C++ Course 2024

Explicit Object Parameters

CSCS

Explicit Object Parameters: a new C++23 language feature

(const-) reference qualified member functions

```
struct A {
    int& foo(...) &;
    int const& foo(...) const &;
    int&& foo(...) &&;
    int const&& foo(...) const &&;
};
```

explicit parameter for self-reference

```
struct A {
    int& foo(this A& self, ...);
    int const& foo(this A const& self, ...);
    int&& foo(this A&& self, ...);
    int const&& foo(this A const&& self, ...);
};
```

- can also be used for additonal `volatile` constraint
- access to member variables:

```
int& A::foo(this A& self, ...) { return self.m; }

int&& A::foo(this A&& self, ...) { return std::move(self.m); }
```

- pass self by value?

```
struct A {
    int& foo(this A self, ...);
};
```

Deducing `this` for de-quadruplication

```
struct A {
    template<typename Self>
    auto&& foo(this Self&& self, ...) {
        return std::forward<Self>(self).m_;
    }
    int m_;
};
```

- one function declaration and definition!
- self parameter is deduced
- return type is deduced: `auto&&`, or `auto foo(this Self&& self) -> decltype(auto)`
- helper functions: `std::forward_like` for returning the correct type:

```
template<typename Self>
auto&& foo(this Self&& self, ...) {
    return std::forward_like<Self>(self.m_);
}
```

Deducing `this` for derived types

```
struct base {
    int m_;

    auto foo(this base const& self) { return self.m_; }

    template<typename Self>
    auto bar(this Self const& self) { return self.m_; }

    template<typename Self>
    auto baz(this Self const& self) { return self.base::m_; }
};

struct derived : base {
    int m_;
};

auto main() -> int {
    base b{42};
    std::println("b.foo() = {}", b.foo());
    std::println("b.bar() = {}", b.bar());
    std::println("b.baz() = {}", b.baz());

    derived d{{42}, 99};
    std::println("d.foo() = {}", d.foo());
    std::println("d.bar() = {}", d.bar());
    std::println("d.baz() = {}", d.baz());
}
```

Deducing `this` for derived types

```cpp
struct base {
    int m_;

    auto foo(this base const& self) { return self.m_; }

    template<typename Self>
    auto bar(this Self const& self) { return self.m_; }

    template<typename Self>
    auto baz(this Self const& self) { return self.base::m_; }
};

struct derived : base {
    int m_;
};

auto main() -> int {
    base b{42};
    std::println("b.foo() = {}", b.foo()); // base const &
    std::println("b.bar() = {}", b.bar()); // base const &
    std::println("b.baz() = {}", b.baz()); // base const &

    derived d{{42}, 99};
    std::println("d.foo() = {}", d.foo()); // base const &
    std::println("d.bar() = {}", d.bar()); // derived const &
    std::println("d.baz() = {}", d.baz()); // derived const &
}
```

- template type deduction remains unchanged
- Self: statically most derived type
- output:

```
b.foo() = 42
b.bar() = 42
b.baz() = 42
d.foo() = 42
d.bar() = 99
d.baz() = 42
```

Deducing `this` for Curiously Recurring Template Pattern

```
template<class T>
struct add_postfix_increment {
    auto operator++(int) {
        auto& this_ = static_cast<T&>(*this);
        auto tmp = this_;
        ++this_;
        return tmp;
    }
};
struct A : add_postfix_increment<A> {
    using add_postfix_increment<A>::operator++;
    A& operator++() { ++m_; return *this; }
    int m_ = 0;
};
```

- templated base class (template parameter is derived class)
- static cast to derived type
- recurring: derived class inherits from base templated on itself

Deducing `this` for Curiously Recurring Template Pattern

```
template<class T>
struct add_postfix_increment {
    auto operator++(int) {
        auto& this_ = static_cast<T&>(*this);
        auto tmp = this_;
        ++this_;
        return tmp;
    }
};
struct A : add_postfix_increment<A> {
    using add_postfix_increment<A>::operator++;
    A& operator++() { ++m_; return *this; }
    int m_ = 0;
};
```

