Expressive Compile-time Parsers

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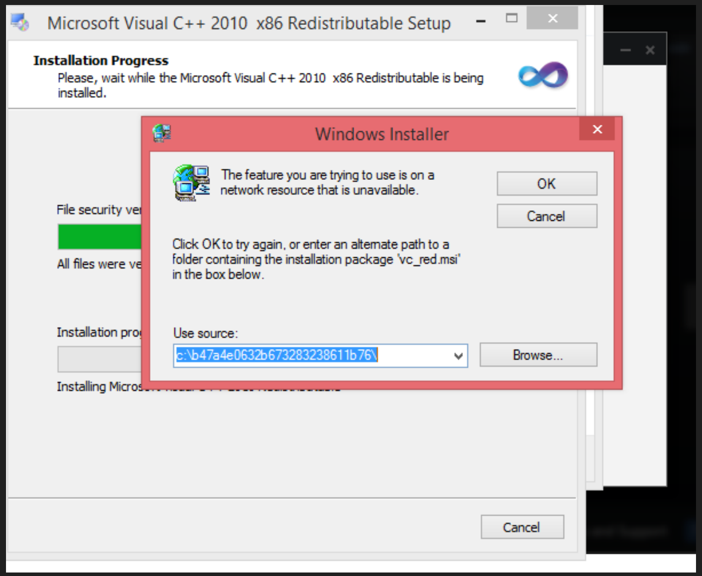
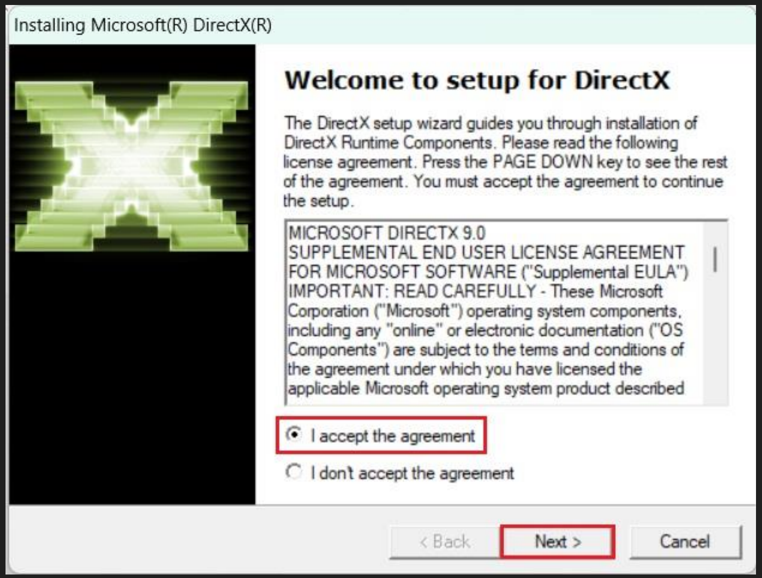
About me

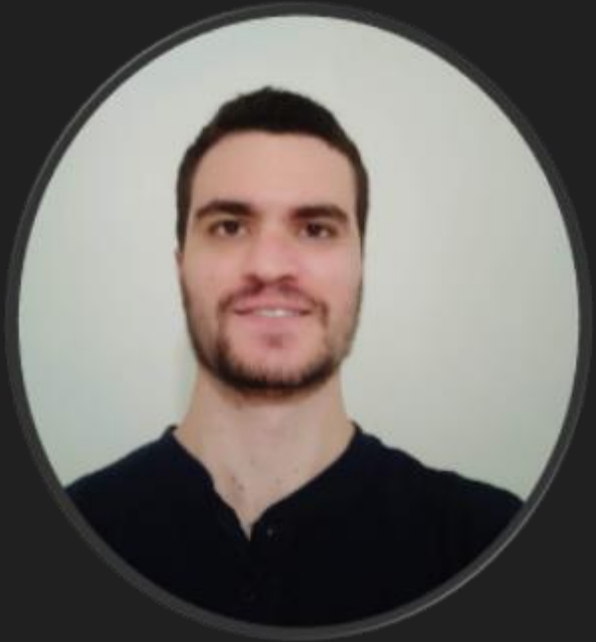
- Started learning C++ in high school with a passion for making video games.





About me

- Started learning C++ in high school with a passion for making video games.
- Senior software engineer at Medtronic.
- Writes a technical blog and participate in game jams.
- Enjoy experimenting, exploring, and trying new things in C++.



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Dive Into Compile-Time Parsers

Libraries

Use Cases

Implementation Techniques

Reflection

Language Evolution

API Design

Metaprogramming Tricks

About the talk

- Expressiveness in C++
  - Parsers
  - Operator overloading
  - Domain specific languages
- Open source compile-time libraries
  - API
  - Design
  - Implementation details
- Using compile-time parsers
  - Reflection
  - Examples: functions, types, trees

Parser

```
parse(text or tokens) -> value or error
```

In a compiler:

tokens -> parser -> syntax tree

In a web browser:

text -> JSON parser -> JS object

Parser Combinators

Create a parser by combining existing parsers.

```
parse_string_or_int(text, pos) ->
    parse_string(text, pos) || parse_int(text, pos)
```

Simplified syntax:

```
parse_string_or_int -> parse_string | parse_int
```

Parser Generators

Create a parser from a grammar.

Popular parsing algorithms used in generators are LL, LL(k), LR, LR(k), LALR, GLR...

EBNF grammar example:

```
identifier = alphabetic character, { alphabetic character | digit } ;
number = [ "-" ], digit, { digit } ;
string = '"' , { all characters - '"' }, '"' ;
assignment = identifier , ":=" , ( number | identifier | string ) ;
```

Expressive C++ Syntax

Expressive Code

Refers to the style of writing code in a way that ***communicates its purpose***.

Relies on both the ***syntax*** of the programming language and the quality of ***naming*** conventions.

Syntax Evolution

C++ 98:

```
static const int arr[] = {1,2,3,4};
vector<int> v(arr, arr + sizeof(arr) / sizeof(arr[0]));
```

C++ 11:

```
vector<int> v = {1,2,3,4};
```

Operator Overloading

Use operators to call custom functions for specific types.

```
std::filesystem::path p = "C:";
return concat(concat(concat(p, "files"),"images"), "cat.png");
```

```
std::filesystem::path p = "C:";
return p / "files" / "images" / "cat.png";
```

DSL - Domain Specific Language

A programming language tailored to solve problems within a specific domain or application context.

Examples:

- SQL
- CSS
- Regular Expressions (PCRE)
- Make (makefile)

DSL Example – Boost Spirit

Boost Spirit library has a DSL for creating parsers.

Example code from XML parser:

```
text %= lexeme[+(char_ - '<')];
node %= xml | text;

start_tag %= '<' >> !lit('/') >> lexeme[+(char_ - '>')] >> '>';
end_tag = "</" >> string(_r1) >> '>';

xml %= start_tag[_a = _1] >> *node >> end_tag(_a);
```

Limitation

The syntax must be valid C++ syntax because it needs to be parsed by the compiler

✓

```
>> *node >>
```

Limitation

The syntax must be valid C++ syntax because it needs to be parsed by the compiler

```
>> node* >>
```

Example – Filter Transform

```
vector<Cat> cats = { /*...*/ };
vector< tuple<int, string> > result;

for(auto itr = cats.cbegin(); itr != cats.cend(); ++itr)
    if(itr->age > 42)
        result.emplace_back(tuple{
            itr->id,
            itr->name
        });
```

Example – Filter Transform

```
vector<Cat> cats = { /*...*/ };
vector< tuple<int, string> > result;

for(const auto& cat : cats)
    if(cat.age > 42)
        result.emplace_back(tuple{
            cat.id,
            cat.name
        });
```

Example – Filter Transform

```
vector<Cat> cats = { /*...*/ };

namespace v = std::views;

auto result = cats |
    v::filter([](const Cat& cat) {
        return cat.age > 42;
    }) |
    v::transform([](const Cat& cat) {
        return tuple{ cat.id, cat.name };
    }) |
    ranges::to< vector >( );
```

Example – Runtime Parsers

```cpp
std::vector<Cat> cats = { /*...*/ };

auto parser = create_parser();
auto func = parser("SELECT id, name WHERE age > 42");

std::vector<std::any> result = func(cats);
```

Example – Compile Time Parsers

```
std::vector<Cat> cats = { /*...*/ };

constexpr auto parser = create_parser();
constexpr auto func = parser(
    "SELECT id, name WHERE age > 42");

auto result = func(cats);
```

Example – Compile Time Parsers

```
template<fixed_str str>
constexpr auto operator""_FROM() {
    constexpr auto parser = create_parser();
    return parser(str);
}

/*...*/
std::vector<Cat> cats = { /*...*/ };
auto result = "SELECT id, name WHERE age > 42"_FROM(cats);
```

Compile Time Parsers - Generalization

Specific: `"SELECT id, name WHERE age > 42"`

```
[](auto arg) { /*...*/ };
```

Generalized: `"any custom syntax"`

`any compile time value`

Me: "Hey Google, did anyone try to do this crazy thing in C++?"

Me: "Hey Google, did anyone try to do this crazy thing in C++?"

Google: “Of course! There is a boost library for it called boost metaparse”

Chapter 23. Boost.Metaparse

Abel Sinkovics

Boost Metaparse

A compile time parsing library by Abel Sinkovics.

The library uses C++98 except for creating compile-time strings.

