A Tasty Intro to Generic Programming in C++

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(Containing many references to food, templates, and an occasional gratuitous pic)

An Overview of the Tasty Contents

- What is a type? Why is understanding types so important in C++?
- Operator function call syntax, why it is foundational in C++
- Ducks, or more specifically, duck typing
- Function templates, from basics to a nibble of concept constraints
- Functors and lambdas and closures, oh my!
- Class templates (just a taste), with examples from the C++ standard library
- Gratuitous photos that may pop up here and there
- Hand off for additional scrumptious morsels from Lou

Types - What Are They?

And why are they important?

Types Are an Essential Component of C++

- Traditional definition: a type has data (but not always) and a set of operations on that data
  - `int` in C or C++ is 32 or 64 (or other size) bits, and +, -, *, /, %, etc operations
- Types can be created in C++ with `class` or `struct` declaration
- Types also have names
  - Fundamental types (names are language keywords)
  - Name of the `class` or `struct`
  - Sometimes the name is anonymous (more on this later)
- Instantiation of a type creates an object
  - An object may be named (variable) or might be a temporary / unnamed object

A Type is an Important C++ Entity

- Types form the basis of compile time / static checking
- In C++, types are used in many ways besides simple object creation
  - Template / generic programming (focus of this presentation)
  - Function overloading
  - Encoding static / compile time design or constraints - e.g. units libraries
  - Metaprogramming - containers and algorithms on types (vs runtime values)
- Conditional logic, at compile time, based on type
  - `<type_traits>` header in C++ has extensive queryable info
    - e.g. `is_arithmetic`, `is_trivially_copyable`, `is_copy_constructible`
  - `if constexpr` allows enabling / disabling of statements at compile time
- Takeaway - types, in and of themself, are a powerful design tool

Function Overloading by (Empty) Type - Using Types Never Meant to be Objects

```
struct bidirectional_iterator_tag { }; // simplified, see iterator_tags doc
struct random_access_iterator_tag : public bidirectional_iterator_tag { };

template <typename RAIter>
void sort_alg (RAIter begin, RAIter end, random_access_iterator_tag) {
// sort with random access indices, note third parameter is unused
}
template <typename RAIter>
void sort_alg (RAIter begin, RAIter end, bidirectional_iterator_tag) {
// sort with bidirectional iterator, such as provided by std::list
}

std::vector v;
sort_alg(v.begin(), v.end(), random_access_iterator_tag{});
std::list ls;
sort_alg(ls.begin(), ls.end(), bidirectional_iterator_tag{});
```

Is C++ a Strongly Typed Language?

- Discussion - state arguments pro and con
- Consider another definition / comparison:
  - Dynamically typed languages - types are attached to values at run time
  - Statically typed languages - types are defined and constrained at compile time
- Both C and C++ have typecasting
- Do C and C++ differ in their use of types?

C++ Type System (From cppreference Page)

- Fundamental types
  - Arithmetic types
    - Integral: `bool`, char types, signed and unsigned `int`
    - Floating point: `float`, `double`, `long double`, fixed width floating (C++ 23)
  - `void`, `std::null_ptr_t` (type of null pointer)
- Compound types
  - `class` / `struct`, `union`
  - Reference types (lvalue, rvalue)
  - Pointer types (ptr to obj, ptr to func, ptr to member data or func)
  - Array types
  - Function types
  - Enumeration types (scoped, unscoped)

Function Call Operator Overloading and Ducks

Does a duck quack?

What is Duck Typing?