- templated base class (template parameter is derived class)
- static cast to derived type
- recurring: derived class inherits from base templated on itself

```
struct add_postfix_increment {
    template<typename Self>
    auto operator++(this Self&& self, int) {
        auto tmp = self;
        ++self;
        return tmp;
    }
};
struct A : add_postfix_increment {
    using add_postfix_increment::operator++;
    A& operator++() { ++m_; return *this; }
    int m_ = 0;
};
```

- no more templates (non-template base class)
- no casts
- no recursion

Deducing `this` for constraining derived types

```
struct add_postfix_increment {
    template<typename Self>
    auto operator++(this Self&& self, int) {
        auto tmp = self;
        ++self;
        return tmp;
    }
};
struct A : add_postfix_increment {
    using add_postfix_increment::operator++;
    A& operator++() { ++m_; return *this; }
    int m_ = 0;
};
```

- `A` should only be able to inherit from `add_postfix_increment` if it fulfills the interface
- Print a human-readable error message if this is not the case

Deducing `this` for constraining derived types

```
struct add_postfix_increment {
    template<typename Self>
    auto operator++(this Self&& self, int) {
        auto tmp = self;
        ++self;
        return tmp;
    }
};
struct A : add_postfix_increment {
    using add_postfix_increment::operator++;
    A& operator++() { ++m_; return *this; }
    int m_ = 0;
};
```

- `A` should only be able to inherit from `mixin` if it fulfills the interface
- Print a human-readable error message if this is not the case

```
struct add_postfix_increment {
    template<typename Self> requires requires(Self&& self) {
        {++self}->std::convertible_to<std::remove_cvref_t<Self>>;}
    auto operator++(this Self&& self, int) {
        auto tmp = self;
        ++self;
        return tmp;
    }
};
struct A : add_postfix_increment {
    using add_postfix_increment::operator++;
    A& operator++() { ++m_; return *this; }
    int m_ = 0;
};
```

- Wherever we have templates, we can use concepts!

Deducing `this` for lambdas

```
auto fib = [](this auto self, int n) {
    if (n<2) return n;
    return self(n-1) + self(n-2);
};
```

- same syntax for lambdas
- reference lambda from within lambda
- recursion!
- `this` in lambda body still refers to the captured object

- get type of lambda

```
auto lambda = []<typename Lambda>(this Lambda&& self, int n) {
    using type = std::remove_cvref_t<Lambda>;
};
```

- constrain value category

```
auto lambda = [](this auto& self, int n) {
    std::println("{}", n);
};
decltype(lambda){}(42); // compile error
```

- `mutable` cannot be used anymore

```
int m = 0;
auto lambda = [m](this auto& self, int n) {
    m = n;
    std::println("{}", m);
};
lambda(42);
```

Simplifying the visitor pattern: simple calculator

> The Visitor Pattern encapsulates an operation executed on an object hierarchy as an object and enables it to define new operations without changing the object hierarchy. (Rainer Grimm)

- uses double dispatch
  - visitor gets passed to object via accept member function
  - visitor will be invoked in the body with the object as parameter
- uses virtual function calls
- complicated

- goal: write a simple calculator
  - only doubles
  - only add and subtract operations
- assume: parser is supplying us with expression tree

```
// 3 + 4 - 5 = 2
auto expr =
    make_expression<sum_expression>(
        make_expression<number_expression>(3),
        make_expression<difference_expression>(
            make_expression<number_expression>(4),
            make_expression<number_expression>(5)
        )
    );
```

