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# Concepts

## An introduction

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# Why do we need generic programming?

# Strong Typing

C++ is a strongly typed language.

This means that each variable is assigned a type at definition, and it cannot change over time.

This gives a lot of safety, plus it allows the language(=compiler) to do assumptions and optimize the code.

# 💪 Strong typing vs 🦆 duck typing?

```
class Person:
    def feed(self, food):
        print(f"lets eat some {food}")

class Fireplace:
    def feed(self, fuel):
        print(f"let's burn some {fuel}")

def feed_all(storage, obj):
    for element in storage:
        obj.feed(element)

storage_basement = ["🪵", "🍹"]
storage_1st_floor = ["🍝", "🍗", "🧁",]

print("not a big problem... 🗑️")
feed_all(storage_1st_floor, Fireplace())

print("unless you start eating it! 💀")
feed_all(storage_basement, Person())
```

```
not a big problem... 🗑️
let's burn some 🍝
let's burn some 🍗
let's burn some 🧁
unless you start eating it! 💀
lets eat some 🪵
lets eat some 🍹
```

# It's better safe than sorry

# It's better typesafe than sorry

(cit)

Yeah, but having to write a function/class for every single type (and combination) does not scale...

```
int subtract(unsigned int a, unsigned int b);
int subtract(int a, int b);
int subtract(int a, unsigned int b);
float subtract(float a, float b);
```

**Oh! That's why we need generic programming!**

# C++ GENERIC PROGRAMMING = TEMPLATE!

```
template <class T>
T add(T a, T B) {
    return a + b;
}

auto add(auto a, auto B) {
    return a + b;
}
```

We can have template specialization for different types and combinations, but the template "placeholder" accepts anything.

If at template instantiation time, it addresses a problem with the given type (e.g. we call a functon that this type does not have), it would complain with a build error 💥.

Basic template generic programming sounds a bit like "duck typing", but at compile time.

It's slightly better, but in C++ we are not satisfied with sub-optimal solutions...we want the best! 😄

# SFINAE

**SFINAE** allows to disable/enable some overloads at certain conditions.

```
template <class T,
    std::enable_if_t<
            std::is_integral_v<T>
            || std::is_integral_v<T>,
            int> = 0>
void add(T a, T b) {
    return a + b;
}
```

With **SFINAE** we have a finer control on the overload set, in practice **it enables constraining template**!

**Exactly what we wanted!**

# SFINAE is powerful and is supported by STL

Actually, SFINAE allows us to do many things in a quite rigorous way.

SFINAE is supported by the STL with:

- `std::enable_if`
  it can be used in many ways to enable or disable a specialization (class, function, ...)
- `#include <type_traits>`
  it provides some common and useful requirements and transformers for types

# SFINAE errors

It's nice that we can figure out at compile time about errors instead of facing them at runtime...we like it!

It means less error in production, safer code. Nice! 🤩

```
#include <vector>
#include <algorithm>

struct Number {
    long long value_;
};

int main() {
    std::vector<int> integers;
    std::sort(integers.begin(), integers.end());

    std::vector<Number> numbers;
    std::sort(numbers.begin(), numbers.end());
}
```