C++ 98:

```
string<'H','e','l','l','o'>
```

C++ 11:

```
BOOST_METAPARSE_STRING("Hello")
```

More information available at this C++now 2012 talk:
https://www.youtube.com/watch?v=v3XoWi0XbZk

Boost Metaparse - Meta Functions

The library uses template structs also known as meta functions to create and combine parsers.

```
struct custom_parser {
    template<class Str, class Pos>
    struct apply {
        using result = /*...*/
        using remaining = /*...*/
        /*...*/
    };
};
```

Boost Metaparse - Example

“...The syntax and techniques needed are pretty horrendous.” - C++ core guidelines (template metaprogramming)

```
struct plus_exp : foldl_reject_incomplete_start_with_parser<
    sequence<one_of<plus_token, minus_token>, prod_exp>,
    prod_exp,
    eval_plus>{};
/*...*/
constexpr auto result = apply_wrap1<
    calculator_parser,
    BOOST_METAPARSE_STRING("2 * 3 + 4")>::type::value;
```

Boost Metaparse - Functions

Create runtime and compile-time functions from a custom syntax

Compile-time function:

```
typedef META_LAMBDA(2 * _) mult2;
typedef boost::mpl::int_<11> int11;

constexpr auto result = apply_wrap1<
    mult2,
    int11>::type::value;
```

Runtime function:

```
LAMBDA(2 * _) mult2;

auto result = mult2(11);
```

Boost Metaparse - Haskell

Create metafunctions with Haskell like syntax.

Import and export metafunctions between C++ and the Haskell like environment.

```
typedef meta_hs
    ::import1<_STR("f"), double_number>::type
    ::define<_STR("fib n = if n<2 then 1 else fib(n-2) + fib(n-1)")>::type
    ::define<_STR("times4 n = f (f n)")>::type
  metafunctions;

typedef metafunctions::get<_STR("fib")> fib;
typedef metafunctions::get<_STR("times4")> times4;
```

Boost Metaparse - Grammar

Create a parser from grammar rules

```
typedef grammar<_STR("plus_exp")>
    ::rule<_STR("int ::= ('0'|'1'|'2'|...|'9')+"), int_action>::type
    ::rule<_STR("ws ::= (' ' | '\n' | '\r' | '\t')*")>::type
    ::rule<_STR("int_token ::= int ws"), front<_1>>::type
    ...
    ::rule<_STR("plus_exp ::= prod_exp (..."), plus_action>::type
    ::rule<_STR("prod_exp ::= int_token (..."), prod_action>::type
  expression;
```

BOOST_METAPARSE_STRING

```
BOOST_METAPARSE_STRING("hello")
```

```
make_string<
    sizeof("hello") - 1,
    str_at("hello",0), str_at("hello",1), ..., str_at("hello",2047)>()
```

BOOST_METAPARSE_STRING

```
make_string<
    sizeof("hello") - 1,
    str_at("hello",0), str_at("hello",1), ..., str_at("hello",2047)>()
```

```
template<int N>
constexpr auto str_at(
    const char (&s)[N], int index){
    return i >= N ? 0 : s[index];
}
```

```
make_string<5,'h','e','l','l','o',0,0,0,...,0>()
```

BOOST_METAPARSE_STRING

```
make_string<5,'h','e','l','l','o',0,0,0,...,0>()
```

```
template<char... rest>
struct make_string<0, rest...>: string<> {};

template<int size, char first, char... rest>
struct make_string<size, first, rest...>:
    concat<first, make_string<size-1, rest...>> {};
```

```
string<'h','e','l','l','o'>
```

Time Skip to C++17

Lexy

- Created by Jonathan Müller
- Parser combinator library for C++17 and onwards
- Has expressive DSL
- Supports unicode strings
- Can parse at runtime and compile-time

More information available at this Meeting C++ talk:
https://www.youtube.com/watch?v=Cb0j6DVmwzY

Lexy - DSL

Create parsers by defining a struct with rule and value.

Combine parsers with operators.

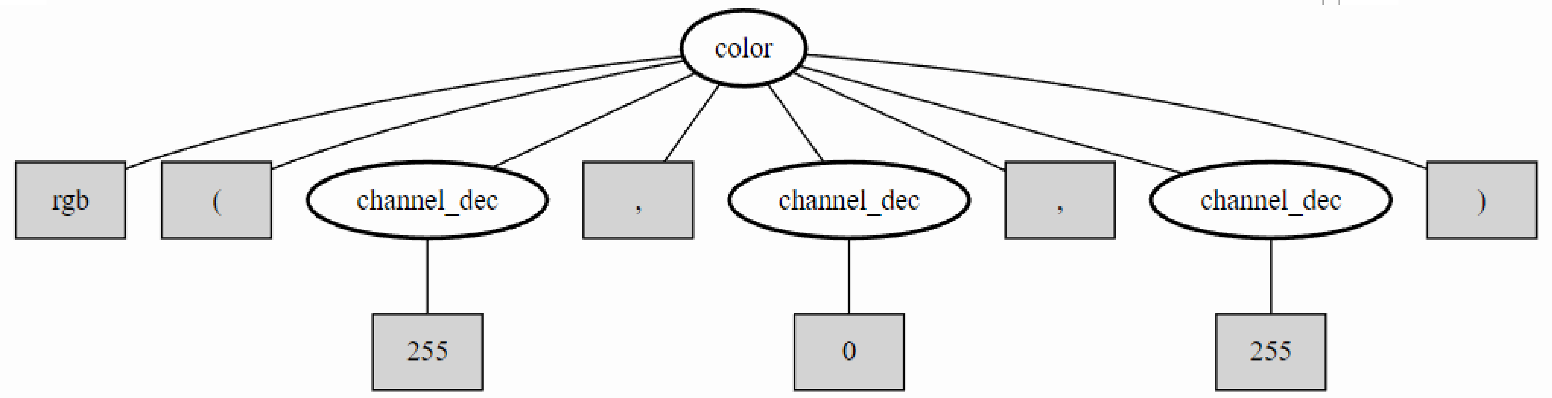
```
struct json_value : /*...*/ {
    static constexpr auto rule = [] {
        auto primitive = dsl::p<null> | dsl::p<boolean> | ...
        auto complex  = dsl::p<object> | dsl::p<array>;
        return primitive | complex | dsl::error<expected_json_value>;
    }();
    static constexpr auto value = lexy::construct<ast::json_value>;
};
```

Lexy - Playground

Visualize and try parsers in an online playground

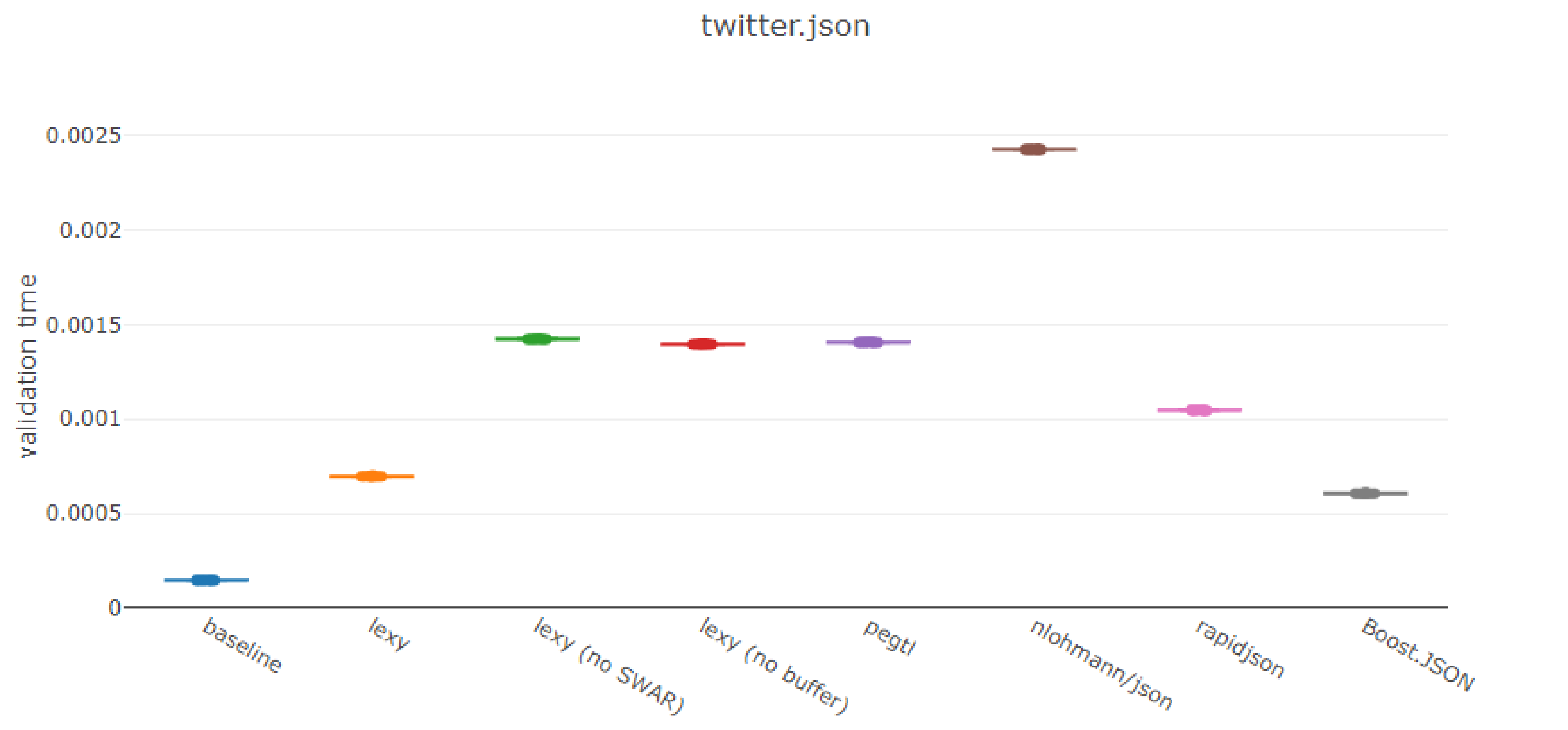
```
struct channel_hex
{
    static constexpr auto rule = dsl::integer<std::uint8_t>(dsl::n_digits<2, dsl::hex>);
};

struct channel_dec
{
    static constexpr auto rule = dsl::integer<std::uint8_t>;
};

struct color
{
    static constexpr auto rule = [] {
        auto hex_color = dsl::hash_sign >> dsl::times<3>(dsl::p<channel_hex>);

        auto dec_channels = dsl::times<3>(dsl::p<channel_dec>, dsl::sep(dsl::comma));
        auto fnc_color    = LEXY_LIT("rgb") >> dsl::parenthesized(dec_channels);

        return hex_color | fnc_color;
    }();
};

using production = color;
```

```
rgb(255,0,255)
```



