>
decltype(auto) amountOfSeeds(ShapeType const & shape) {
  auto area = shape.area();
  return area * seedsPerSquareMeter;
};
```

Instance

```
decltype(auto) amountOfSeeds(Square const & shape) {
  auto area = shape.area();
  return area * seedsPerSquareMeter;
};
```



Object Layout (Visual Studio)

- **Object is smaller**
  - No vtable
- **Compiler flag for (cl.exe)**
  - /d1reportSingleClassLayout<ClassName>
  - /d1reportAllClassLayout

```
class Shape        size(4):
         +---
 0       | {vfptr}
         +---

Shape::$vftable@:
         | &Shape_meta
         |  0
 0       | &Shape::area
 1       | &Shape::{dtor}

class Square       size(8):
         +---
 0       | +--- (base class Shape)
 0       | | {vfptr}
         | +---
 4       | side_length
         +---

Square::$vftable@:
         | &Square_meta
         |  0
 0       | &Square::area
 1       | &Square::{dtor}
```

```
class Shape        size(1):
         +---
         +---

class Square       size(4):
         +---
 0       | +--- (base class Shape)
         | +---
 0       | side_length
         +---
```

Template Instances

- **Copy-pasting at compile-time**
  - Instances for `Square`, `Circle` and `Triangle`
  - The optimizer might get rid of them

```cpp
template<typename ShapeType>
decltype(auto) amountOfSeeds(ShapeType const & shape) {
  auto area = shape.area();
  return area * seedsPerSquareMeter;
};
```

```cpp
unsigned amountOfSeeds(Square const & shape) {
  auto area = shape.area();
  return area * seedsPerSquareMeter;
};
```

```cpp
Circle const & shape) {
a();
rSquareMeter;
};
```

```cpp
Triangle const & shape) {
a();
rSquareMeter;
};
```

Substitution Failure Is Not An Error (SFINAE)

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Overload Selection

- **What do you expect is the return value of the program on the right?**
  - None, the program does not compile!

Name `increment` is looked up

`increment(unsinged)`	`increment` Template

Template arguments are deduced

`increment(unsigned)`	`increment<int>(int)`

Best overload is selected

`increment(int)`

```
auto increment(unsigned i) -> unsigned {
  return i++;
}

template <typename T>
auto increment(T value) -> T {
  return value.increment();
}

auto main() -> int {
  return increment(42);
}
```

```
error: request for member 'increment' in 'value',
which is of non-class type 'int'
```

- **During overload resolution the template parameters in a template declaration are substituted with the deduced types**
  - This may result in template instances that cannot be compiled
  - Or otherwise suboptimal selection
- **If the substitution of template parameter fails that overload candidate is discarded**
- **Substitution failure might happen in**
  - Function return type
  - Function parameter
  - Template parameter declaration
  - And expressions in the above
- **Errors in the instance body are still errors**

Substitution

Substitution

Substitution

```
template <typename T>

auto increment(T value) -> T {
  return value.increment();
}
```

```
auto increment(int value) -> int {
  return value.increment();
} //T = int
```

Possible Solution (Not Recommended)

```
template <typename T>
auto increment(T value) -> decltype(value.increment()) {
  return value.increment();
}
```

- **We can break the return type**
- **If we tell the compiler to use the type of `value.increment()` as return type for `increment<int>`**
  - That type cannot be determined during substitution

```
error: no matching function for call to 'increment(int)'
  increment(42);
              ^
note: candidate: template<class T> decltype (value.increment()) increment(T)
 auto increment(T value) -> decltype(value.increment()) {
      ^~~~~~~~~
note:   template argument deduction/substitution failed:
In substitution of 'template<class T> decltype (value.increment()) increment(T) [with T = int]':
error: request for member 'increment' in 'value', which is of non-class type 'int'
 auto increment(T value) -> decltype(value.increment()) {
```

- **Since there is a problem during substitution that overload is discarded**

Name increment is looked up

`increment(unsinged)`	`increment` Template

Template arguments are deduced

`increment(unsigned)`	~~`increment<int>(int)`~~

Best overload is selected

`increment(unsigned)`

- **Now the result is 42**

