C++ is a Metacompiler

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Outline

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2. Demonstration

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2. Demonstration
3. Philosophy
4. Methodology

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Introduction

Who am I?

- I'm a self-taught coder.
- I've been programming in C++ since 2005.
- I don't currently work in the tech industry.
- I have a Bachelor of Arts majoring in mathematics, minoring in economics.
- I am an Inuit person (specifically Inuvialuit) from Canada's western Arctic.
- I am devoted to the continued renewal of my people's language and culture.

Why C++?

- It is a life goal of mine to build a programming language for multimedia production.
- I hope to offer said language as an option for telling and retelling my people's stories, traditional and new.

Figure: inuksuk

- Such a language will generally require systems level performance, and so C++ is a good fit for writing its first compiler.

Demonstration

- What is a metacompiler?

- What is a metacompiler?
- The Philosophy section discusses this design.

- What is a metacompiler?
- The Philosophy section discusses this design.
- Here we show a few code examples:

Example 1: Factorial

chord language, factorial:

```
constexpr auto _chord_factorial_v0()
{
        return source
        (
                "type T                ;"
                "factorial n -> T      ;"

                "body:                 ;"
                "  test equal n 0      ;"
                "  branch done         ;"
                "  . = subtract n 1    ;"
                "  . = factorial _     ;"
                "  . = multiply n _    ;"
                "  return _            ;"

                "done:                 ;"
                "  return 1:T          ;"
        );
}
```

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chord language, factorial:

Example 1:

- A C++17 constexpr function.

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- This function takes no input.

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                "   return _            ;"

                "done:                  ;"
                "   return 1:T          ;"
        );
}
```

chord language, factorial:

Example 1:

- This function returns “source” data.

chord language, factorial:

```
constexpr auto _chord_factorial_v0()
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        return source
        (
                "type T                ;"
                "factorial n -> T      ;"

                "body:                 ;"
                "   test equal n 0     ;"
                "   branch done        ;"
                "   . = subtract n 1   ;"
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                "  return _            ;"

                "done:                 ;"
                "  return 1:T          ;"
        );
}
```

chord language, factorial:

Example 1:

- The source data is a string literal.

chord language, factorial:

```
constexpr auto _chord_factorial_v0()
{
        return source
        (
                "type T                 ;"
                "factorial n -> T       ;"

                "body:                  ;"
                "   test equal n 0      ;"
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                "   . = subtract n 1    ;"
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chord language, factorial:

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- The string literal is source from another language.

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- This other source is a domain specific language (DSL).

chord language, factorial:

Example 1:

- The string literal is source from another language.
- This other source is a domain specific language (DSL).
- This DSL is an assembly inspired language called chord.

chord language, factorial:

```
constexpr auto _chord_factorial_v0()
{
        return source
        (
                "type T                ;"
                "factorial n -> T      ;"

                "body:                 ;"
                "   test equal n 0     ;"
                "   branch done        ;"
                "   . = subtract n 1   ;"
                "   . = factorial _    ;"
                "   . = multiply n _   ;"
                "   return _           ;"

                "done:                 ;"
                "   return 1:T         ;"
        );
}
```

chord language, factorial:

Example 1:

- Relevance?

chord language, factorial:

```
using factorial_v0 = chord::metacompile
<
        _chord_factorial_v0,
        null_env, unsigned long
>;

static_assert(factorial_v0::result(9) == 362880);
```

chord language, factorial:

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using factorial_v0 = chord::metacompile
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In effect:

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chord language, factorial:

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- We metacompile our DSL source code.
- We pass it as a template parameter.
- It returns as a constexpr function.

chord language, factorial:

```
using factorial_v0 = chord::metacompile
<
        _chord_factorial_v0,
        null_env, unsigned long
>;

static_assert(factorial_v0::result(9) == 362880);
```

chord language, factorial:

```
using factorial_v0 = chord::metacompile
<
        _chord_factorial_v0,
        null_env, unsigned long
>;


static_assert(factorial_v0::result(9) == 362880);
```

chord language, factorial:

- Our metacompiled function can be used either at compile time or run time.

For those who want a bit more detail. . .

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A metacompiler turns this:

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A metacompiler turns this:

```
constexpr auto _chord_factorial_v0()
{
	return source
	(
		"type T                ;"
		"factorial n -> T      ;"

		"body:                 ;"
		"   test equal n 0     ;"
		"   branch done        ;"
		"   . = subtract n 1   ;"
		"   . = factorial _    ;"
		"   . = multiply n _   ;"
		"   return _           ;"

		"done:                 ;"
		"   return 1:T         ;"
	);
}
```

into this:

into this:

```
constexpr size_type value[][8] =
{
    { AN::id        , AT::id        ,  0,  0,  0,  0,  0,  1 },
    { AN::hash      , AT::port      ,  5,  0,  0,  0,  0,  1 },
    { AN::pad       , AT::select    ,  0,  1,  0,  0,  0,  1 },
    { AN::pad       , AT::id        ,  0,  0,  0,  0,  0,  1 },
    { AN::go_to     , AT::id        , 50,  0,  0,  0,  0,  1 },
    { AN::id        , AT::id        ,  0,  0,  0,  0,  0,  1 },
    { AN::eval      , AT::back      ,  7,  0,  0,  0,  0,  4 },
    { AN::id        , AT::id        ,  0,  0,  0,  0,  0,  1 },
    { AN::lookup    , AT::first     ,  0,  7,  0,  0,  0,  1 },
    { AN::halt      , AT::first     ,  0,  0,  0,  0,  0,  1 },
    { AN::eval      , AT::back      , 11,  0,  0,  0,  0,  5 },
    { AN::id        , AT::id        ,  0,  0,  0,  0,  0,  1 },
    { AN::arg       , AT::select    ,  1,  0,  0,  0,  0,  1 },
    { AN::arg       , AT::drop      ,  0,  0,  0,  0,  0,  1 },
    { AN::halt      , AT::first     ,  0,  0,  0,  0,  0,  1 },
    { AN::type      , AT::n_number  ,  0,  0,  0,  0,  0,  1 },
    { AN::literal   , AT::back      ,  0,  0,  0,  0,  0,  1 },
```

which we then pass to this:

which we then pass to this:

```
template<auto... filler>
struct T_assembly<AN::hash, AT::id, filler...>
{
    template<NIK_ASSEMBLY_PARAMS(c, i, l, t, r), typename... Ts>
    constexpr static auto result(Ts... vs)
    {
            constexpr auto ni = AD<c>::pos(i);
            constexpr auto nv = U_assembly_compound<c, ni>;

            return NIK_ASSEMBLY_TEMPLATE(c, i)
                    ::NIK_ASSEMBLY_RESULT_2TS(c, i, l, t, r, decltype(nv), Ts...)
                            (nv, vs...);
    }
};
```

which finally turns into a constexpr function.

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But we're getting ahead of ourselves.

