Dynamic Compiler Pass Injection for Julia

Jarrett Revels, MIT

First Things First: Hello!

- I’m Jarrett, I work at MIT on Julia
- I’ve authored a bunch of AD packages, some performance tooling packages, and a smattering of other things
- Cassette was originally motivated by AD. I needed to extend Julia at the language-level - existing interfaces were insufficient

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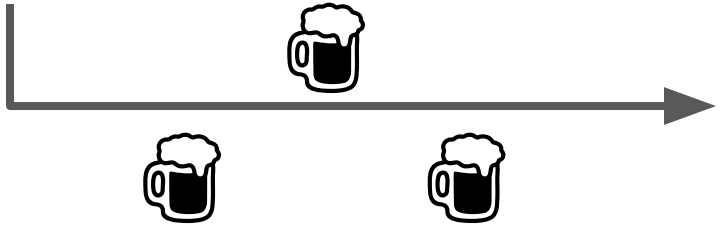
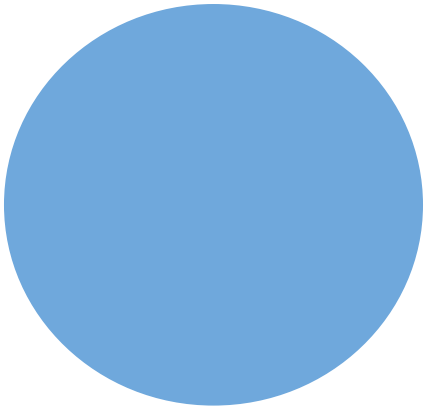
- I owe Jameson Nash several beers



many julia packages try to fit a

peg into a



hole

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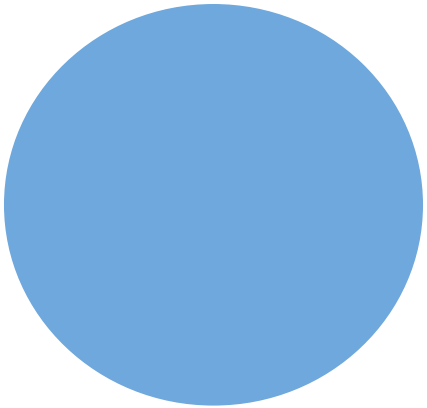


hole

many julia packages try to fit a

peg into a

hole

method overloading

```
immutable Dual{T}
   value::T
   deriv::T
end

sin(d::Dual) =
    Dual(sin(d.value), cos(d.value) * d.deriv)

cos(d::Dual) =
    Dual(cos(d.value), -sin(d.value) * d.deriv)

(+)(a::Dual, b::Dual) =
    Dual(a.value + b.value, a.deriv + b.deriv)

(*)(a::Dual, b::Dual) =
    Dual(a.value * b.value,
         b.value * a.deriv + a.value * b.deriv)
```

nonstandard interpretation

reinterpret a Julia program into the Julia program that calculates the original's derivative

method overloading

```
immutable Interval{T}
    lo::T
    hi::T
end

(+)(x::Interval, y::Interval) =
  Interval(x.lo + y.lo, x.hi + y.hi)

(-)(x::Interval, y::Interval) =
  Interval(x.lo - y.hi, x.hi - y.lo)

(*)(x::Interval, y::Interval) = begin
  a,b,c,d = x.lo*y.lo, x.hi*y.lo, x.lo*y.hi, x.hi*y.hi
  Interval(min(a,b,c,d), max(a,b,c,d))
end
```

nonstandard interpretation

reinterpret a Julia program into the Julia program that calculates rigorous bounds on the original's output

method overloading

```
immutable Track{T}
    value::T
    tape::Vector{Any}
end

function sin(x::Track)
    push!(x.tape, (sin, x))
    Track(sin(x.value), x.tape)
end

function (*)(x::Track, y::Track)
    tape = mergetapes(x.tape, y.tape)
    push!(tape, (sin, x))
    Track(x.value * y.value, tape)
end
```