Lexy - Performance

Similar performance to other runtime parsers



Lexy – Parser Implementation

Adds a level of indirection that takes the next parser as template parameter

```
struct custom_parser {
    template <class NextParser>
    struct indirect {
        template <class Ctx, class Reader, class... T>
        constexpr static bool parse(Ctx& ctx, Reader& r, T&&... args){
            auto value = /*...*/;
            return Invoke<NextParser>(ctx, r, value, FWD(args)...);
        }
    };
};
```

Lexy – Parser Implementation

Sequence parser combinator can be implemented as an alias that rewires NextParser

```
template <class P1, class P2>
struct seq {
    template<clsas NextParser>
    using indirect =
        P1::indirect<
            P2::indirect<
                NextParser>>;
};
```

CTRE - Compile Time Regular Expressions

- Created by Hana Dusíková
- Match/search/capture during compile-time or runtime
- Supports unicode strings
- C++ 17 onwards

More information at this CppCon 2018 talk:
https://www.youtube.com/watch?v=QM3W36COnE4

CTRE - Usage

C++17 with extension N3559:

```
auto [success, value] = "REGEX"_ctre.match(s);
```

C++20:

```
auto [success, value] = ctre::match<"REGEX">(s);
```

Capturing:

```
auto result = ctre::match<"(?<month>\\d{1,2})/(?<day>\\d{1,2})">(s);
Date date{
    result.get<"month">(),
    result.get<"day">()
};
```

CTRE - Performance

Constructs regex at compile time.

Runtime performance is much faster than std::regex and similar to other runtime libraries.

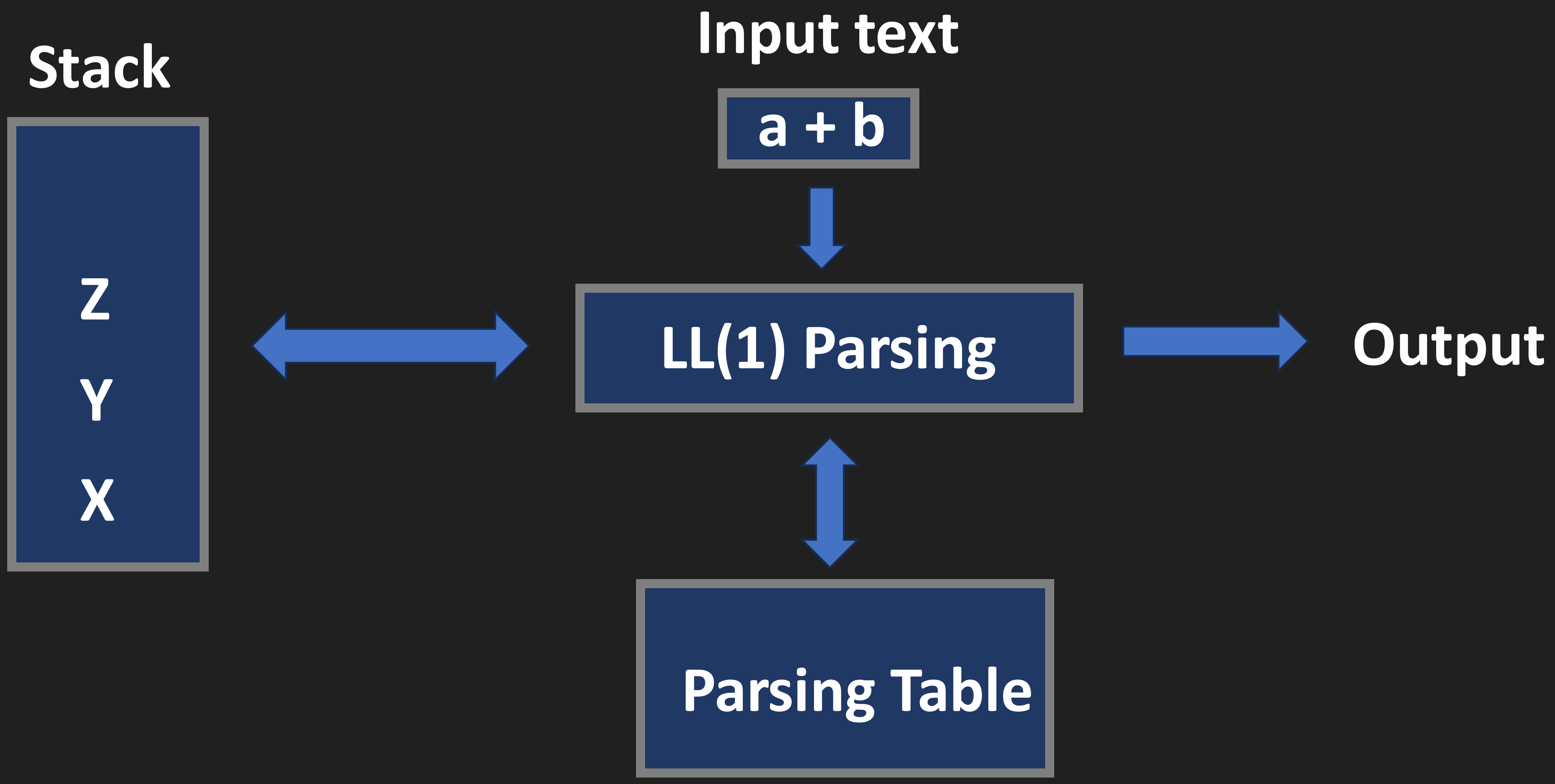
Regex	boost	cppstd	ctre
Twain	9.8	246	8.8
(?i)Twain	78	n/a	n/a
[a-z]shing	335.6	364	40.4
Huck[a-zA-Z]+|Saw[a-zA-Z]+	10.4	341.2	13
\b\w+nn\b	194.6	2301.9	n/a
[a-q][^u-z]{13}x	376.5	786.6	90.2
Tom|Sawyer|Huckleberry|Finn	13.5	538.5	21.8
(?i)Tom|Sawyer|Huckleberry|Finn	205.7	n/a	n/a
.{0,2}(Tom|Sawyer|Huckleberry|Finn)	906.9	1736.9	1083.2
.{2,4}(Tom|Sawyer|Huckleberry|Finn)	907.4	1860.7	1415.7
Tom.{10,25}river|river.{10,25}Tom	31.7	354.3	102.7
[a-zA-Z]+ing	172.4	795.9	648
\s[a-zA-Z]{0,12}ing\s	227.8	514.1	337.7
([A-Za-z]awyer|[A-Za-z]inn)\s	869.1	615.3	48.4
["'][^"']{0,30}[?!\.]["']	16.6	285.9	121.8

CTRE – Literal Operator

fixed_string enables passing compile-time string as non-type template parameter

```
template<int I> struct fixed_string{
    constexpr fixed_string(const char (&s)[I]){ /*...*/}
};

template<fixed_string str>
constexpr auto operator""_ctre(){
    ... parse string to regex
}

constexpr auto regex = "abc|[0-9]+"_ctre;
```

LL(1) Parser Overview



CTRE – LL(1) Parser

The regex pattern is parsed by an LL(1) parser called CTLL.

The stack of the parser is implemented as a type list.

```
template<class... Ts> struct list{};
struct empty_list{};

template <class T, class... As>
auto pop_front(list<T, As...>) -> list<As...>;
auto pop_front(empty_list) -> empty_list;
```

CTRE – LL(1) Parser

The grammar rules lookup table is implemented as empty structs and function overloads

```
struct pcre {
    struct backslash{};
    struct hexdec_repeat {};

    auto rule(backslash, term<'d'>) -> push<anything, class_digit>;
    auto rule(hexdec_repeat, term<'\x7D'>) -> epsilon;
}
```

CTRE – LL(1) Parsing Loop

Simplified code of the parsing loop

```
template<auto input, auto stack, auto pos>
constexpr auto parse(){
    constexpr auto action = grammar::rule(top(stack), input[pos]);
    if constexpr(action == reject)
        return error;

    if constexpr(action == accept)
        return success;

    if constexpr(action == pop_input)
        return parse<input, stack, pos + 1>();
    ...
}
```

CTPG – Compile Time Parser Generator

- Created by Piotr Winter
- Written in C++17
- Library for generating LR(1) parsers from a grammar
- Can generate a lexer or use custom one

More information available at CppCast episode 332:
https://www.youtube.com/watch?v=8nGWxh3tnRY

CTPG – Example

Define terminals and non-terminals.