Example 2: Factorial

hustle language, factorial:

```
constexpr auto _hustle_factorial_v0()
{
    return source
    (
        "(type T                              "
        "  (define (factorial n) -> T         "
        "    (if (= n 0)                      "
        "      1:T                            "
        "      (* n (factorial (- n 1)))      "
        "    )                                "
        "  )                                  "
        ")                                    "
    );
}
```

hustle language, factorial:

Example 2:

- We have another C++17 constexpr function.

hustle language, factorial:

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- We have another C++17 constexpr function.
- This function also takes no input.

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- We have another C++17 constexpr function.
- This function also takes no input.
- This function again returns “source” data.

hustle language, factorial:

Example 2:

- We have another C++17 constexpr function.
- This function also takes no input.
- This function again returns “source” data.
- The source data embeds another string literal.

hustle language, factorial:

```
constexpr auto _hustle_factorial_v0()
{
    return source
    (
        "(type T                               "
        "  (define (factorial n) -> T          "
        "    (if (= n 0)                       "
        "      1:T                             "
        "      (* n (factorial (- n 1)))       "
        "    )                                 "
        "  )                                   "
        ")                                     "
    );
}
```

hustle language, factorial:

```
constexpr auto _hustle_factorial_v0()
{
    return source
    (
        "(type T                                "
        "  (define (factorial n) -> T           "
        "    (if (= n 0)                        "
        "      1:T                              "
        "      (* n (factorial (- n 1)))        "
        "    )                                  "
        "  )                                    "
        ")                                      "
    );
}
```

hustle language, factorial:

Example 2:

- The string literal encodes source from yet another language.

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hustle language, factorial:

Example 2:

- The string literal encodes source from yet another language.
- This source is again a domain specific language (DSL).
- This DSL is a scheme (lisp) inspired language called hustle.

hustle language, factorial:

```
constexpr auto _hustle_factorial_v0()
{
    return source
    (
        "(type T                          "
        "  (define (factorial n) -> T     "
        "    (if (= n 0)                  "
        "      1:T                        "
        "      (* n (factorial (- n 1)))  "
        "    )                            "
        "  )                              "
        ")                                "
    );
}
```

hustle language, factorial:

Example 2:

- Finally. . .

hustle language, factorial:

```
using factorial_v0 = hustle::metacompile
<
        _hustle_factorial_v0,
        null_env, unsigned long
>;

static_assert(factorial_v0::result(9) == 362880);
```

hustle language, factorial:

Example 2:

- We can metacompile
  and apply this function as well.

Philosophy

- C++ is a metacompiler.

- C++ is a metacompiler.
- We've seen what a metacompiler *does*.

- C++ is a metacompiler.
- We've seen what a metacompiler *does*.
- We now ask what a metacompiler *is*.

Let's take a short tour
of related concepts.

We start by asking:

We start by asking:

- What is a compiler?

We start by asking:

- What is a compiler?
- What is an interpreter?

We start by asking:

- What is a compiler?
- What is an interpreter?
- What is a transpiler?

To keep things simple:

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- A *compiler* takes source code and translates it into assembly.

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- An *interpreter* takes source code, translates, then executes it directly.

To keep things simple:

- A *compiler* takes source code and translates it into assembly.
- An *interpreter* takes source code, translates, then executes it directly.
- A *transpiler* takes source code and translates it into the source code of another language.

Do these ideas apply to a metacompiler?

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- Compiler: Yes, a metacompiler takes source code and translates it into an intermediate assembly.

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- Compiler: Yes, a metacompiler takes source code and translates it into an intermediate assembly.
- Interpreter: Maybe, a metacompiled function can be executed at compile time.

Do these ideas apply to a metacompiler?

- Compiler: Yes, a metacompiler takes source code and translates it into an intermediate assembly.
- Interpreter: Maybe, a metacompiled function can be executed at compile time.
- Transpiler: Maybe, a metacompiler takes source code and does translate it into C++, but only C++.

So I've called it a metacompiler.

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What makes it "meta?"

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What makes it "meta?"

- The prefix comes from metaprogramming.

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So I've called it a metacompiler.

What makes it "meta?"

- The prefix comes from metaprogramming.
- In C++ this means compile time programming.
- This includes constexpr time programming, as well as template metaprogramming.

As such, a metacompiler requires
we refine our notion of time.

We ask:

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- What is a timescape?

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- What is a timescape?
- What is a timescope?

The short answer:

> When observing the lifespan of a program,
> a timescape allows us to decompose it into timescopes.

As for specific timescopes:

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- Run time is when a program is being executed.

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- Run time is when a program is being executed.
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- Metarun time is when a metaprogram is being executed. . .

As for specific timescopes:

- Run time is when a program is being executed.
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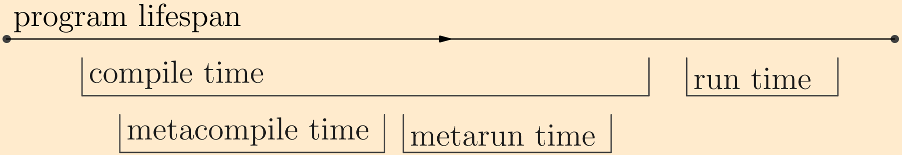
As for specific timescopes:

- Run time is when a program is being executed.
- Compile time is when a program is being translated for execution.
- Metarun time is when a metaprogram is being executed. . . *within the scope of compile time.*
- Metacompile time is when a metaprogram is being translated for execution. . .

As for specific timescopes:

- Run time is when a program is being executed.
- Compile time is when a program is being translated for execution.
- Metarun time is when a metaprogram is being executed. . . *within the scope of compile time.*
- Metacompile time is when a metaprogram is being translated for execution. . . *within the scope of compile time.*


program lifespan
compile time
run time
metacompile time
metarun time

What about constexpr time?

What about constexpr time?

- This is C++ specific.

What about constexpr time?

- This is C++ specific.
- This timescope in effect represents either run time or metarun time.

A metacompiler requires we also consider ideas of self similarity.

Why?

Why?

Because in theory we could metacompile source code from the same language that is otherwise being compiled.

Given this, we ask:

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- What is a metacircular evaluator?

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- What is a self-hosting compiler?

Given this, we ask:

- What is a metacircular evaluator?
- What is a self-hosting compiler?
- What is an abstract machine?

Given this, we ask:

- What is a metacircular evaluator?
- What is a self-hosting compiler?
- What is an abstract machine?
- What is a virtual machine?

A metacircular evaluator:

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- Starts with interpreted language.
- Builds a metacircular library.
- Builds a function called an evaluator.
- This evaluator simulates the language's own interpreter.
- This evaluator can execute source code from the same language.

A self-hosting compiler:

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What's the difference?

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- An interpreter is allowed to interleave source code translation with execution.
- A compiler is restricted to modularizing source code translation and execution. It *must* translate first, only then can it execute.

A self-hosting compiler:

- Is the compiled version of a metacircular evaluator.

What's the difference?

- An interpreter is allowed to interleave source code translation with execution.
- A compiler is restricted to modularizing source code translation and execution. It *must* translate first, only then can it execute.
- This creates subtle differences in their respective designs.