nonstandard interpretation

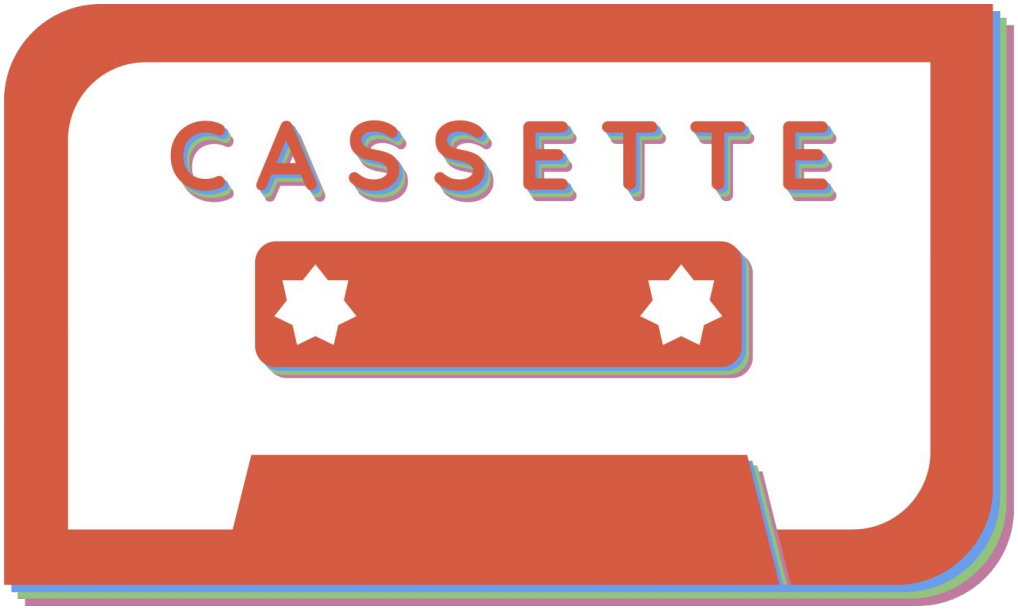
reinterpret a Julia program into the Julia program that produces a linear “instruction tape” for the original

This Approach Stinks

- commonly overloaded methods with multiple arguments will quickly run into ambiguity errors when composing with other packages (potentially load order dependent behavior)

- structural and/or dispatch type constraints in target programs can easily thwart these implementations

- not all relevant language-level mechanisms are exposed via overloadable method calls (e.g. control flow, literals, bindings)



mmm...smells nice

like a warm tape machine or baked bread or something

But what *is* Cassette?

- Cassette allows you to inject your own **code transformation passes** into Julia's JIT compilation cycle, enabling normal Julia packages to **analyze, optimize, and modify Cassette-unaware Julia programs.**

- On top of this pass injection mechanism, Cassette exposes **contextual dispatch**. With Cassette, you can overload arbitrary Julia methods - even builtins like `throw` - by dispatching on hidden "context" type parameters.

- Cassette solves the aforementioned problems by allowing Julia package developers to **arbitrarily redefine the execution of Julia programs within a given "context"**, effectively exposing a nice interface to nonstandard interpretation.

...wat

Example: Simple Logging

```
julia> using Cassette: @context, @prehook, @overdub

julia> @context PrintCtx

julia> @prehook (f::Any)(args...) where {__CONTEXT__<:PrintCtx} = println(f, args)

julia> @overdub(PrintCtx(), sin(1))
sin(1,)
float(1,)
AbstractFloat(1,)
Float64(1,)
sitofp(Float64, 1)
⋮ # skipped for brevity
+(-5.551115123125783e-17, 0.004375208149169746)
add_float(-5.551115123125783e-17, 0.004375208149169746)
+(0.8370957766587268, 0.004375208149169691)
add_float(0.8370957766587268, 0.004375208149169691)
0.8414709848078965
```

Example: Counting Calls

```
julia> using Cassette: @context, @overdub, @prehook

julia> mutable struct Count{T}
           count::Int
       end

julia> @context CountCtx

# Here we are dispatching on the type of the context's
# metadata to define a prehook that increments a counter
# every time one or more arguments of type `T` are
# encountered in the execution trace.
julia> @prehook function (::Any)(arg::T, args::T...)
           where {T,__CONTEXT__<:CountCtx{Count{T}}}
           __context__.metadata.count += 1
       end
```

```
# let's count the number of calls that have
# arguments that are subtypes of `Union{String,Int}`
julia> c = Count{Union{String,Int}}(0)
Count{Union{Int64, String}}(0)

julia> @overdub(CountCtx(metadata = c),
                map(string, 1:10))
10-element Array{String,1}:
 "1"
 "2"
 "3"
 "4"
 "5"
 "6"
 "7"
 "8"
 "9"
 "10"

julia> c
 Count{Union{Int64, String}}(1643)
```