There's an error in the code above... 🧐

# GCC 13.2 - 79 lines of output

```
In file included from /opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algobase.h:71,
                 from /opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/vector:62,
                 from :1:
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/predefined_ops.h: In instantiation of 'constexpr bool __gnu_cxx::__ops::_Iter_less_iter::operator()(_Iterator1, _Iterator2) const [with _Iterator1 = __gnu_cxx::__normal_iterator<Number*, std::vector >; _Iterator2 = __gnu_cxx::__normal_iterator<Number*, std::vector >]':
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algo.h:1819:14:   required from 'void std::__insertion_sort(_RandomAccessIterator, _RandomAccessIterator, _Compare) [with _RandomAccessIterator = __gnu_cxx::__normal_iterator<Number*, vector >; _Compare = __gnu_cxx::__ops::_Iter_less_iter]'
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algo.h:1859:25:   required from 'void std::__final_insertion_sort(_RandomAccessIterator, _RandomAccessIterator, _Compare) [with _RandomAccessIterator = __gnu_cxx::__normal_iterator<Number*, vector >; _Compare = __gnu_cxx::__ops::_Iter_less_iter]'
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algo.h:1950:31:   required from 'void std::__sort(_RandomAccessIterator, _RandomAccessIterator, _Compare) [with _RandomAccessIterator = __gnu_cxx::__normal_iterator<Number*, vector >; _Compare = __gnu_cxx::__ops::_Iter_less_iter]'
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algo.h:4861:18:   required from 'void std::sort(_RAIter, _RAIter) [with _RAIter = __gnu_cxx::__normal_iterator<Number*, vector >]'
:13:14:   required from here
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/predefined_ops.h:45:23: error: no match for 'operator<' (operand types are 'Number' and 'Number')
   45 |       { return *__it1 < *__it2; }
      |                  ~~~~~~~^~~~~~~
In file included from /opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algobase.h:67:
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_iterator.h:1250:5: note: candidate: 'template bool __gnu_cxx::operator<(const __normal_iterator<_IteratorL, _Container>&, const __normal_iterator<_IteratorR, _Container>&)'
 1250 |     operator<(const __normal_iterator<_IteratorL, _Container>& __lhs,
      |     ^~~~~~~~
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_iterator.h:1250:5: note:   template argument deduction/substitution failed:
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/predefined_ops.h:45:23: note:   'Number' is not derived from 'const __gnu_cxx::__normal_iterator<_IteratorL, _Container>'
   45 |       { return *__it1 < *__it2; }
      |                  ~~~~~~~^~~~~~~
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_iterator.h:1258:5: note: candidate: 'template bool __gnu_cxx::operator<(const __normal_iterator<_Iterator, _Container>&, const __normal_iterator<_Iterator, _Container>&)'
 1258 |     operator<(const __normal_iterator<_Iterator, _Container>& __lhs,
      |     ^~~~~~~~
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_iterator.h:1258:5: note:   template argument deduction/substitution failed:
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/predefined_ops.h:45:23: note:   'Number' is not derived from 'const __gnu_cxx::__normal_iterator<_Iterator, _Container>'
   45 |       { return *__it1 < *__it2; }
      |                  ~~~~~~~^~~~~~~
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/predefined_ops.h: In instantiation of 'bool __gnu_cxx::__ops::_Val_less_iter::operator()(_Value&, _Iterator) const [with _Value = Number; _Iterator = __gnu_cxx::__normal_iterator<Number*, std::vector >]':
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algo.h:1799:20:   required from 'void std::__unguarded_linear_insert(_RandomAccessIterator, _Compare) [with _RandomAccessIterator = __gnu_cxx::__normal_iterator<Number*, vector >; _Compare = __gnu_cxx::__ops::_Val_less_iter]'
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algo.h:1827:36:   required from 'void std::__insertion_sort(_RandomAccessIterator, _RandomAccessIterator, _Compare) [with _RandomAccessIterator = __gnu_cxx::__normal_iterator<Number*, vector >; _Compare = __gnu_cxx::__ops::_Iter_less_iter]'
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algo.h:1859:25:   required from 'void std::__final_insertion_sort(_RandomAccessIterator, _RandomAccessIterator, _Compare) [with _RandomAccessIterator = __gnu_cxx::__normal_iterator<Number*, vector >; _Compare = __gnu_cxx::__ops::_Iter_less_iter]'
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algo.h:1950:31:   required from 'void std::__sort(_RandomAccessIterator, _RandomAccessIterator, _Compare) [with _RandomAccessIterator = __gnu_cxx::__normal_iterator<Number*, vector >; _Compare = __gnu_cxx::__ops::_Iter_less_iter]'
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algo.h:4861:18:   required from 'void std::sort(_RAIter, _RAIter) [with _RAIter = __gnu_cxx::__normal_iterator<Number*, vector >]'
:13:14:   required from here
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/predefined_ops.h:98:22: error: no match for 'operator<' (operand types are 'Number' and 'Number')
   98 |       { return __val < *__it; }
      |                ~~~~~~^~~~~~
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_iterator.h:1250:5: note: candidate: 'template bool __gnu_cxx::operator<(const __normal_iterator<_IteratorL, _Container>&, const __normal_iterator<_IteratorR, _Container>&)'
 1250 |     operator<(const __normal_iterator<_IteratorL, _Container>& __lhs,
      |     ^~~~~~~~
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_iterator.h:1250:5: note:   template argument deduction/substitution failed:
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/predefined_ops.h:98:22: note:   'Number' is not derived from 'const __gnu_cxx::__normal_iterator<_IteratorL, _Container>'
   98 |       { return __val < *__it; }
      |                ~~~~~~^~~~~~
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_iterator.h:1258:5: note: candidate: 'template bool __gnu_cxx::operator<(const __normal_iterator<_Iterator, _Container>&, const __normal_iterator<_Iterator, _Container>&)'
 1258 |     operator<(const __normal_iterator<_Iterator, _Container>& __lhs,
      |     ^~~~~~~~
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_iterator.h:1258:5: note:   template argument deduction/substitution failed:
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/predefined_ops.h:98:22: note:   'Number' is not derived from 'const __gnu_cxx::__normal_iterator<_Iterator, _Container>'
   98 |       { return __val < *__it; }
      |                ~~~~~~^~~~~~
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/predefined_ops.h: In instantiation of 'bool __gnu_cxx::__ops::_Iter_less_val::operator()(_Iterator, _Value&) const [with _Iterator = __gnu_cxx::__normal_iterator<Number*, std::vector >; _Value = Number]':
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_heap.h:140:48:   required from 'void std::__push_heap(_RandomAccessIterator, _Distance, _Distance, _Tp, _Compare&) [with _RandomAccessIterator = __gnu_cxx::__normal_iterator<Number*, vector >; _Distance = long int; _Tp = Number; _Compare = __gnu_cxx::__ops::_Iter_less_val]'
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_heap.h:247:23:   required from 'void std::__adjust_heap(_RandomAccessIterator, _Distance, _Distance, _Tp, _Compare) [with _RandomAccessIterator = __gnu_cxx::__normal_iterator<Number*, vector >; _Distance = long int; _Tp = Number; _Compare = __gnu_cxx::__ops::_Iter_less_iter]'
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_heap.h:356:22:   required from 'void std::__make_heap(_RandomAccessIterator, _RandomAccessIterator, _Compare&) [with _RandomAccessIterator = __gnu_cxx::__normal_iterator<Number*, vector >; _Compare = __gnu_cxx::__ops::_Iter_less_iter]'
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algo.h:1635:23:   required from 'void std::__heap_select(_RandomAccessIterator, _RandomAccessIterator, _RandomAccessIterator, _Compare) [with _RandomAccessIterator = __gnu_cxx::__normal_iterator<Number*, vector >; _Compare = __gnu_cxx::__ops::_Iter_less_iter]'
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algo.h:1910:25:   required from 'void std::__partial_sort(_RandomAccessIterator, _RandomAccessIterator, _RandomAccessIterator, _Compare) [with _RandomAccessIterator = __gnu_cxx::__normal_iterator<Number*, vector >; _Compare = __gnu_cxx::__ops::_Iter_less_iter]'
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algo.h:1926:27:   required from 'void std::__introsort_loop(_RandomAccessIterator, _RandomAccessIterator, _Size, _Compare) [with _RandomAccessIterator = __gnu_cxx::__normal_iterator<Number*, vector >; _Size = long int; _Compare = __gnu_cxx::__ops::_Iter_less_iter]'
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algo.h:1947:25:   required from 'void std::__sort(_RandomAccessIterator, _RandomAccessIterator, _Compare) [with _RandomAccessIterator = __gnu_cxx::__normal_iterator<Number*, vector >; _Compare = __gnu_cxx::__ops::_Iter_less_iter]'
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_algo.h:4861:18:   required from 'void std::sort(_RAIter, _RAIter) [with _RAIter = __gnu_cxx::__normal_iterator<Number*, vector >]'
:13:14:   required from here
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/predefined_ops.h:69:22: error: no match for 'operator<' (operand types are 'Number' and 'Number')
   69 |       { return *__it < __val; }
      |                ~~~~~~^~~~~~
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_iterator.h:1250:5: note: candidate: 'template bool __gnu_cxx::operator<(const __normal_iterator<_IteratorL, _Container>&, const __normal_iterator<_IteratorR, _Container>&)'
 1250 |     operator<(const __normal_iterator<_IteratorL, _Container>& __lhs,
      |     ^~~~~~~~
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_iterator.h:1250:5: note:   template argument deduction/substitution failed:
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/predefined_ops.h:69:22: note:   'Number' is not derived from 'const __gnu_cxx::__normal_iterator<_IteratorL, _Container>'
   69 |       { return *__it < __val; }
      |                ~~~~~~^~~~~~
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_iterator.h:1258:5: note: candidate: 'template bool __gnu_cxx::operator<(const __normal_iterator<_Iterator, _Container>&, const __normal_iterator<_Iterator, _Container>&)'
 1258 |     operator<(const __normal_iterator<_Iterator, _Container>& __lhs,
      |     ^~~~~~~~
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/stl_iterator.h:1258:5: note:   template argument deduction/substitution failed:
/opt/compiler-explorer/gcc-13.2.0/include/c++/13.2.0/bits/predefined_ops.h:69:22: note:   'Number' is not derived from 'const __gnu_cxx::__normal_iterator<_Iterator, _Container>'
   69 |       { return *__it < __val; }
      |                ~~~~~~^~~~~~
Compiler returned: 1
```