```
auto increment(unsigned i) -> unsigned {
  return i++;
}

template <typename T>
auto increment(T value) ->
    decltype(value.increment()) {
  return value.increment();
}

auto int main() -> int {
  return increment(42);
}
```

- **This approach, using decltype(...) as trailing return type, is infeasible in general**
  - Function might have return type `void`
  - It is not elegant for complex bodies

- **The standard library provides many predefined checks for type traits[1]**
- **A trait contains a `boolean` value**
- **Usually, they are available in two versions**
- **Example:**
  - `std::is_same<T, U>`
  - `std::is_same_v<T, U>`

```
template <typename T, typename U>
struct is_same : false_type {
  // inherits
  // static constexpr bool value = false;
};

template <typename T>
struct is_same<T, T> : true_type {
  // inherits
  // static constexpr bool value = true;
};

template <typename T, typename U>
constexpr bool is_same_v = is_same<T, U>::value;
```

[1] https://en.cppreference.com/w/cpp/header/type_traits

`std::is_class`

`#include <type_traits>`

- **Let's examine our example again**
  - We want the `increment` template to be selected only for class type arguments
- **There exists a template `std::is_class<T>`**
  - contains `static constexpr bool value;`
  - `value` is `true` if `T` is a class, `false` otherwise
- **Variable template: `std::is_class_v<T>`**
  - Type `bool` (direct access of `::value`)
- **Can we apply this to the increment template directly?**
  - No, either value (`true` or `false`) is still valid
  - We need something to create an error in the type of the function

```cpp
template <typename T>
auto increment(T value) -> T {
  return value.increment();
}

auto main() -> int {
  return increment(42);
}
```

```cpp
#include <type_traits>

struct S{};

auto main() -> int {
  std::is_class<S>::value; // true
  std::is_class<int>::value; // false
}
```

```
template <bool expr, typename T = void>
struct enable_if;
```

- **The `std::enable_if_t` template takes an expression and a type**
  - If the expression evaluates to `true` `std::enable_if_t` represents the given type
  - Otherwise it does NOT represent a type

```
auto main() -> int {
  std::enable_if_t<true, int> i;       // int
  std::enable_if_t<false, int> error; // no type
}
```

- **Inside `std::enable_if`**

```
template <bool expr,
          typename T = void>
struct enable_if{};
```

```
template <typename T>
struct enable_if<true, T> {
  using type = T;
};
```

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

std::enable_if Applied


```
template <typename T,   >

auto increment( T  value) -> T {
  return value.increment();
}
```

Spots to apply enable_if (SFINAE)

- **Possibilities**

```
template <typename T>
auto increment(T value) -> std::enable_if_t<std::is_class_v<T>, T> {
  return value.increment();
}
```

enable_if as parameter impairs type deduction

```
template <typename T>
auto increment(std::enable_if_t<std::is_class_v<T>, T> value) -> T {
  return value.increment();
}
```

```
template <typename T, typename = std::enable_if_t<std::is_class_v<T>, void>>
auto increment(T value) {
  return value.increment();
}
```

would be void per default

SFINAE Applied to Constructors

- **Example: Box-Container with**
  - Default constructor
  - Copy constructor
  - Move constructor
  - Size constructor

```
Box<MemoryOperationCounter> b{1};
```

```
template <typename T>
struct Box {
  Box() = default;
  Box(Box const& box)
    : items{box.items}{}
  Box(Box&& box)
    : items{std::move(box.items)} {}
  explicit Box(size_t size)
    : items(size) {}
  //...
private:
  std::vector<T> items{};
};
```

- **What if we replace the copy/move constructors with a forwarding constructor?**

```
Box<MemoryOperationCounter> b{1};
```

```
template <typename T>
struct Box {
  Box() = default;
  template <typename BoxType>
  explicit Box(BoxType&& other)
    : items(std::forward<BoxType>(other).items) {}
  explicit Box(size_t size)
    : items(size) {}
  //...
private:
  std::vector<T> items{};
};
```

```
Test.cpp:14:41: error: request for member 'items' in 'std::forward<int>((* & other))',
                              which is of non-class type 'int'
    : items(std::forward<BoxType>(other).items) {}
            ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~^~~~~
```

- **We don't want the forwarding constructor to match anything else than Boxes**
  - Type traits can be used to narrow down the valid calls.