- "If it walks like a duck and it quacks like a duck, then it must be a duck"
- Template / generic functions apply the duck test in a static typing context
  - All templates in C++ do some form of static typing “duck test”
  - Every type passed in to a template must pass the “duck test”
- More on the “duck test” requirements presented later

Function Call Operator Overloading

- Adding `ret-type operator() (parameter-list)` to a class declaration allows an object of it's type to be treated like a function
  - Terminology is "function call operator overloading"
  - Can only be a member function (not a stand-alone operator overload)
  - Usual member function qualifiers apply (`const`, `noexcept`, etc)
- Allows an object to be used like a function
  - Functions don't have local state (static local is global state)
  - An object *does* have state (one of the main purposes of an object)

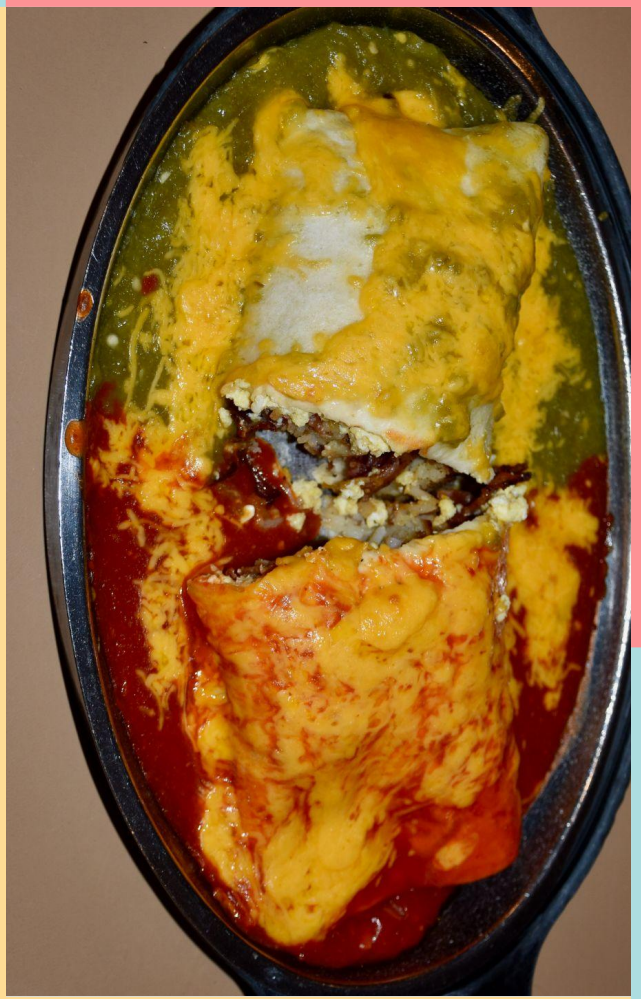
Function Call Operator Overloading Example

```
struct cnt_cmp {
  int cnt {0};
  bool operator() (int a, int b) { ++cnt; return a < b; }
};
bool traditional_comp_func(int a, int b) { return a < b; }

cnt_cmp obj;
obj(5, 10); obj(1000, 500); obj(0, 0);
// what is the current value of obj.cnt?

std::vector<int> v { 5, 3, 1, 1 };

std::sort(v.begin(), v.end(), cnt_cmp{});
std::sort(v.begin(), v.end(), obj);
std::sort(v.begin(), v.end(), std::ref(obj));
std::sort(v.begin(), v.end(), traditional_comp_func);
```

- What is the difference between the above four calls to `std::sort`?
- Contrast C++ std lib sort to C std lib sort

Gratuitous Photo 1

My company glider, a Puchacz SZD-50-3 (manufactured in Poland), tail number N503S, contest number 10, at Moriarty, NM



Function Templates

From basics to an advanced topic or two

A Simple Arithmetic Function with Two Parameters and a Return Value

```
int add_div_by_3 (int a, int b) {
  return (a + b) / 3;
}
int tmp {20}; int result = add_div_by_3 (tmp, 30);
// what are the types and what are the type requirements?

// let's change to float and add constexpr
constexpr float add_div_by_3 (float a, float b) {
  return (a + b) / 3;
}
// note auto return type in calls, also types of literals
float tmp {20.0}; auto result1 = add_div_by_3 (tmp, 30.0);
auto result2 = add_div_by_3 (20.0, 30.0);
```