- use visitor pattern for traversing expression tree

Classical Visitor Pattern

- runtime polymorphic (virtual)
- hierarchy of classes to visit

- each expression must accept the visitor
- and call the visit member function

```
struct expression;
struct number_expression;
struct binary_expression;
struct sum_expression;
struct difference_expression;

struct visitor {
    virtual void visit(number_expression&) = 0;
    virtual void visit(binary_expression&) = 0;
    virtual void visit(sum_expression&) = 0;
    virtual void visit(difference_expression&) = 0;
};

struct expression {
    virtual void accept(visitor&) = 0;
    virtual ~expression() = default;
};
using expression_ptr = std::unique_ptr<expression>;

template<typename T, typename... Args>
auto make_expression(Args&&... args) {
    return std::make_unique<T>(std::forward<Args>(args)...);
}
```

```
struct number_expression : expression {
    number_expression(double v) :  value_{v} {}
    virtual void accept(visitor& v) override { v.visit(*this); }
    double value_;
};

struct binary_expression : expression {
    binary_expression(expression_ptr lhs, expression_ptr rhs) :
        lhs_{std::move(lhs)}, rhs_{std::move(rhs)} {}
    expression_ptr lhs_;
    expression_ptr rhs_;
    double left_value_ = 0;
    double right_value_ = 0;
};

struct sum_expression : binary_expression {
    using binary_expression::binary_expression;
    virtual void accept(visitor& v) override { v.visit(*this); }
};

struct difference_expression : binary_expression {
    using binary_expression::binary_expression;
    virtual void accept(visitor& v) override { v.visit(*this); }
};
```

Classical Visitor Pattern

```
struct calculator : visitor {
    void visit(number_expression& e) override {
        stack_.push(e.value_);
    }

    void visit(binary_expression& e) override {
        e.lhs_->accept(*this);
        e.rhs_->accept(*this);
        e.right_value_ = stack_.top();
        stack_.pop();
        e.left_value_ = stack_.top();
        stack_.pop();
    }

    void visit(sum_expression& e) override {
        visit(static_cast<binary_expression&>(e));
        stack_.push(e.left_value_ + e.right_value_);
    }

    void visit(difference_expression& e) override {
        visit(static_cast<binary_expression&>(e));
        stack_.push(e.left_value_ - e.right_value_);
    }

    std::stack<double> stack_;
};
```

```
void calculate(auto& expr) {
    calculator calc;
    calc.visit(*expr);
    std::println("result = {}", calc.stack_.top());
}
```

- abstract base visitor class
    - must change if we add for example `product_expression`
- virtual function overhead
- double dispatch
- boilerplate accept member functions
- hard to reason about

Overload Pattern with deducing `this`

- overload pattern: modern "visitor pattern" in C++23
- uses variadic templates and `std::variant`
- no virtual function calls
- no explicit double dispatch
- no accept member functions
- simpler to understand

```
struct number_expression;
struct sum_expression;
struct difference_expression;

using expression = std::variant<
    number_expression, sum_expression, difference_expression>;

using expression_ptr = std::unique_ptr<expression>;

template<typename T, typename... Args>
auto make_expression(Args&&... args) {
    return std::make_unique<expression>(
        std::in_place_type<T>, std::forward<Args>(args)...);
}
```

```
struct number_expression {
    number_expression(double v) :  value_{v} {}
    double value_;
};

struct binary_expression {
    binary_expression(expression_ptr lhs, expression_ptr rhs) :
        lhs_{std::move(lhs)}, rhs_{std::move(rhs)} {}
    expression_ptr lhs_;
    expression_ptr rhs_;
    double left_value_ = 0;
    double right_value_ = 0;
};

struct sum_expression {
    sum_expression(expression_ptr lhs, expression_ptr rhs) :
        impl_{std::move(lhs), std::move(rhs)} {}
    binary_expression impl_;
};

struct difference_expression {
    difference_expression(expression_ptr lhs, expression_ptr rhs) :
        impl_{std::move(lhs), std::move(rhs)} {}
    binary_expression impl_;
};
```

Overload Pattern with deducing `this`

```
template<typename... Ts> struct overloaded : Ts... {
    using Ts::operator()...; };

void calculate(auto& expr) {
    std::stack<double> stack_;

    overloaded calculator {
        [&](number_expression& e) { stack_.push(e.value_); },
        [&](this auto& self, sum_expression& e) {
            self(e.impl_);
            stack_.push(e.impl_.left_value_+e.impl_.right_value_);
        },
        [&](this auto& self, difference_expression& e) {
            self(e.impl_);
            stack_.push(e.impl_.left_value_-e.impl_.right_value_);
        },
        [&](this auto& self, binary_expression& e) {
            std::visit(self, *e.lhs_);
            std::visit(self, *e.rhs_);
            e.right_value_ = stack_.top();
            stack_.pop();
            e.left_value_ = stack_.top();
            stack_.pop();
        },
    };
    std::visit(calculator, *expr);
    std::println("result = {}", stack_.top());
}
```