Supports regular expressions, precedence and associativity.

```
constexpr nterm<int> expr("expr");

constexpr char_term o_minus('-', 1, associativity::ltor);
constexpr char_term o_mul('*', 2, associativity::ltor);

constexpr char number_pattern[] = "[1-9][0-9]*";
constexpr regex_term<number_pattern> number("number");
```

CTPG – Example

Generate parser from grammar rules

```
constexpr parser p(
    expr, terms(number, o_minus, o_mul, '(', ')'), nterms(expr),
    rules(
        expr(expr, '-', expr) >= binary_op{},
        expr(expr, '*', expr) >= binary_op{},
        expr('-', expr)[3] >= [](char, int x) { return -x; },
        expr('(', expr, ')') >= _e2,
        expr(number) >= [](const auto& sv){ return get_int(sv); }
    ));

constexpr auto res = p.parse(
    cstring_buffer("-120 * 2 - 10")).value();
```

LR(1) Parser Generator Overview

Grammar

Item Sets (states)

Parsing tables

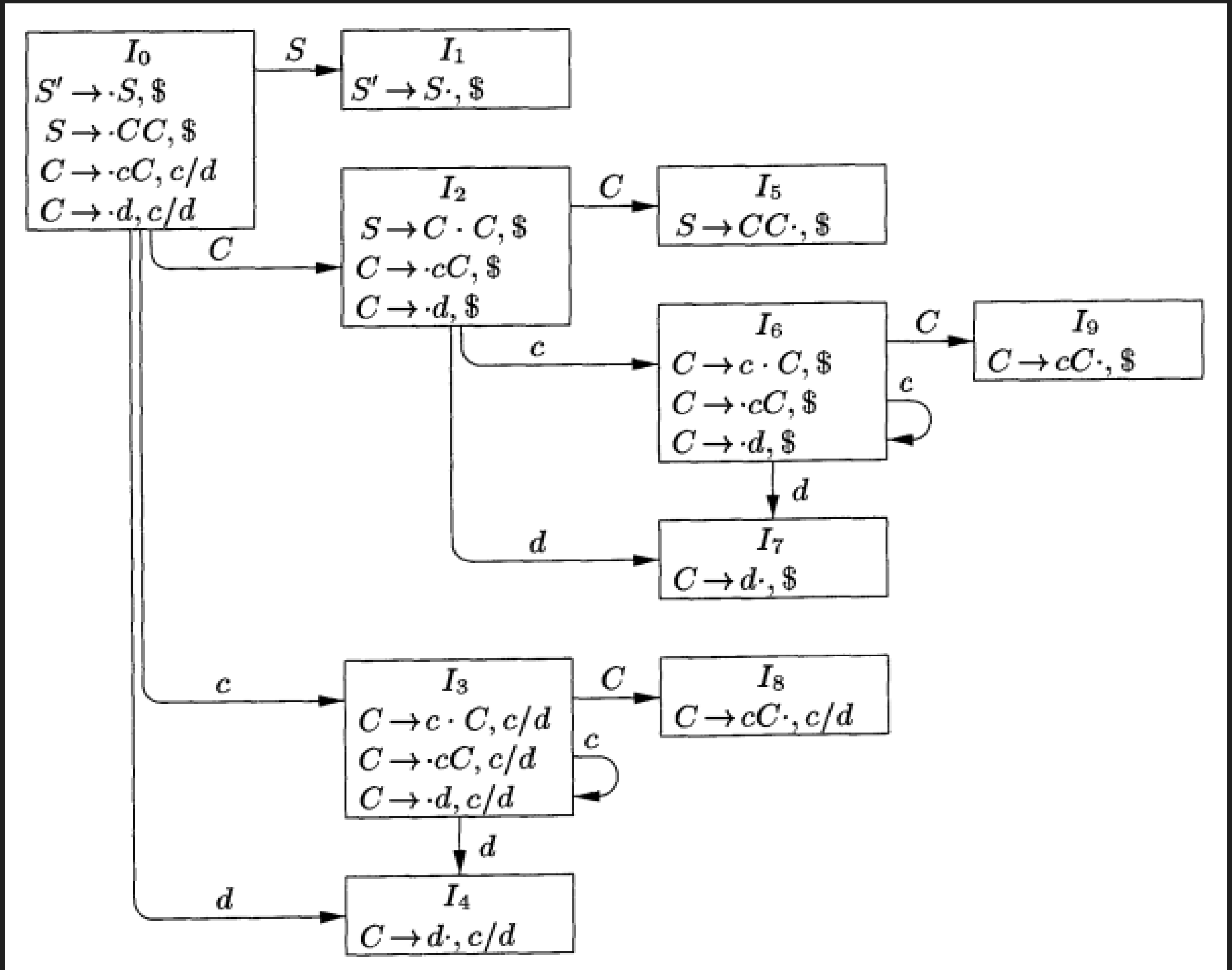


Image from: “Compilers: Principles, Techniques, and Tools” (dragon book)

CTPG – LR(1) Item

```
struct item {
    int rule;
    int pos;
    int term;
};
```

CTPG – LR(1) Item Sets

Uses a fixed size bitset

```
constexpr auto rules = sizeof...(Rules);
constexpr auto positions = max(Rules.length...) + 1;
constexpr auto terms = sizeof...(Terms);

constexpr auto address_space_size =
    rules * positions * terms;

using item_set = bitset<address_space_size>;
```

CTPG – LR(1) Item Sets

Convert between index and item

```
constexpr uint32_t to_index(item i){
    return i.rule * positions * terms +
        i.position * terms +
        i.lookahead;
}

constexpr item from_index(uint32_t idx){
    auto term = idx % terms;
    /*...*/
    return item{ rule, position, term };
}
```

Compile Time Parsing in C++23

Macro Rules

- Created by Maksym Pasichnyk
- Uses C++23
- Create DSL with Rust’s macro rules syntax
- More of an experimental proof of concept than a full library

Rust Macros – Overview

Procedural macro is a compile-time function that modifies the token stream

```
#[proc_macro]
pub fn my_macro(input: TokenStream) -> TokenStream {
    /*...*/
}

my_macro!(tokens);

#[derive(Clone, Debug, my_macro)]
struct MyStruct;
```

Rust Macros – Overview

Macro rules matches a syntax pattern and produces an AST

```
macro_rules! vec {
    ( $( $x:expr ),* ) => { {
        let mut temp_vec = Vec::new();
        $(
            temp_vec.push($x);
        )*
        temp_vec
    } }
}

let v2 = vec![1,2,3];
```

Macro Rules – Example

```
struct Sum : macro_rules(sum $(args:number)*) {
    consteval static auto transform(auto ctx) {

    }
};
```

Macro Rules – Example

```
struct Sum : macro_rules(sum $(args:number)*) {
    consteval static auto transform(auto ctx) {
        return std::apply([](auto... args) {
                return (static_cast<int>(args.id) + ...);
            },
            meta::parse::get<"args">(ctx.value())
        );
    }
};

static_assert(apply_rules(Sum, sum 1 2 3) == 6);
```

Macro Rules – Parsing

Parse the pattern into a template instantiation

```
macro_rules(sum $(args:number)*)
```

```
meta::parse::group<
    meta::parse::ident<fnv1a("sum")>,
    meta::parse::list<
        meta::parse::with_name<
            fnv1a("args"),
            meta::parse::token<TokenType::Number>
        >
    >
>
```

Macro Rules – Identifiers

Identifier strings are stored as 32bit hash values because they are only used for lookup and equality comparison

```
meta::parse::ident<fnv1a("sum")>,
```

Macro Rules – Input String

The library uses a macro to convert text to string

```cpp
#define apply_rules(rules, ...) \
meta::parse::compile<rules, #__VA_ARGS__>()

#define TO_STRING(...) #__VA_ARGS__

static_assert(TO_STRING(
    // comments won't be stringified
    int highlight_works = 42;
    spaces     will      collapse
) == std::string_view(
    "int highlight_works = 42; spaces will collapse"));
```

YACP – Yet Another Compile-Time Parser

DSL and operators similar to Lexy and Boost::Spirit.

Uses fixed size containers as return type.

```
auto choice_parser = int_parser | double_parser;
variant<int, double> v1 = choice_parser("42"_ctx).value();

auto seq_parser = int_parser >> ","_lit >> double_parser;
tuple<int, double> v2 = seq_parser("42,13.37"_ctx).value();

auto list_parser = *(int_praser >> +","_lit);
fixed_vec<int, 16> v3 = list_parser("1,2,3"_ctx).value();

auto add2 = int_parser >>= [](auto v){ return v.value()+2; };
```

Parser

A wrapper around a stateless lambda that takes a context and returns std::expected

```
template<class T>
using parse_result = std::expected<T, parse_error>;

auto int_parser = Parser([]
    (ContextConcept auto& context) -> parse_result<int>{
    /*...*/
});
```

Parser Concept

Checks if type is an instantiation the parser template

```
template<class T>
concept ParserConcept = requires(T arg) {
    { Parser{ arg } } -> std::same_as<T>;
};
```

Overloading with Concepts

Use concepts to pick the correct operator overload

```
template <class T>
concept SequenceParserConcept =
    ParserConcept<T> &&
    SequenceParserFuncConcept<typename T::FuncType>;

template <ParserConcept T, ParserConcept U>
constexpr auto operator >> (T lhs, U rhs) {/*...*/}

template <SequenceParserConcept T, ParserConcept U>
constexpr auto operator >> (T lhs, U rhs) {/*...*/}
```

Question

What kind of string is used in every C++ application and must always be known at compile time?

