Implementing variant visitation using lambdas

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About me

- Developer at **Bloomberg L.P.**
- Modern C++ enthusiast
  - Conference talks
  - Video tutorials & articles
  - Open-source projects

Overview

1. **What is a *variant* and why is it useful?**
2. **Variant visitation**
3. **Recursive variants**

part 1

What is a *variant* and why is it useful?

- Variant types and use cases
- Variant implementations
- `std::variant`

To understand variants, let's begin by understanding `struct` and `enum class`.

What is a `struct`?

A `struct` models **aggregation of types**.

```
struct point
{
    int _x;
    int _y;
};
```

A `point` is an `int` **AND** an `int`.

What is an `enum class`?

An `enum class` models **a choice between values**.

```
enum class traffic_light
{
    red,
    yellow,
    green
};
```

A `traffic_light` is **EITHER** `red` **OR** `yellow` **OR** `green`.

What is a `variant`?

A `variant` models **a choice between types**.

```
struct on  { int _temperature; };
struct off { };

using oven_state = std::variant<on, off>;
```

- The oven is `off`.

  ...or...

- The oven is `on`, with `_temperature` $= 200°C$.

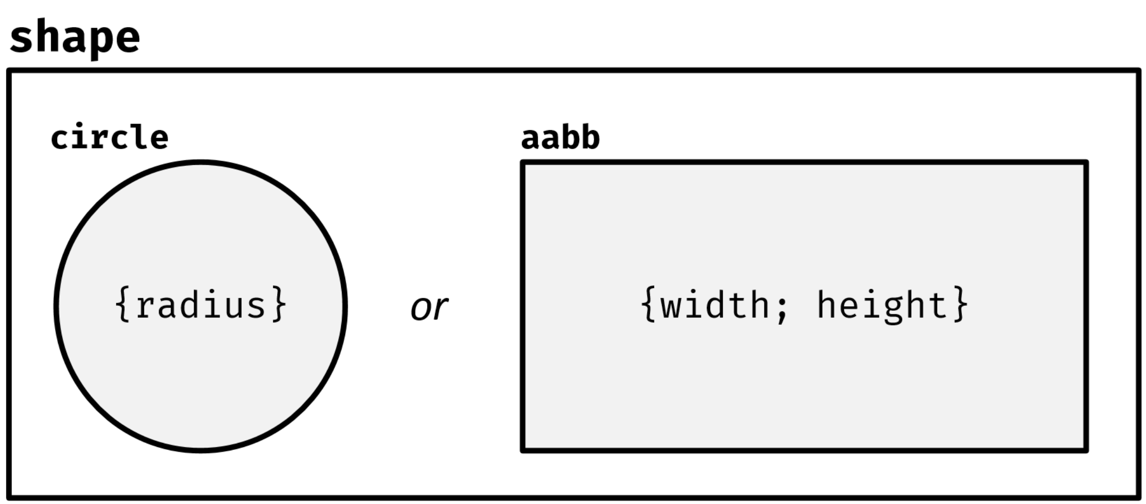
	`struct`	`enum class`	`variant`
model	*aggregation:* types	*choice:* values	*choice:* types
class	product type	sum type	sum type

Variant types can be thought of as **type-safe tagged unions** that:

- Require significantly less boilerplate.
- Automatically deal with constructors/destructors and assignment.
- Immensely increase **safety**.

Those claims are easy to verify through an *example*. Let's...

- Define a `shape` **sum type** which can be a **circle** or an **axis-aligned bounding box**.
- Define an `area` function that, given a `shape` instance, calculates and returns its **surface area**.



We will start with a "*traditional*" *tagged union* first.

```cpp
enum class shape_type{circle, aabb};

struct shape
{
    shape_type _type;

    union
    {
        struct { float _radius;         } circle_data;
        struct { float _width, _height; } aabb_data;
    } _u;
};
```

When defining a "*traditional*" *tagged union* type, we need:

- An `enum class` with a value for every *alternative*.
- A `struct` for every alternative that defines its *state*.
- An `union` that wraps all the state `struct` types.
- An interface `struct` that wraps the `union` and `enum class`.

```cpp
auto area(const shape& s)
{
    switch(s._type)
    {
        case shape_type::circle:
        {
            const auto& r = s._u.circle_data._radius;
            return pi * r * r;
        }
        case shape_type::aabb:
        {
            const auto& x = s._u.aabb_data;
            return x._width * x._height;
        }
    };

    assert(false);
    __builtin_unreachable();
}
```

[on *gcc.godbolt.org*]

When visiting it, we need:

- A `switch` with a `case` for every alternative.
- Every `case` needs to access the relevant state by going through the `union`.
- An *unreachable* guard at the end of the visitation.

Let's now see how `std::variant` compares.

```cpp
struct circle { float _radius; };
struct aabb   { float _width, _height; };
using shape = std::variant<circle, aabb>;
```

```cpp
auto area(const shape& s)
{
    struct {
        auto operator()(const circle& x) const
        {
            return pi * x._radius * x._radius;
        }
        auto operator()(const aabb& x) const
        {
            return x._width * x._height;
        }
    } visitor;

    return std::visit(visitor, s);
}
```

[on **gcc.godbolt.org**]

- Defining a variant type is trivial: all that's required is listing the alternative types.
- Visitation allows easy access to the members of currently active variant alternative.
- `visitor` is checked to be *exhaustive* at compile-time.