# Clang 17.0.1 - (extent of) 9 errors, 200+ lines of output

```
/opt/compiler-explorer/gcc-13.2.0/lib/gcc/x86_64-linux-gnu/13.2.0/../../../../include/c++/13.2.0/bits/predefined_ops.h:69:22: error: invalid operands to binary
expression ('Number' and 'Number')
   69 |       { return *__it < __val; }
      |                ~~~~~ ^ ~~~~~
/opt/compiler-explorer/gcc-13.2.0/lib/gcc/x86_64-linux-gnu/13.2.0/../../../../include/c++/13.2.0/bits/stl_heap.h:140:42: note: in instantiation of function
template specialization '__gnu_cxx::__ops::_Iter_less_val::operator()<__gnu_cxx::__normal_iterator<Number *, std::vector>, Number>' requested here
  140 |       while (__holeIndex > __topIndex && __comp(__first + __parent, __value))
      |                                          ^
/opt/compiler-explorer/gcc-13.2.0/lib/gcc/x86_64-linux-gnu/13.2.0/../../../../include/c++/13.2.0/bits/stl_heap.h:247:12: note: in instantiation of function
template specialization 'std::__push_heap<__gnu_cxx::__normal_iterator<Number *, std::vector>, long, Number, __gnu_cxx::__ops::_Iter_less_val>' requested here
  247 |       std::__push_heap(__first, __holeIndex, __topIndex,
      |            ^
/opt/compiler-explorer/gcc-13.2.0/lib/gcc/x86_64-linux-gnu/13.2.0/../../../../include/c++/13.2.0/bits/stl_heap.h:356:9: note: in instantiation of function template
specialization 'std::__adjust_heap<__gnu_cxx::__normal_iterator<Number *, std::vector>, long, Number, __gnu_cxx::__ops::_Iter_less_iter>' requested here
  356 |           std::__adjust_heap(__first, __parent, __len, _GLIBCXX_MOVE(__value),
      |                ^
/opt/compiler-explorer/gcc-13.2.0/lib/gcc/x86_64-linux-gnu/13.2.0/../../../../include/c++/13.2.0/bits/stl_algo.h:1635:12: note: in instantiation of function
template specialization 'std::__make_heap<__gnu_cxx::__normal_iterator<Number *, std::vector>, __gnu_cxx::__ops::_Iter_less_iter>' requested here
 1635 |       std::__make_heap(__first, __middle, __comp);
      |            ^
/opt/compiler-explorer/gcc-13.2.0/lib/gcc/x86_64-linux-gnu/13.2.0/../../../../include/c++/13.2.0/bits/stl_algo.h:1910:12: note: in instantiation of function
template specialization 'std::__heap_select<__gnu_cxx::__normal_iterator<Number *, std::vector>, __gnu_cxx::__ops::_Iter_less_iter>' requested here
 1910 |       std::__heap_select(__first, __middle, __last, __comp);
      |            ^
/opt/compiler-explorer/gcc-13.2.0/lib/gcc/x86_64-linux-gnu/13.2.0/../../../../include/c++/13.2.0/bits/stl_algo.h:1926:13: note: in instantiation of function
template specialization 'std::__partial_sort<__gnu_cxx::__normal_iterator<Number *, std::vector>, __gnu_cxx::__ops::_Iter_less_iter>' requested here
 1926 |               std::__partial_sort(__first, __last, __last, __comp);
      |                    ^
/opt/compiler-explorer/gcc-13.2.0/lib/gcc/x86_64-linux-gnu/13.2.0/../../../../include/c++/13.2.0/bits/stl_algo.h:1947:9: note: in instantiation of function
template specialization 'std::__introsort_loop<__gnu_cxx::__normal_iterator<Number *, std::vector>, long, __gnu_cxx::__ops::_Iter_less_iter>' requested here
 1947 |           std::__introsort_loop(__first, __last,
      |                ^
/opt/compiler-explorer/gcc-13.2.0/lib/gcc/x86_64-linux-gnu/13.2.0/../../../../include/c++/13.2.0/bits/stl_algo.h:4861:12: note: in instantiation of function
template specialization 'std::__sort<__gnu_cxx::__normal_iterator<Number *, std::vector>, __gnu_cxx::__ops::_Iter_less_iter>' requested here
 4861 |       std::__sort(__first, __last, __gnu_cxx::__ops::__iter_less_iter());
      |            ^
```