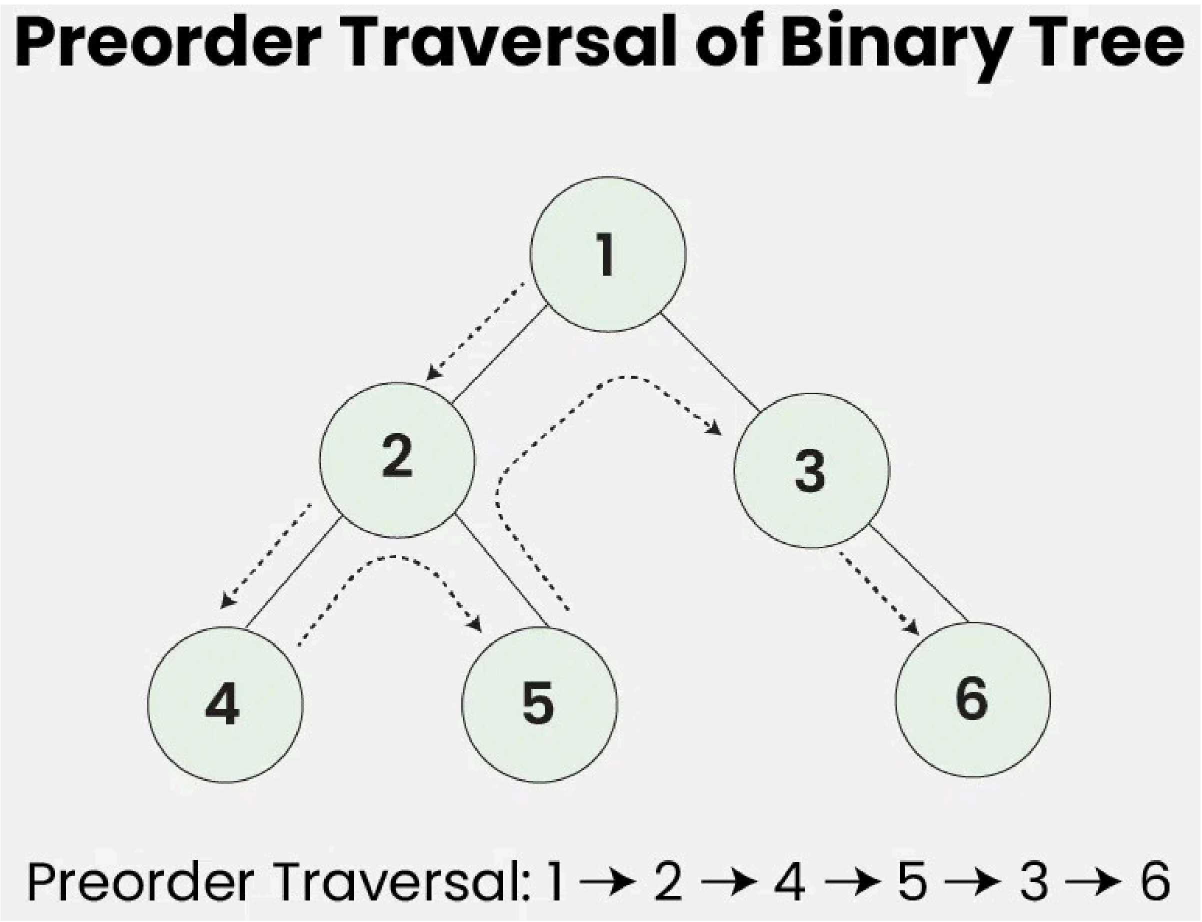
- `overloaded` : variadic template class
- inherits from its template parameters
- makes base classes call operators visible as overloads
- can be initialized without spelling out templates (CTAD)
  - Template types deduced from lambda initializers
- deducing `this` in lamdas:
  - `decltype(self)` = `overloaded&` -> most statically derived type