Examples of structures elegantly modeled by variants are:

- JSON
- ASTs *(abstract syntax trees)*
- State machines
- Error handling

```cpp
using json_value = std::variant
<
    json_object,
    json_array,
    json_string,
    json_number,
    json_boolean,
    json_null
>;
```

```cpp
template <typename T>
json_value serialize(const T&);

template <typename T>
T deserialize(const json_value&);
```

```cpp
struct success              { data _contents; }
struct file_not_found       { };
struct invalid_permissions { };

using file_open_result = std::variant
<
    success,
    file_not_found,
    invalid_permissions
>;
```

```cpp
file_open_result open_file(const std::string& path);
```

The examples used `std::variant`, standardized in **C++17**.

Several other implementations are available today:

- `boost::variant`
- `eggs::variant`
- `type_safe::variant`
- `bdlb::Variant`

They differ in their:

- Interface
- Default initialization semantics
- Existence of an "empty" state
- Strategy of dealing with exceptions
- Rules for duplicate types

The visitation techniques that will be covered in this talk will be applicable to **any variant implementation**.

For simplicity, we're going to keep using `std::variant` for the rest of the talk.

`std::variant<Ts...>` can be constructed/assigned with any instance of `Ts...` or with any other `variant` instance.

```
std::variant<int, std::string> v0{1};
v0 = "hello!"s;

std::variant<int, std::string> v1{"bye!"s};
v0 = std::move(v1);
```

The active alternative in an `std::variant` instance can be accessed with any of the following:

- `std::variant::get`
- `std::variant::get_if`

```
std::variant<int, std::string> v0{1};

assert(v0.holds_alternative<int>());
assert(v0.get<int>() == 1);

auto v0_str = v0.get_if<std::string>();
if(v0_str != nullptr)
{
    // ...
}
```

- `get<T>` requires the user to be aware of the currently active alternative of the variant. In case of error, an *exception* will be thrown.
- `get_if<T>` requires syntactical overhead that does not scale well with a large number of types.

That's why the standard library provides `std::visit`, which allows **variant visitation**. We'll take a look at it in **part 2**.

part 1 - recap

- Variants are **sum types** that model a **choice between types**.
- Variants are **safer** and **more expressive** than "*traditional*" *tagged unions*.
- *Recursive node-based structures*, *error handling*, *state machines*, etc... are examples of concepts that can be **elegantly** modeled with variants.
- `std::variant` is a **vocabulary type** introduced in C++17.

part 2

Variant visitation

- What is "*visitation*"?
- "Traditional" visitation
- "Lambda-based" visitation
    - Arbitrary *function object* overloading

What is "*visitation*"?

Visitation can be defined as an **abstraction** over accessing the currently active variant *alternative* in an **exhaustive** and **expressive** manner.

"Traditional" visitation

overview

- Visitation requires a `Callable` object which can be invoked with every possible variant alternative.
- The "traditional" way of creating such as object is defining a `struct`.

"Traditional" visitation

example - one variant

```
struct printer
{
    void operator()(int x)    { cout << x << "i\n"; }
    void operator()(float x)  { cout << x << "f\n"; }
    void operator()(double x) { cout << x << "d\n"; }
};
```

```
using my_variant = std::variant<int, float, double>;
my_variant v0{20.f};

// Prints "20f".
std::visit(printer{}, v0);
```

[on *gcc.godbolt.org*]

"Traditional" visitation

example - two variants

```
struct collision_resolver
{
    void operator()(circle, circle) { /* ... */ }
    void operator()(circle, aabb)   { /* ... */ }
    void operator()(aabb,   circle) { /* ... */ }
    void operator()(aabb,   aabb)   { /* ... */ }
};
```

```
using my_variant = std::variant<circle, aabb>;
my_variant v0{circle{}};
my_variant v1{aabb{}};

std::visit(collision_resolver{}, v0, v1);
```

[on *gcc.godbolt.org*]

"Traditional" visitation

shortcomings

- **Syntactical overhead**: a `struct` with multiple `operator()` overloads must be defined.
- **Lack of locality**: sometimes the `struct` cannot be defined locally *(e.g. contains template methods)*.
- **Readabily impact**: the visitation logic is defined far away from the visitation site.

> Can we do better?

Let's take some inspiration from *Rust*.

Rust *variants*: `enum`

example

```
enum MyVariant {
    IntTag(i32),
    FloatTag(f32),
    DoubleTag(f64)
}
```

```
let v0 = FloatTag(2.0);
match v0 {
    IntTag(x)    ⇒ println!("{}i", x),
    FloatTag(x)  ⇒ println!("{}f", x),
    DoubleTag(x) ⇒ println!("{}d", x)
}
```

[on ***rust.godbolt.org***]

Rust has *language-level* **variants** and **pattern-matching**. This allows expressive and safe local visitation of variants.

```rust
match v0 {

    IntTag(x)    => println!("{}i", x),
//  ^^^^^^^^^
//  pattern


    FloatTag(x)  => println!("{}f", x),
//          ^^^
//          decomposition


    DoubleTag(x) => println!("{}d", x)
//                  ^^^^^^^^^^^^^^^^^^^
//                  expression
}
```