An abstract machine:

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- Such states are usually expected to have the same shape. In effect, you can consider them to be a data structure.
- These machines are generally given some kind of controller (sometimes source code) to direct their computation.

A virtual machine

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- Is an abstract machine.
- Has states that represent actual hardware.
- Can be used to simulate hardware on top of actual hardware.

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- metacircular evaluator: Sort of, in theory we can interleave translation and execution to interpret.
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Do these ideas apply to a metacompiler?

- metacircular evaluator: Sort of, in theory we can interleave translation and execution to interpret.
- self-hosting compiler: Maybe, in theory we could rebuild C++ itself, but done at compile time it might not be performant enough to be worth it.
- abstract machine: Yes, such machines underly the implementation design.

Do these ideas apply to a metacompiler?

- metacircular evaluator: Sort of, in theory we can interleave translation and execution to interpret.
- self-hosting compiler: Maybe, in theory we could rebuild C++ itself, but done at compile time it might not be performant enough to be worth it.
- abstract machine: Yes, such machines underly the implementation design.
- virtual machine: Somewhat, in theory optimized state transitions can be designed with hardware in mind.

What then is a metacompiler?

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- It is a toolchain of related technologies which translate source code into assembly.

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- In terms of the technologies that make up this chain,

What then is a metacompiler?

- It is a toolchain of related technologies which translate source code into assembly.
- In terms of the technologies that make up this chain, it is the idea of a DSL engine that is most relevant to this talk.

What is a DSL engine?

What is a DSL engine?

It is an abstract machine which translates domain specific languages into assembly.

To finish this section we ask one more question.

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We've discussed the idea of a metacompiler more broadly,

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Why is C++ a metacompiler?

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To finish this section we ask one more question.

We've discussed the idea of a metacompiler more broadly, so now we specifically ask:

Why is C++ a metacompiler?

- It is a metacompiler because of its specification, C++17 and later.

To finish this section we ask one more question.

We've discussed the idea of a metacompiler more broadly, so now we specifically ask:

Why is C++ a metacompiler?

- It is a metacompiler because of its specification, C++17 and later.
- C++17 has an emergence of grammar and rules to support a DSL engine,

To finish this section we ask one more question.

We've discussed the idea of a metacompiler more broadly, so now we specifically ask:

Why is C++ a metacompiler?

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We've discussed the idea of a metacompiler more broadly, so now we specifically ask:

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- C++17 has an emergence of grammar and rules to support a DSL engine, one which is also performant.
- It is independent of vendor implementation.

Methodology

- C++ is a metacompiler.

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- C++ is a metacompiler.
- We've seen what a metacompiler *does*.
- We've seen what a metacompiler *is*.
- We now ask how a metacompiler *works*.

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Why talk about methods?

> A general purpose DSL engine needs to be able to metacompile any language, and so we need its implementation design to be based on expressive theoretical foundations.

We start with the methods of compiler theory, which is divided into the frontend and backend.

The frontend focuses on the lexing and parsing of source code.

*Intermediate Representation.

The frontend focuses on the lexing and parsing of source code.

The backend focuses on multilayed translations from an initial IR* assembly, to the final target assembly.

*Intermediate Representation.

Lexing

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- Read source code.

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- Translate words into tokens.

Lexing

To keep things simple, lexers:

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- Are constructed from regular languages and regular automata.

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To keep things simple, parsers:

- Read tokenized source code.
- Confirm “sentence” structure.
- Translate sentences into IR assembly.
- Are constructed from context free grammars and pushdown automata.

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- Such methods coincide well with implementing imperative DSLs.
- Such methods are less effective when implementing functional DSLs.

We need methods that can implement both imperative and functional languages.

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To motivate such methods, let's now take a quick tour of computing history.

Turing machines:

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- Equivalent to μ-recursive functions (math).
- Well suited for modeling theoretical properties of computable functions.
- Less well suited for modeling practical or performant computable functions.

Lambda calculus $[\lambda x.x]$:

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- Well suited for modeling theoretical grammar of computable functions.
- Less well suited (on its own) for modeling certain *consistency* semantics of computable functions.

LISP programming language:

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- Influenced by the lambda calculus.
- Is now a family of languages, including Common Lisp, Scheme, Clojure, and Racket.
- Aligns well with the functional programming paradigm.

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But first. . .

Set Theory [math]:

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Set Theory [math]:

- Georg Cantor, late 1800s.
- A foundational language of mathematics.
- Proof that there are "different sizes of infinity."
- If taken as a naive theory, it leads to contradictions.[†]

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- Helped advance the subject of symbolic logic.

Type Theory [computing]:

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Type Theory [computing]:

- Multiple contributors (here unnamed), mid 1900s.
- More recently Per Martin-Löf, late 1900s.
- Well suited for modeling certain *consistency* semantics of computable functions.
- Aligns well with the lambda calculus[‡], functional programming, and the family of LISPs.

[‡]See Lambda Cube.

This leads us to. . .

This leads us to... abstract machines.

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Each uses different grammatical artifacts from the untyped lambda calculus to implement its own version of an abstract machine.

Abstract machines

vs

Register machines

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- They transition states by updating these components, which is how they perform their computations.

Register machines:

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- The only difference is their design more closely resembles actual computer architecture.

Compile time register machines:[§]

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Compile time register machines:[§]

- Use continuation passing style to transition from state to state.

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Compile time register machines:[§]

- Use continuation passing style to transition from state to state.
- Use template parameters to carry their respective controllers, registers, and call stacks.
- Use nesting depth counters to implement trampolining as well as prevent recursive closure.

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Library

In this section we finally discuss how to implement a DSL engine in C++.

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In order to do so I introduce my cctmp library.

cctmp library[¶]:

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What about the metacompiler?

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We begin with its frontend:

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- An LL(1) parser generator is used to construct transition tables for DSL context free grammars.

hustle language, context free grammar:

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constexpr auto source()
{
    return generator::context_free_grammar
    (
        // start:

            "Start",

        // hustle:

            "Start   -> ( Generic )                    ;"
            "Generic -> type Param Params ( Main ) ;"
            "        -> Main                            ;"
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            "        -> empty                           ;"
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- Syntax tree implementations inherit from a DSL engine base class.
- DSL source code translates into meta-assembly which acts as a controller for constructing constexpr functions.

As for meta-assembly:

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How does such assembly translate into constexpr functions?

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How does such assembly translate into constexpr functions?

We now turn our attention to the metacompiler backend:

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- States are implemented using continuation passing style.