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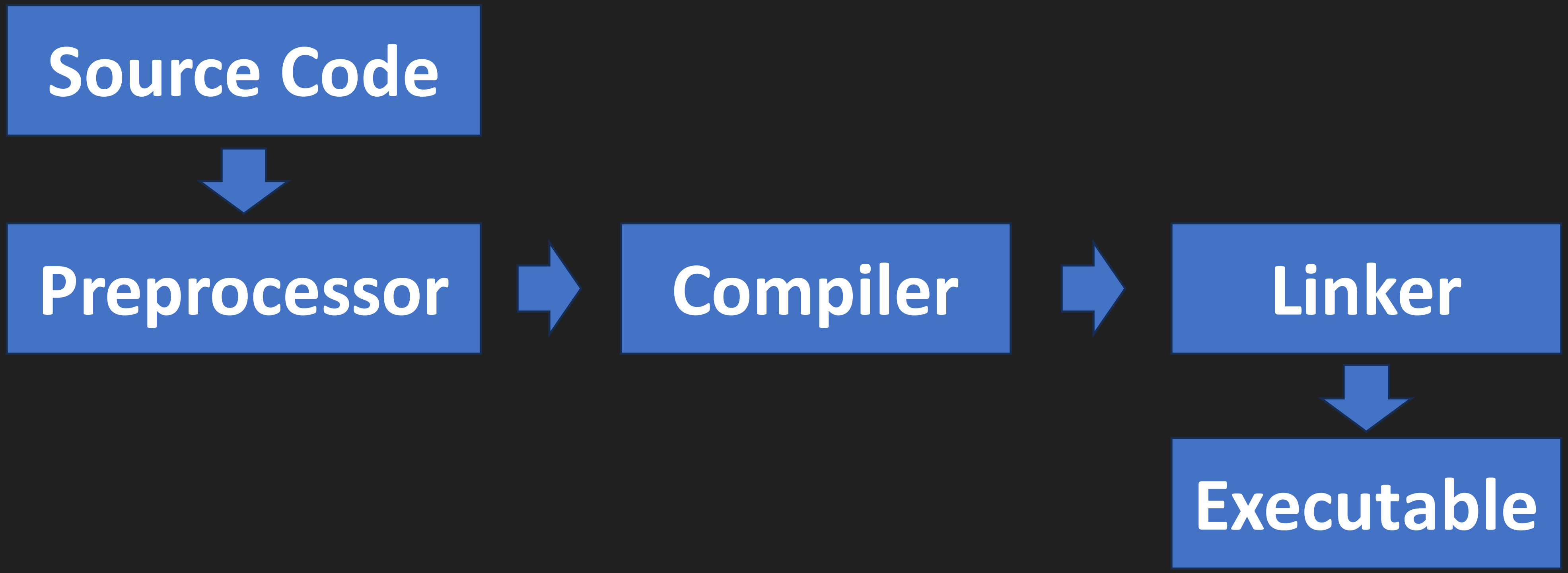


Reflection

C++ has introspection features but reflection is still far away.

Reflection libraries:

1. Boost Describe: A C++14 Reflection Library
2. Reflect: github.com/M-Fatah/reflect
3. Reflcpp: github.com/veselink1/reflp-cpp
4. RareCpp: github.com/TheNitesWhoSay/RareCpp

Reflection

Most reflection libraries use macros to generate the reflection metadata

```
struct MyObj {
    int a;
    float b;

    REFLECT(MyObj, a, b)
};
```

Reflect Code with Parser

Pass code as string input to a compile-time parser

```
#define REFLECT_ATTRIBUTES(type, ...)\
__VA_ARGS__ \
constexpr auto get_attributes(type_wrapper<type>){\
    return attributes_parser(#__VA_ARGS__);\
}

REFLECT_ATTRIBUTES(MyObj,
struct
    [[custom::serialize]]
    [[custom::debug_name(my object)]] MyObj{
    int a;
    double b;
};)
```

Reflect Code with Parser

```
#define REFLECT_ATTRIBUTES(type, src)\
constexpr auto get_attributes(type_wrapper<type>){\
    return attributes_parser(src);\
}


#define REFLECT_MEMBERS(type, src)\
constexpr auto get_members(type_wrapper<type>){\
    return members_parser(src);\
}
```

Reflect Code with Parser

```
#define DERIVE(macros, type, ...)\
__VA_ARGS__ \
FOR_EACH((type, #__VA_ARGS__), CALL_MACRO, EVAL macros)


DERIVE((REFLECT_ATTRIBUTES, REFLECT_MEMBERS), MyObj,
struct [[custom::serialize]]
       [[custom::debug_name(my object)]] MyObj {
    int a;
    double b;
};)
```

Reflect by Identifier

Resolve identifier maps from an identifier hash to a value – in this case a pointer to a data member

```
struct MyObj {
    int a;

    static
    constexpr auto resolve_ident(ident_hash<"x">) {
        return &MyObj::x;
    }
};
```

Reflect by Identifier

Use repeating macro to generate a resolve identifier function for each data member

```
struct MyObj {
    int a;
    int b;

    REFLECT_MEMBERS(MyObj,(a)(b))
};
```

Get Member by Identifier

Call the static resolve identifier function to get a pointer to member

```
template <class T, class Ident>
constexpr decltype(auto) get_member(T&& obj, Ident) {
    using TT = std::decay_t<T>;

    constexpr auto member = TT::resolve_ident(Ident{});
    return FWD(obj).*member;
}

constexpr auto obj = MyObj{1,2};
constexpr auto v = GetMember(obj, ident_hash<"x">{});
```

Example – Get Nested Member

Desired Syntax:

```
auto width = "character.texture.width"_in(player);
```

Parser:

```
constexpr auto parser = separate_by(ident, "."_lit);

fixed_vec<uint32_t, 16> members = parser("a.b.c");
```

Example – Get Nested Member

Pseudo code of the desired logic

```
constexpr auto& get_nested(auto members, auto& obj)
{
    auto* result = &obj;
    for(auto member : members){
        result = get_member(*result, member);
    }
    return *result;
}
```

Example – Get Nested Member

Move compile-time argument to a template parameter

```
template<auto members>
constexpr auto& get_nested(auto& obj) {
    auto* result = &obj;
    for(auto member : members){
        result = get_member(*result, member);
    }
    return *result;
}
```

Example – Get Nested Member

Raplace loops with recursion or fold expression

```
template<auto members>
constexpr decltype(auto) get_nested(auto&& obj){
    return [](this auto&& self, auto&& obj, auto idx)->decltype(auto){
        if (idx == members.size()){
            return FWD(obj);
        }
        else {
            return self(
                get_member(FWD(obj), ident_t<members[idx]>()),
                idx.increment());
        }
    }(FWD(obj), index_wrapper<0>());
}
```

Example – Get Nested Member

Replace branches with ifconstexpr

```
template<auto members>
constexpr decltype(auto) get_nested(auto&& obj){
    return [](this auto&& self, auto&& obj, auto idx)->decltype(auto){
        if constexpr (idx == members.size()){
            return FWD(obj);
        }
        else {
            return self(
                get_member(FWD(obj), ident_t<members[idx]>()),
                idx.increment());
        }
    }(FWD(obj), index_wrapper<0>());
}
```

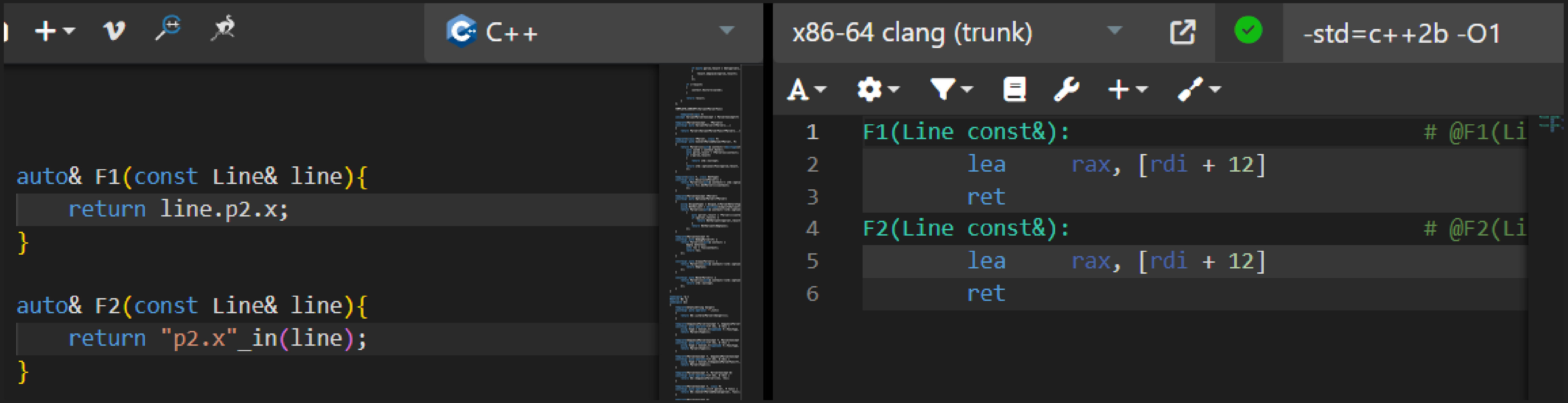
Example – Get Nested Member

Wrap implementation with a literal operator

```
template<fixed_str str>
constexpr auto operator""_in() {
    return [](auto&& v) -> decltype(auto) {
        constexpr auto members = parser(str);
        return get_nested<members>(FWD(v));
    };
}

auto width = "character.texture.width"_in(player);
```

Compare Assembly

Compiler Explorer: https://godbolt.org/z/xzeT7rM7Y



Extended Syntax

Desired syntax:

```
"character.items:texture.width|sqr|print"_of(player);
```

`":"` performs range based for loop

`"|func"` calls a function with the current value

Example inspired by Vittorio Romeo's blogpost:
https://vittorioromeo.info/index/blog/gamedev_modern_cpp_thoughts.html

Extended Syntax Parser

```
auto pipe = "|"_lit >> ident >>= [](auto&& value) {
    return Pipe{ value.get_value() };
};

auto iterate = ":"_lit >>= [](auto) {
    return Iterate{};
};

auto extended_p = *(pipe | iterate | nested_members);
```

Extended Implementation Function

```
[](this auto&& self, auto&& obj, auto index) {
    /*...*/
    if constexpr(members){
        self(get_nested<*members>(obj), index.inc());
    }
    else if constexpr (iterate) {
        for (auto&& v : obj) { self(v, index.inc()); }
    }
    else if constexpr (pipe) {
        constexpr auto ident = pipe->m_Ident;
        /*… now what? ...*/
    }
}(obj, 0_idx);
```