# 🌹 Every rose has its torn

I haven't said that SFINAE was fantastic...

Don't get me wrong: it is a super tool, but it looks more like a workaround than a proper tool of the language.

The typical *"it's not a bug is a feature"* applied to the C++ language. Morover, SFINAE has some limitations (e.g. there is no place for it in constructors).

Different techinques and language evolutions overcome some of this limitations improving this situation:
*tag dispatching*, `constexpr`, and ...

## CONCEPTS

### C++20™

# Concepts

- nothing dramatically new
- it can be seen as a more readable way for SFINAE constraints
- more readable code, and clearer error messages
- that does not look like an incident

They introduce some new language keywords and construct:

- `requires`
- `concept`

**From templates to concepts in three moves!**

# Ready?

# Template

```cpp
#include <type_traits>
#include <vector>

template <class Float>
Float mean(const Float a, const Float b) {
    return (a + b) / 2;
}

float res_00 = mean(2.0, 3.0);      // 2.5
double res_01 = mean(2.0, 3.0);     // 2.5

float res_02 = mean(1, 2);          // 1
int res_03 = mean('a', 'd');        // 98 (= 'b')

// compile error: std::vector does not have `+`
std::vector<float> res_v = mean(
    std::vector<float>{1,2,3},
    std::vector<float>{4,5,6});
```

👍 no code duplication thanks to templates!

👎 one fits all...unconstrained!
👎 error message is not straightforward

# SFINAE

```cpp
#include <type_traits>

template <class Float,
          class = std::enable_if_t<std::is_floating_point_v<Float>>>
Float mean(const Float a, const Float b) {
    return (a + b) / 2;
}

float res_00 = mean(2.0, 3.0);
double res_01 = mean(2.0, 3.0);

// compile error
// float res_02 = mean(1, 2);
// int res_03 = mean('a', 'd');
```

```
error: no type named 'type' in 'struct std::enable_if<false, void>'
 2514 |     using enable_if_t = typename enable_if<_Cond, _Tp>::type;
```

🍾 `Float` is now constrained!