C++

```cpp
struct printer
{
    void operator()(int x)    { cout << x << "i\n"; }
    void operator()(float x)  { cout << x << "f\n"; }
    void operator()(double x) { cout << x << "d\n"; }
};

my_variant v0{20.f};
std::visit(printer{}, v0);
```

Rust

```rust
let v0 = FloatTag(2.0);
match v0 {
    IntTag(x)    => println!("{}i", x),
    FloatTag(x)  => println!("{}f", x),
    DoubleTag(x) => println!("{}d", x)
}
```

"Lambda-based" visitation

overview

- Visitation is done **locally** by using a set of exhaustive *lambda expressions*.
- *"Pattern matching"-like* syntax.
- Minimal syntactical boilerplate.
- No additional run-time overhead.

"Lambda-based" visitation

example

```cpp
using my_variant = std::variant<int, float, double>;
my_variant v0{20.f};

// Prints "20f".
match(v0)([](int x)   { cout << x << "i\n"; },
          [](float x) { cout << x << "f\n"; },
          [](double x){ cout << x << "d\n"; });
```

Almost no syntactical overhead!

Let's compare again to Rust's `match`...

C++

```cpp
my_variant v0{20.f};

// Prints "20f".
match(v0)([](int x)   { cout << x << "i\n"; },
          [](float x) { cout << x << "f\n"; },
          [](double x){ cout << x << "d\n"; });
```

Rust

```rust
let v0 = FloatTag(2.0);
match v0 {
    IntTag(x)    => println!("{}i", x),
    FloatTag(x)  => println!("{}f", x),
    DoubleTag(x) => println!("{}d", x)
}
```

*(Note: Rust's `match` can be **way** more powerful than shown here.)*

Before diving into `match`'s implementation, let's look at an additional example.

"Lambda-based" visitation

example

```cpp
struct payload { int _data; };
struct error   { std::string _what; };

using request = std::variant<payload, error>;
```

```cpp
match(make_request("legitwebsite.com"))(
      [](const payload& p)
      {
          match(make_request("abc.com", p._data))(
                [](const payload& p){ /* ... */ },
                [](const error& e)  { /* ... */ });
      },
      [](const error& e){ /* ... */ });
```

"Lambda-based" visitation

implementation - overview

- `match` will be a function that takes N_v *variants* and returns a function that takes N_f *function objects*.

```
match(v0, v1, ... , vN_v)(f0, f1, ... , fN_f);
```

- In order to create a *visitor* from the passed function objects, an *overload set* must be built out of them.
- Internally, `std::visit` will be called with the *variants* and the newly-built *overload set*.

Let's begin with the creation of an **overload set**.

Let's start by looking at *non-member functions*.

```cpp
int foo(float) { return 0; }
int foo(char)  { return 1; }
```

`foo` is an *overloaded function*.

```cpp
auto x0 = foo(0.f); // `x0` is `0`.
auto x1 = foo('a'); // `x1` is `1`.
```

> Can we "*generate*" an overload set out of them?

There is no way of defining *overloaded functions* locally:

```
void f()
{
    int foo(float) { return 0; }
    int foo(char)  { return 1; }
    // Nope. COMPILER ERROR!
}
```

...this doesn't help.

What about *function objects*?

```cpp
struct foo
{
    int operator()(float) { return 0; }
    int operator()(char)  { return 1; }
};
```

`foo` is a *function object*.

```cpp
auto x0 = foo{}(0.f); // `x0` is `0`.
auto x1 = foo{}('a'); // `x1` is `1`.
```

> Can we "*generate*" an overload set out of them?

We can define them locally:

```
void f()
{
    struct foo
    {
        int operator()(float) { return 0; }
        int operator()(char)  { return 1; }
    };
}
```

We can also compose them **via inheritance**!

```
struct foo_float { int operator()(float){ return 0; } };
struct foo_char  { int operator()(char) { return 1; } };
```

```
struct foo : foo_float, foo_char
{
    using foo_float::operator();
    using foo_char::operator();
};
```

```
auto x0 = foo{}(0.f); // `x0` is `0`.
auto x1 = foo{}('a'); // `x1` is `1`.
```

> "Why do we need the `using` declarations?"

```cpp
struct foo : foo_float, foo_char
{
    // using foo_float::operator();
    // using foo_char::operator();
};

foo{}(0.f); // Nope. COMPILER ERROR!
```

[on **gcc.godbolt.org**]

Without the `using`*-declarations* the code would generate a compiler error.

The reason is that the call to `foo::operator()` would be **ambiguous** because *name resolution* is performed before *overload resolution*. See **§13.2 "Member name lookup"**.

We're on the right track - all that's needed is some *generalization* via `template` metaprogramming.

First attempt:

```
template <typename... TFs>
struct overload_set : TFs...
{
    using TFs::operator()...;
};
```

```
using foo = overload_set<foo_float, foo_char>;
auto x0 = foo{}(0.f);
auto x1 = foo{}('a');
```

...will it work?

The following code...

```
template <typename... TFs>
struct overload_set : TFs...
{
    using TFs::operator()...;
};
```

...works perfectly in **C++17**, thanks to **P0195** *("Pack expansions in using-declarations")*.