Reflect Value by Identifier

Use resolve identifier to map identifier to value

```
constexpr auto sqr = [](auto v) {
    return v * v;
};

constexpr auto resolve_ident(ident_hash<"sqr">) {
    return sqr;
}
// same as
REFLECT_IDENTIFIER(sqr)
```

Reflect Value by Identifier

```
constexpr auto extended_syntax_impl(auto&& obj){
    /*...*/
    else if constexpr (pipe) {
        constexpr auto ident = pipe->m_Ident;
        constexpr auto func = resolve_ident(ident_t<ident>());
        /*...*/
    }
```

Scope

```
constexpr auto extended_syntax_impl(auto&& obj){
    /*...*/
    else if constexpr (pipe) {
        constexpr auto ident = pipe->m_Ident;
        constexpr auto func = resolve_ident(ident_t<ident>());
        /*...*/
    } /*...*/

namespace ns {
    constexpr auto sqr = [](auto v) { return v * v; };
    REFLECT_IDENTIFIER(sqr)

    auto foo(){ "|sqr"_of(42); }
}
```

Scope

```
constexpr auto extended_syntax_impl(auto&& obj, auto&& scope){
    /*...*/
    else if constexpr (pipe) {
        constexpr auto ident = pipe->m_Ident;
        constexpr auto func = scope(ident_t<ident>());
        next(func(obj), index.inc());
    } /*...*/

namespace ns{
    constexpr auto sqr = [](auto v) { return v * v; };
    REFLECT_IDENTIFIER(sqr)

    auto foo(){
        "|sqr"_of(42, [](auto v){ return resolve_ident(v); });
    }
}
```

Scope

```
constexpr auto extended_syntax_impl(auto&& obj, auto&& scope){
    /*...*/
    else if constexpr (pipe) {
        constexpr auto ident = pipe->m_Ident;
        constexpr auto func = scope(ident_t<ident>());
        self(func(FWD(obj)), index.inc());
    } /*...*/

namespace ns{
    constexpr auto sqr = [](auto v) { return v * v; };
    REFLECT_IDENTIFIER(sqr)

    auto foo(){ "|sqr"_of(42, SCOPE); }
}
```

Get Local Variable by Identifier

```
auto foo(){
    int x = 42;
    auto local_scope = [&](auto ident) -> decltype(auto){
        if constexpr(ident == hash_str("x")){
            return REF(x);
        } else {
            return resolve_ident(ident);
        }
    };
    /* ... */
}
```

Compare Syntax

Custom syntax:

```
"players:character.items:textures:height|sqr|print"_of(game, SCOPE);
```

Regular C++ syntax:

```
for (auto& player : game.players)
    for (auto& item : player.character.items)
        for (auto& texture : item.textures)
            print(sqr(texture.height));
```

Compare Assembly

Compiler Explorer: https://godbolt.org/z/fP6cose6q

C++

```cpp
void F1(const Game& game){
    "players:character.items:textures:height|squ
}

void F2(const Game& game){
    for (auto& player : game.players) {
        for (auto& item : player.character.items
            for (auto& texture : item.textures)
                print(square(texture.height));
            }
        }
    }
}
```

x86-64 clang (trunk) -std=c++2b -O1

```asm
F1(Game const&):                                        # @F1(Ga
        push    rbp
        push    r15
        push    r14
        push    r13
        push    r12
        push    rbx
        sub     rsp, 24
        mov     rax, qword ptr [rdi]
        mov     rcx, qword ptr [rdi + 8]
        mov     qword ptr [rsp + 8], rcx            # 8
        cmp     rax, rcx
        je      .LBB0_12
        mov     rbx, qword ptr [rip + std::cout@GOT
        lea     r14, [rsp + 7]
        jmp     .LBB0_2
.LBB0_11:                                       #   in Loop
        mov     rax, qword ptr [rsp + 16]           # 8
        add     rax, 24
        cmp     rax, qword ptr [rsp + 8]            # 8
        je      .LBB0_12
.LBB0_2:                                        # =>This Lo
        mov     r13, qword ptr [rax]
        mov     qword ptr [rsp + 16], rax           # 8
        mov     rbp, qword ptr [rax + 8]
        jmp     .LBB0_3
.LBB0_10:                                       #   in Loop
```

x86-64 clang (trunk) -std=c++2b -O1

```asm
F2(Game const&):                                        # @F2(
        push    rbp
        push    r15
        push    r14
        push    r13
        push    r12
        push    rbx
        sub     rsp, 24
        mov     rax, qword ptr [rdi]
        mov     rcx, qword ptr [rdi + 8]
        mov     qword ptr [rsp + 8], rcx            #
        cmp     rax, rcx
        je      .LBB1_5
        mov     rbx, qword ptr [rip + std::cout@G
        lea     r14, [rsp + 7]
        jmp     .LBB1_2
.LBB1_4:                                        #   in Lo
        mov     rax, qword ptr [rsp + 16]           #
        add     rax, 24
        cmp     rax, qword ptr [rsp + 8]            #
        je      .LBB1_5
.LBB1_2:                                        # =>This
        mov     r13, qword ptr [rax]
        mov     qword ptr [rsp + 16], rax           #
        mov     rbp, qword ptr [rax + 8]
        jmp     .LBB1_3
.LBB1_8:                                        #   in Lo
```

Non-Type Template Parameters

Does this code compile?

```
class C {
    int x = 0;
};

template<C param>
auto foo(){}

constexpr auto obj = C{};

foo<obj>();
```

Non-Type Template Parameters

Does this code compile? No

```
error: 'C' is not a valid type for a
template non-type parameter because
it is not structural
```

```
class C {
    int x = 0;
};

template<C param>
auto foo(){}

constexpr auto obj = C{};

foo<obj>();
```

Structural Type (since C++20)

A literal(constexpr) class type with the following properties:

- All base classes and non-static data members are public and non-mutable
- The types of all base classes and non-static data members are structural types.

Solution – Structural Containers

Implement a structural version of std::tuple and std::variant where all the data members are public

```
template<class T, int I>
struct tuple_leaf {
    template<class S>
    constexpr decltype(auto) get(this S&& self, Index<I>) {
        return FWD(self).tuple_leaf::value;
    }
    T value;
};
```

Example – Struct Parser

Syntax:

```
STRUCT(Person, {
    name: string
    age: int
})
```

Parser:

```
auto parser = "{"_lit >>
    *(ident >> ":"_lit >> ident) >>
"}"_lit;
```

Parsing Struct Member

Text:

```
age: int
```

Parser

Output:

```
tuple {
    hash("age"),
    hash("int")
};
```

Identifier to Type

Map identifier to type wrapper

```
template<class T>
struct type_wrapper{ T get() const; };

constexpr auto resolve_ident(ident_hash<"int">){
    return type_wrapper<int>();
}

// same as
REFLECT_TYPE(int)
```

Struct Member

Contains data member and getter function

```
template<ident id, type_wrapper type>
struct struct_member {
    decltype(type.get()) value;

    constexpr decltype(auto)
    operator[](this auto&& self, ident_t<id>)
    {
        return FWD(self).struct_member::value;
    }
};
```

Combine Members

Combine multiple data members into a struct by inheriting from all of them

```
template<class... Ts>
struct combine_members : Ts... {
   using Ts::operator[]...;
};
```

Struct Parser – All Together

```
template<fixed_str str, class Scope>
constexpr auto create_struct(Scope)
{
    constexpr auto members = struct_parser(str);

    return expand([](auto... i) {
        /*...*/
    }, std::make_index_sequence<members.size()>());
}
```

Struct Parser – All Together

```
using struct_type = combine_members<
    struct_member<
        members[i].get(0_idx),
        Scope{}(ident_t<members[i].get(1_idx)>{})
    >...
>;
```

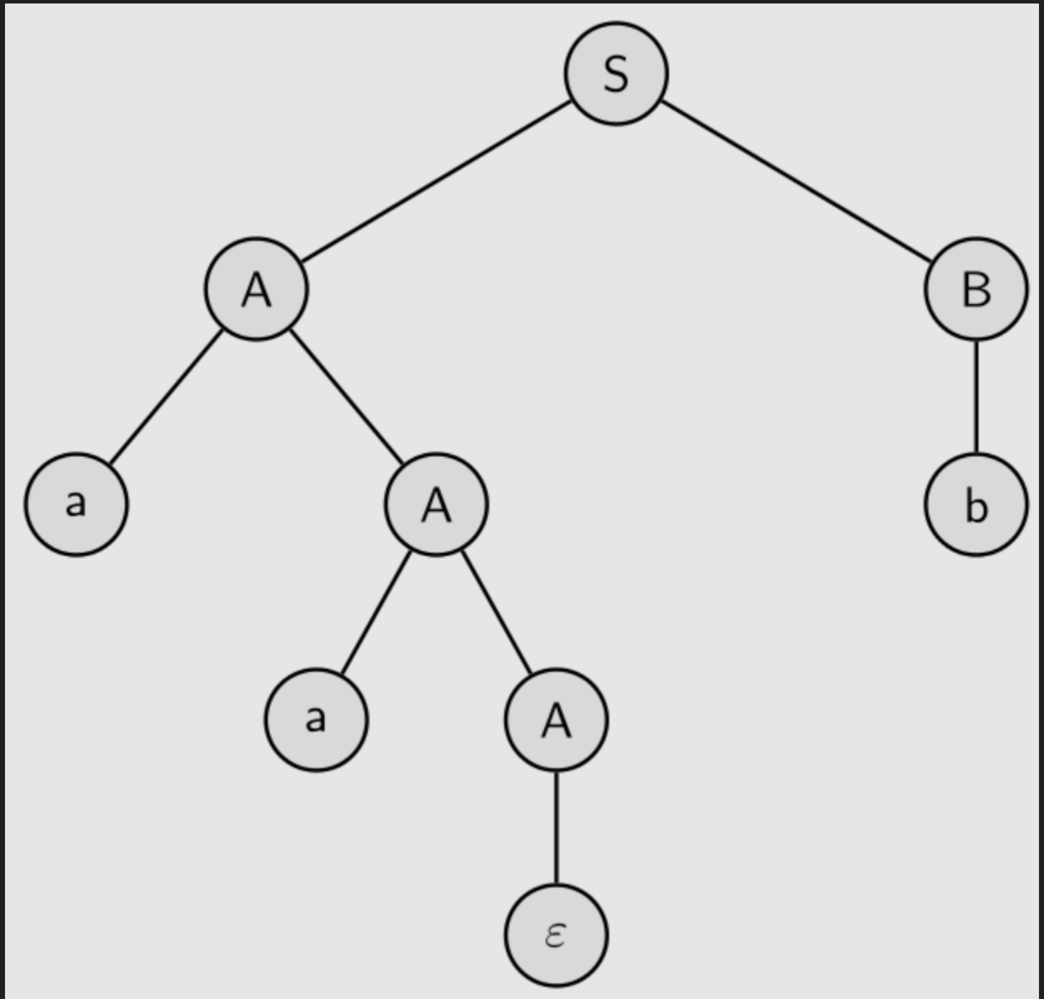
Struct Parser – All Together

```
return expand([](auto... i) {
    using struct_type = /*...*/

    return type_wrapper<struct_type>{};
}, /*...*/);
```