👎 code readability is affected

🤨 error message is "a bit" cryptic

# Concepts

```cpp
#include <concepts>
template <std::floating_point Float>
Float mean(const Float a, const Float b) {
    return (a + b) / 2;
}

float res_00 = mean(2.0, 3.0);
double res_01 = mean(2.0, 3.0);

// compile error
// float res_02 = mean(1, 2);
```

```
error: no matching function for call to 'mean(int, int)'
   15 |     float res_02 = mean(1, 2);
      |                    ~~~~^~~~~
...
required for the satisfaction of 'floating_point<Float>' [with Float = int]
note: the expression 'is_floating_point_v<_Tp> [with _Tp = int]' evaluated to 'false'
  111 |     concept floating_point = is_floating_point_v<_Tp>;
      |                              ^~~~~~~~~~~~~~~~~~~~~~~~
```

😉 same semantic

👍 better error message

👍 better code readability

# SFINAE ⏩ CONCEPTS

## SFINAE

```
template <class Float,
          class = std::enable_if_t<std::is_floating_point_v<Float>>>
Float mean(const Float a, const Float b) {
    return (a + b) / 2;
}
```

## Concepts

```
template <std::floating_point Float>
Float mean(const Float a, const Float b) {
    return (a + b) / 2;
}
```

**We didn't introduce any new language keyword (yet), and we already achieved a more terse and readable code, in addition to better error messages, expressing exactly the same thing!**

A couple of notes:

| | SFINAE | Concepts |
|---|---|---|
| STL definitions | `#include <type_traits>` | `#include <concepts>` |
| Names | verb-like (e.g. `is_floating_point`) | adjective-like (e.g. `floating_point`) |

# Exploring Concepts

# Syntactic variants

```
template <std::floating_point Float>
Float mean(const Float a, const Float b) {
    return (a + b) / 2;
}
```

In this way we defined a named placeholder `Float`, on which we constrain `Float` to be a `std::floating_point`.

This syntax can be used directly "in-place" using `auto` for creating the placeholder

```
std::floating_point auto mean(
    const std::floating_point auto a,
    const std::floating_point auto b) {
        return (a + b) / 2;
}
```

**Are they semantically the same?**

🧐 *hint: how many placeholders there are?*

```cpp
template <std::floating_point Float>
Float mean(const Float a, const Float b) {
    return (a + b) / 2;
}

float res_00 = mean(2.0, 3.0);
double res_01 = mean(2.0, 3.0);

float res_02 = mean<float>(2.0f, 3.0);

// compiler error
float res_03 = mean(2.0f, 3.0);
```

```
<source>: In function 'int main()':
<source>:28:24: error: no matching function for call to 'mean(float, double)'
   28 |     float res_03 = mean(2.0f, 3.0);
      |                    ~~~~^~~~~~~~~~
<source>:10:7: note: candidate: 'template<class Float>  requires  floating_point<Float> Float mean(Float, Float)'
   10 | Float mean(const Float a, const Float b) {
      |       ^~~~
<source>:10:7: note:   template argument deduction/substitution failed:
<source>:28:24: note:   deduced conflicting types for parameter 'Float' ('float' and 'double')
   28 |     float res_03 = mean(2.0f, 3.0);
      |                    ~~~~^~~~~~~~~~
```

# Multiple placeholder

This fixes the problem of different types for arguments, because they can be deduced separately.

```
template <
    std::floating_point FloatA,
    std::floating_point FloatB>
float mean(const FloatA a, const FloatB b) {
    return (a + b) / 2;
}

float res_00 = mean(2.0, 3.0);
double res_01 = mean(2.0, 3.0);
float res_02 = mean(2.0f, 3.0);
```

But now the return type is fixed to `float` ...

If we add a placeholder `FloatR`, since it cannot deduce the return type, it has to be explicitly indicated in the call!

# return-type contract

Without constraints this is correct, since the floating point type used for `a` will be implicitly cast to `int`.

```
int floor(const std::floating_point auto a) {
    return a;
}
```

Here we are constraining the return type by asking it to be integral...

```
std::integral auto floor(const std::floating_point auto a) {
    return a;
}
```

```
<source>:29:16: error: deduced return type does not satisfy placeholder constraints
   29 |         return a;
      |                ^
<source>:29:16: note: constraints not satisfied
<concepts>:102:24: note: the expression 'is_integral_v<_Tp> [with _Tp = float]' evaluated to 'false'
  102 |     concept integral = is_integral_v<_Tp>;
```

# ❤️ Concepts ❤️

We didn't see much about concepts, but they already proved to be very useful! 😍

Just by using them like this, we can easily constrain a type (better, a placeholder of a type, e.g. `auto`).

```
<concept_name> <type_placeholder>
```

We've already seen them in action in various places for functions, lastly for return types, but also for arguments...