Example: GPU primitives

```
using Cassette: @context, @overdub, @primitive

using CUDAnative, CuArrays

# Define a new context type `GPUCtx`.
@context GPUCtx

# Define some `GPUCtx` "primitives". If, while executing
# code in a GPU context, some method is encountered that
# matches the signature of one of these primitives, that
# method call will dispatch to the primitive definition
# provided here.
@primitive Base.tanh(x::Number) where
      {__CONTEXT__<:GPUCtx} = CUDAnative.tanh(x)
@primitive Base.exp(x::Number) where
      {__CONTEXT__<:GPUCtx} = CUDAnative.exp(x)
```

```
sigm(x) = 1.0 / (1.0 + exp(-x))

function hmlstm_kernel(z, zb, c, f, i, g)
   if z == 1 # FLUSH
       return sigm(i) * tanh(g)
   elseif zb == 0 # COPY
       return c
   else # UPDATE
       return sigm(f) * c + sigm(i) * tanh(g)
   end
end

n = 2048
z, zb = cu(rand(n)), cu(rand(n))
c, f, i, g = ntuple(i -> cu(rand(n, n)), 4)

# execute the given code in a `GPUCtx`.
@overdub(GPUCtx(), hmlstm_kernel.(z, zb, c, f, i, g))
```

Example: Literal Translation

```
using Cassette: @context, @overdub, @pass


is32bit(x) = false
is32bit(x::Integer) = (typemin(Int32) <= x <= typemax(Int32))
is32bit(x::AbstractFloat) = (typemin(Float32) <= x <= typemax(Float32))

to32bit(x::Integer) = convert(Int32, x)
to32bit(x::AbstractFloat) = convert(Float32, x)

@context Bit32Ctx

bit32pass = @pass (sig, codeinfo) -> begin
    # applies the first function to any piece of the
    # IR for which the second function returns `true`
    Cassette.replace_match!(to32bit, is32bit, codeinfo.code)
    return codeinfo
end

z, zb, c, f, i, g = rand(Float32, 6)

@overdub(Bit32Ctx(pass = bit32pass), hmlstm_kernel(z, zb, c, f, i, g))
```

Example: Nested Trace

```
julia> using Cassette: @context, @primitive, @overdub

julia> @context TraceCtx

julia> @primitive function (f::Any)(args...) where {__CONTEXT__<:TraceCtx}
           subtrace = Any[]
           push!(__context__.metadata, (f, args) => subtrace)
           if Cassette.is_core_primitive(__context__, f, args...)
               return f(args...)
           else
               newctx = Cassette.similar_context(__context__, metadata = subtrace)
               return Cassette.overdub_recurse(newctx, f, args...)
           end
       end

julia> trace = Any[]; x, y, z = rand(3);

julia> f(x, y, z) = x*y + y*z;

julia> @overdub(TraceCtx(metadata = trace), f(x, y, z));

julia> trace == Any[(f,(x,y,z)) => Any[
                        (*,(x,y)) => Any[(Base.mul_float,(x,y))=>Any[]]
                        (*,(y,z)) => Any[(Base.mul_float,(y,z))=>Any[]]
                        (+,(x*y,y*z)) => Any[(Base.add_float,(x*y,y*z))=>Any[]]]]
true
```

Nifty. But how does Cassette *work*?

```
@overdub(Ctx(), f(x))
```

```
overdub_recurse(Ctx(), f, x)
```