Struct Parser – Example

```
STRUCT(Item, {
    name: string
    unique: bool
})
STRUCT(Person, {
    name: string
    age: int
    item: Item
})
/*...*/
Person bilbo{ "Bilbo", 111, {"the one ring", true} };

std::cout << bilbo["item"_id]["name"_id] << '\n'
```

Parsing Tree Data Structures



Example – JSON Parser

```
using Arr = fixed_vec<Var, 16>;

using Member = tuple<String*, Var>;
using Obj = fixed_vec<Member, 16>;

using String = fixed_vec<char, 256>;

using Var = variant<
    Obj*, Arr*, String*,
    double, bool, std::nullptr_t>;
```

Runtime Allocators

Creating JSON at runtime

```
auto json = Arr({
    new Obj(/*...*/),
    new Arr(/*...*/),
    42.33 });
```

Runtime Allocators with Constexpr

error: '...' is not a constant expression because it refers to a result of 'operator new'

```
constexpr auto json = Arr({
    new Obj(/*...*/),
    new Arr(/*...*/),
    42.33 });
```

Compile-Time Allocators

Fixed capacity compile-time allocator

```
template<int Capacity, class... Ts>
struct Allocator {
    template<class T>
    constexpr auto&& add(const T& value) {
        return get_vec<T>(data).push_back(value);
    }

    tuple< fixed_vec<Ts, Capacity>... > data;
};
```

Compile-Time Allocators

```
constexpr auto json = Arr({
    &allocator.add(Obj(/*...*/)),
    &allocator.add(Arr(/*...*/)),
    42.33 });
```

JSON Parser with Allocator

```
struct JSON {
    constexpr JSON(fixed_str str) {
        root = json_parser(str, allocator);
    }

    Allocator<100, String, Obj, Arr> allocator;
    Var root;
};
```

JSON Parser with Allocator

```cpp
constexpr auto json = JSON(R"({
    "prop1": {
        "arr": [
            45.32,
            [true, false],
            { "inner": 33.45 }
        ]
    },
    "prop2": null
})");
```

Binary Size

Will large constexpr object affect the binary size?

- If it is only used at compile-time it will not be included
- Calculate needed capacity:

```
constexpr auto capacity = json_capacity_parser(str);
constexpr auto json = JSON<capacity>(str);
```

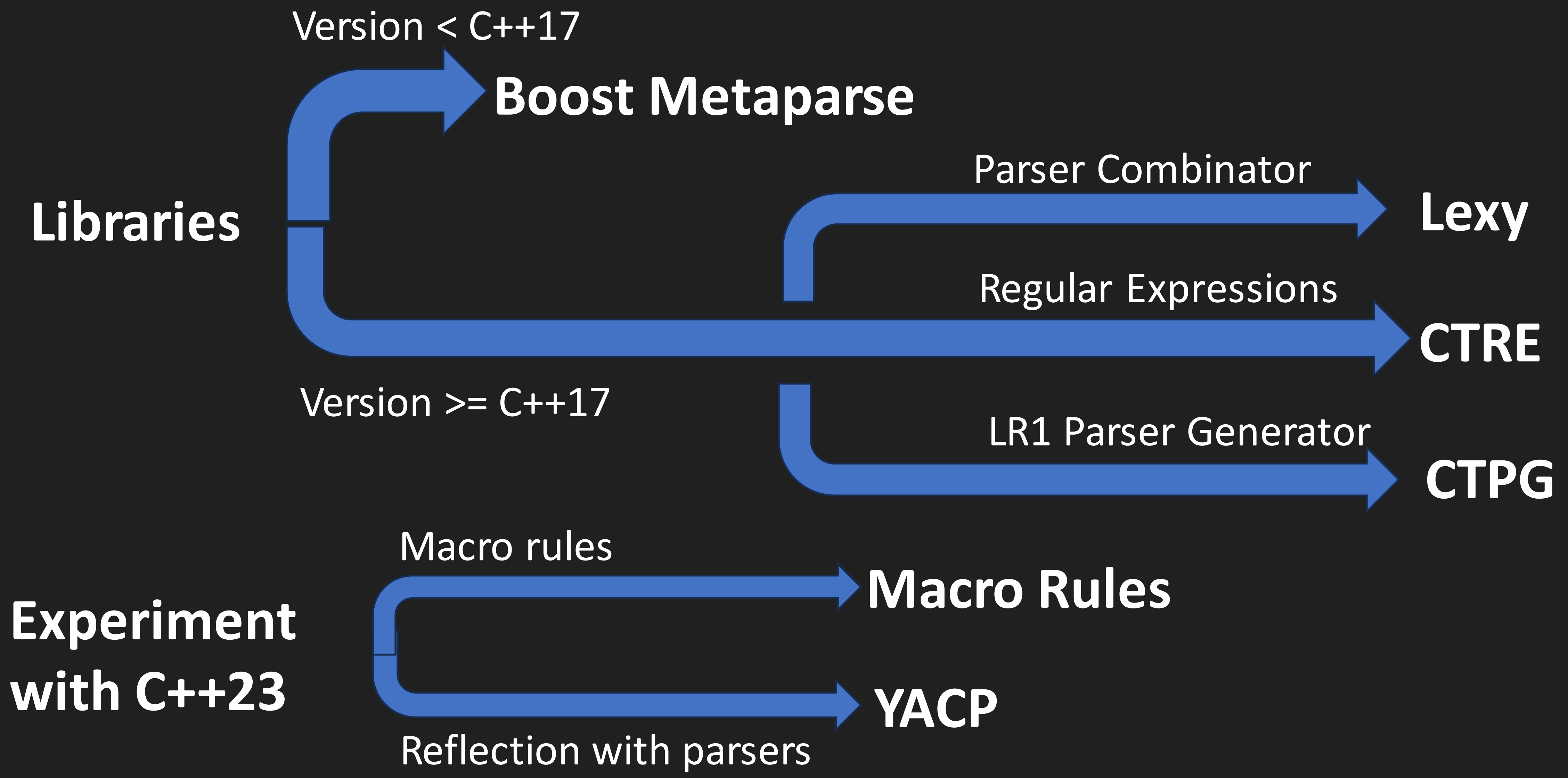
- Copy to smaller container:

```
constexpr auto capacity = 100;
constexpr auto tmp = JSON<capacity>(str);
constexpr auto json = JSON<tmp.size()>(tmp);
```

Using Compile-Time Parsers

- Do you need a DSL or a general purpose language?
- Can it be expressed with C++ operators?
- Interactions with C++
  - Self-contained
    - Regex `"[a-z]+([0-9]+)"`, Einsum `"ij,jk -> ki"`
  - Explicit access
    - Import table
  - Scope based lookup
    - Reflection: resolve identifier

Compile-Time Parsing Libraries



Errors

The error I would like to get:

```
<source>: In function 'int main()':
<source>:2:13: error: expected ';' before '}' token
2 | return 0
| ^
| ;
3 | }
```

The error I actually get:

```
/opt/compiler-explorer/libs/ctre/main/include/ctre/wrapper.hpp:299:42: error: invalid use of incomplete type 'struct ctre::problem_at_position<4>'
299 | static_assert(result::is_correct && problem_at_position<n>{}, "Regular Expression contains syntax error.");
| ~~~~~~~~~~~~^~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
/opt/compiler-explorer/libs/ctre/main/include/ctre/wrapper.hpp:277:26: note: declaration of 'struct ctre::problem_at_position<4>'
277 | template <size_t> struct problem_at_position; // do not define!
```

Compile-Time Printing

Error messages can be improved with compile-time printing.

Compile time wordle by Vittorio Romeo:

https://vittorioromeo.info/index/blog/wordlexpr.html

Compile time code generation library:

https://github.com/a10nw01f/Gen/

```
<source>: In instantiation of 'static constexpr void StaticPrint<<anonymous> >::Print() [with auto
...<anonymous> = {StaticString<53>{"Hello CppCon2023 :) compile time printing with c++20"}}]':
```

Compile Times - Benchmark

Measuring compile times of code that uses compile-time parsers depends on:

- Complexity of the syntax
- Parsing algorithm and optimizations
- Compiler and compiler version
- Hardware
- Other...