**Are arguments so different from variable definition!?** Nope! Actually we can use concepts also for variable definition!

```
const std::integral auto res = mean(1.0f, 2.0f);
```

# Concepts

(syntax and new language constructs)

# `requires` clause

Till now we used concepts without using any new keyword.

```
template <std::floating_point T>
T foo(const T a, const T b) {}
```

Actually there are more ways to express the same constraint using the `requires` keyword.

### Constraining the template

```
template <class T> requires std::is_floating<T>
T foo(const T a, const T b) {}
```

### Or **constraining the function**

```
template <class T>
T foo(const T a, const T b) requires std::is_floating<T> {}
```

# `requires` expression

```
requires (parameter-list) {
    requirement_1;
    requirement_2;
    ...
    requirement_n;
}
```

- `parameter-list` like for functions (optional)
  Useful to get an instance of a particular type on which to define requirements
- Each requirement has to match in order for a requirement expression to be true (lines are considered to have AND between them)

# Requirements

**1 SIMPLE**: does it build?

```
a + b;
```

**2 TYPE**: does it represent a type?

```
typename A<B>;
typename B::type;
```

**3 COMPOUND**: does it build and return type?

```
{ x + b } noexcept -> std::same_as<T>;
```

**4 NESTED**: does it evaluate true?

```
requires Same<T*, decltype(&a)>;
```

# `requires requires`

- `requires` clause evaluates a boolean expression
- `requires` expression returns a boolean value

💡 Wait... I can combine them! 💡

```
template <class T, class U>
requires requires {
    std::floating_point<T>;
    std::integral<U>;
    } void foo(T a, U b) {
}
```

## ...and is it a good idea?

# NO.

## `requires requires` is generally a code smell.

It might be better to define a concept for it instead of having something ad-hoc.

# Can I define a new custom concept?!?!

# Yes!

# `concept` keyword

Till now we used already defined concept, all the ones already available in STL.

But we can define our ones!

```
template <class>
concept concept_name = bool_expression;
```

Where `bool_expression` can be whatever returns a compile time boolean value.

For example a `type_trait`

```
template <class T>
concept blas_type = std::is_floating_point_v<T>;
```

Or...do you recall any other way of returning a bool value, which expresses a **requirement**?

# `concept` keyword

A `requires` expression!

```
template <class T>
concept Num = requires (T a, T b) {
    {a + b} -> std::same_as<T>;
    {a - b} -> std::same_as<T>;
    {a * b} -> std::same_as<T>;
    {-a}  -> std::same_as<T>;
};
```

However we define a concept with the `concept` keyword, this is identified as a **named concept**.

This is how they are actually defined in STL the ones that we used in our initial examples, e.g. `std::floating_point` and `std::integral`.

# STL Concepts Library

**en.cppreference.com/w/cpp/concepts**

**(Core, Comparison, Object, Callable, Iterator, Algorithm, Ranges)**

# Concept guidelines

- Naming
  e.g. `is_floating_point` becomes `floating_point`
- It should not be used for implementation requirements; it's for describing a concept.
- Writing a good concept, from the "design" point of view, is difficult. It's good to start with a partial concept (even useful for debugging) and refine it step by step over time.