- Compare the assembly between the two calls in Compiler Explorer

Change the Code to a Function Template

```
template <typename T>
constexpr T add_div_by_3 (T a, T b) {
  return (a + b) / 3;
}

add_div_by_3 (20, 30); add_div_by_3(20u, 30u);
add_div_by_3 (20.0, 30.0); add_div_by_3(20.0f, 30.0f);

// in C++ 20, template syntax can be simplified (more on next slide)
constexpr auto add_div_by_3 (auto a, auto b) {
  return (a + b) / 3;
}
```

- What are the types in use now?
- How many functions are being generated?

Auto Template Parameters in C++ 20

```
constexpr auto add_sub_div (auto a, auto b) {
  return (a + b) / (a - b);
}

#include <complex>

auto res1 = add_sub_div (15, 44);
auto res2 = add_sub_div(3.3f, 22.1f);
auto res3 = add_sub_div(std::complex<double>{5.0, 2.0}, std::complex<double>{3.0, 4.0});
// values of res1, res2, res3 are -2  -1.35106  (0.5,3.5)
```

- In C++ 20, template syntax can be simplified (called “abbreviated function template syntax”); `auto` for generic parameters came from lambdas, but added to templates
- Previous example does not compile: `<complex>` type defined for `operator /` with scalar (i.e. `3` should be of type `double`, or `3.0` instead of `3`)

Notes and Gotchas

- Compiler must have all template code available when instantiating a function template (i.e. when it is called) or a class template
  - Varying styles to achieve this (I put everything in same header file)
  - No longer `.hpp` / `.cpp` separation of declaration and definition
- ODR (one-definition-rule) can cause differences between functions and function templates
  - `inline` typically needed for (regular) functions fully defined in a header
  - Templates are not functions (or classes) so ODR does not apply
- Remember that a function template is a function generator, not a function (similar thought process for class template)

Tasty Subtleties

```
template <typename T>
constexpr T add_div_by_3 (T a, T b) {
  return (a + b) / 3;
}
auto res1 = add_div_by_3 (20, 30.0); // Does not compile!
// what would be the types of a, b, res1 if it did compile?

auto res2 = add_div_by_3<double>(20, 30u); // explicitly specify the type
// what are the types of a, b, res2 now? what happens with 20 and 30u?
```

- 3 (in the func impl) is `int` literal; what does that affect? What if it was 3.3 (`double` literal)?
- Parameter types are “deduced types” (i.e. based on the type of the argument when calling), unless explicitly specified as shown above

More Tasty Subtleties

```
template <typename T, int SZ>
constexpr T* gen_array () {
  return new T[SZ];
}
// what is this "int SZ" thingie in the template declaration?
auto* my_arr1 = gen_array<double, 20>(); // why can't sz be passed in as normal parm?
auto* my_arr2 = gen_array<std::string, 66>(); // what is the type of the pointer?
auto* my_arr3 = gen_array<double, 44>(); // different than the first func call? in
// what way?
```

- There are no "deduced types" for a return type, must be explicit
- Parameter types are "deduced types" (i.e. based on the type of the argument when calling), unless explicitly specified as shown above
- `SZ` is a non-type template parameter (more on this later)

Gratuitous Photo 2

Santa Fe 2926, a beautifully restored steam engine, on a short outing at Albuquerque, NM

Expand the Palate Beyond Fundamental Types

```
#include "math_utils/big_honkin_nums.hpp" // “bhn” namespace

template <typename T>
constexpr T add_div_by_3 (T a, T b) {
  return (a + b) / 3;
}

bhn::big_num big_honkin_num1 { "776665554443332221110000888999" };
bhn::big_num big_honkin_num2 { "555666777888999000555777888" };
auto res1 = add_div_by_3 (big_honkin_num1, big_honkin_num2);
```

- How are `a` and `b` passed in to the function template?
- What operations and / or methods must the `big_num` type support? (4 used above - 2 inside function, 2 elsewhere)