Compile Times - Benchmark

Benchmarked compiling the previous examples which uses unoptimized code.

Compiled with MSVC 19.36.32535.

Time is in seconds.

Average of 5 runs.

Compile-time parsing	Debug	Release
Enabled	**8.115**	**7.834**
Removed	**6.709**	**6.274**

Benchmark – Struct Parsing (1000 structs)

	Debug	Release
Baseline	**0.986**	**1.046**
Regular C++	**1.22**	**1.134**
Compile-time parser	**15.583**	**15.345**
Difference per struct	**0.0143**	**0.0142**

Compile-Time Like Runtime

Prefer writing compile-time code like runtime code:

- Easier to understand – similar syntax
- Easier to debug – remove constexpr and put breakpoints
- Can be used in runtime
- Faster compile times
- Less compile time memory usage – reduce template instatiations

Parsing JSON into a template tree took over 1 minute and 4GB of ram instead of 1.563 seconds

```
type_list<
    type_list<
        value_wrapper<false>,
        value_wrapper<42>,...
   >...
```

Past - Present - Future

The viability of compile-time parsers is directly related to:

- Difficulty of writing and using compile-time code
- Compilation speed

These will continue to improve through:

- New language features
- Discovery of new techniques
- Compiler improvements
- Faster hardware

C++23 ifconsteval

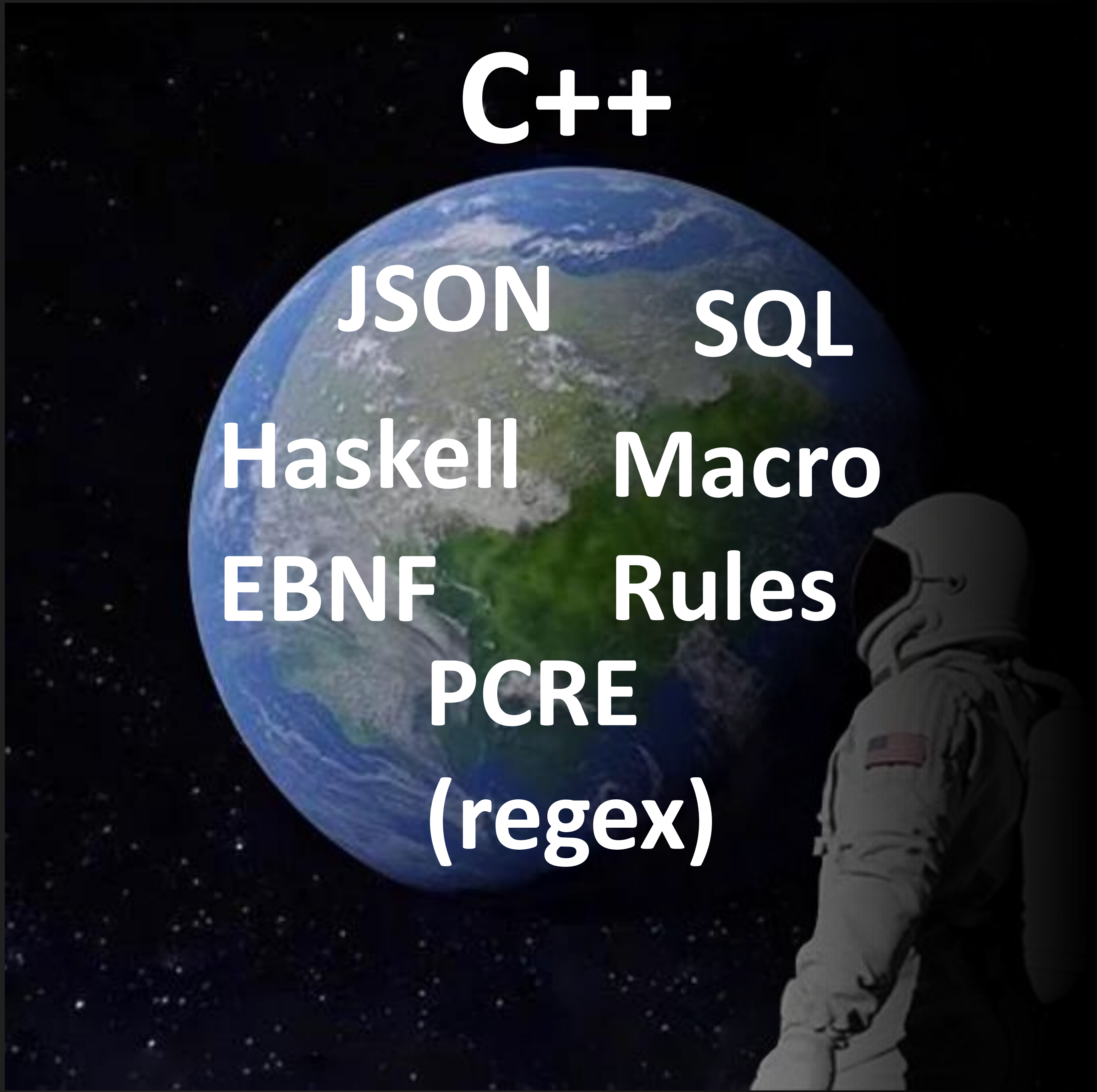
Reuse the same function at compile-time and runtime and provide different optimizations for each of them

```
constexpr uint64_t ipow(uint64_t base, uint8_t exp) {
    if consteval { // use a compile-time friendly algorithm
        return ipow_ct(base, exp);
    }
    else { // use runtime evaluation
        return std::pow(base, exp);
    }
}
```

C++26 (P2741R3)

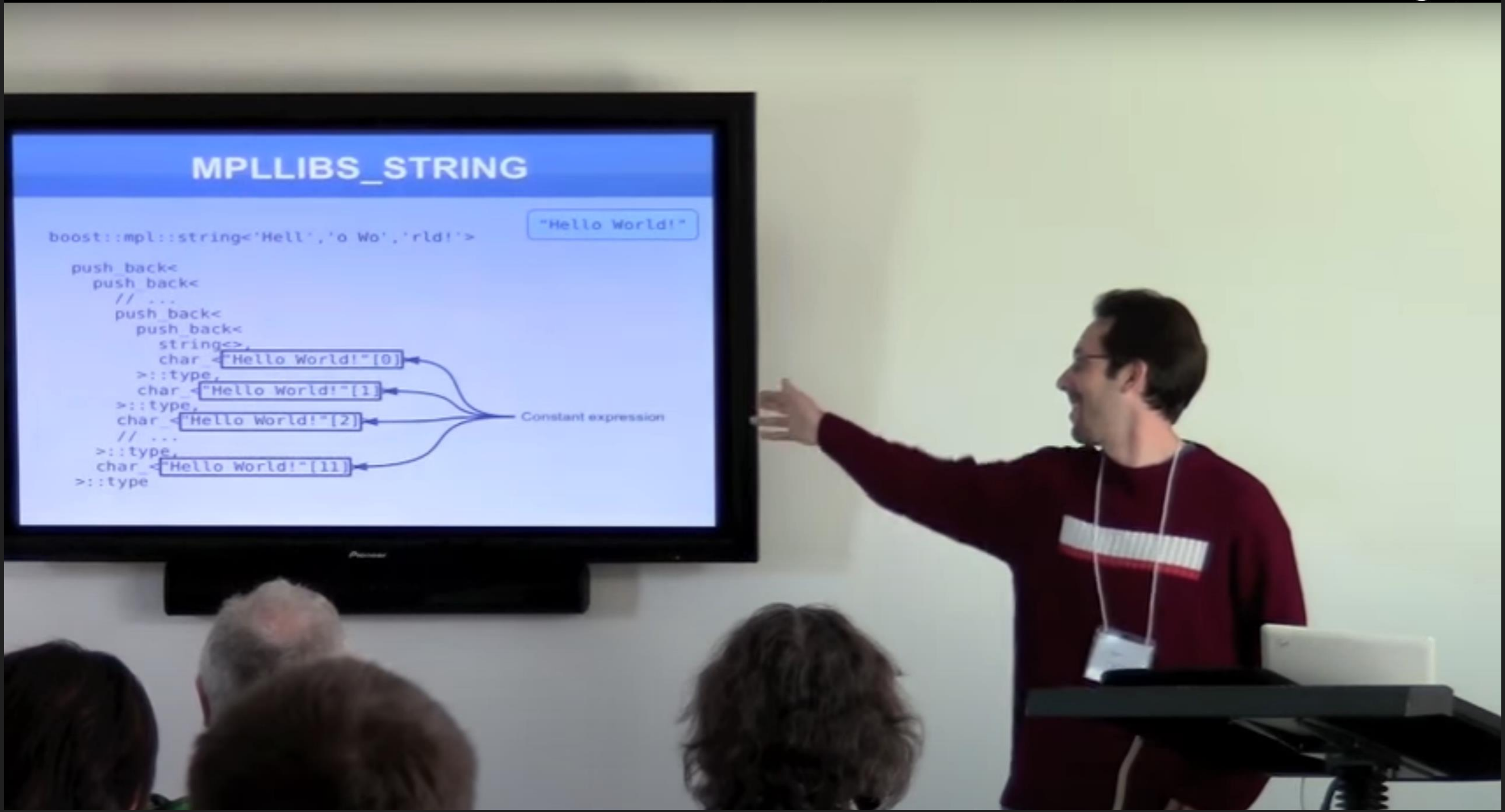
Adds support for user generated error messages in static_assert

```
constexpr std::string_view generate_error(){
    /*...*/
}

static_assert(false, generate_error());
```


C++
JSON
SQL
Haskell
Macro
EBNF
Rules
PCRE
(regex)


Always has been
It's all C++?
AI
Developers

Zoltan Porkolab, Abel Sinkovics: Metaparse – Compile-time parsing with template metaprogramming



Thank You

Questions?