It unfortunately causes a compiler error in **C++14**:

```
error: parameter packs not expanded with '...':
struct overload_set : TFs...
{ using TFs::operator()...; };
//                    ^^^^
```

This happens because C++14 `using`*-declarations* don't support multiple comma-separated items. E.g.

```
struct a : b, c
{
    using b::foo, c::bar; // Error before C++17.
};
```

The problems therefore are:

- Only one of the base classes' `operator()` can be introduced in the scope of `overload_set` with the `using` keyword.
- There's no way of generating all the *`using`-declarations* at once.

...how can we work around these limitations?

The first one gives us an hint: let's try to separately match the first base class.

```cpp
template <typename TF, typename... TFs>
struct overload_set : TF, TFs...
{
    using TF::operator();
    // ...what to do with `TFs...`?
};
```

Can you see the pattern? This looks like a job for **recursion**!

Recursive case:

```cpp
template <typename TF, typename... TFs>
struct overload_set : TF, overload_set<TFs...>
{
    using TF::operator();
    using overload_set<TFs...>::operator();
};
```

Base case *(specialization)*:

```cpp
template <typename TF>
struct overload_set<TF> : TF
{
    using TF::operator();
};
```

Great! Let's try out our new `overload_set`:

```
struct foo_float
{
    constexpr int operator()(float) { return 0; }
};

struct foo_char
{
    constexpr int operator()(char)  { return 1; }
};
```

```
overload_set<foo_float, foo_char> o;

static_assert(o(0.f) == 0);
static_assert(o('a') == 1);
```

[on **gcc.godbolt.org**]

In order to support *lambda expressions* and automatically deduce the passed *function object* types, we need to make two improvements:

- Have a *perfect-forwarding* constructor inside `overload_set`.
    - Lambdas are **not** `DefaultConstructible`!
- Provide an `overload` interface *variadic function template* that deduces the types of *function objects* and returns an `overload_set`.

The *base case*'s *perfect-forwarding* constructor is trivial to implement:

```
template <typename TF>
struct overload_set<TF> : TF
{
    using TF::operator();

    template <typename TFFwd>
    overload_set(TFFwd&& f)
        : TF{std::forward<TFFwd>(f)}
    {
    }
};
```

Note that we're not using `TF` as the type of the `f` argument because we want a *forwarding reference*, **not** an *rvalue reference*.

The *recursive case*'s constructor is slightly more complicated:

```
template <typename TF, typename... TFs>
struct overload_set : TF, overload_set<TFs...>
{
    using TF::operator();
    using overload_set<TFs...>::operator();

    template <typename TFFwd, typename... TRest>
    overload_set(TFFwd&& f, TRest&&... rest) :

        // Construct the current function.
        TF{std::forward<TFFwd>(f)},

        // Construct the base class.
        // Pay attention to the ellipses' positions.
        overload_set<TFs...>{
            std::forward<TRest>(rest)...}
    { }
};
```

The last piece of the puzzle is the aforementioned `overload` *variadic function template* interface:

```cpp
template <typename... TFs>
auto overload(TFs&&... fs)
{
    return
        overload_set<std::remove_reference_t<TFs>...>(
        std::forward<TFs>(fs)...);
}
```

`std::remove_reference_t` is used to convert `T&` to `T` for the special *lvalue forwarding-reference* template deduction rules.

With everything in place, we can finally write the code below:

```
auto o = overload([](float){ return 0; },
                  [](char) { return 1; });

static_assert(o(0.f) == 0);
static_assert(o('a') == 1);
```

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Note that lambdas in C++17 are *implicitly* `constexpr` if possible - `static_assert` therefore works with them. *(See **N4487** and **P0170**.)*

Now that we have a working `overload_set`, let's go back to the original task: making the snippet below compile and work.

```
using my_variant = std::variant<int, float, double>;
my_variant v0{20.f};

// Prints "20f".
match(v0)([](int x)   { cout << x << "i\n"; },
          [](float x) { cout << x << "f\n"; },
          [](double x){ cout << x << "d\n"; });
```

Let's implement `match`!

Remember:

> `match` will be a function that takes N_v *variants* and returns a function that takes N_f *function objects*.
>
> ```
> match(v0, v1, ..., vN_v)(f0, f1, ..., fN_f);
> ```

Therefore it will roughly look like this:

```
template <typename... TVariants>
auto match(TVariants&&... vs)
{
    return [](auto&&... fs){ /* ... */ };
}
```

Thanks to `overload_set` and `std::visit`, the real implementation is *trivial*.

```
template <typename... TVariants>
constexpr auto match(TVariants&&... vs)
{
    return [&vs...](auto&&... fs) -> decltype(auto)
    {
        auto visitor =
            overload(std::forward<decltype(fs)>(fs)...);

        return std::visit(visitor,
            std::forward<TVariants>(vs)...);
    };
}
```

Finally...

```cpp
using my_variant = std::variant<int, float, double>;
my_variant v0{20.f};

// Prints "20f".
match(v0)([](int x)   { cout << x << "i\n"; },
          [](float x) { cout << x << "f\n"; },
          [](double x){ cout << x << "d\n"; });
```

[on **gcc.godbolt.org**] | [on **melpon.org/wandbox**]

...compiles and prints `"20f"`!