An example of
a continuation passing state:

continuation machine:

```
template<auto... filler>
struct T_assembly<name::go_to, note::id, filler...>
{
    template<assembly_params(c, i, l, t, r), typename... Ts>
    constexpr static auto result(Ts... vs)
    {
        constexpr auto ni = dispatch<c>::pos(i);

        return assembly_template(c, ni)
            ::assembly_result_ts(c, ni, l, t, r, Ts...)
                (vs...);
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If states are implemented as continuation passing functions, then meta-assembly not only controls state transitions, it also constructs a constexpr function along the way.

metacompiler backend (refinements):

‖ Structure and Interpretation of Computer Programs.

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metacompiler backend (refinements):

- It is designed to simulate an abstract machine to achieve compilation.
- It constructs a sequence of state transitions, rather than applying them directly.
- Although it is not an interpreter, its implementation is still inspired by SICP's‖ metacircular evaluator (for the Scheme language).

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- expression: is the source code being translated and executed.
- environment: is a list of frames. Each frame is a list of bindings. A binding is a (variable, value) pair.
- call stack: is an expression constructed solely to apply a function to its respective values.

The crucial process for us to understand. . .

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is how the call stack and environment interact when the source expression is being evaluated.

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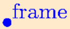
is how the call stack and environment interact when the source expression is being evaluated.

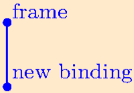
With that in mind, we have the following illustration:

environment

environment



environment



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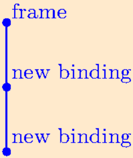

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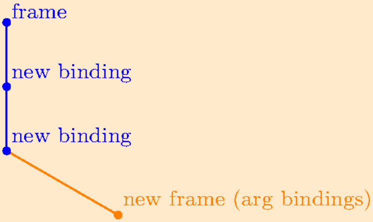

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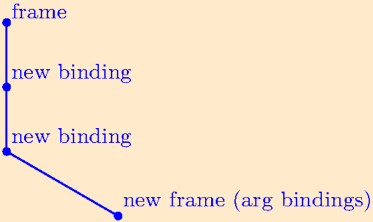

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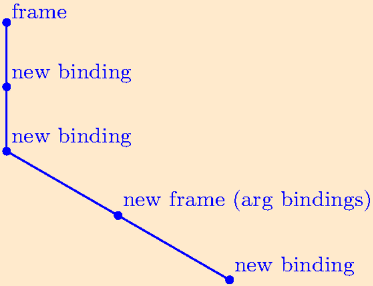

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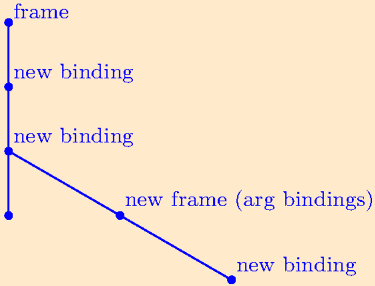

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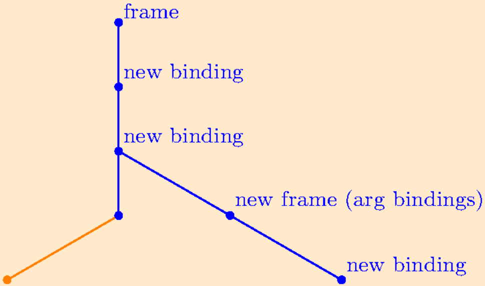

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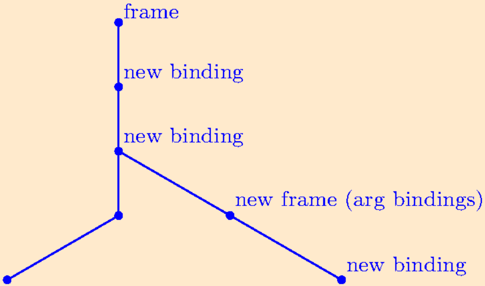

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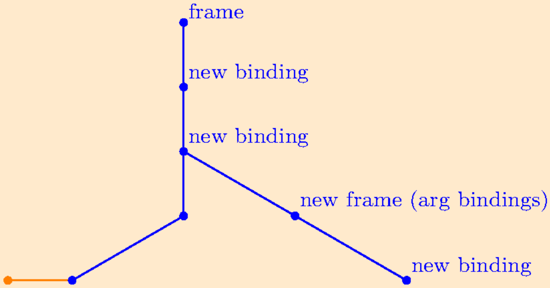

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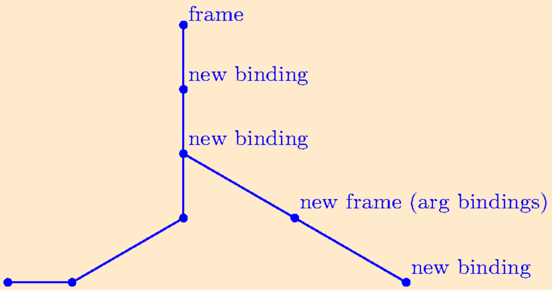

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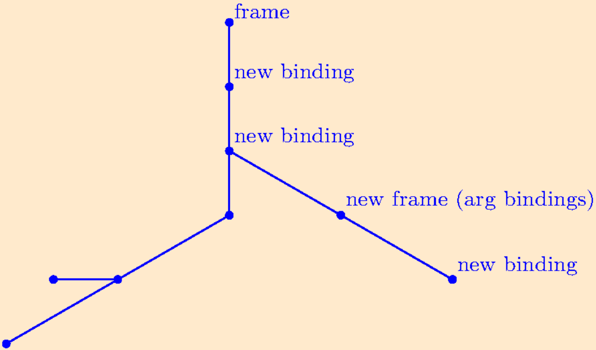

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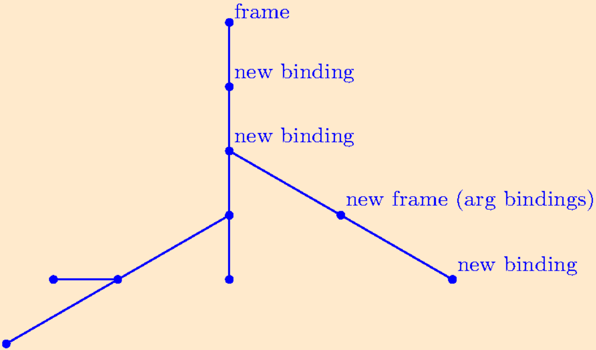

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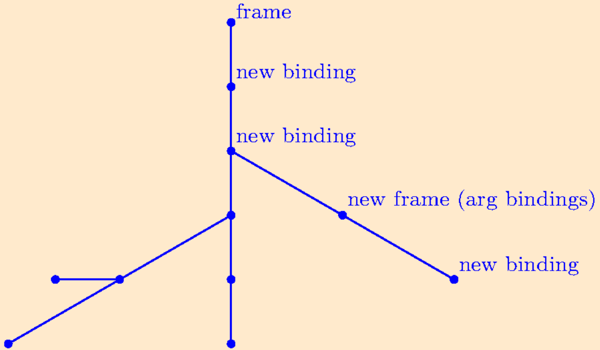

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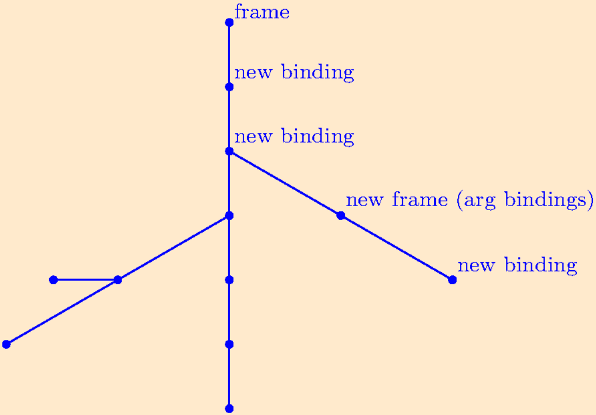

Returning to our metacompiler abstract machine, let's review its components.

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Starting with the controller.

continuation machine controller:

continuation machine controller:

- It is a program composed of meta-assembly.

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- It is implemented as an array of instructions.

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- It is a program composed of meta-assembly.
- It is implemented as an array of instructions.
- Each instruction is an array of unsigned integers.

What does this assembly look like?

What does this assembly look like?

We saw it once before:

meta-assembly controller:

```
constexpr size_type value[][8] =
{
    { AN::id        , AT::id        ,  0,  0,  0,  0,  0,  1 },
    { AN::hash      , AT::port      ,  5,  0,  0,  0,  0,  1 },
    { AN::pad       , AT::select    ,  0,  1,  0,  0,  0,  1 },
    { AN::pad       , AT::id        ,  0,  0,  0,  0,  0,  1 },
    { AN::go_to     , AT::id        , 50,  0,  0,  0,  0,  1 },
    { AN::id        , AT::id        ,  0,  0,  0,  0,  0,  1 },
    { AN::eval      , AT::back      ,  7,  0,  0,  0,  0,  4 },
    { AN::id        , AT::id        ,  0,  0,  0,  0,  0,  1 },
    { AN::lookup    , AT::first     ,  0,  7,  0,  0,  0,  1 },
    { AN::halt      , AT::first     ,  0,  0,  0,  0,  0,  1 },
    { AN::eval      , AT::back      , 11,  0,  0,  0,  0,  5 },
    { AN::id        , AT::id        ,  0,  0,  0,  0,  0,  1 },
    { AN::arg       , AT::select    ,  1,  0,  0,  0,  0,  1 },
    { AN::arg       , AT::drop      ,  0,  0,  0,  0,  0,  1 },
    { AN::halt      , AT::first     ,  0,  0,  0,  0,  0,  1 },
    { AN::type      , AT::n_number  ,  0,  0,  0,  0,  0,  1 },
    { AN::literal   , AT::back      ,  0,  0,  0,  0,  0,  1 },
```

We now have enough to put some of these ideas together:

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- The metacompiler frontend uses a SICP-style environment to keep track of variables.

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We now have enough to put some of these ideas together:

- The metacompiler frontend uses a SICP-style environment to keep track of variables.
- Instead of keeping track of values, it holds an index (a promise) of where those values will eventually be in the continuation passing universe.
- This is why the meta-assembly controller consists of numerical content only.

Next we discuss the universe:

continuation machine universe:

continuation machine universe:

- It is implemented using the left side of a variadic pack.

continuation machine universe:

- It is implemented using the left side of a variadic pack.
- New values are inserted at the end of the left side of the pack.

Finally, we have the stage:

continuation machine stage:

continuation machine stage:

- It is implemented using the right side of a variadic pack.

continuation machine stage:

- It is implemented using the right side of a variadic pack.
- New values are pushed to the back of the pack.

continuation machine stage:

- It is implemented using the right side of a variadic pack.
- New values are pushed to the back of the pack.
- Argument order is preserved when applying functions to their values.

Why use a variadic pack for both the universe and stage?

Why use a variadic pack for both the universe and stage?

To make it absolutely clear at this point, we are using the same pack ($Ts \ldots vs$) that is passed along the continuation machine states.

This works because of
a correspondence between:

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- Environment variables (indices).

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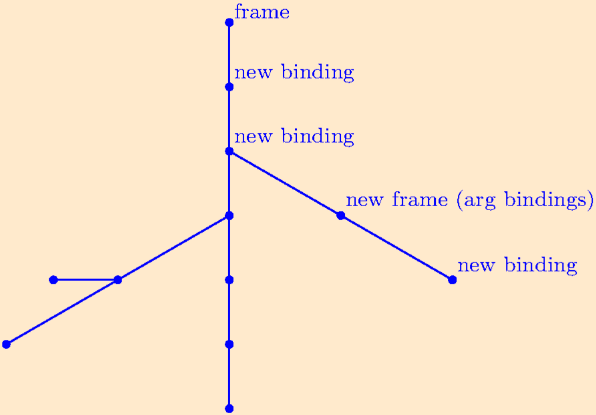
- Environment variables (indices).
- The *flat* positions within a universe.

environment to universe correspondence:



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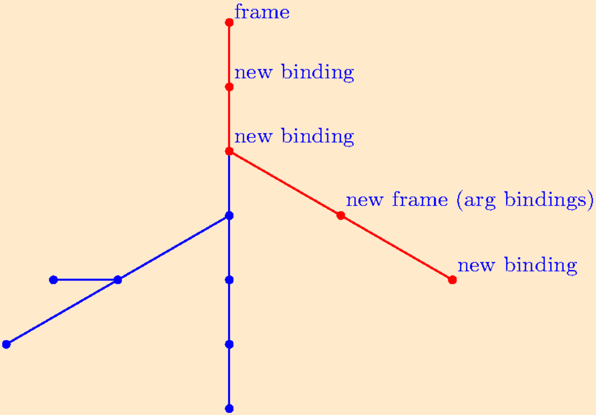

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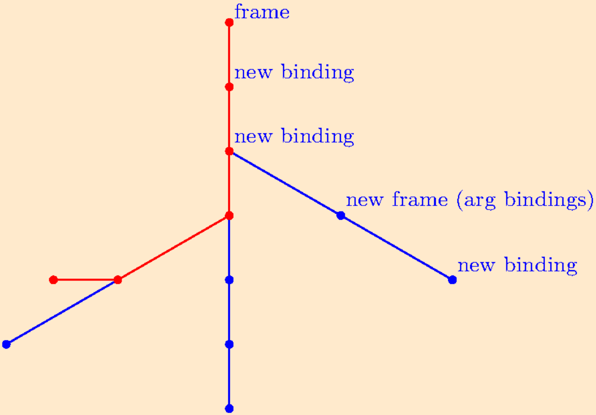

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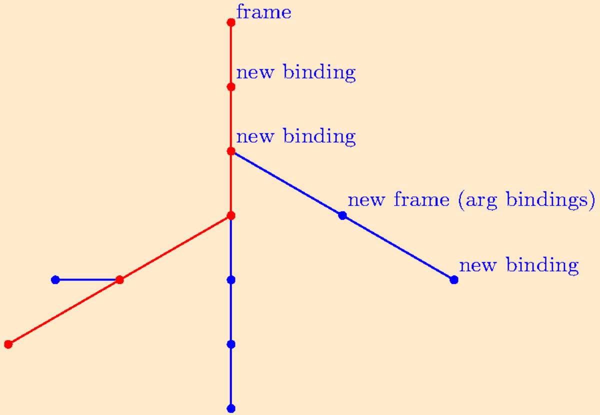

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Recursion.

How do you construct a recursive function from continuation passing style?

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To do this in practice, we only need keep track of the initial context when defining the recursive function.

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The trick is to realize we only need call the same continuation machine with the same typed input.

To do this in practice, we only need keep track of the initial context when defining the recursive function.

We then supply that context before the arguments when applying said function.

This concludes how a metacompiler works in the context of this cctmp library.

Are there side effects in using continuation machines?

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- Type checking is deferred until a function is constructed.

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- Caveat: Recursive functions are the exception to this because C++ compilers don't like to *auto* deduce such things.

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- Type checking is deferred until a function is constructed.
- This means that within DSL source code, literals, variables, and function definitions don't require type info.
- Caveat: Recursive functions are the exception to this because C++ compilers don't like to *auto* deduce such things.
- Mutability semantics have an added level of semantic indirection.

As for recursive functions requiring type info?

As for recursive functions requiring type info?

It is easy enough to bake the necessary grammar into our DSLs:

chord language, factorial:

```
constexpr auto _chord_factorial_v0()
{
        return source
        (
                "type T                 ;"
                "factorial n -> T       ;"

                "body:                  ;"
                "   test equal n 0      ;"
                "   branch done         ;"
                "   . = subtract n 1    ;"
                "   . = factorial _     ;"
                "   . = multiply n _    ;"
                "   return _            ;"

                "done:                  ;"
                "   return 1:T          ;"
        );
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		"  . = multiply n _  ;"
		"  return _          ;"

		"done:               ;"
		"  return 1:T        ;"
	);
}
```

hustle language, factorial:

```
constexpr auto _hustle_factorial_v0()
{
    return source
    (
        "(type T                                    "
        "  (define (factorial n) -> T               "
        "    (if (= n 0)                            "
        "      1:T                                  "
        "      (* n (factorial (- n 1)))            "
        "    )                                      "
        "  )                                        "
        ")                                          "
    );
}
```

hustle language, factorial:

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constexpr auto _hustle_factorial_v0()
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        "    (if (= n 0)                         "
        "      1:T                               "
        "      (* n (factorial (- n 1)))         "
        "    )                                   "
        "  )                                     "
        ")                                       "
    );
}
```

Language

This section showcases an inventory of distinct grammars that I have introduced into my chord language.

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It presents some of the expressive potential in using this paradigm of embedded DSLs.

chord language, void effects (mutability):

```
constexpr auto _chord_void_effects_v0()
{
	return source
	(
		"main x y              ;"

		"body:                 ;"
		"   . = increment y    ;"
		"   void appoint !x _  ;"
		"   return x           ;"
	);
}
```

Here *appoint* is defined as:

$$\text{void appoint}(u, v)\ \{\ *u = v;\ \}$$

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Here *appoint* is defined as:

$$\text{void appoint}(u, v)\ \{\ *u = v;\ \}$$

chord language, factorial (goto):

```
constexpr auto _chord_factorial_v3()
{
        return source
        (
                "main p n           ;"

                "loop:              ;"
                "test is_zero n     ;"
                "branch done        ;"
                "p = multiply p n ;"
                "n = decrement n    ;"
                "goto loop          ;"

                "done:              ;"
                "return p           ;"
        );
}
```

chord language, factorial (goto):

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	return source
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		"main p n            ;"

		"loop:               ;"
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		"p = multiply p n    ;"
		"n = decrement n     ;"
		"goto loop           ;"

		"done:               ;"
		"return p            ;"
	);
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                "p = multiply p n      ;"
                "n = decrement n       ;"
                "goto loop             ;"

                "done:                 ;"
                "return p              ;"
        );
}
```

chord language, square (argument compose):

```
constexpr auto _chord_square_v1()
{
        return source
        (
                "main x                          ;"

                "vars:                           ;"
                "declare sq                      ;"

                "defs:                           ;"
                "sq # argpose[1]{multiply 0 0} ;"

                "body:                           ;"
                ". = sq x                        ;"
                "return _                        ;"
        );
}
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		"body:                               ;"
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		"defs:                                   ;"
		"sq # argpose[1]{multiply 0 0}           ;"

		"body:                                   ;"
		". = sq x                                ;"
		"return _                                ;"
	);
}
```

chord language, sum of squares (subcompose):

```
constexpr auto _chord_sum_of_squares_v1()
{
    return source
    (
        "main x y                                    ;"

        "vars:                                       ;"
        "declare sq sum_of_sq                        ;"

        "defs:                                       ;"
        "sq        # argpose[1]{multiply 0 0}        ;"
        "sum_of_sq # subpose[2]{add sq sq}           ;"

        "body:                                       ;"
        ". = sum_of_sq x y                           ;"
        "return _                                    ;"
    );
}
```

chord language, sum of squares (subcompose):

```
constexpr auto _chord_sum_of_squares_v1()
{
    return source
    (
        "main x y                                       ;"

        "vars:                                          ;"
        "declare sq sum_of_sq                           ;"

        "defs:                                          ;"
        "sq        # argpose[1]{multiply 0 0}           ;"
        "sum_of_sq # subpose[2]{add sq sq}              ;"

        "body:                                          ;"
        ". = sum_of_sq x y                              ;"
        "return _                                       ;"
    );
}
```

chord language, sum of squares (subcompose):

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constexpr auto _chord_sum_of_squares_v1()
{
    return source
    (
        "main x y                                  ;"

        "vars:                                     ;"
        "declare sq sum_of_sq                      ;"

        "defs:                                     ;"
        "sq         # argpose[1]{multiply 0 0}     ;"
        "sum_of_sq  # subpose[2]{add sq sq}        ;"

        "body:                                     ;"
        ". = sum_of_sq x y                         ;"
        "return _                                  ;"
    );
}
```

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constexpr auto _chord_sum_of_squares_v1()
{
    return source
    (
        "main x y                                    ;"

        "vars:                                       ;"
        "declare sq sum_of_sq                        ;"

        "defs:                                       ;"
        "sq        # argpose[1]{multiply 0 0}        ;"
        "sum_of_sq # subpose[2]{add sq sq}           ;"