```
template <typename T>
struct Box {
  Box() = default;
  template <typename BoxType, typename = std::enable_if_t<std::is_same_v<Box, BoxType>>>
  explicit Box(BoxType && other)
    : items(std::forward<BoxType>(other).items) {}
  explicit Box(size_t size)
    : items(size) {}
  //...
private:
  std::vector<T> items{};
};
```

- **This is just an example for demonstrating the mechanism. Do not implement a forwarding constructor as replacement for the move and copy constructor.**

Right or Wrong? (Preview)

?

```
template <typename T>
auto consume(T&& value)
            -> std::enable_if_t<
                 std::negation_v<
                   std::is_reference<T>
                 >
               >
 { /*...*/ }
//This function can only be called with rvalues
```

```
template <typename T>
auto convert(T value) -> int {
  using namespace std;
  enable_if_t<
    is_constructible_v<int, T>, int
  > converted{value};
  return converted;
}
//This function can be eliminated by SFINAE
```

?

```
template <typename T>
auto consume(T&& value)
            -> std::enable_if_t<
                 std::negation_v<
                   std::is_reference<T>
                 >
               >
 { /*...*/ }
//This function can only be called with rvalues
```

Correct

`std::is_reference` is `std::true_type` if T is a reference otherwise `std::false_type`. If the forwarding reference is initialized with an lvalue T is a reference. `std::negation_v` negates the `true/false_type`. The overload is only enabled for rvalues.

```
template <typename T>
auto convert(T value) -> int {
  using namespace std;
  enable_if_t<
    is_constructible_v<int, T>, int
  > converted{value};
  return converted;
}
//This function can be eliminated by SFINAE
```

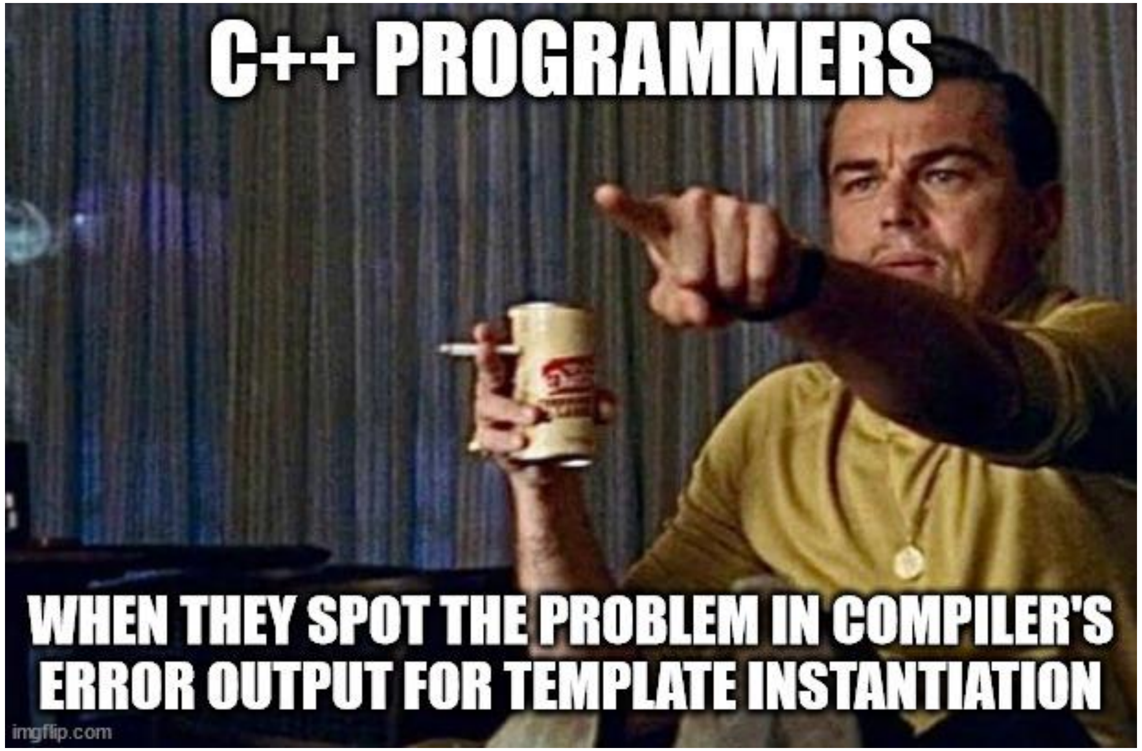
Incorrect

This is not SFINAE! It will compile if called with something that can be used to construct an int, but the overload will be taken anyway.

Template Parameter Constraints

C++20 introduced constraints for template parameters

- **Provide a means to specify the characteristics of a type (requirement) in template contexts**
  - Opposed to the implicit syntactic requirements imposed by the use of the template parameter
- **Earlier detection of violation in the template instantiation process**
  - Better error messages
- **More expressive SFINAE**



Constraints with Keyword `requires`

- So called `requires` clauses allow constraining template parameters
- `requires` is followed by a compile-time constant boolean expression
- `requires` clauses are either placed after the template parameter list…