Flexibility is Good (Two Template Parms!)

```
template <typename N1, typename N2>
constexpr N1 add_div_by_3 (N1 a, N2 b) {
  return (a + b) / 3;
}
auto res1 = add_div_by_3 (20, 30.0); // now compiles! what are the types?
auto res2 = add_div_by_3<double, float>(20, 30);
auto res3 = add_div_by_3 (big_honkin_num1, 30.0);
```

- What is the value of `res1`? is it 16 or 16.667? what about `res2`?
- What does the big number type now need to support (in the way of operations)?
- Should the return type be `N2` instead of `N1`? Why?

Let's Add Even More Flexibility

```
template <typename N1, typename N2>
constexpr auto add_div_by_3 (N1 a, N2 b) -> decltype((a+b)/3) {
  return (a + b) / 3;
}
auto res1 = add_div_by_3 (20, 30.0); // what is the return type?
auto res2 = add_div_by_3<double, float>(20, 30);
auto res3 = add_div_by_3 (big_honkin_num1, 30.0);
```

- Allow the compiler to decide the return type based on the result type of the expression (note trailing return type syntax)
- Does this affect the operations that must be supported by big num type?

A Quick Taste of Requires

```
#include <complex>
#include <type_traits>

template <typename T>
constexpr std::complex<T> some_complex_math(std::complex<T> a, T b) {
  return a + b;
}
template <typename C, typename T>
requires (std::is_same_v<C, std::complex<T>>)
constexpr C similar_complex_math(C a, T b) {
  return a + b;
}

std::complex<float> x {3.0f, 4.0f};
some_complex_math(x, 5.0f); similar_complex_math(x, 5.0f);
```

- Both function template interfaces are similar, requiring a `std::complex` and a scalar (but compiler error messages may differ)

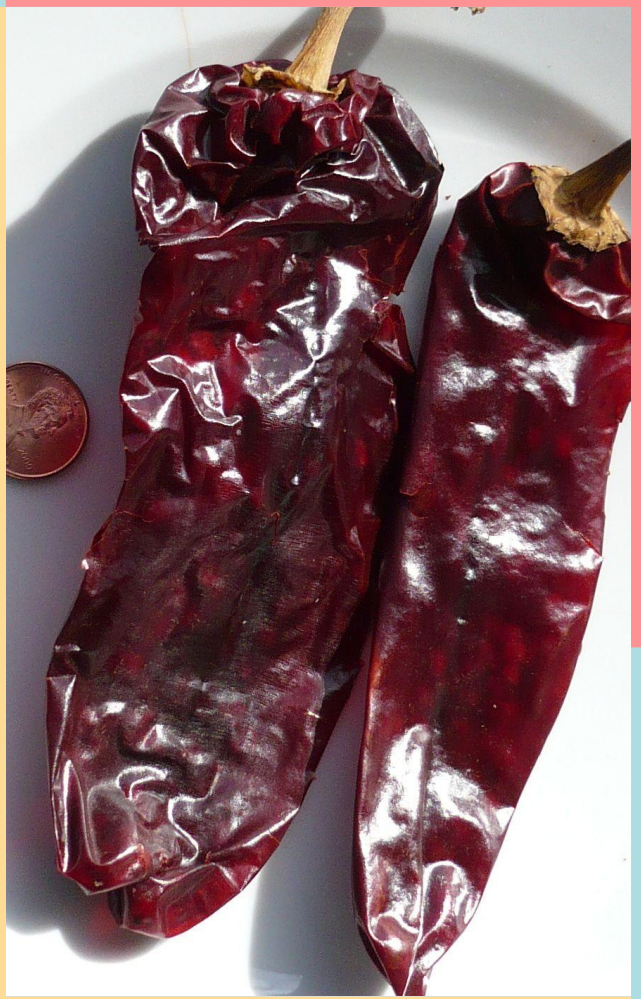
A Quick Taste of Concepts

```
#include <type_traits>

template <typename T>
concept big_math_capable = std::is_copy_constructible_v<T> &&
                           requires (T x) {
  x + x;
  x / x;
};

void math_func (big_math_capable auto a) {
// do addition and division with a
}
// the above is equivalent to (other than naming T):
template <big_math_capable T>
void math_func(T a) {
}
```