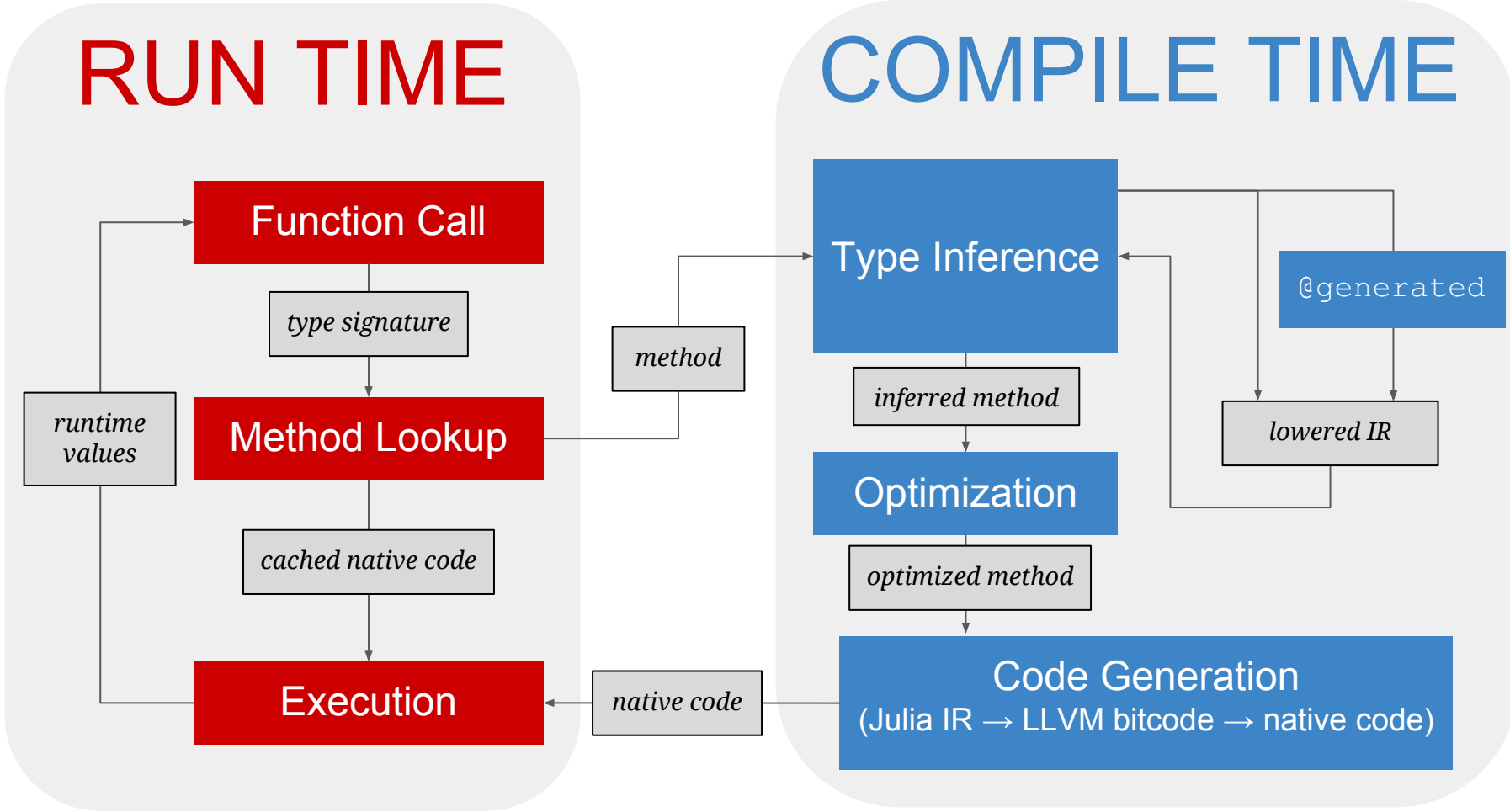
overdub_recurse

```
function f(x)
    T = eltype(x)
    n = length(x)
    result = zero(T)
    oneT = one(T)
    k = 100 * oneT
    for i in 1:n
        tmp1 = oneT - i
        tmp2 = k * tmp1
        result += tmp2
    end
    return result
end
```