Overload Pattern with deducing `this` for Tree traversal

```cpp
struct node;
using sentinel = std::monostate;
using tree = std::variant<sentinel, node*>;
struct node { int data; tree left; tree right; };

template <typename... Ts> struct overloaded : Ts... {
    using Ts::operator()...; };

auto preorder_traversal = [](tree const& t, auto&& f) {
    std::visit(
        overloaded{
            [ ] (sentinel const&) {}, // do nothing
            [&] (this auto self, node const* n) {
                f(*n);
                std::visit(self, n->left);
                std::visit(self, n->right);
            }
        },
        t
    );
};
```




```cpp
auto n6 = node{6, {   }, {   }};
auto n3 = node{3, {   }, {&n6}};
auto n4 = node{4, {   }, {   }};
auto n5 = node{5, {   }, {   }};
auto n2 = node{2, {&n4}, {&n5}};
auto n1 = node{1, {&n2}, {&n3}};
preorder_traversal(tree{&n1},
    [](node const& n) { std::println("{}", n.data); });
```

Deducing `this` for handling captured variables

- problem: perfect-forwarding captured values based on whether lambda is l- or r-value

```
template<typename Func>
struct factory {
    int i_;
    Func create_;

    template<typename Self>
    auto make(this Self&& self) {
        return std::forward<Self>(self).create_(self.i_); }
};

struct A {
    int m_;
    std::vector<int> v_;
};

template<typename Lambda>
void test(Lambda&& create) {
    factory f{42, std::forward<Lambda>(create)};
    auto a = f.make();              // from lvalue, reuse lambda
    auto b = std::move(f).make(); // from rvalue, consume capture
}
```

Deducing `this` for handling captured variables

- problem: perfect-forwarding captured values based on whether lambda is l- or r-value

```
template<typename Func>
struct factory {
    int i_;
    Func create_;

    template<typename Self>
    auto make(this Self&& self) {
        return std::forward<Self>(self).create_(self.i_); }
};

struct A {
    int m_;
    std::vector<int> v_;
};

template<typename Lambda>
void test(Lambda&& create) {
    factory f{42, std::forward<Lambda>(create)};
    auto a = f.make();              // from lvalue, reuse lambda
    auto b = std::move(f).make(); // from rvalue, consume capture
}
```

- without deduced lambda type: cannot determine if it is safe to move

```
test(
    [msg = std::vector{1,2,3,4,5,6}]
    (int i)->A {
        return {i, msg}; // std::move?
    });
```

- with deduced lambda type: perfect forwarding

```
test(
    [msg = std::vector{1,2,3,4,5,6}]<typename Self>
    (this Self&&, int i)->A {
        return {i, std::forward_like<Self>(msg)};
    });
```

Explicit copy by value for chaining computations

Explicit copy by value for lifetime management

Explicit copy by value for performance improvement

- compiler can optimize away reference-forming and passing of object
- `this` by value: small objects can be passed by register
- https://godbolt.org/z/zrqTn7Yh1, gcc 14.2 -std=c++23 -Ofast (x86-64)

```cpp
struct A {
    int m;
    int foo() const;
};
auto main() -> int {
    A a{42};
    return a.foo();
}
```

```cpp
struct A {
    int m;
    int foo(A self);
};
auto main() -> int {
    A a{42};
    return a.foo();
}
```

Explicit copy by value for performance improvement

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- `this` by value: small objects can be passed by register
- https://godbolt.org/z/zrqTn7Yh1, gcc 14.2 -std=c++23 -Ofast (x86-64)

```cpp
struct A {
    int m;
    int foo() const;
};
auto main() -> int {
    A a{42};
    return a.foo();
}
```

```cpp
struct A {
    int m;
    int foo(A self);
};
auto main() -> int {
    A a{42};
    return a.foo();
}
```

```asm
sub     rsp, 24                 ; reserve 24 bytes on stack
lea     rdi, [rsp+12]           ; load address into register
mov     DWORD PTR [rsp+12], 42  ; move 42 into mem (16B align.)
call    A::foo() const          ; call foo, rdi: first argument
add     rsp, 24                 ; clean up stack
ret                             ; return to caller
```

