

Implementing variant visitation using lambdas

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Overview

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

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.

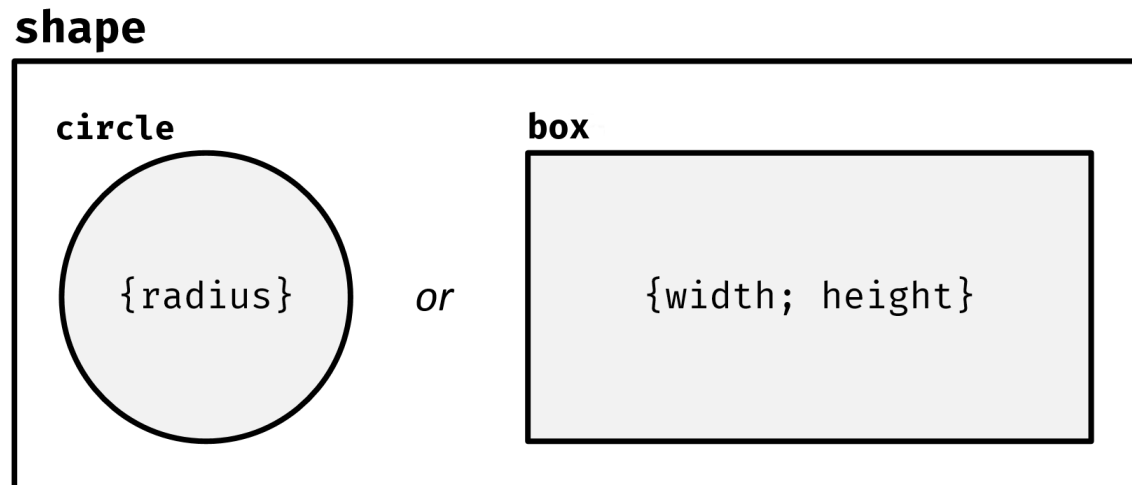
	struct	enum class	variant
model	<i>aggregation: types</i>	<i>choice: values</i>	<i>choice: types</i>
class	product type	sum type	sum type

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 a **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.

```
enum class shape_type{circle, box};

struct shape
{
    shape_type _type;

    union
    {
        struct { float _radius;          } circle_data;
        struct { float _width, _height; } box_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`.


```
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::box:
        {
            const auto& x = s._u.box_data;
            return x._width * x._height;
        }
    };

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

[on [gcc.godbolt.org](https://gcc.gnu.org/bugzilla/show_bug.cgi?id=86343)]

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.

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

```
auto area(const shape& s)  
{  
    struct {  
        auto operator()(const circle& x) const  
        {  
            return pi * x._radius * x._radius;  
        }  
        auto operator()(const box& 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

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

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

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

```
struct success          { data _contents; }  
struct file_not_found   { };  
struct invalid_permissions { };  
  
using file_open_result = std::variant  
<  
    success,  
    file_not_found,  
    invalid_permissions  
>;
```

```
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`
- `mpark::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, box)    { /* ... */ }
    void operator()(box, circle)  { /* ... */ }
    void operator()(box, box)     { /* ... */ }
};
```

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

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

[on [gcc.godbolt.org](https://gcc.gnu.org/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*).
- **Readability 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!("{}", x),  
    FloatTag(x)    ⇒ println!("{}", x),  
    DoubleTag(x)   ⇒ println!("{}", x)  
}
```

[on rust.godbolt.org]

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

```
match v0 {  
    IntTag(x)      ⇒ println!("{}", x),  
    // ^^^^^^^^^  
    // pattern  
  
    FloatTag(x)    ⇒ println!("{}", x),  
    // ^^^  
    // decomposition  
  
    DoubleTag(x)   ⇒ println!("{}", x)  
    // ^^^^^^^^^^^^^^^^^^^^^  
    // expression  
}
```


C++

```
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

```
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

```
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++

```
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

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

```
struct payload { int _data; };  
struct error    { std::string _what; };  
  
using request = std::variant<payload, error>;
```

```
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*.

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

`foo` is an *overloaded function*.

```
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*?

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

`foo` is a *function object*.

```
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?"

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

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

[on [gcc.godbolt.org](https://gcc.gnu.org/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.

```
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:

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

Base case (*specialization*):

```
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);
```

[\[on gcc.godbolt.org\]](https://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:

```
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);
```

[on gcc.godbolt.org]

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...

```
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 box    { /* ... */ };

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

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

[on gcc.godbolt.org] | [on melpom.org/wandbox]

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){ /* ... */ }); });
```

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

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	<code>expr<number></code>
$9 + 3$	<code>expr<number + expr<number>></code>
$1 - (3 + 7)$	<code>expr<number - expr<number + expr<number>>></code>

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>
```

```
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](https://gcc.gnu.org/bugzilla/show_bug.cgi?id=86441)]

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?

```
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) = ∞

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](https://gcc.gnu.org/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; });
    }
};
```

```
// 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))};
```

```
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 readability 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.


