C++ PROGRAMMING

Lecture 7

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1. Template metaprogramming
2. Variadic template arguments
3. Smart pointers

Template metaprogramming

- Template metaprogramming is a Turing complete language
  - Every intuitive computable number can be computed
    - Meaning: we can basically compute anything
  - Funny implication
    - There cannot be a correct C++ compiler!
- TMP is a bit esoteric
  - Some software companies do not allow it
  - However, there are some users
    - Boost.Hana – your standard library for metaprogramming
- Try to use `constexpr` (since C++11) instead of TMP
  - You will see why that is one the next few slides!

Template metaprogramming prerequisites

- `static` variables in `struct` / `class`
  - Are shared across all variables of that type
  - They belong to the type itself
  - Similar to global variables but with limited scope
- Great news
  - Types can store values
    - And with values we can perform computations
      - So we can perform computations with types
    - Templates are processing types!
    - We just discovered metaprogramming

- TMP uses types to express computations

```
#include <iostream>
struct A {
  // ´value´ exists only once-across all
  // variables of type A
  static const int value = 100;
};
int main() {
  A a, b;
  std::cout << a.value << '\n';
  std::cout << b.value << '\n';
  std::cout << A::value << '\n';
  return 0;
}
```

Template metaprogramming

- Functional language
  - Compute using pattern matching and recursion
- Example: computing the power function

```
#include <iostream>
template<int B, unsigned E>
struct power {
  static const int value = B * power<B, E - 1>::value;
};
template<int B>
struct power<B, 0> { // template specialization on the power template type
  static const int value = 1;
};
```

```
int main() {
  const int p = power<2, 10>::value;
  std::cout << p << '\n';
  return 0;
}
```

Template metaprogramming

```
#include <iostream>
template<int B, unsigned E>
struct power {
  static const int value = B *
        power<B, E - 1>::value;
};
template<int B>
struct power<B, 0> {
  static const int value = 1;
};
int main() {
  const int p = power<2, 10>::value;
  std::cout << p << '\n';
  return 0;
}
```

- In programming using templates
  - Types are used as functions
  - They can get
    1. Types
    2. Constant values
    3. References to functions
    - as input parameters
    - They can store a
      1. type with `typedef`
      2. constant with `enum` or `static const`
  - Template specialization directs control flow (pattern matching and recursion)
- In our example
  - templates get instantiated …
    - until the base case is reached

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Template metaprogramming

```
#include <iostream>
template<int B, unsigned E>
struct power {
  static const int value = B *
                 power<B, E - 1>::value;
};
template<int B>
struct power<B, 0> {
  static const int value = 1;
};
int main() {
  const int p = power<2, 10>::value;
   std::cout << p << '\n';
  return 0;
}
```

```
#include <iostream>
constexpr int power(int base,
                    unsigned exp) {
  return (exp == 0) ? 1
       : base * power(base, exp-1);
}
int main {
  constexpr p = power(2, 10);
  std::cout << p << '\n';
  return 0;
}
```

Template metaprogramming

- Even data structures can be realized
- Remember the triple type from the exercises
- C++'s tuple data type is implemented using template metaprogramming
- Lists are also possible

Computing Euler's number at compile time using TMP

- Use this formula for e

$$
\begin{aligned}
e &= 1 + \frac{1}{1} + \frac{1}{1 \cdot 2} + \frac{1}{1 \cdot 2 \cdot 3} + \frac{1}{1 \cdot 2 \cdot 3 \cdot 4} + \cdots \\
&= \frac{1}{0!} + \frac{1}{1!} + \frac{1}{2!} + \frac{1}{3!} + \frac{1}{4!} + \cdots \\
&= \sum_{k=0}^{\infty} \frac{1}{k!}
\end{aligned}
$$

Computing Euler's number at compile time (TMP) I

```
#include <iostream>

template<int N, int D>
struct Frac {
  const static int Num = N;
  const static int Den = D;
};

template<int X, typename F>
struct Mult {
  typedef Frac<X*F::Num, X*F::Den> value;
};

template<int X, int Y>
struct GCD {
  const static int value = GCD<Y, X % Y>::value
};

template<int X>
struct GCD<X, 0> {
  const static int value = X;
};
```

```
template<typename F>
struct Simplify {
  const static int gcd = GCD<F::Num, F::Den>::value;
  typedef Frac<F::Num / gcd, F::Den / gcd> value;
};

template<typename X1, typename Y1>
struct SameBase {
  typedef typename Mult<Y1::Den, X1>::value X;
  typedef typename Mult<X1::Den, Y1>::value Y;
};

template<typename X, typename Y>
struct Sum {
  typedef SameBase<X, Y> B;
  const static int Num = B::X::Num + B::Y::Num;
  const static int Den = B::Y::Den;
  typedef typename Simplify<Frac<Num, Den>>::value value;
};
```