Here's an example with *multiple variants*:

```
struct circle { /* ... */ };
struct aabb   { /* ... */ };

using shape = std::variant<circle, aabb>;
shape s0{circle{}};
shape s1{aabb{}};

match(s0, s1)(
    [](circle, circle){ cout << "circle vs circle\n"; },
    [](circle, aabb)  { cout << "circle vs aabb\n"; },
    [](aabb,   circle){ cout << "aabb vs circle\n"; },
    [](aabb,   aabb)  { cout << "aabb vs aabb\n"; });
```

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One more, with *nested variants*:

```
struct format  { /* ... */ };
struct timeout { /* ... */ };
using error = std::variant<format, timeout>;

struct accept { /* ... */ };
struct reject { /* ... */ };
using ok = std::variant<accept, reject>;
```

```
using response = std::variant<error, ok>;
response r{error{timeout{}}};

match(r)(
    [](ok x)   { match(x)([](accept) { /* ... */ },
                          [](reject) { /* ... */ }); },

    [](error x){ match(x)([](format) { /* ... */ },
                          [](timeout){ /* ... */ }); });
```

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part 2 - recap

- Variant visitation works by invoking the *overload* matching the active *alternative* on an overloaded visitor *function object*.
- `using`*-declarations* and *inheritance* can be used to **create overloads** of arbitrary *function objects*.
- Lambdas are just syntactic sugar for *function objects*.
- Overloads of lambdas built *on-the-spot* **reduce boilerplate** and **increase locality** when visiting variants.

part 2 - recap

- Note that `struct`*-based "traditional" visitation* is **still useful**!
- `struct` visitors can...
  - Contain internal state and a richer interface.
  - Be more easily shared/reused in a large codebase.
  - Provide *customization points (e.g. via a* `template` *parameter)*.
- If your *visitation logic* is simple and local, prefer "*lambda-based*" *visitation*.

`match` can be implemented in less than 40 *well-formatted* lines of C++14 code

> "...what's the catch?"

part 3

Recursive variants

- What is a "*recursive variant*"?
- "Traditional" recursive visitation
- "Lambda-based" recursive visitation
  - Recursive lambdas via **Y combinator**

A "*recursive*" variant is a variant which can **contain itself**, and can be used to represent **recursive structures** *(e.g. JSON objects)*.

Let's assume we want to define a *recursive variant* that models simple arithmetical expressions.

5	`expr<number>`
$9 + 3$	`expr<number + expr<number>>`
$1 - (3 + 7)$	`expr<number - expr<number + expr<number>>>`

Here's a possible grammar:

```
<number> ::= `int`
<op>     ::= `plus` | `minus`
<expr>   ::= <number> | <number> <op> <expr>
```

```
<number> ::= `int`
<op>     ::= `plus` | `minus`
<expr>   ::= <number> | <number> <op> <expr>
```

```cpp
using number = int;

struct plus  { };
struct minus { };
using op = std::variant<plus, minus>;

using expr = std::variant<number,
                          std::tuple<number, op, expr>>;
```

[on **gcc.godbolt.org**]

> error: **'expr' was not declared in this scope**

The previous error makes sense, because we're basically trying to define:

```
using r_expr = std::tuple<number, op, expr>;
using expr = std::variant<number, r_expr>;
```

Could a *forward-declaration* help?

```cpp
struct expr;

using r_expr = std::tuple<number, op, expr>;

struct expr
{
    std::variant<number, r_expr> _data;
};
```

[on ***gcc.godbolt.org***]

> error: **invalid use of incomplete type 'struct expr'**

Again, the error makes sense:

`sizeof(expr)` $= \infty$

Introducing a *layer of indirection* solves the issue...

```
struct expr;

using r_expr = std::tuple<number, op, expr>;

struct expr
{
    std::variant<number, std::unique_ptr<r_expr>> _data;
};
```

[*on* ***gcc.godbolt.org***]

- The size of any instantiation of `std::variant` must be fixed.
- Recursive variants can be defined by using *forward-declarations* and *indirection*.

Let's also add a *perfect-forwarding* constructor to simplify usage:

```
struct expr
{
    std::variant<number, std::unique_ptr<r_expr>> _data;

    template <typename... Ts>
    expr(Ts&&... xs) : _data(std::forward<Ts>(xs)...)
    {
    }
};
```

```
expr e{5};
```

`e0`	5
`e1`	$9 + 3$
`e2`	$1 - (3 + 7)$

```
expr e0{5};

expr e1{make_unique<r_expr>(9, plus{}, 3)};

expr e2{make_unique<r_expr>(1, minus{},
            make_unique<r_expr>(3, plus{}, 7))};
```

[on ***gcc.godbolt.org***]

> "How can we visit recursive variants?"

Recursive "traditional" visitation

overview

- A `struct` with overloaded `operator()` will be used.
- One or more `operator()` overloads will *recursively visit* the variant by invoking `std::visit` on the parent `struct`.