```
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.

```

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; });
    }
};

```

```
// 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))};
```

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

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

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](#):

```
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?

```
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);
```

[on gcc.godbolt.org]

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

There is some syntactical overhead though...

```
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:

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

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

```
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));
}
```

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

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

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

[on [gcc.godbolt.org](https://gcc.gnu.org/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!

```
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`.
```

```
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`.

```

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` !

```

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) ... );
    });
}

```

```
[&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"
```

[\[on gcc.godbolt.org\]](https://gcc.godbolt.org) | [\[on melpon.org/wandbox\]](https://melpon.org/wandbox)

The last missing facility is `match_recursively`, which performs in-place recursive visitation. 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`.

```
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); });
    });
```

[\[on gcc.godbolt.org\]](https://gcc.godbolt.org) | [\[on melpon.org/wandbox\]](https://melpon.org/wandbox)

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!

part 4

Minimizing syntactical overhead

- The struggle with `auto`
- Deducing lambda arity

In my [latest article](#) I rambled about my attempts in cleaning up the user syntax of recursive lambda-based visitation.

```

auto printer = make_recursive_visitor<std::string>(
    [](auto, const json_null& x)    { /* ... */ },
    [](auto, const json_true& x)   { /* ... */ },
    [](auto, const json_false& x)  { /* ... */ },
    [](auto, const json_string& x) { /* ... */ },
    [](auto, const json_number& x) { /* ... */ },
    [](auto recurse, const json_array& x)
    {
        /* ... */
    },
    [](auto recurse, const json_object& x)
    {
        /* ... */
    }
);

```

The unnecessary `auto` parameter incredibly bothers me.

Ideally, it should look like this:

```
auto printer = make_recursive_visitor<std::string>(
    [](const json_null& x)    { /* ... */ },
    [](const json_true& x)   { /* ... */ },
    [](const json_false& x)  { /* ... */ },
    [](const json_string& x) { /* ... */ },
    [](const json_number& x) { /* ... */ },
    [](auto recurse, const json_array& x)
    {
        /* ... */
    },
    [](auto recurse, const json_object& x)
    {
        /* ... */
    }
);
```

Can we achieve **zero** syntactical overhead?

Spoilers: not really.

attempt #0

Deducing lambda arity

- The user provides lambdas of arity N and $N + 1$.
- Assume that lambdas of arity N are base cases.
- Assume that lambdas of arity $N + 1$ are recursive cases.
 - Provide a `recurse` argument only for recursive cases.

The idea is to "*adapt*" the lambdas provided by the user:

- Binary lambdas (*recursive cases*) are untouched.
- Unary lambdas (*base cases*) must be converted to binary lambdas.

```
template <typename ... TFs>
auto make_recursive_visitor(TFs&& ... fs)
{
    auto o = overload(adapt(std::forward<TFs>(fs) ... ));
    // ...
}
```

```
template <typename TF>
decltype(auto) adapt(TF&& f)
{
    if constexpr(is_recursive_case<TF>())
    {
        return std::forward<TF>(f);
    }
    else
    {
        return adapt_unary(std::forward<TF>(f));
    }
}
```



```

template <typename TF>
decltype(auto) adapt_unary(TF&& f)
{
    if constexpr(is_overloaded<std::decay_t<TF>>())
    {
        return [&](auto, auto&& x) → decltype(auto)
        {
            return FWD(f)(FWD(x));
        };
    }
    else
    {
        using arg_type = /* ... */;
        return [&](auto, arg_type x) → decltype(auto)
        {
            return FWD(f)(FWD(x));
        };
    }
}

```

`is_recursive_case<TF>` needs to know whether or not `TF` is binary.

| How can we deduce the arity of a lambda?

If it's not a *generic lambda*, we can use *template specialization*:

```
template <typename T, typename Return, typename ... Args>
struct function_traits<Return (T::*)(Args ... )>
{
    static constexpr auto arity = sizeof ... (TArgs);
};
```

CallableTraits by *Barret Adair* properly deals with this issue. It was "conditionally accepted" into Boost.

It also allows us to retrieve `arg_type` for `adapt_unary` .

If it's a *generic lambda*, we could attempt invoking it... with a type that's *implicitly convertible* to anything else!

```
struct any_type
{
    template <typename T>
    constexpr operator T() noexcept
    {
        return {};
    }
};

template <typename TF>
using is_binary =
    std::is_invocable<TF, any_type, any_type>;
```

The initial results are promising...

```
auto l0 = [](int)      { };  
auto l1 = [](auto)     { };  
auto l2 = [](int, int) { };  
auto l3 = [](int, auto) { };  
auto l4 = [](auto, auto) { };  
  
static_assert(!is_binary<decltype(l0)>::value);  
static_assert(!is_binary<decltype(l1)>::value);  
static_assert( is_binary<decltype(l2)>::value);  
static_assert( is_binary<decltype(l3)>::value);  
static_assert( is_binary<decltype(l4)>::value);
```

[\[on melpon.org/wandbox\]](https://onmelpon.org/wandbox)

...unfortunately things break almost immediately:

```
auto l = [](int, auto x){ x.foo(); };  
static_assert(is_binary<decltype(l)>::value);
```

```
error: 'struct any_type' has no member named 'foo'  
    auto l = [](int, auto x){ x.foo(); };  
                             ~^~
```

[on melpon.org/wandbox]

The `static_assert` doesn't fail - the error happens during template instantiation. This is **not** SFINAE-friendly!