[Example taken from https://monoinfinito.wordpress.com/series/introduction-to-c-template-metaprogramming/]

Computing Euler's number at compile time (TMP) II

```
template<int N>
struct Fact {
  const static int value = N*Fact<N-1>::value;
};

template<>
struct Fact<0> {
  const static int value = 1;
};

template<int N>
struct E {
  const static int Den = Fact<N>::value;
  typedef Frac<1, Den> term;
  typedef typename E<N-1>::value next_term;
  typedef typename Sum<term, next_term>::value value;
};

template<>
struct E<0> {
  typedef Frac<1, 1> value;
};
```

```
int main() {
  typedef E<12>::value X;
  std::cout << "e = " << (1.0 * X::Num / X::Den) << '\n';
  std::cout << "e = " << X::Num << " / " << X::Den << '\n';
  return 0;
}
```

[Example taken from https://monoinfinito.wordpress.com/series/introduction-to-c-template-metaprogramming/]

Computing Euler's number at compile time (constexpr) III

- Using the same formula

```
#include <iostream>
constexpr unsigned factorial(unsigned n) {
  return (n == 0) ? 1 : n * factorial(n-1);
}
constexpr double euler(unsigned n) {
  double e = 1;
  for (unsigned i = 1; i <= n; ++i) {
    e += 1.0 / factorial(i);
  }
  return e;
}
int main() {
  constexpr double e = euler(12);
  std::cout << "Eulers number is: " << e << '\n';
  return 0;
}
```

- Let's see what the compiler does
- Compile with:

```
clang++ -std=c++17 -Wall -emit-llvm -S
-fno-discard-value-names euler.cpp
```

(obtain LLVM compiler's internal representation)

```
; Function Attrs: norecurse uwtable
define i32 @main() #4 {
  %1 = alloca i32, align 4
  %2 = alloca double, align 8
  store i32 0, i32* %1, align 4
  store double 0x4005BF0A8B0E66C6, double* %2, align 8
  %3 = call dereferenceable(272) %"class.std::basic_ostrea
  getelementptr inbounds ([19 x i8], [19 x i8]* @.str, i32
  %4 = call dereferenceable(272) %"class.std::basic_ostrea
  %5 = call dereferenceable(272) %"class.std::basic_ostrea
  ret i32 0
}
```

Pros and cons using template metaprogramming

- Pros
  - Evaluated at compile time
  - Higher abstraction possible

- Cons
  - Longer compile times
  - Hard to read / write
  - Functional style does not match C++
  - Not supported by development tools
  - Error messages usually make no sense
  - Heavily overused
  - “No type information”

- Use C++ `constexpr` instead!
- Unless you have good reason to do otherwise

Variadic template arguments

```
#include <iostream>
template<typename T>
T sum(T t) {
  return t;
}
template<typename T, typename... Args>
T sum(T t, Args... args) {
  return t + sum(args...);
}

int main() {
  int res = sum(1, 2, 3, 4, 5, 6, 7, 8, 9, 10);
  std::cout << res << '\n';
  return 0;
}
```

Compiler can oftentimes deduce template parameter(s)

- Using C++17 fold expressions

```
template<typename... Args>
auto sum(Args&&... args) {
  return (args + ...);
}
```


[Have a look at http://eli.thegreenplace.net/2014/variadic-templates-in-c/]

Variadic template arguments

- Another example: printing everything
- Print arbitrary many arguments of arbitrary type

```
#include <iostream>
#include <string>
template<class T>
void print_everything(T t) {
  std::cout << t << '\n';
}

template<class T, class... Args>
void print_everything(T t, Args... args) {
  std::cout << t << ' ';
  print_everything(args...);
}
```

```
int main() {
  print_everything("Hello",
    1,
    2.333,
    std::string("World"));
  return 0;
}
```

- Using C++17 fold expressions

```
template<typename... Args>
void print(Args&&... args) {
  ((std::cout << t << ' '), ...);
}
```