Recursive "traditional" visitation

example

```
struct evaluator
{
    auto operator()(number x) { return x; }
    auto operator()(const std::unique_ptr<r_expr>& x)
    {
        const auto& [lhs, op, rhs] = *x;
        const auto rest = std::visit(*this, rhs._data);

        return match(op)(
            [&](plus) { return lhs + rest; },
            [&](minus){ return lhs - rest; });
    }
};
```

```cpp
// 5
expr e0{5};

// 9 + 3
expr e1{make_unique<r_expr>(9, plus{}, 3)};

// 1 - (3 + 7)
expr e2{make_unique<r_expr>(1, minus{},
            make_unique<r_expr>(3, plus{}, 7))};
```

```cpp
cout << std::visit(evaluator{}, e0._data); // "5"
cout << std::visit(evaluator{}, e1._data); // "12"
cout << std::visit(evaluator{}, e2._data); // "-9"
```

[on **gcc.godbolt.org**] | [on **melpon.org/wandbox**]

Recursive "traditional" visitation

shortcomings

- **Syntactical overhead**, **lack of locality**, and **readabily impact**.
- **Explicit nested visitation**: recursing requires an explicit call to `std::visit` inside the visitation logic.

We can make a small improvement here.

Did you notice that we're forced to specify the `_data` member while using `std::visit`?

Let's create a `visit_recursively` wrapper that does that for us.

```cpp
template <typename TVisitor, typename... TVariants>
constexpr decltype(auto) visit_recursively(
    TVisitor&& visitor, TVariants&&... variants)
{
    return std::visit(
        std::forward<TVisitor>(visitor),
        std::forward<TVariants>(variants)._data...
    );
}
```

This very simple change makes the code much cleaner.

```cpp
struct evaluator
{
    int operator()(int x) { return x; }
    int operator()(const std::unique_ptr<r_expr>& x)
    {
        const auto& [lhs, op, rhs] = *x;
        const auto rest = visit_recursively(*this, rhs);

        return match(op)(
            [&](plus) { return lhs + rest; },
            [&](minus){ return lhs - rest; });
    }
};
```

```cpp
// 5
expr e0{5};

// 9 + 3
expr e1{make_unique<r_expr>(9, plus{}, 3)};

// 1 - (3 + 7)
expr e2{make_unique<r_expr>(1, minus{},
            make_unique<r_expr>(3, plus{}, 7))};
```

```cpp
cout << visit_recursively(evaluator{}, e0);
cout << visit_recursively(evaluator{}, e1);
cout << visit_recursively(evaluator{}, e2);
```

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Our small improvement does not however address the primary shortcomings of this technique.

Let's try to apply our **"lambda-based"** visitation here.

Remember our recursive variant type?

```
using r_expr = std::tuple<number, op, expr>;
struct expr
{
    std::variant<number, std::unique_ptr<r_expr>> _data;
};
```

Intuitively, the following "lambda-based" visitor should work:

```
auto vis = overload(
    [](int x) { return x; },
    [](const std::unique_ptr<r_expr>& x)
    {
        const auto& [lhs, op, rhs] = *x;
        const auto rest = visit_recursively(vis, rhs);

        return match(op)(
            [&](plus) { return lhs + rest; },
            [&](minus){ return lhs - rest; });
    });
```

That unfortunately results in a *compile-time* error.

```
error: use of 'vis' before deduction of 'auto'
  const auto rest = visit_recursively(vis, rhs);
                                      ^~~
```

[on **gcc.godbolt.org**]

The issue is that the language **does not provide a way of referring to the current *closure* in a *lambda expression***.

A *lambda-expression* is just syntactic sugar for a *function object*:

```
[]{ return 0; }
```

...is roughly equivalent to...

```
struct ??
{
    int operator() const { return 0; }
};
```

Inside the definition of *member functions*, we can refer to the current instance of the parent object with the `this` keyword.

```
struct foo
{
    int operator()(int x)
    {
        if(x == 0) return 0;
        return (*this)(x - 1);
    }
};
```

Inside a *lambda-expression*, `this` does not refer to the current instance of the generated *closure* - it instead refers to the outer context!

```
auto foo = [](int x) -> int
{
    if(x == 0) return 0;
    return (*this)(x - 1);
};
```

> **error**: `this` was not captured for this lambda function

Here's an example on how the language could allow this in the future, taken from proposal P0200:

```cpp
auto foo = [] self (int x) -> int
{
    if(x == 0) return 0;
    return self(x - 1);
};
```

Let's try to find a solution that doesn't require *run-time overhead*.

```
auto fact = [](int n)
{
    if(n == 0)
    {
        return 1;
    }

    return n * ??(n - 1);
};
```

...what if we bind `fact` to itself and pass it as an extra argument?

```cpp
auto fact = [](auto self, int n) -> int
{
    if(n == 0)
    {
        return 1;
    }

    return n * self(self, n - 1);
};
```

```cpp
static_assert(fact(fact, 3) == 3 * 2 * 1);
```

[on ***gcc.godbolt.org***]

It works! *(Note the **mandatory** trailing return type.)*

There is some syntactical overhead though...

```cpp
auto fact = [](auto self, int n) -> int
{
    if(n == 0)
    {
        return 1;
    }

    return n * self(self, n - 1);
//             ^^^^^^^^^^
};

static_assert(fact(fact, 3) == 3 * 2 * 1);
//            ^^^^^^^^^^
```

...can we do anything about it?

Yes! We can use the **Y combinator**.