- The concept requires a trait (copyable) and two valid expressions (add, div)

A Pause For Digestion

- Write one algorithm that can be used with multiple types! Type based decisions allow writing generic functions that can be used by multiple users (generic libraries)
- Many details and subtleties have not been covered, this presentation is for whetting the appetite
- Concepts, traits, requires, etc are all ways of constraining and making decisions at compile time based on the type
- Note the concept that requires two valid expressions (addition, division) - this is one form of “duck typing” (“if it adds like a duck and divides like a duck, then I’m going to use it like a duck”)



Functors and Lambdas and Closures

Oh My!

Remember Function Call Overloading?

```
template <typename Ctr, typename F>
void traverse(Ctr& container, F func) {
  for (auto& elem : container) {
    func(elem);
  }
}

void square_val(int& x) {
    x = x*x;
}
void incr_char(char& c) {
    c += 1;;
}
```

- Note template param `F` - func must a function *or a function object* that takes one argument (of container element type) and returns `void` (i.e. no return)

Similar to std library `std::for_each`

```
std::vector<int> v { 1, 3, 5, 7 };
std::list<int> lst { 2, 4, 6, 8 };

traverse(v, square_val);
traverse(lst, square_val);

std::string str { "Howdy!"};
traverse(str, incr_char);
```

- Simple enough, one function template used with any container and multiple simple functions; but what if state is wanted?
- Iterators or C++ 20 ranges preferable to passing in whole container (why?)

Define a Functor Type With `operator()`

```
struct add_x {
  int x { 0 };
  void operator() (int& elem) { elem += x; x += 1; }
};

traverse(v, add_x(42)); // add 42, then 43, then 44, etc to each element
traverse(lst, add_x(11)); // add 11, then 12, then 13, etc to each element
```

- Remember the “duck rule” - `traverse` takes a container (1st arg), 2nd arg looks like a function, but isn’t (in above example) - it’s a function object
- The function object is first constructed, passed in (by value), then invoked through the `operator()()` overload on each element of the container

An Example With `std::sort`

```
#include <functional> // for std::ref or std::cref
struct cnt_cmp { // count number of comparisons
  int cmp { 0 };
  template <typename T>
  bool operator() (T a, T b) { ++cmp; return a < b; }
};

std::vector<int> v1 { 3, 5, 1, 7, -4, 55, 44 };
std::vector<double> v2 { 26.0, -2.0, -1.4, 0.5, 8.0 };
std::string str { "Howdy!" };

std::sort(v1.begin(), v1.end(), cnt_cmp{});
cnt_cmp cntr{};
std::sort(v2.begin(), v2.end(), std::ref(cntr)); // what is purpose of this line and line above?
std::sort(str.begin(), str.end(), cnt_cmp{});
```

- The `operator()()` overload is a member function template, can take any type as long as requirements are met (what are the two requirements?)

Member Function Template can be Written With `auto` in C++ 20

```
struct cnt_cmp { // count number of comparisons
  int cmp { 0 };
  bool operator() (auto a, auto b) { ++cmp; return a < b; }
};  // behaves exactly as before, valid only in C++ 20 and later
```

- `auto` works well (in C++ 20) as long as a type parameter name *is not* needed; e.g. if a type trait needs to be queried, `template <typename T>` (or similar) would be needed for `T` (or other name)
- How to access the function object state may require thinking or design (note the use of `std::ref` in the previous example)

What is a Lambda?

```
struct person {
  std::string name;
  unsigned int age;
};

std::vector<person> v { { "Cliff", 35u }, { "Lou", 77u }, { "Nathan", 23u } };
std::sort(v.begin(), v.end(), // let's sort by age
          [] (auto a, auto b) { return a.age < b.age; } );
std::sort(v.begin(), v.end(), // now sort by name
          [] (auto a, auto b) { return a.name < b.name; } );
```

- A functor (type with `operator()()`) or regular function can't alway be defined close to where it is used; what if it is needed in only one place?
- A lambda is a nameless / anonymous functor, complete with parameters and implementation written as an expression (capture list coming up)

What About a Closure?