[Have a look at http://eli.thegreenplace.net/2014/variadic-templates-in-c/]

Smart pointers

- Remember (raw) pointers

```
int i = 42;
int *i_ptr = &i;
```

  - Pointers are necessary for dynamically memory allocation

```
int *dyn_int = new int;
delete dyn_int;
int *dyn_array = new int[12];
delete[] dyn_array;
```

    - What was the problem here?
      - You probably will forget to use `delete` / `delete[]` at some point
      - Finding memory leaks is expensive
- Smart pointers (SPs) are safe wrappers for raw pointers

Ownership problematic

```
matrix *matrix_multiply(matrix *a, matrix *b) {
	matrix *c = new matrix(a->rows(), b->cols());
	// perform the computation c = a * b;
	return c;
}
```

- Problem
  - Who frees matrix `c`, allocated in `matrix_multiply()`?
  - It has to be deleted at some point
- Problem in general: Who is responsible, who owns the resource(s)?
  - Who allocates memory and who frees it after usage?
    1. Caller allocates, caller frees (cf. right)
    2. Callee allocates, caller frees (cf. above)
    3. Callee allocates, callee frees (cf. `std::string`, `std::vector`)

```
void matrix_multiply(matrix *a,
                     matrix *b,
                     matrix *c);
```

Smart pointers

- Help with ownership problematic
  - SPs know who owns what resource
- SPs do the clean-up (`delete`) themselves
  - They automatically call the destructor if the managed resource has no owner anymore
    - “Are no longer used by anyone”
  - How?
    - SPs calls `delete` for object pointing-to when their own destructor is called
    - Smart pointer know about ownership!
- That is not a real garbage collector
- It is just reference counting – “The poor man’s garbage collector.”
  - “Only pay for counter-variables and incrementing / decrementing counters”
- By the way: it is possible to leak resources in Java (although it has a garbage collector)

Smart pointers

- Three types of smart pointers exist
  - `std::unique_ptr` `// for unique ownership`
    - One user at a time
  - `std::shared_ptr` `// for shared ownership`
    - One or more users at a time
  - `std::weak_ptr` `// for non-owned things`
    - Does not own, but is allowed to use the underlying object
    - Not commonly used in practice

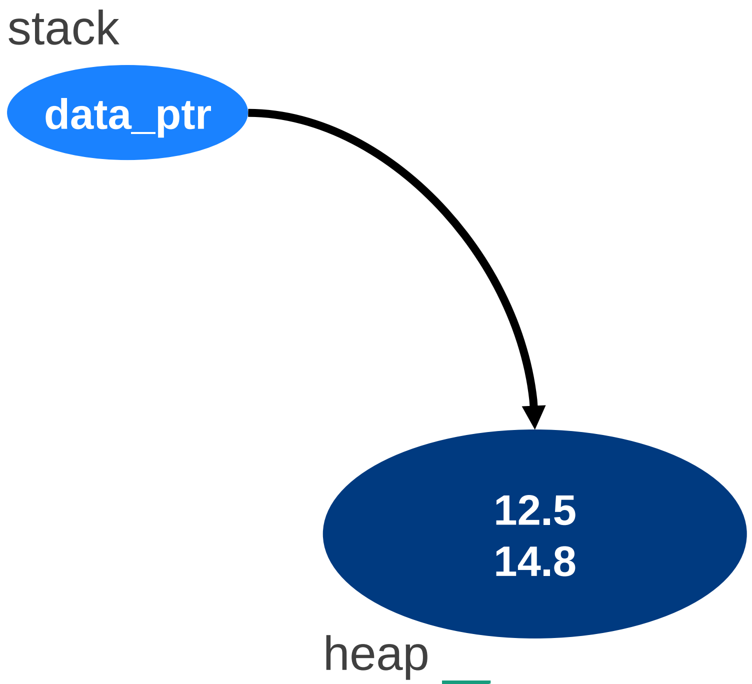
- SPs are implemented in the STL
- All SPs defined in `<memory>`
  - Use `#include <memory>`

std::unique_ptr

- `std::unique_ptr` behaves like an ordinary pointer
- Example

```
struct Data {
  double x;
  double y;
  Data(double x, double y) : x(x), y(y) {}
};
int main() {
  std::unique_ptr<Data> data_ptr(new Data(12.5,14.8));
  return 0;
}
```