Explicit copy by value for performance improvement

- compiler can optimize away reference-forming and passing of object
- `this` by value: small objects can be passed by register
- https://godbolt.org/z/zrqTn7Yh1, gcc 14.2 -std=c++23 -Ofast (x86-64)

```cpp
struct A {
    int m;
    int foo() const;
};
auto main() -> int {
    A a{42};
    return a.foo();
}
```

```cpp
struct A {
    int m;
    int foo(A self);
};
auto main() -> int {
    A a{42};
    return a.foo();
}
```

```asm
sub     rsp, 24                  ; reserve 24 bytes on stack
lea     rdi, [rsp+12]            ; load address into register
mov     DWORD PTR [rsp+12], 42   ; move 42 into mem (16B align.)
call    A::foo() const           ; call foo, rdi: first argument
add     rsp, 24                  ; clean up stack
ret                              ; return to caller
```

```asm
mov     edi, 42                  ; move 42 directly into edi reg.
jmp     A::foo(this A)           ; jump to foo, rdi/edi: first arg.
                                 ; tail call optimization
```

- if definition of `A::foo()` is visible: compiler optimizes redundant stack away

Member function pointers

```
struct A {
    int m_;
    int foo(int n) const noexcept {return m_*n;}
    int bar(this A const& self, int n) noexcept {return self.m_*n;}
    template<typename Self>
    int baz(this Self& self, int n) noexcept {return self.m_*n;}
};

auto a = A{42};
int result = 0;

auto foo_ptr = &A::foo;





auto bar_ptr = &A::bar;





auto baz_ptr = &A::template baz<A const&>;
```

Member function pointers

```
struct A {
    int m_;
    int foo(int n) const noexcept {return m_*n;}
    int bar(this A const& self, int n) noexcept {return self.m_*n;}
    template<typename Self>
    int baz(this Self& self, int n) noexcept {return self.m_*n;}
};

auto a = A{42};
int result = 0;

auto foo_ptr = &A::foo;
static_assert(std::is_same_v<decltype(foo_ptr),
    int (A::*)(int) const noexcept>);



auto bar_ptr = &A::bar;
static_assert(std::is_same_v<decltype(bar_ptr),
    int (*)(A const&, int) noexcept>);



auto baz_ptr = &A::template baz<A const&>;
static_assert(std::is_same_v<decltype(baz_ptr),
    int (*)(A const&, int) noexcept>);
```

Member function pointers

```
struct A {
    int m_;
    int foo(int n) const noexcept {return m_*n;}
    int bar(this A const& self, int n) noexcept {return self.m_*n;}
    template<typename Self>
    int baz(this Self& self, int n) noexcept {return self.m_*n;}
};

auto a = A{42};
int result = 0;

auto foo_ptr = &A::foo;
static_assert(std::is_same_v<decltype(foo_ptr),
    int (A::*)(int) const noexcept>);
result = (a.*foo_ptr)(2);
result = std::invoke(foo_ptr, a, 2);

auto bar_ptr = &A::bar;
static_assert(std::is_same_v<decltype(bar_ptr),
    int (*)(A const&, int) noexcept>);
result = bar_ptr(a, 2);
result = std::invoke(bar_ptr, a, 2);

auto baz_ptr = &A::template baz<A const&>;
static_assert(std::is_same_v<decltype(baz_ptr),
    int (*)(A const&, int) noexcept>);
result = baz_ptr(a, 2);
result = std::invoke(baz_ptr, a, 2);
```

- normal member function
  - pointer to member function type
  - arcane syntax
- with explicit object parameter
  - pointer to free function type
  - simpler to invoke
- `std::invoke` can be used generically

References

- P0847R6: https://www.open-std.org/jtc1/sc22/wg21/docs/papers/2021/p0847r6.html
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