        "body:                                       ;"
        ". = sum_of_sq x y                           ;"
        "return _                                    ;"
    );
}
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chord language, sum of squares (subcompose):

```
constexpr auto _chord_sum_of_squares_v1()
{
    return source
    (
        "main x y                                  ;"

        "vars:                                     ;"
        "declare sq sum_of_sq                      ;"

        "defs:                                     ;"
        "sq        # argpose[1]{multiply 0 0}      ;"
        "sum_of_sq # subpose[2]{add sq sq}         ;"

        "body:                                     ;"
        ". = sum_of_sq x y                         ;"
        "return _                                  ;"
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}
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constexpr auto _chord_sum_of_squares_v1()
{
    return source
    (
        "main x y                                  ;"

        "vars:                                     ;"
        "declare sq sum_of_sq                      ;"

        "defs:                                     ;"
        "sq        # argpose[1]{multiply 0 0}      ;"
        "sum_of_sq # subpose[2]{add sq sq}         ;"

        "body:                                     ;"
        ". = sum_of_sq x y                         ;"
        "return _                                  ;"
    );
}
```

chord language, twice (currying):

```
constexpr auto _chord_twice_v0()
{
    return source
    (
        "main x                              ;"

        "vars:                               ;"
        "declare twice                       ;"

        "defs:                               ;"
        "twice # curry[1]{multiply two}      ;"

        "body:                               ;"
        ". = twice x                         ;"
        "return _                            ;"

        , binding("two", 2)
    );
}
```

chord language, twice (currying):

```
constexpr auto _chord_twice_v0()
{
    return source
    (
        "main x                                    ;"

        "vars:                                     ;"
        "declare twice                             ;"

        "defs:                                     ;"
        "twice # curry[1]{multiply two}            ;"

        "body:                                     ;"
        ". = twice x                               ;"
        "return _                                  ;"

        , binding("two", 2)
    );
}
```

chord language, map operator (functional programming):

```
constexpr auto _chord_array_square_v0()
{
    return source
    (
        "main out in end                          ;"

        "vars:                                    ;"
        "   declare arr_sq                        ;"

        "defs:                                    ;"
        "   arr_sq # map[1]{square||} [) [,)      ;"

        "body:                                    ;"
        "   . = arr_sq !out in end                ;"
        "   return _                              ;"

        , binding( "square" , _square_ )
    );
}
```

chord language, map operator (functional programming):

```
constexpr auto _chord_array_square_v0()
{
    return source
    (
        "main out in end                    ;"

        "vars:                              ;"
        "  declare arr_sq                   ;"

        "defs:                              ;"
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        "body:                              ;"
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The options are defined as follows:

- [ ] - `closed`: acts on the left and right endpoints.
- ( ] - `opening`
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- [ ) - `closing`

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The options are defined as follows:

- [] - `closed`
- (] - `opening`: skips the left, acts on the right.
- () - `open`
- [) - `closing`

The interval symbols [) and [,) are options which communicate how the functional algorithm acts with regard to iterator endpoints.

The options are defined as follows:

- [ ] - `closed`
- ( ] - `opening`
- ( ) - `open`: skips the left, doesn't act on the right.
- [ ) - `closing`

The interval symbols [) and [,) are options which communicate how the functional algorithm acts with regard to iterator endpoints.

The options are defined as follows:

- [ ] - `closed`
- ( ] - `opening`
- ( ) - `open`
- [ ) - `closing`: acts on the left, not on the right.

chord language, vector addition (functional programming):

```
constexpr auto _chord_vector_add_v0()
{
    return source
    (
        "main out in end in1                    ;"

        "vars:                                  ;"
        "   declare vec_add                     ;"

        "defs:                                  ;"
        "   vec_add # map[2]{add||} [) [,) [)   ;"

        "body:                                  ;"
        "   . = vec_add !out in end in1         ;"
        "   return _                            ;"
    );
}
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        "body:                                  ;"
        "   . = vec_add !out in end in1         ;"
        "   return _                            ;"
    );
}
```

chord language, fold operator (functional programming):

```
constexpr auto _chord_sum_v0()
{
    return source
    (
        "main out in end                             ;"

        "vars:                                       ;"
        "   declare sum                              ;"

        "defs:                                       ;"
        "   sum # fold[1]{add * @|@ @||} <> [,]      ;"

        "body:                                       ;"
        "   . = sum !out in end                      ;"
        "   return _                                 ;"
    );
}
```

chord language, fold operator (functional programming):

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constexpr auto _chord_sum_v0()
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    (
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        "vars:                                              ;"
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        "body:                                              ;"
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constexpr auto _chord_sum_v0()
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        "   . = sum !out in end                             ;"
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constexpr auto _chord_sum_v0()
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        "vars:                                        ;"
        "  declare sum                                ;"

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        "  sum # fold[1]{add * @|@ @||} <> [,]        ;"

        "body:                                        ;"
        "  . = sum !out in end                        ;"
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}
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constexpr auto _chord_sum_v0()
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    return source
    (
        "main out in end                                        ;"

        "vars:                                                  ;"
        "   declare sum                                         ;"

        "defs:                                                  ;"
        "   sum # fold[1]{add * @|@ @||} <> [,]                 ;"

        "body:                                                  ;"
        "   . = sum !out in end                                 ;"
        "   return _                                            ;"
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constexpr auto _chord_sum_v0()
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    return source
    (
        "main out in end                                  ;"

        "vars:                                            ;"
        "   declare sum                                   ;"

        "defs:                                            ;"
        "   sum # fold[1]{add * @|@ @||} <> [,]           ;"

        "body:                                            ;"
        "   . = sum !out in end                           ;"
        "   return _                                      ;"
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        "   sum # fold[1]{add * @|@ @||} <> [,]       ;"

        "body:                                        ;"
        "   . = sum !out in end                       ;"
        "   return _                                  ;"
    );
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constexpr auto _chord_sum_v0()
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    return source
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        "vars:                                            ;"
        "   declare sum                                   ;"

        "defs:                                            ;"
        "   sum # fold[1]{add * @|@ @||} <> [,]           ;"

        "body:                                            ;"
        "   . = sum !out in end                           ;"
        "   return _                                      ;"
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chord language, fold operator (functional programming):

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constexpr auto _chord_sum_v0()
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    return source
    (
        "main out in end                                    ;"

        "vars:                                              ;"
        "   declare sum                                     ;"

        "defs:                                              ;"
        "   sum # fold[1]{add * @|@ @||} <> [,]             ;"

        "body:                                              ;"
        "   . = sum !out in end                             ;"
        "   return _                                        ;"
    );
}
```

chord language, dot product (functional programming):

```
constexpr auto _chord_dot_product_v0()
{
    return source
    (
        "main out in end in1                                        ;"

        "vars:                                                      ;"
        "  declare dot_prod                                         ;"

        "defs:                                                      ;"
        "  dot_prod # fold[2]{add * @|multiply||} <> [,) [)         ;"

        "body:                                                      ;"
        "  . = dot_prod !out in end in1                             ;"
        "  return _                                                 ;"
    );
}
```

chord language, dot product (functional programming):

```
constexpr auto _chord_dot_product_v0()
{
    return source
    (
        "main out in end in1                                        ;"

        "vars:                                                      ;"
        "   declare dot_prod                                        ;"

        "defs:                                                      ;"
        "   dot_prod # fold[2]{add * @|multiply||} <> [,) [)        ;"

        "body:                                                      ;"
        "   . = dot_prod !out in end in1                            ;"
        "   return _                                                ;"
    );
}
```

chord language, convolution (functional programming):

```
constexpr auto _chord_convolution_v0()
{
    return source
    (
        "main out in end in1                                          ;"

        "vars:                                                        ;"
        "  declare conv                                               ;"

        "defs:                                                        ;"
        "  conv # fold[2]{add * @|multiply||} <> (-|+,] []            ;"

        "body:                                                        ;"
        "  . = conv !out end in in1                                   ;"
        "  return _                                                   ;"
    );
}
```

chord language, convolution (functional programming):

```
constexpr auto _chord_convolution_v0()
{
    return source
    (
        "main out in end in1                                        ;"

        "vars:                                                      ;"
        "   declare conv                                            ;"

        "defs:                                                      ;"
        "   conv # fold[2]{add * @|multiply||} <> (-|+,] []         ;"

        "body:                                                      ;"
        "   . = conv !out end in in1                                ;"
        "   return _                                                ;"
    );
}
```

Performance

Performance at this stage of development is informal.