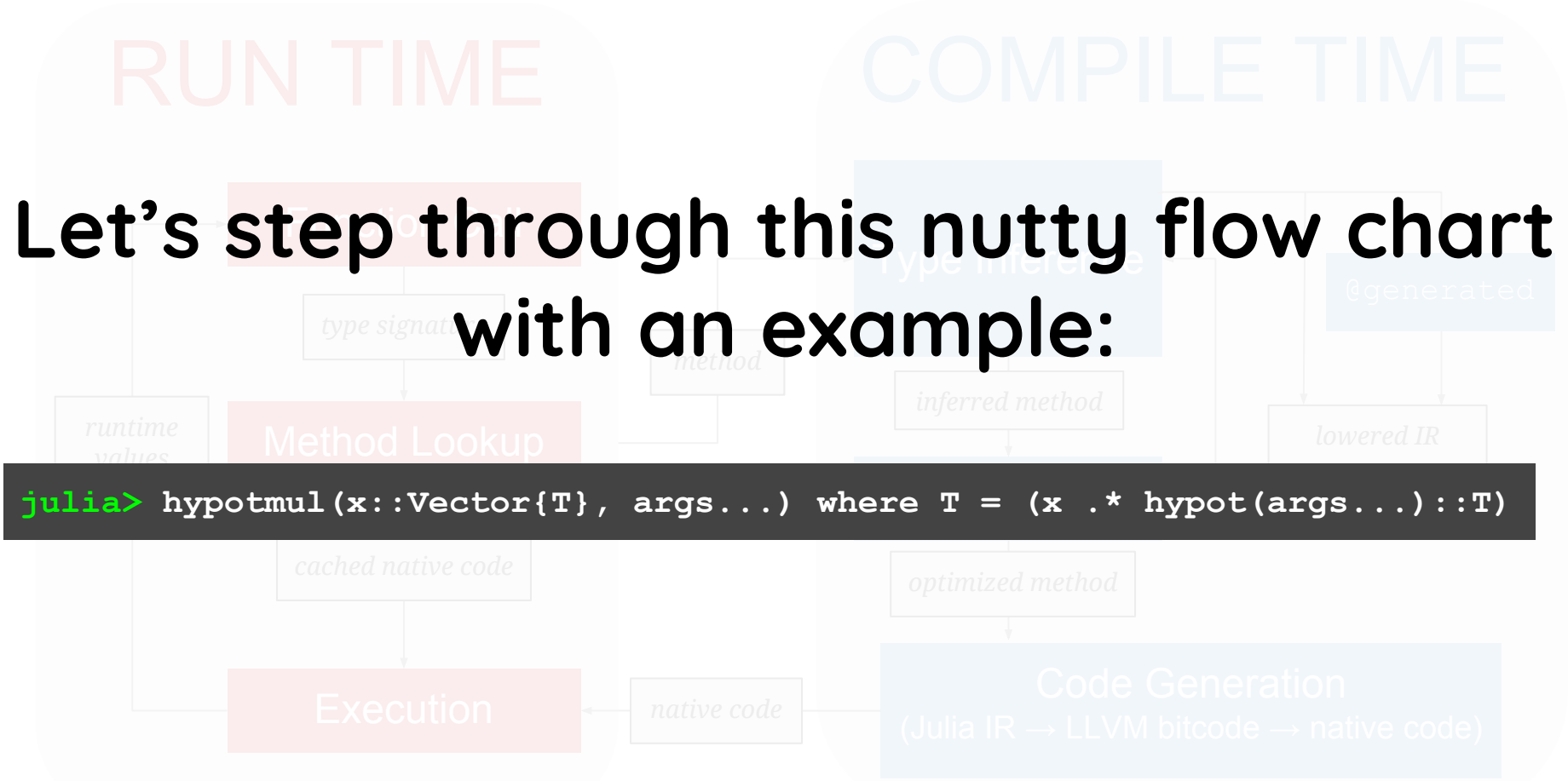
```
function overdub_recurse(ctx, ::typeof(f), x)
    T = overdub_execute(ctx, eltype, x)
    n = overdub_execute(ctx, length, x)
    result = overdub_execute(ctx, zero, T)
    oneT = overdub_execute(ctx, one, T)
    k = overdub_execute(ctx, *, 100, oneT)
    for i in overdub_execute(ctx, :, 1, n)
        tmp1 = overdub_execute(ctx, -, oneT, i)
        tmp2 = overdub_execute(ctx, *, k, tmp1)