```
template <typename T>
requires true
auto function(T argument) -> void {
}
```

- … or after the function template's declarator

```
template <typename T>
auto function(T argument) -> void requires true {
}
```

Example requires Clause


```cpp
template <typename T>
requires std::is_class_v<T>
auto function(T argument) -> void {
}
```

```cpp
function(1);
function(std::string{});
```

```
Function.cpp:87:11: error: no matching function for call to 'function(int)'
   87 |   function(1);
      |   ~~~~~~~~^~~
Function.cpp:75:6: note: candidate: 'template<class T>  requires  is_class_v<T> void function(T)'
   75 | auto function(T argument) -> void {
      |      ^~~~~~~~
Function.cpp:75:6: note:   template argument deduction/substitution failed:
Function.cpp:75:6: note: constraints not satisfied
Function.cpp: In substitution of 'template<class T>  requires  is_class_v<T> void function(T) [with T = int]':
Function.cpp:87:11:   required from here
Function.cpp:75:6:   required by the constraints of 'template<class T>  requires  is_class_v<T> void function(T)'
Function.cpp:74:15: note: the expression 'is_class_v<T> [with T = int]' evaluated to 'false'
   74 | requires std::is_class_v<T>
      |          ~~~~~^~~~~~~~~~~~~
```

requires Expression

- **requires also starts an expression that evaluates to bool**

```
requires {
  // Sequence of requirements
}
```

```
requires ($parameter-list$) {
  // Sequence of requirements
}
```

- **Requirements overview**
  - Simple requirements are statements that are true when they can be compiled
  - Type requirements check whether a specific type exists (typically, for nested types)
  - Compound requirements checks constraints on an expression's type
  - Nested requirements contain further (nested) requires expressions

- **Simple requirements are statements that are true when they can be compiled**

```
requires (T v) {
  v.increment();
}
```

- **Applied to our previous «incrementable» example**

```
template <typename T>
requires requires (T const v) { v.increment(); }
auto increment(T value) -> T {
  return value.increment();
}
```

Type Requirements

- **Type requirements check whether a specific type exists (typically, for nested types)**
- **Starts with `typename` keyword**

```
requires {
    typename $type$;
}
```

- **To check the types on BoundedBuffer the requirements could look as follows**

```
requires {
    typename BoundedBuffer<int>::value_type;
    typename BoundedBuffer<int>::size_type;
    typename BoundedBuffer<int>::reference;
    typename BoundedBuffer<int>::const_reference;
}
```

- **Compound requirements check whether an expression is valid and can check constraints on the expression’s type**

- **The return-type-requirement is optional**

```
requires (T v) {
  { $expression$ } -> $type-constraint$;
}
```

- **Applied to our previous «incrementable» example**

```
template <typename T>
requires requires (T const v) {
  { v.increment() } -> std::same_as<T>;
}
auto increment(T value) -> T {
  return value.increment();
}
```

Named Constraints with Keyword `concept`

- **Specifies a named type requirement**

```
template <typename T>
concept NameTypeRequirement = $bool-expression$;
```

- **Typically, a `requires` expression is used as bool expression (or is at least part of it)**
- **Conjunctions (&&) and disjunctions (||) can be used to combine constraints**