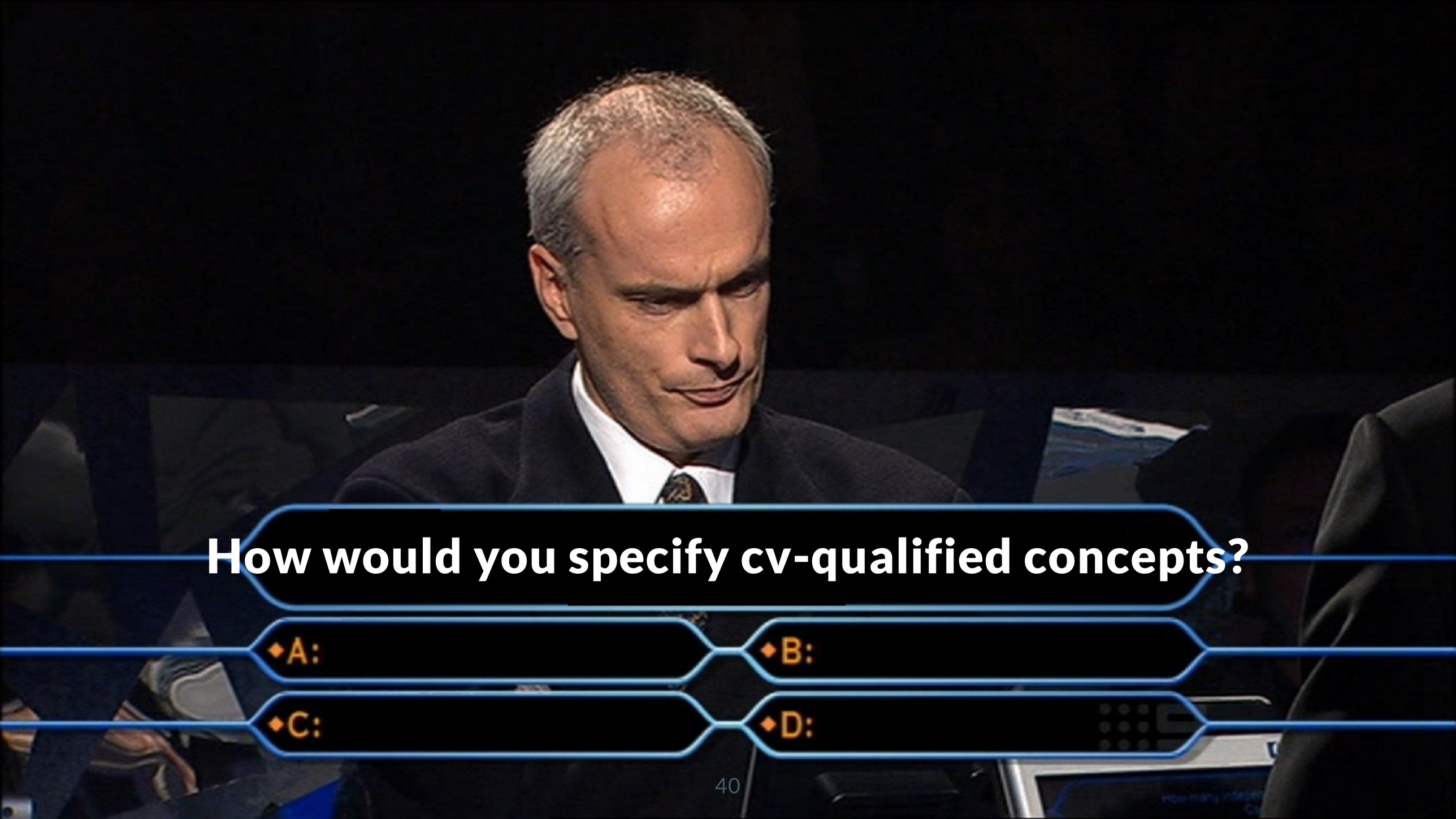
# An example: `Num`

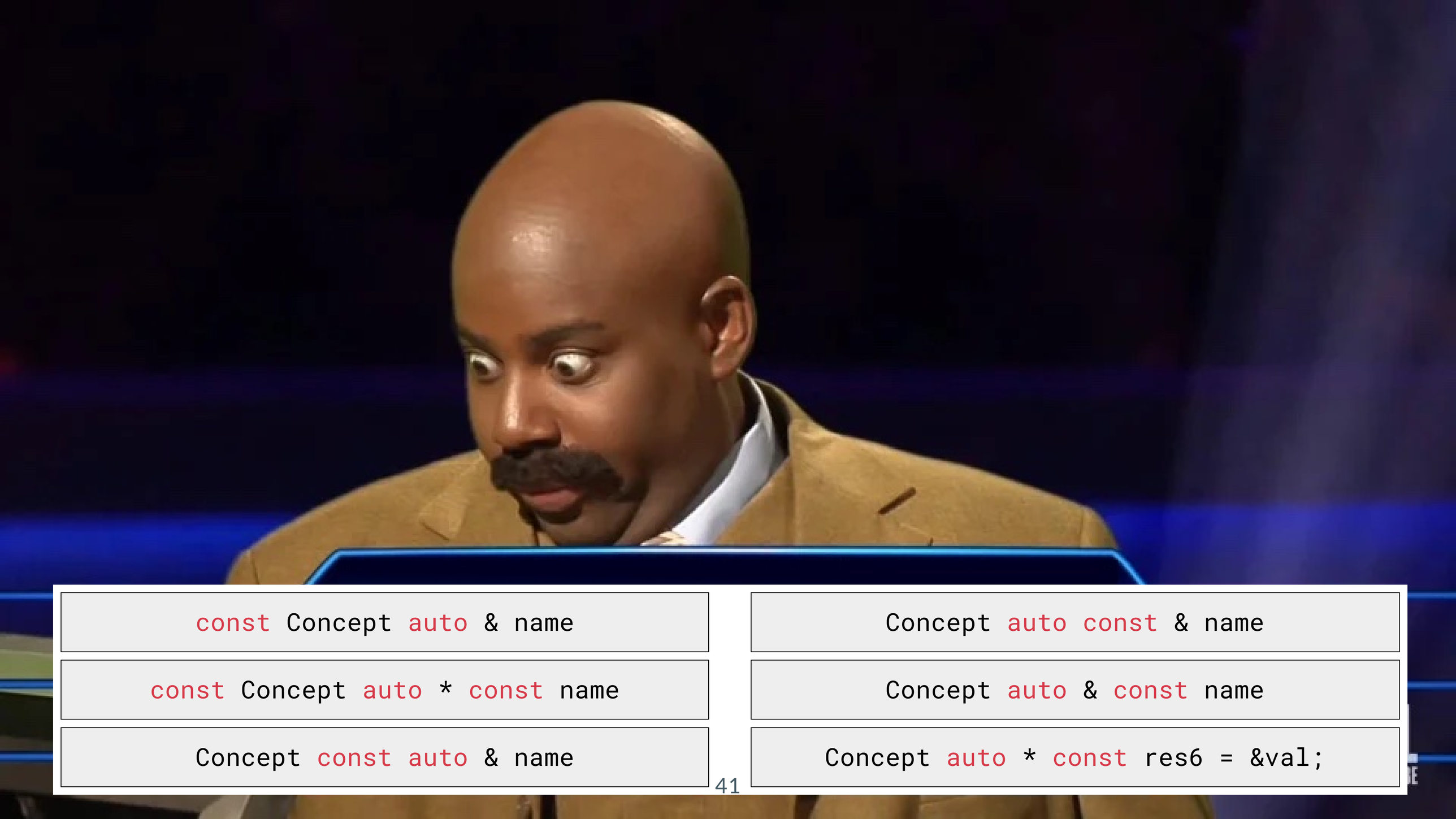
```
#include <concepts>
#include <string>
#include <cmath>

template <class T>
concept Num = requires (T a, T b) {
    {a + b} -> std::same_as<T>;
    {a - b} -> std::same_as<T>;
    {a * b} -> std::same_as<T>;
    {-a}  -> std::same_as<T>;
};
```