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With that said, I can still offer some basic stats.

C++17 language, square root (newton's method):

```
template<typename T>
constexpr auto sqrt_iter(T x, T guess) -> T
{
    auto tolerance          = 0.0001;
    auto square             = [](T y){ return y * y; };
    auto abs                = [](T y){ return (y < 0) ? -y : y; };
    auto good_enough        = [&](T g) { return (abs(square(g) - x) < tolerance); };

    auto average            = [](T y, T z){ return (y + z) / 2; };
    auto improve            = [&](T g){ return average(g, x/g); };

    if (good_enough(guess)) return guess;
    else                    return sqrt_iter(x, improve(guess));
}

template<typename T>
constexpr auto sqrt(T x) { return sqrt_iter<T>(x, 1.0); }
```

This isn't a DSL.

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It is standard C++17.

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This is our baseline.

- Compile times:

- Compile times:
  - GCC - 0.100s
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  - GCC - 0.100s
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  - GCC - 16 176 B
  - Clang - 16 104 B

- Compile times:
  - GCC - 0.100s
  - Clang - 0.114s
- Run times:
  - GCC - 0.001s
  - Clang - 0.001s
- -01 binary size:
  - GCC - 16 176 B
  - Clang - 16 104 B
- -02/03 binary size:

- Compile times:
  - GCC - 0.100s
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- -01 binary size:
  - GCC - 16 176 B
  - Clang - 16 104 B
- -02/03 binary size:
  - GCC - 16 128 B
  - Clang - 16 104 B

hustle language, square root (newton's method):

```
constexpr auto _hustle_square_root_v0()
{
  return source
  (
    "(type T                                                                  "
    "  (define (sqrt x)                                                       "

    "    (define (square y) (* y y))                                          "
    "    (define (abs y) (if (< y 0) (- y) y))                                "
    "    (define (good-enough? guess) (< (abs (- (square guess) x)) tolerance)) "
    "    (define (average y z) (/ (+ y z) 2))                                 "
    "    (define (improve guess) (average guess (/ x guess)) )                "
    "    (define (sqrt-iter guess) -> T                                       "
    "      (if (good-enough? guess) guess (sqrt-iter (improve guess)))        "
    "    )                                                                    "

    "    (sqrt-iter 1:T)                                                      "
    "  )                                                                      "
    ")                                                                        "

    , binding("tolerance", 0.0001)
  );
}
```

This is the same function implemented in hustle code.

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- Compile times:
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  - GCC - 0.002s
  - Clang - 0.001s

This is the same function implemented in hustle code.

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  - Clang - 0.001s
- -01 binary size:

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- Compile times:
  - GCC - 1.644s
  - Clang - 2.982s
- Run times:
  - GCC - 0.002s
  - Clang - 0.001s
- -01 binary size:
  - GCC - 17 432 B
  - Clang - 16 624 B

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- Compile times:
  - GCC - 1.644s
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- Run times:
  - GCC - 0.002s
  - Clang - 0.001s
- -01 binary size:
  - GCC - 17 432 B
  - Clang - 16 624 B
- -02/03 binary size:
  - GCC - 16 272 B
  - Clang - 16 632 B

Finally, I have a test suite of 20 chord functions.

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  - GCC - 4.108s
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- Run times:
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  - Clang - 0.002s
- -01 binary size:
  - GCC - 19 320 B
  - Clang - 18 152 B

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  - Clang - 9.004s
- Run times:
  - GCC - 0.002s
  - Clang - 0.002s
- -01 binary size:
  - GCC - 19 320 B
  - Clang - 18 152 B
- -02/03 binary size:
  - GCC - 17 896 B / 17 896 B
  - Clang - 17 320 B / 16 568 B

Roadmap

As previously stated, this project and its library are still proof of concept.

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As such, and to wind down this talk, I offer a roadmap for future directions.

The thing to note is that for as much as this paradigm is stabilizing, there are still open areas of research.

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I'm willing to say the main reason for this is because of the self-similarity of these designs.

This self-similarity creates what I would call a two-tier system.

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The first tier is C++ itself. It has a first tier type system, and mutability semantics, etc.

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The first tier is C++ itself. It has a first tier type system, and mutability semantics, etc.

The second tier is any given DSL, which can potentially have their own type systems, mutability semantics, etc.

For example the C++ compiler offers error messages, but what about the DSLs?

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Also, as there's very little TMP magic in this library, and given that continuation machines have a *step-by-step* nature,

For example the C++ compiler offers error messages, but what about the DSLs?

Currently they do not, but they will.

What's more, you can design for their inclusion the same way you would for any compiler.

Also, as there's very little TMP magic in this library, and given that continuation machines have a *step-by-step* nature, this means that errors at their level are relatively easy to track.

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For example, there may be some new details, but if you already know how assembly works then meta-assembly is largely the same.

With that said, everything has a tradeoff, and there are some disadvantages as well.

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In the realm of context-switching, names matter. This is to prevent confusion and general misunderstanding.

To use assembly as example again, if you say the word “assembly” do you mean hardware or continuation machine?

As for open areas of research, I offer the two-tier type system as example:

The two-tier type system:

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- Metacompiled DSLs are deferentially typed.

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  - What if we want our DSL to have a complete type system of its own?

The two-tier type system:

- Metacompiled DSLs are deferentially typed.
  - They are statically typed, but defer type checking until the constexpr function is built.
  - What if we want our DSL to have a complete type system of its own?
  - How best to negotiate between the tiers?

The two-tier type system [con't]:

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  - DSL variables are untyped, and so you can assign new values of different types to these variables.
  - What safeguards should be set, and how best to do it?

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  - Do we create a second tier of data structures specific to DSL languages?
  - How should they interoperate with compile time C++ more generally?

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For example, the following code does not yet work:

```
constexpr auto _hustle_conditional_operator_v0()
{
	return source
	(
		"(define (main n)          "
		"   ((if (= n 0) + *) 2 3) "
		")                         "
	);
}
```

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  - A data structure generator.
- Use this extended library to research and resolve open problems.

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I have no ideal timeline for resolving these open problems, but I'm *hoping* to code the semiself hosting library, with extensions, within a year.

End

(thank you)

Questions?