The "solution" to that is providing a SFINAE-friendly lambda:

```
auto l = [](int, auto x)  
    → decltype(x.foo()) { x.foo(); };
```

- This prevents the "hard error", but the `static_assert` fails!
- For a user of a pattern matching library, that's undesirable.

More problems: concepts and SFINAE constraints.

```
template <typename T>
concept bool HasFoo = requires(T x) { x.foo(); };

auto l1 = [](auto, HasFoo x) { x.foo(); };
static_assert(is_binary<decltype(l1)>::value); // fails!
```

```
auto l2 = [](auto, auto x)
           → decltype(x.foo()) { x.foo(); };
static_assert(is_binary<decltype(l2)>::value); // fails!
```

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attempt #1

Using existing knowledge

- We know that the visitor is going to be used with a `variant<Ts ... >`.
- Instead of `any_type`, we could check if any of `Ts ...` can be used to call the lambdas.

We know that a *recursive case* is going to look like this:

```
[ ](auto recurse, T x){ /* ... */ }
```

- `recurse` only needs to support invocation.
- `T` is one of the variant alternatives.

We can therefore check if invoking a lambda with a "`recurse placeholder`" and any of the alternatives is valid.

```
template <typename Return>
struct recurse_placeholder
{
    template <typename ... Ts>
    Return operator()(Ts&& ... ) const noexcept
    {
        return {};
    }
};
```

```
template <typename F, typename Return,
          typename ... Alternatives>
using is_recursive_case = std::disjunction<
    std::is_invocable<F, recurse_placeholder<Return>,
        Alternatives> ...
>;
```

This approach works with concepts and SFINAE:

```
struct bar { void foo(); };  
using v = std::variant<int, bar>;  
  
auto l1 = [](auto, HasFoo x) { x.foo(); };  
static_assert(  
    is_recursive_case<decltype(l1), void, v>()); // OK
```

```
auto l2 = [](auto, auto x)  
    → decltype(x.foo()) { x.foo(); };  
static_assert(  
    is_recursive_case<decltype(l2), void, v>()); // OK
```

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But still fails in "pathological" cases:

```
auto l = [](auto, auto x){ x.foo(); };  
  
static_assert(  
    is_recursive_case<decltype(l), void, v>());  
// Hard error! :(
```

It should be clear now that approaches revolving around `std::is_invocable` are not going to work.

What I really need is **function signature reflection**:

```
// (Pseudocode.)  
  
auto l = [](auto, int, float) { whatever(); };  
constexpr auto arity = $l.arity();  
static_assert(arity == 3);
```

Unfortunately the current proposals (see [P0590](#) and [P0578](#)) do not seem to allow this for lambdas and/or function templates.

attempt #2

Human arity deduction

- Change the user syntax slightly: have the caller separate base and recursive cases for us.

```

auto printer = make_recursive_visitor<std::string>
(
    [](const json_null& x)    { /* ... */ },
    [](const json_true& x)   { /* ... */ },
    [](const json_false& x)  { /* ... */ },
    [](const json_string& x) { /* ... */ },
    [](const json_number& x) { /* ... */ }
)(
    [](auto recurse, const json_array& x)
    {
        /* ... */
    },
    [](auto recurse, const json_object& x)
    {
        /* ... */
    }
);

```


We will eventually end up with two sets of lambdas:

- One for the *base cases*.
- One for the *recursive cases*.

Only the base cases have to be "adapted" prior to overloading.

```
// (Pseudocode.)
```

```
template <typename ... BaseCases>  
auto make_recursive_visitor(BaseCases ... bs)  
{  
    return [bs ... ](auto ... rs) // recursive cases  
    {  
        auto o = overload(adapt(bs) ... , rs ... );  
        // ...  
    };  
}
```

This seems to work, but I still need to research possible gotchas/issues before introducing it to my `scelta` library.

```

make_recursive_visitor<std::string>
(
    [](json_null)      { return "null"; },
    [](json_bool x)    { return x ? "true" : "false"; },
    [](json_number x)  { return std::to_string(x); },
    [](json_string x)  { return '"' + x + '"'; }
)(
    [](auto recurse, const json_array& x)
    {
        return "[" + join(", ",
                           map_vector(x, recurse)) + "]";
    },
    [](auto recurse, const json_object& x)
    {
        return "{" + join(", ",
                           map_map(x, to_key, recurse, std::plus{}))
                  + "}";
    }
);

```

[on melpon.org/wandbox]

Resources

- My articles: [part 1](#), [part 2](#), and [part 3](#).
- My WIP library, [scelta](#).
- "[Pattern Matching and Language Variants](#)", by David Sankel.

Thanks!

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