- Note that we do not use `delete` explicitly



std::unique_ptr

- Using a factory function

```
struct Data {
  double x;
  double y;
  Data(double x, double y) : x(x), y(y) {}
};
int main() {
  std::unique_ptr<Data> data_ptr(std::make_unique<Data>(12.5,14.8));
  return 0;
}
```

  - Caution: `std::make_unique()` has been introduced in C++14
    - It has been “kind of” forgotten in C++11
    - In C++11 just use `new`

`std::unique_ptr`

1. How to model a `std::unique_ptr`?
   - Make it a class providing a pointer to the resource
2. How to ensure `data_ptr` is the only user?
   - Disallow copying the smart pointer

```
unique_ptr(const unique_ptr& up) = delete;
unique_ptr& operator= (const unique_ptr& up) = delete;
```

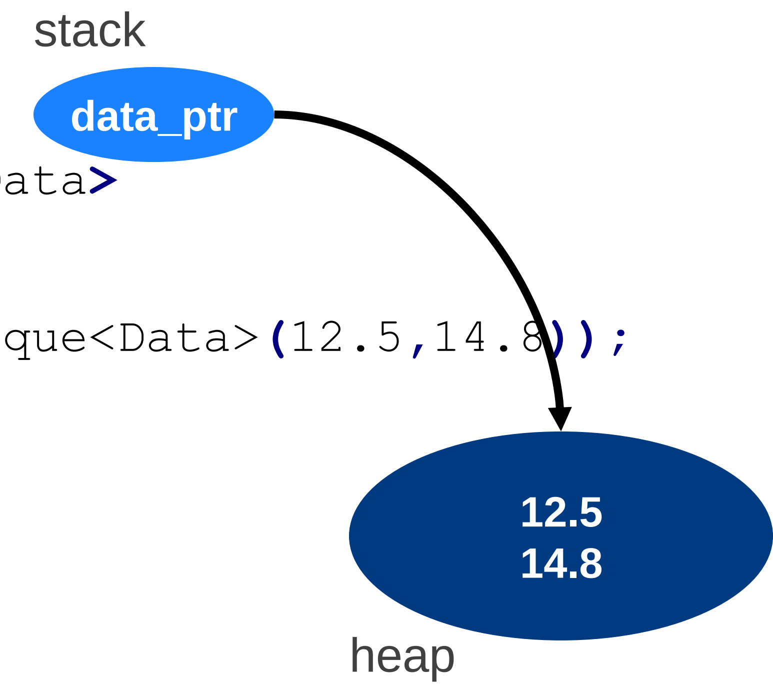
   - Now we can only have one user at a time
   - Attempts of copying result in an compiler error
3. How is `data_ptr` able to delete its resource?
   - It uses the destructor

```
~unique_ptr() { delete resource; }
```

   - Now the resource is cleaned up for us
4. How to use it elsewhere without copying?
   - Use `std::move()`

- Actual implementation is more advanced

```
struct Data {
  double x;
  double y;
  Data(double x, double y) : x(x),
                             y(y) {}
};
int main() {
  std::unique_ptr<Data>
    data_ptr(
      std::make_unique<Data>(12.5,14.8));
  return 0;
}
```



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How to use smart pointers and what about dereferencing?

- Operators are overloaded to make the smart pointer behave like a raw pointer
- Dereference and obtain the managed resource
  - `T& operator* ()`
- Dereference and access a member of the managed resource
  - `T* operator-> ()`

std::unique_ptr

```
struct Data {
  double x;
  double y;
  Data(double x, double y) : x(x), y(y) {}
};
std::unique_ptr<Data> setZero(std::unique_ptr<Data> d) {
  d->x = 0.0;
  d->y = 0.0;
  return d;
}
int main() {
  std::unique_ptr<Data> data_ptr(new Data(12.5, 14.8));
  std::unique_ptr<Data> zero = setZero(data_ptr);
  std::cout << zero->x << '\n';
  std::cout << zero->y << '\n';
  return 0;
}
```

- This code does not compile
  - Why?
    - `std::unique_ptr` cannot be copied
    - Because copying results in more than one user!
  - Here we would have two owners
    - `main()`
    - `setZero()`
  - Move data instead of copying to have one user at a time
    - `std::move()` `data_ptr` into `setZero()`
    - and back from `setZero()` to `main()`

std::unique_ptr

```
struct Data {
  double x;
  double y;
  Data(double x, double y) : x(x), y(y) {}
};
std::unique_ptr<Data> setZero(std::unique_ptr<Data> d) {
  d->x = 0.0;
  d->y = 0.0;
  return d;
}
int main() {
  std::unique_ptr<Data> data_ptr(new Data(12.5, 14.8));
  std::unique_ptr<Data> zero = setZero(std::move(data_ptr));
  std::cout << zero->x << '\n';
  std::cout << zero->y << '\n';
  return 0;
}
```