        result = overdub_execute(ctx, +, result, tmp2)
    end
    return result
end
```

overdub_execute

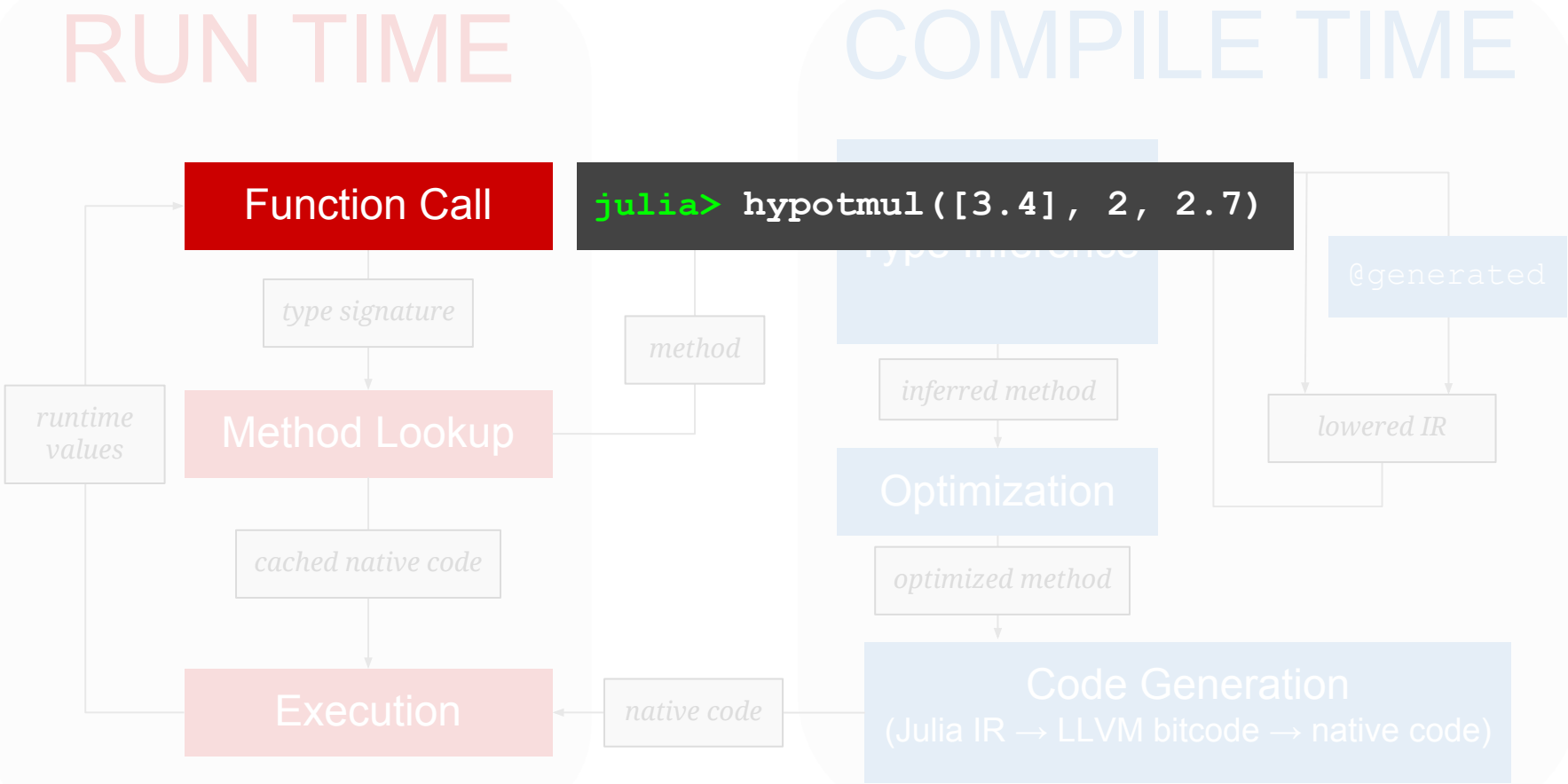
```
function overdub_execute(ctx, f, args...)
    prehook(ctx, f, args...)
    if is_user_primitive(ctx, f, args...)
        output = execution(ctx, f, args...)
    else
        output = overdub_recurse(ctx, f, args...)
    end
    posthook(ctx, output, f, args...)
    return output
end
```