The **Y combinator** is commonly found in *functional programming* languages. It's an *higher-order function* that can be used to **implement recursion**.

This will be our final result:

```cpp
auto fact = y_combinator([](auto self, int n) -> int
{
    if(n == 0)
    {
        return 1;
    }

    return n * self(n - 1);
});
```

```cpp
static_assert(fact(3) == 3 * 2 * 1);
```

You can think of `y_combinator` as a *function template* which:

- Accepts any *function object* f of arity N.
- Returns a wrapper f' around f of arity $N - 1$.

The arity gets decremented because one of the arguments is bound to f' itself.

Here's a possible implementation:

```
template <typename TF>
struct y_combinator_wrapper
{
    TF _f;

    template <typename TFFwd>
    y_combinator_wrapper(TFFwd&& f)
        : _f{std::forward<TFFwd>(f)}
    {
    }

    template <typename... Ts>
    decltype(auto) operator()(Ts&&... xs)
    {
        return _f(std::ref(*this),
                  std::forward<Ts>(xs)...);
    }
};
```

That's it! An helper `y_combinator` function will return `y_combinator_wrapper`:

```
template <typename TF>
auto y_combinator(TF&& f)
{
    return y_combinator_wrapper<std::decay_t<TF>>(
        std::forward<TF>(f));
}
```

```cpp
auto fact = y_combinator([](auto self, int n) -> int
{
    if(n == 0)
    {
        return 1;
    }

    return n * self(n - 1);
});
```

```cpp
static_assert(fact(3) == 3 * 2 * 1);
```

[on *gcc.godbolt.org*]

The code above now compiles and works. We now know have all the tools to build **recursive "lambda-based" visitation**!

Recursive "lambda-based" visitation

overview

- Local "pattern-matching"-like visitation.
- Minimal syntactical boilerplate, no run-time overhead.
- Nested visitation abstracted behind a `recurse` call.

Recursive "lambda-based" visitation

example - in-place visitation

```
expr e{make_unique<r_expr>(1, minus{},
          make_unique<r_expr>(3, plus{}, 7))};
```

```
match_recursively<int>(e)(
    [](auto, number x) { return x; },
    [](auto recurse, const std::unique_ptr<r_expr>& x)
    {
        const auto& [lhs, op, rhs] = *x;
        return match(op)(
            [&](plus) { return lhs + recurse(rhs); },
            [&](minus){ return lhs - recurse(rhs); });
    });
```

Recursive "lambda-based" visitation

example - visitor creation

```
auto evaluate = make_recursive_visitor<int>(
    [](auto, number x) { return x; },
    [](auto recurse, const std::unique_ptr<r_expr>& x)
    {
        const auto& [lhs, op, rhs] = *x;
        return match(op)(
            [&](plus) { return lhs + recurse(rhs); },
            [&](minus){ return lhs - recurse(rhs); });
    }
);
```

```
cout << visit_recursively(evaluate, e0); // "5"
cout << visit_recursively(evaluate, e1); // "12"
cout << visit_recursively(evaluate, e2); // "-9"
```

Let's implement `make_recursive_visitor`.

- It will accept a *return type* `T` as a template parameter. Deducing the *return type* is **non-trivial**.
- It will take any number of *function objects* `fs...` as input. These will be the "visitor branches".

```
template <typename TReturn, typename... TFs>
auto make_recursive_visitor(TFs&&... fs)
{
    // ...?
}
```

The signatures of the `fs...` visitors have arity $N + 1$, where:

- N is the number of variants.
- The extra $+1$ is the `recurse` *function object*.

Example:

```
[](auto recurse, const std::unique_ptr<r_expr>& x)
{
    // ...
}
```

The visitor is going to be used via `visit_recursively`. Example:

```
visit_recursively(evaluator, e0)
```

`visit_recursively` accesses the `._data` member of the variants.

```
template <typename TVisitor, typename... TVariants>
decltype(auto) visit_recursively(
    TVisitor&& visitor, TVariants&&... variants)
{
    return std::visit(std::forward<TVisitor>(visitor),
        std::forward<TVariants>(variants)._data...);
}
```

Therefore, the *function object* passed to `visit_recursively` must have arity N, which is the number of variants.

We can use `y_combinator` to reduce the arity from $N + 1$ to N and to implement recursion!

```cpp
template <typename TReturn, typename... TFs>
auto make_recursive_visitor(TFs&&... fs)
{
    return y_combinator([](auto self, auto&&... xs)
        -> TReturn
    {
        // ...?
    });
}
```

To create a visitor out of `fs ...`, we can safely reuse our `overload` function.

Overload resolution will work as expected even with the extra `auto` parameter used for recursion.

Example:

```
auto v = make_recursive_visitor<bool>(
    [](auto, int)  { return false; },
    [](auto, char) { return true;  });

v([]{}, 'a'); // Will return `true`.
```

```cpp
template <typename TReturn, typename... TFs>
auto make_recursive_visitor(TFs&&... fs)
{
    return y_combinator(
        [o = overload(std::forward<TFs>(fs)...)]
        (auto self, auto&&... xs) -> TReturn
    {
        // ...?
    });
}
```

Our goal is to call `o` with the currently active variant *alternatives*.