- That works
- Caution:
  - Do not use `data_ptr` after you moved it somewhere else!
    - Undefined behavior
    - Segmentation fault
- The second `std::move()` is “hidden”
  - `setZero()` moves `d` back to `main()` into the variable zero
- Compiler will complain if you forget `move()`

std::shared_ptr

- Allows multiple owners

```
struct Data {
  double x; double y;
  Data(double x, double y) : x(x), y(y) {}
};
std::shared_ptr<Data> setZero(std::shared_ptr<Data> d) {
  d->x = 0.0;
  d->y = 0.0;
  return d;
}
int main() {
  std::shared_ptr<Data> data_ptr(new Data(12.5, 14.8));
  std::shared_ptr<Data> zero = setZero(data_ptr);
  std::cout << zero->x << '\n';
  std::cout << zero->y << '\n';
  return 0;
}
```

- Keeps track of its owners using an internal counter
- `setZero()` can now be used without `std::move()`
  - It can be copied
  - We allow more than one user!

std::shared_ptr

- Improved example

```
struct Data {
  double x; double y;
  Data(double x, double y) : x(x), y(y) {}
};
std::shared_ptr<Data> setZero(std::shared_ptr<Data> d) {
  d->x = 0.0;
  d->y = 0.0;
  return d;
}
int main() {
  std::shared_ptr<Data> data_ptr(std::make_shared<data>(12.5,14.8));
  std::shared_ptr<Data> zero = setZero(data_ptr);
  std::cout << zero->x << '\n';
  std::cout << zero->y << '\n';
  return 0;
}
```

- `std::make_shared()` makes a difference
  - Performs only one allocation for data *and* reference counter
  - Data and reference counter sit in one block of memory
  - More efficient because of data locality

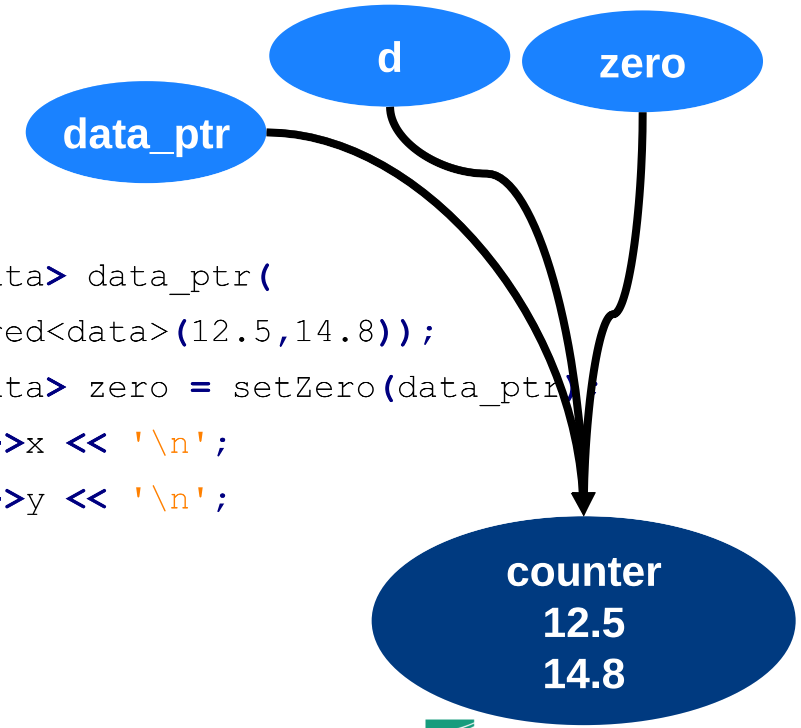
std::shared_ptr

- Actual implementation is more advanced

1. How to model a `shared_ptr`?
   - Make it a class providing a pointer to a resource
2. How to store the number of users/references?
   - Store them in a counter
3. How to copy?
   - Just perform a **flat copy** of the handle (do not copy the managed resource)
   - Increment the reference counter on copy
4. When to delete the resource?

```
~shared_ptr  {
    if (--refcounter == 0) delete resource;
}
```

```
struct Data {
  double x; double y;
  Data(double x, double y) : x(x), y(y) {}
};
std::shared_ptr<Data> setZero(std::shared_ptr<Data> d) {
  d->x = 0.0;
  d->y = 0.0;
  return d;
}
int main() {
  std::shared_ptr<Data> data_ptr(
      std::make_shared<data>(12.5,14.8));
  std::shared_ptr<Data> zero = setZero(data_ptr);
  std::cout << zero->x << '\n';
  std::cout << zero->y << '\n';
  return 0;
}
```