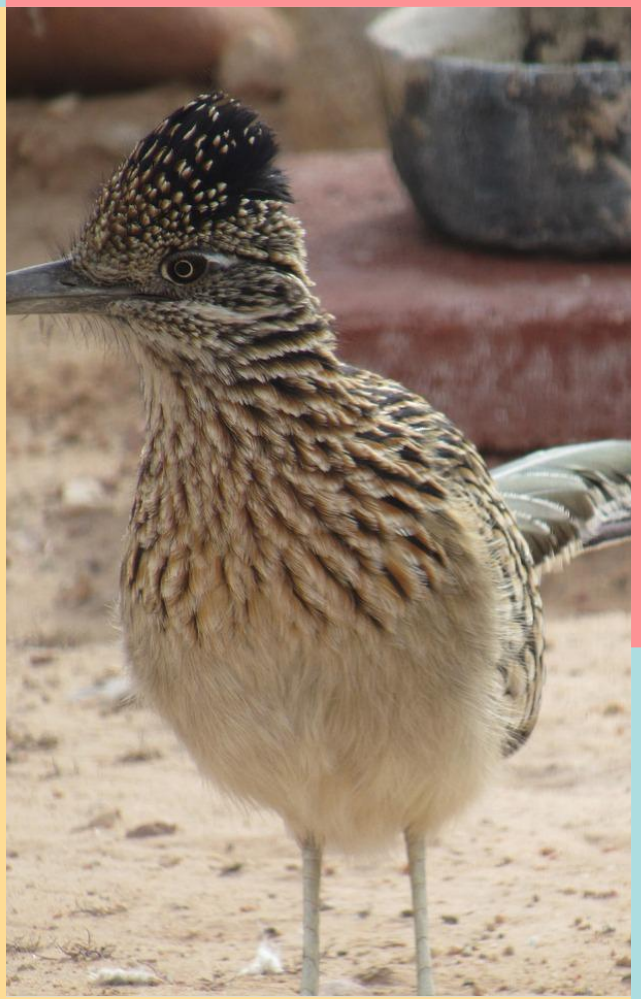
```
int cnt { 0 };
std::vector<person> v { { "Cliff", 35u }, { "Lou", 77u }, { "Nathan", 23u } };
std::sort(v.begin(), v.end(), // sort by name, but also count comparisons
          [&cnt] (auto a, auto b) { ++cnt; return a.name < b.name; } );
std::cout << "Count of name comparisons: " << cnt;
```

- Square brackets on a lambda define the capture list; the variables become "member data" of the lambda, this is sometimes called a closure
- Variables can be captured by value or reference; syntax allows capturing "all variables" in the current scope, or selecting specific ones
- C++ 20 allows specifying template parameters instead of only using `auto`
- Be careful capturing all variables, as well as scoping of the variables

Can a Lambda be Reused? What Are Other Cool Aspects of Lambdas?

```
auto lam = [] (auto a, auto b) { return a.age < b.age; };
std::sort(v.begin(), v.end(), lam); // sort by age
other_alg(lam);
```

- `lam` is of anonymous type known only to the compiler, so `auto` must be used
- `lam` can be used repeatedly as needed
- A lambda with no captures can be used as a regular function pointer
- Lambdas are `const` by default, `mutable` must be used in certain contexts (opposite of typical C++ syntax)
- The `this` pointer of an object can be passed in to a lambda, convenient in some contexts



Class Templates, Just a Nibble or Two

And please don’t eat the cute Roadrunner!