In the context of the lambda passed to `y_combinator`, the argument pack `xs...` represents exactly that, as the *recursive visitor* is going to be invoked through `visit_recursively`.

```cpp
template <typename TReturn, typename... TFs>
auto make_recursive_visitor(TFs&&... fs)
{
    return y_combinator(
        [o = overload(std::forward<TFs>(fs)...)]
        (auto self, auto&&... xs) -> TReturn
    {
        return o(/* ?? */,
            std::forward<decltype(xs)>(xs)...);
    });
}
```

The last missing piece is the `recurse` argument that will allow recursion directly through the visitor's lambdas. It is called with *variants*. Example:

```
[](auto recurse, const std::unique_ptr<r_expr>& x)
{
    const auto& [lhs, op, rhs] = *x;
    return match(op)(
        [&](plus) { return lhs + recurse(rhs); },
        [&](minus){ return lhs - recurse(rhs); });
}
```

`rhs` is a *variant* of type `expr`.

...what can we use to invoke *recursive visitors* with *variants*?

Yes, `visit_recursively`!

```cpp
template <typename TReturn, typename... TFs>
auto make_recursive_visitor(TFs&&... fs)
{
    return y_combinator(
        [o = overload(std::forward<TFs>(fs)...)]
        (auto self, auto&&... xs) -> TReturn
    {
        return o([&self](auto&&... vs)
        {
            return visit_recursively(
                self,
                std::forward<decltype(vs)>(vs)...);
        },
        std::forward<decltype(xs)>(xs)...);
    });
}
```

```cpp
[&self](auto&&... vs)
{
    return visit_recursively(
        self,
        std::forward<decltype(vs)>(vs)...);
}
```

- We're binding `self` as the first argument for the next recursive step.
- The variants `vs...` obtained from a `recurse(vs...)` call are then being forwarded to `visit_recursively`.

That's it! Let's try `make_recursive_visitor` out.

```
auto evaluate = make_recursive_visitor<int>(
    [](auto, number x) { return x; },
    [](auto recurse, const std::unique_ptr<r_expr>& x)
    {
        const auto& [lhs, op, rhs] = *x;
        return match(op)(
            [&](plus) { return lhs + recurse(rhs); },
            [&](minus){ return lhs - recurse(rhs); });
    }
);
```

```
cout << visit_recursively(evaluate, e0); // "5"
cout << visit_recursively(evaluate, e1); // "12"
cout << visit_recursively(evaluate, e2); // "-9"
```

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The last missing facility is `match_recursively`, which performs in-place recursive visitaton. Example:

```
match_recursively<int>(e)(
    [](auto, number x) { return x; },
    [](auto recurse, const std::unique_ptr<r_expr>& x)
    {
        const auto& [lhs, op, rhs] = *x;
        return match(op)(
            [&](plus) { return lhs + recurse(rhs); },
            [&](minus){ return lhs - recurse(rhs); });
    });
```

It's trivial to implement it by slightly changing `match`'s implementation.

```
template <typename... TVariants>
constexpr auto match(TVariants&&... vs)
{
    return [&vs...](auto&&... fs) -> decltype(auto)
    {
        auto visitor = overload(std::forward<decltype(fs)>(fs)...);
        return std::visit(visitor, std::forward<TVariants>(vs)...);
    };
}
```

- An additional return type *template parameter* will be added.
- `overload` will be replaced by `make_recursive_visitor`.
- `std::visit` will be replaced by `visit_recursively`.

```cpp
template <typename TReturn, typename... TVariants>
constexpr auto match_recursively(TVariants&&... vs)
{
    return [&vs...](auto&&... fs) -> decltype(auto)
    {
        auto visitor = make_recursive_visitor<TReturn>(
            std::forward<decltype(fs)>(fs)...);

        return visit_recursively(visitor,
            std::forward<TVariants>(vs)...);
    };
}
```

Example:

```
expr e{make_unique<r_expr>(1, minus{},
            make_unique<r_expr>(3, plus{}, 7))};

std::cout << match_recursively<int>(e)(
    [](auto, number x) { return x; },
    [](auto recurse, const std::unique_ptr<r_expr>& x)
    {
        const auto& [lhs, op, rhs] = *x;
        return match(op)(
            [&](plus) { return lhs + recurse(rhs); },
            [&](minus){ return lhs - recurse(rhs); });
    });
```

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part 3 - recap

- Variants can be used to elegantly model **recursive structures** *(e.g. JSON, ASTs, lists, ...)*.
- A **layer of indirection** must be used to define recursive variants and keep their size fixed.
- "Traditional" recursive variant visitation using a `struct` is trivial, but suffers from the usual issues.

part 3 - recap

- Lambdas cannot recursively call themselves, as it's **impossible to refer to the *current* closure from the closure itself**.
- Recursion can be implemented by **passing the lambda as one of its own arguments**. This doesn't introduce any unnecessary run-time or memory overhead.
- The **Y combinator** higher-order function generalizes that solution and minimizes boilerplate.

part 3 - recap

- When visiting recursive variants with *simple* or *one-off* logic, **prefer the "lambda-based" approach**.
- When the logic is *complex* and *reusable*, **prefer the "traditional" approach**.
  - Note that all the utilities covered in this talk can be *harmoniously* used together.
  - ...and can be adapted to `optional` as well!

Thanks!

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