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`std::weak_ptr`

- Can hold a reference but is not an owner

```
#include <iostream>
#include <memory>

std::weak_ptr<int> wp;

void f(){
  if (std::shared_ptr<int> spt = wp.lock()) {
    std::cout << *spt << '\n';
  } else {
    std::cout << "wp is expired" << '\n';
  }
}

int main() {
  {
    auto sp = std::make_shared<int>(42);
    wp = sp;
    f();
  }
  f();
  return 0;
}
```

- You rarely use it
- A `std::weak_ptr` must be copied into a `std::shared_ptr` in order to be used

A note on smart pointers

- Massively reduce probability of introducing memory leaks
- Always prefer using smart pointers when managing resources
- Prefer `std::unique_ptr` over `std::shared_ptr`, if possible
- Custom deleters are possible
- Smart pointers behave like raw pointers
  - Just need a tiny little bit more memory in case of `std::shared_ptr`
- Only fallback to raw pointers …
  - if you cannot afford a few bytes more per variable
  - if your platform does not provide an STL implementation
  - if you implement algorithms
  - if you have another good reason

std::unique_ptr

Defined in header `<memory>`

```
template<
    class T,
    class Deleter = std::default_delete<T>
> class unique_ptr;                              (1) (since C++11)

template <
    class T,
    class Deleter
> class unique_ptr<T[], Deleter>;                (2) (since C++11)
```


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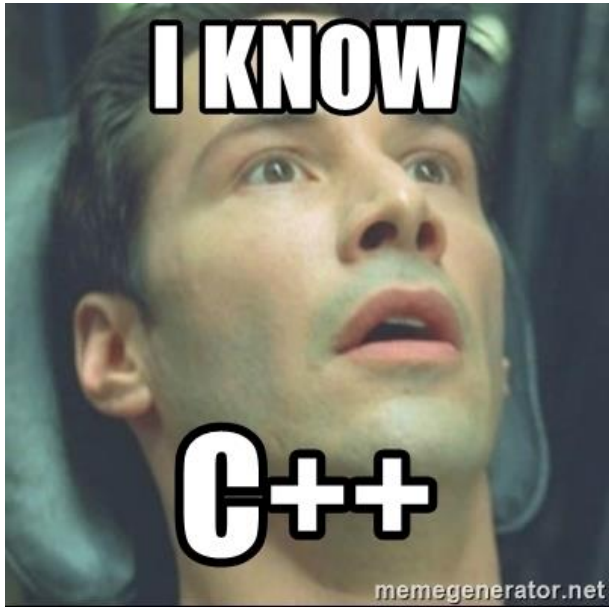
A note on dynamic memory allocation

- If you have to dynamically allocate objects
  - Use smart pointers (`std::unique_ptr`, `std::shared_ptr`)
- If you have to dynamically allocate an array of objects
  - Use `std::vector`

- Do not think there are no exceptions
  - Raw pointers are still needed
    - When implementing algorithms
    - If you are only a user and not an owner of a resource
    - …

Status Quo

- You know very much about modern C++
  - Probably more than your older professors
- What next?
  - We have to deepen your knowledge
  - There will be a summer exercise sheet with 16 additional points
  - Object oriented programming (OOP)
  - Threads and asynchronous tasks (running computations in parallel)
  - High performance computing (HPC) and what you should know about it
  - Static analysis and job offers
  - Introduction to the final project as well as hacks and miscellaneous
- A nice talk by Bjarne Stroustrup that recaps everything so far and more:
  - https://www.youtube.com/watch?v=86xWVb4XIyE



Recap

- Template metaprogramming
- Variadic template arguments
- Ownership – who is responsible for clean-up
- Smart pointers
  - `std::unique_ptr`
  - `std::shared_ptr`
  - `std::weak_ptr`
- Status quo

Thank you for your attention
Questions?