The generic library that uses `Num` concept, can be used with anything that complies with it!

If someone implements `BigIntegers`?! If it respects the concept, the code works™.


How would you specify cv-qualified concepts?
A:
B:
C:
D:



```
const Concept auto & name
```

```
Concept auto const & name
```

```
const Concept auto * const name
```

```
Concept auto & const name
```

```
Concept const auto & name
```

```
Concept auto * const res6 = &val;
```

# How would you specify cv-qualified concepts?

✅ `const Concept auto & name`

✅ `const Concept auto * const name`

❌ `Concept const auto & name`

✅ `Concept auto const & name`

❌ `Concept auto & const name`

✅ `Concept auto * const res6`

*note:*
`const` *applies to the* ***full type*** *(i.e. constraint helps defining the type, so it is part of it)*

# Concepts in reality

# Testing concepts

```cpp
#include <concepts>
#include <complex>
#include <string>

template <class T>
concept Num = requires (T a, T b) {
    {a + b} -> std::same_as<T>;
    {a - b} -> std::same_as<T>;
    {a * b} -> std::same_as<T>;
    {-a}  -> std::same_as<T>;
};
```

Since they are known at compile-time, we can test it with `static_assert`!

```cpp
static_assert(Num<int>);
static_assert(Num<float>);
static_assert(Num<std::complex<float>>);
static_assert(Num<std::string>, "");
```

# Static polymorphism

With **Templates+SFINAE** we can achieve static polymorphism.

*Static polymorphism*, contrarily to its dual *dynamic polymorphism*, happens at **compile time**.

It has some nice implications:

- errors are raised at compile time
- no overhead at runtime (e.g. no `virtual` function call)

**It's nothing new**, but concepts really helps in defining better and easier to maintain "interfaces".

# Type erasure

Specifically, in STL we have `std::function<>`, which hides the type of a functor, allowing us to store in it any function that complies with the function signature we need (i.e. return type, arguments types and their order).

# Recap

# Recap

- Why generic programming?
- (TEMPLATE $\Rightarrow$) SFINAE $\Rightarrow$ CONCEPTS : Step by Step
- Concepts (new syntax and definition of custom concepts)
- Applications (static polymorphism, type erasure, ...)

# Q&A

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# BONUS

# Why nested requirements?

# Why nested requirements?

What the simple requirement `a + b` do?

```
requires {
    a + b;
}
```

1. check if the expression can be compiled;
2. evaluate the expression

# Why nested requirements?

So, what would you expect from this?

```
#include <concepts>

template <class... Args>
requires requires {
    sizeof...(Args) > 1;
}
void foo(Args&& ...) {}

int main() {
    foo(1);
    foo(1, 2);
    foo(1, 2, 3);
}
```

# Why nested requirements?

So, what would you expect from this?

```cpp
#include <concepts>

template <class... Args>
requires requires {
    sizeof...(Args) > 1;
}
void foo(Args&& ...) {}

int main() {
    // foo(1);          // error
    foo(1, 2);
    foo(1, 2, 3);
}
```

# Concepts vs Parameter Pack

# Concepts vs Parameter Pack

```cpp
#include <concepts>

template <class... Args>
concept AtLeast2 = requires sizeof...(Args) >= 2;

template <AtLeast2... Args>
void foo(Args&&...) {}

int main() {
    foo(1, 2);  // error: AtLeast2<int>
}
```

With the syntax

```cpp
template <Concept... Placeholder>
```

we're applying the type constraint to each single type of the parameter pack, **NOT** to the parameter pack as a whole.

# Concepts vs Parameter Pack

```cpp
#include <concepts>

template <class... Args>
concept AtLeast2 = requires sizeof...(Args) >= 2;

template <class... Args>
requires AtLeast2<Args...>
void foo(Args&&...) {}

int main() {
    // foo(1);     // error: as per requirement
    foo(1, 2);
}
```

Now we are requiring that the full parameter pack `Args...` respect the concept `AtLeast2`.