RUN TIME
COMPILE TIME
Function Call
type signature
Method Lookup
cached native code
Execution
runtime values
method
native code
Type Inference
inferred method
Optimization
optimized method
Code Generation
(Julia IR → LLVM bitcode → native code)
@generated
lowered IR

Let’s step through this nutty flow chart with an example:




```
julia> hypotmul(x::Vector{T}, args...) where T = (x .* hypot(args...)::T)
```


RUN TIME
COMPILE TIME
Function Call
julia> hypotmul([3.4], 2, 2.7)
type signature
method
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runtime values
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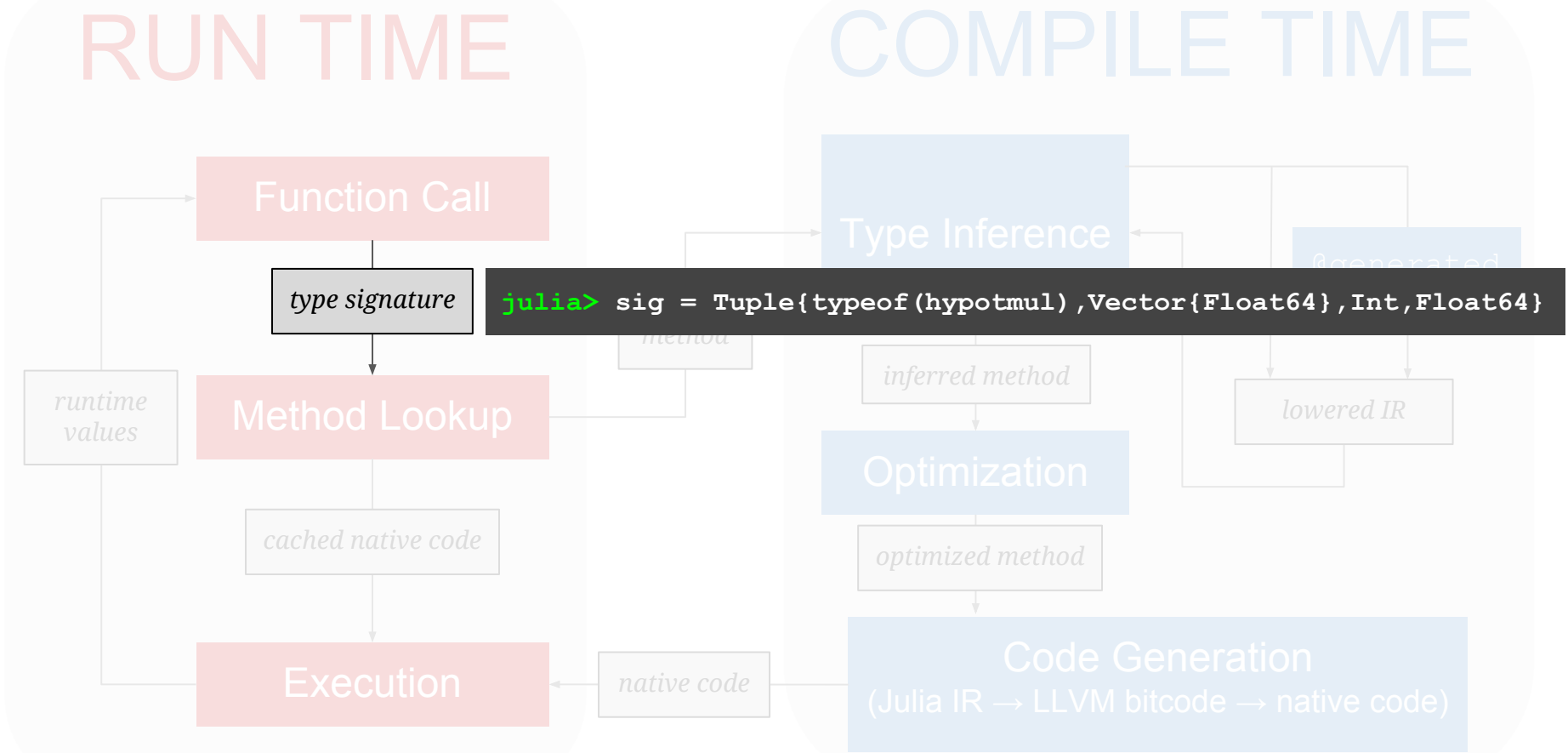
RUN TIME
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julia> sig = Tuple{typeof(hypotmul),Vector{Float64},Int,Float64}
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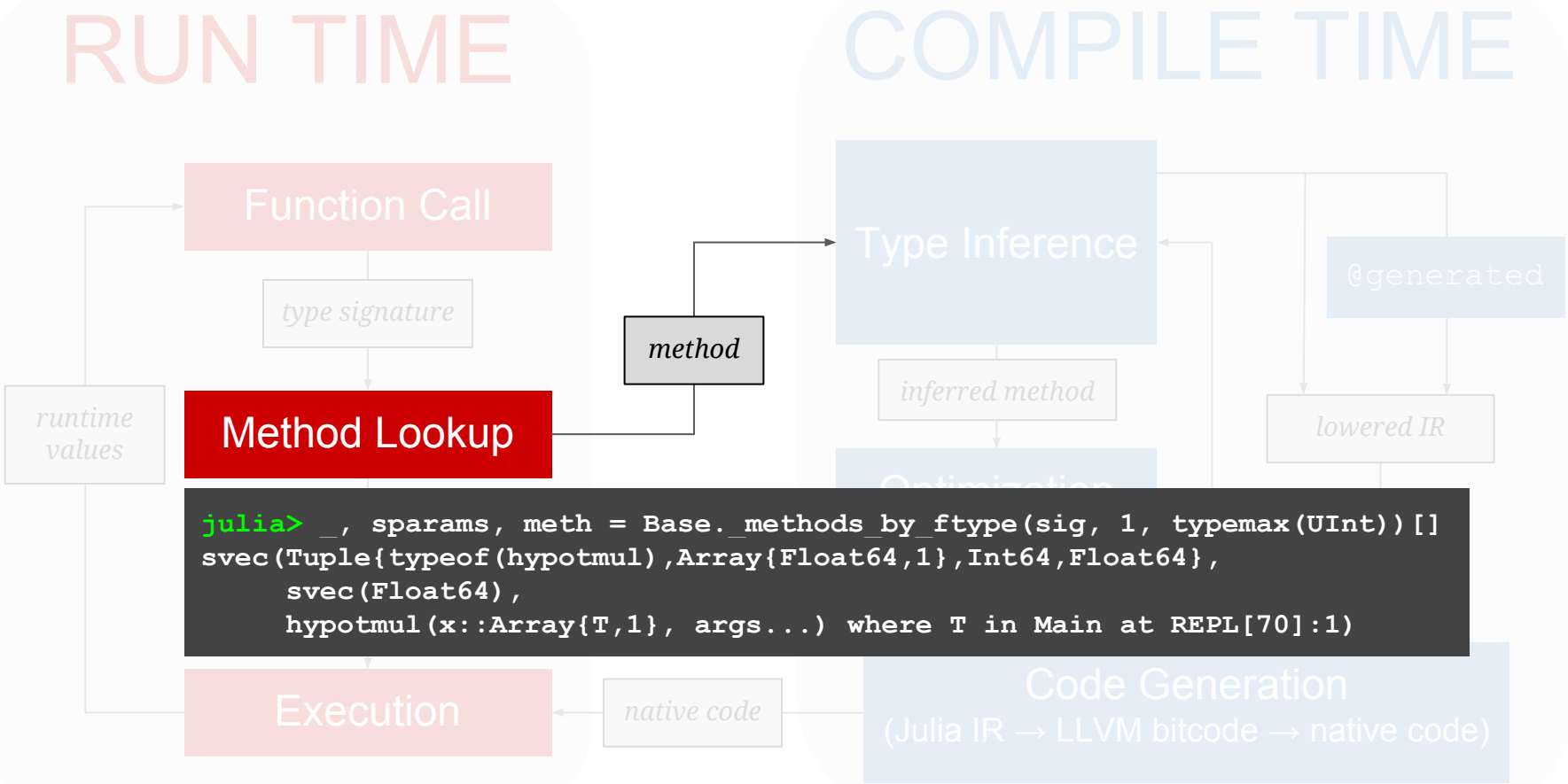
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(Julia IR → LLVM bitcode → native code)
julia> _, sparams, meth = Base._methods_by_ftype(sig, 1, typemax(UInt))[]
svec(Tuple{typeof(hypotmul),Array{Float64,1},Int64,Float64},
svec(Float64),
hypotmul(x::Array{T,1}, args...) where T in Main at REPL[70]:1)