```
template <typename T>
concept Incrementable = requires (T const v){
  {v.increment()} -> std::same_as<T>;
};
```

- **Named constraints can be used in template parameter declarations**

```
template <Incrementable T>
auto increment(T value) -> T {
  return value.increment();
}
```

- **Or as part of a requires clause**

```
template <typename T>
requires Incrementable<T>
auto increment(T value) -> T {
  return value.increment();
}
```

- **Use auto as parameter type instead of template declaration**
  - with an unconstrained parameter

```
auto function(auto argument) -> void {
}
```

- **This is equivalent to**

```
template <typename T>
auto function(T argument) -> void {
}
```

- **What is the equivalent for?**

```cpp
auto function(auto arg1, auto arg1) -> void {
}
```

?

```cpp
template <typename T>
auto function(T arg1, T arg2) -> void {
}
```

```cpp
template <typename T1, typename T2>
auto function(T1 arg1, T2 arg2) -> void {
}
```

Terse Syntax for Constrained Parameters

- **Abbreviated function template parameters can be constrained too**

```
auto increment(Incrementable auto value) -> T {
  return value.increment();
}
```

- **Corresponds to**

```
template <Incrementable T>
auto increment(T value) -> T {
  return value.increment();
}
```

- **Given the following named type constraints**

```
template <typename T>
concept Printable = requires (T const v, std::ostream& os) {
  v.print(os);
};

template <typename T>
concept LeftshiftOutputtable = requires (T const v, std::ostream& os) {
  {os << v} -> std::same_as<std::ostream&>;
};
```

- **Function overloads that have constraints not satisfied are excluded from overload resolution too**

```
auto print(Printable auto const& printable) {
  printable.print(std::cout);
}

auto print(LeftshiftOutputtable auto const& outputtable) {
  std::cout << outputtable;
}

auto printAll(auto const& first, auto const&... rest) -> void {
  print(first);
  if constexpr (sizeof...(rest)) {
    std::cout << ", ";
    printAll(rest...);
  }
}
```

`#include <concepts>`

- **Many predefined type constraints exist in the standard library**
- **Examples**
  - `std::equality_comparable` checks whether a type can be == and != compared
  - `std::default_initializable` checks whether a type can be default constructed
  - `std::floating_point` checks whether a type is a floating-point type
  - Many more

See https://en.cppreference.com/w/cpp/concepts

Summary

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Summary

- **Function calls resolved at compile-time can be much faster**
- **SFINAE is used to eliminate overload candidates**
- **Concepts encode requirements for types and (should) provide compiler error messages that are easier to read**

Templates Recap

Repetition Material for Self-Study

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Function Templates (Recap)

template Keyword

Template Parameters

- **Template declaration**
  - template Keyword
  - Template Parameters
- **Function is implicitly inline**

```
template<typename ShapeType>
decltype(auto) amountOfSeeds(ShapeType const & shape) {
  auto area = shape.area();
  return area * seedsPerSquareMeter;
};
```

- **Template arguments might be deduced from the function call arguments**

ShapeType is deduced to be Rectangle

```
Rectangle r{5, 8};
auto seeds = amountOfSeeds(r);
```

Explicitly specified to be Rectangle

```
Rectangle r{5, 8};
auto seeds = amountOfSeeds<Rectangle>(r);
```

Template Parameters

Template Template Parameter

Template Type Parameter

Template Non-Type Parameter

```
template<template<typename, unsigned> typename Container, typename Target, std::size_t N>
Target extractMiddleElement(Container<Target, N> & container) {
  using std::swap;
  Target middleElement{};
  swap(container.at(N / 2), middleElement);
  return middleElement;
}
```