Photo by HRHCC on pixabay, https://pixabay.com/users/hrhcc-1503522/

A `struct` Containing Two Arbitrary Type Elements is Useful

```
template <typename T1, typename T2>
struct two_items {
  T1 first;
  T2 second;
};

using person = two_items<std::string, unsigned int>;
person cliff { "Cliff", 36u };
person lou { "Lou", 66u };
lou.second += 1u; // Lou just aged a year
```

- The example is essentially the `std::pair` class template in the std library

Generalize to an Arbitrary Number of Elements

```
template <typename... Types>
class many_items {
};

#include <tuple>
std::tuple<int, std::string, double> foo1 { 42, "Howdy!", 44.0 };
auto foo2 = std::make_tuple(42, std::string{"Howdy!"}, 44.0);

std::get<int>(foo1); std::get<std::string>(foo1); std::get<double>(foo1);
// same as:
std::get<0>(foo1); std::get<1>(foo1); std::get<2>(foo1);
```

- The `std::tuple` class template in the std library allows an arbitrary number of elements
- The … is called a “template parameter pack” and specifies 0 to N template types

Let's Define a Class to Provide "Maybe I Have a Value, Maybe I Don't" Functionality

```
template <typename T>
class my_opt {
    T val;
    bool is_present;
public:
    my_opt() : val(), is_present(false) { }
    my_opt(const T& v) : val(v), is_present(true) { }
    T& operator*() { return val; }
    const T& operator*() const { return val; }
    T* operator->() { return &val; }
    const T* operator->() const { return &val; }
    operator bool() const { return is_present; }
    // ...
};
```

- The `std::optional` class template provides this functionality

Function Returns an “Optional” That May or May Not Contain a Value

```
using my_opt_str = my_opt<std::string>;
my_opt_str my_func () {
    // ...
    return some_cond ? my_opt_str("Howdy!") : my_opt_str();
}

#include <optional>
using opt_str = std::optional<std::string>;
// exact same code as above except opt_str instead of my_opt_str

auto res = my_func();
if (res) { // a std::string value is present
  std::cout << “Result is “ << *res;
```

- The `std::optional` class template more flexible and efficient - e.g. default construction (for “no value”) of contained type is not performed or required

Non-Type Template Parameters

```
template <typename T, std::size_t N>  // inside std namespace
struct array {
// implementation details
};
#include <array>
#include <algorithm>

std::array<int, 4> my_array { 46, 20, 44, 77 };
std::sort(my_array.begin(), my_array.end());
for (auto i : my_array) { // ... do something }
my_array[2] = 10; // access 3rd element of array, same syntax as built-in arrays
```

- `std::array` is a class template that encapsulates fixed size arrays
- Each declaration of `std::array` with a different `T` and / or `N` is a different type

C++ 20 Expanded What Can be Used as a Non-Type Template Parameter

```
template <double Percentage>
constexpr double calc (double val) {
    return val * Percentage;
}

calc<0.10> (100.0); // returns 10.0, calculated at compile time
double x { 300.0 };
calc<0.50> (x); // returns 150.0, calculated at runtime
calc<0.90> (100.0); // returns 90.0, calculated at compile time
```

- Non-Type TP can be a pointer type, function type, integer type, lvalue reference type, double type, and others

Gratuitous Photo 3

My son’s cat named Stoney; my wife and I are proud grandparents of our grandcat

Thank You and Final Thoughts!

- Two Essential Online Tools:
  - CPP Reference page: https://en.cppreference.com/w/- have it ready, learn to read / use it
  - Compiler Explorer: https://godbolt.org/ - compile and run your code on multiple compilers, analyze the assembler output
- C++ templates define a turing complete “language within a language”
- Templates, just like all of C++, is a large and complex subject
- Templates provide a powerful ability to design libraries for multiple users / clients