```
std::array<int, 3> values{1, 2, 3};
extractMiddleElement(values);
```

```
Container => std::array
Target    => int
N         => 3
```

```
BoundedBuffer<int, 3> values{1, 2, 3};
extractMiddleElement(values);
```

```
Container => BoundedBuffer
Target    => int
N         => 3
```

- **Before C++17 template template parameter were declared with «`template <...> class`»**

- **We could also implement `extractMiddleElement` differently**
  - Instead of `N` we might use `size()`
  - Instead of `Target` we have the member type `value_type` of `Container`
- **That changes the Concept of the parameter. How?**

Container must have:
- member type `value_type`
- `size()` member function

It does not need to be a template with type and unsigned parameter anymore.

- **The member type `value_type` is a dependent type**
  - The compiler does not know whether `Container::value_type` is a member type, function or variable
  - To tell the compiler that it is a type the `typename` keyword is required (there is also a template keyword for cases where the member is a template)

```
template<typename Container>
auto extractMiddleElement(Container & container) {
  typename Container::value_type middleElement{};
  std::swap(container.at(container.size() / 2), middleElement);
  return middleElement;
}
```

- **In specific cases the number of template parameters might not be fix/known upfront**
- **Thus the template shall take an arbitrary number of parameters**
- **Example:**

```
template<typename First, typename...Types>
void printAll(First const & first, Types const &...rest) {
  std::cout << first;
  if (sizeof...(Types)) {
    std::cout << ", ";
  }
  printAll(rest...);
}
```

- **Syntax (ellipses everywhere): `...`**
  - `...` in template parameter list for an arbitrary number of template parameters (Template Parameter Pack)
  - `...` in function parameter list for an arbitrary number of function arguments (Function Parameter Pack)
  - `...` after `sizeof` to access the number of elements in template parameter pack
  - `...` in the variadic template implementation after a pattern (Pack Expansion)

- **Templates allow generic programming in C++**
- **A template is instantiated for a specific set of template arguments**

Type Parameter

Non-Type Parameter

```
template<typename Freight, unsigned Space>
struct Carriage {
  std::array<Freight, Space> cargo{};
};

decltype(auto) createSmallTankWagon() {
  return Carriage<Oil, 1>{};
}
```

Creates Template Instance

```
struct Carriage {
  std::array<Oil, 1> cargo{};
};
```

- **Templates can be (partially) specialized**

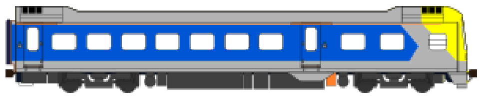
- **Liskov's Substitution Principle does not apply for specializations, i.e. a specialized template does not need to satisfy the interface of the base template!**

```
template<typename Freight, unsigned Space>
struct Carriage;

template<unsigned Space>
struct Carriage<Passenger, Space> {
  unsigned const doors{7};
}

decltype(auto) createPassengerWagon() {
  return Carriage<Passenger, 124>{};
}
```

```
struct Carriage {
  unsigned const doors{7};
}
```



- **When a template is instantiated the compiler has to decide whether to use the base template or one of its specializations**

- **Syntax**

```
template<[Parameters]>
Type name [= initialization];
```

  - Can be specialized
  - Usually `constexpr`
- **Purpose**
  - Compile-time predicates and properties of types
  - Usually applied in template meta programming
  - Before C++14 it was necessary to create a class template with a static member variable
    - Now less code is required for the same effect

```
template<typename T>
constexpr T pi = T(3.14159265358979323850);

template<typename T>
constexpr bool is_integer = false;

template<>
constexpr bool is_integer<int> = true;
```

Deduction Guides

OST
Ostschweizer
Fachhochschule

- **Class template arguments can usually be determined by the compiler**

```
template <typename T>
struct Box {
    Box(T content)
      : content{content}{}
    T content;
};

int main() {
  Box<int> b0{0}; //Before C++17
  Box      b1{1}; //Since C++17
}
```

- **The behavior is similar to pretending as if there was a factory function for each constructor**

```
template <typename T>
Box<T> make_box(T content) {
  return Box<T>{content};
}
```

```
auto gift = make_box(teddy);
```

- **In the following example the only template parameter is `T`, which can be deduced from `std::initializer_list<T>`**

```
template <typename T>
class Sack {
  //...
  Sack(std::initializer_list<T> values)
      : theSack(values) {
  }
  //...
};
```

```
void testImplicitDeductionGuide () {
  Sack charSack{'a', 'b', 'c'};
  ASSERT_EQUAL(3, charSack.size());
}
```

```
std::initializer_list<char>
```

- **There is no direct relation from `Iter` to `T` (constructor parameters to template parameter)**

```
template <typename T>
struct BoundedBuffer {
  //...
  template <typename Iter>
  BoundedBuffer(Iter begin, Iter end);
  //...
};
```

```
void testDeductionFromIterators() {
  std::vector values{3, 1, 4, 1, 5, 9, 2, 6};
  BoundedBuffer buffer{begin(values), end(values)};
  ASSERT_EQUAL(values.size(), buffer.size());
}
```

```
error: class template argument deduction failed:
  Sack aSack(begin(values), end(values));
```

User Provided Deduction Guides

- **User-defined deduction guides can be specified in the same scope as the template**
  - Usually, after the template definition itself

```
TemplateName(ConstructorParameters) -> TemplateID;
```

- **Might be necessary for complex cases, e.g. template constructors if the constructor template parameters do not map directly to the class template parameters**
- **The deduction guide can be (and usually is) a template itself**
- **It looks similar to a free-standing constructor**
- **Unfortunately,** Cevelop **does not recognize the deduction guides yet**

Template declaration for `Iter`

```
template <typename Iter>
BoundedBuffer(Iter begin, Iter end) -> BoundedBuffer<typename std::iterator_traits<Iter>::value_type>;
```

Constructor signature

Deduced template instance

- **Test for deducing template argument from iterator works**

```
void testDeductionFromIterators() {
  std::vector values{3, 1, 4, 1, 5, 9, 2, 6};
  BoundedBuffer buffer{begin(values), end(values)};
  ASSERT_EQUAL(values.size(), buffer.size());
}
```

Pack Expansion (Recap)

Variadic Template Instances Unfolded (Recap)

Variadic Template Instance

- **Template declaration:**

```
template<typename First, typename...Types>
void printAll(First const & first, Types const &...rest);
```

- **Implicit instantiation:**

```
int i{42}; double d{1.25}; std::string book{"Lucid C++"};
printAll(i, f, book);
```

- **Template instance:**

```
void printAll(int const & first, double const & __rest0,
                                 std::string const & __rest1) {
  std::cout << first;
  if (2) { //sizeof...(Types) – Number of arguments in the pack
    std::cout << ", ";
  }
  printAll(__rest0, __rest1); //rest... expansion
}
```

- **`sizeof...(<PACK>)` will be replaced by the number of arguments in the pack parameter**
  - `0, 1, 2, ...`

Pack Expansion of `printAll(rest...);`

```
template<typename First, typename...Types>
void printAll(First const & first, Types const &...rest) {
 //...
 printAll(rest...);
}
```

- **Pattern: `rest`**
- **The pattern must contain at least one pack parameter**
- **An expansion is a coma-separated list of instances of the pattern**
- **For each argument in that pack an instance of the pattern is created**
- **In an instance of the pattern the parameter pack name is replaced by an argument of the pack**

```
void printAll(int const & first, double const & __rest0, std::string const & __rest1) {
  //...
  printAll(__rest0, __rest1); //rest...
}
```

Variadic Template Remaining printAll Instances

- **For the call `printAll(__rest0, __rest1)`: `printAll<double, std::string>`**

```
void printAll(double const & first, std::string const & __rest0) {
  std::cout << first;
  if (1) { //sizeof...(Types) – Number of arguments in the pack
    std::cout << ", ";
  }
  printAll(__rest0); //rest... expansion
}
```

- **For the call `printAll(<rest0>)`: `printAll<std::string>`**

```
void printAll(std::string const & first) {
  std::cout << first;
  if (0) { //sizeof...(Types) – Number of arguments in the pack
    std::cout << ", ";
  }
  printAll(); //rest... expansion
}
```

- **What about `printAll()`?**

- **What about `printAll()`?**
  - The variadic template `printAll` is not viable, as it requires at least one parameter
- **We need a base case for the recursion**

```
void printAll() {
}
```

- **Wouldn't it be feasible to just rearange the code in the variadic template?**

```
template<typename First, typename...Types>
void printAll(First const & first, Types const &...rest) {
  std::cout << first;
  if (sizeof...(Types)) {
    std::cout << ", ";
    printAll(rest...);
  }
}
```

?