RUN TIME

COMPILE TIME

Function Call

type signature

method

Type Inference

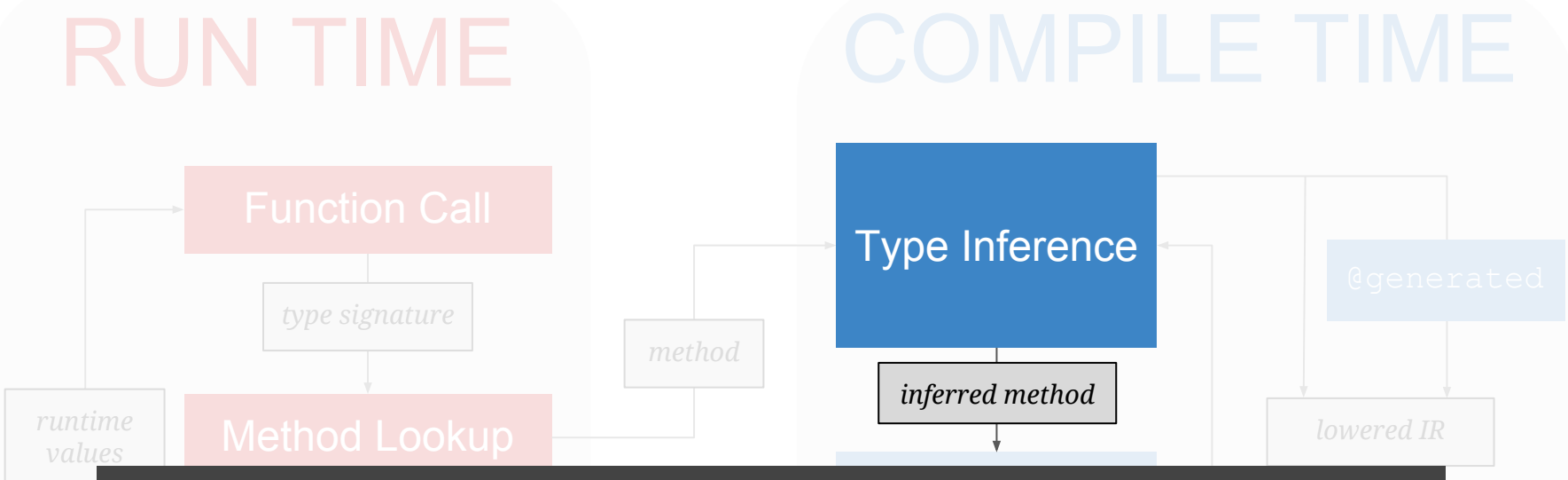
@generated

lowered IR

```
julia> Core.Compiler.uncompressed_ast(meth)
CodeInfo(:(begin
nothing
SSAValue(0)=Base.Broadcast.materialize
SSAValue(1)=Base.Broadcast.broadcasted
SSAValue(2)=(Core._apply)(Main.hypot, args)
SSAValue(3)=(Core.typeassert)(SSAValue(2), $(Expr(:static_parameter, 1)))
SSAValue(4)=(SSAValue(1))(Main.:*, x, SSAValue(3))
SSAValue(5)=(SSAValue(0))(SSAValue(4))
return SSAValue(5)
end))
```

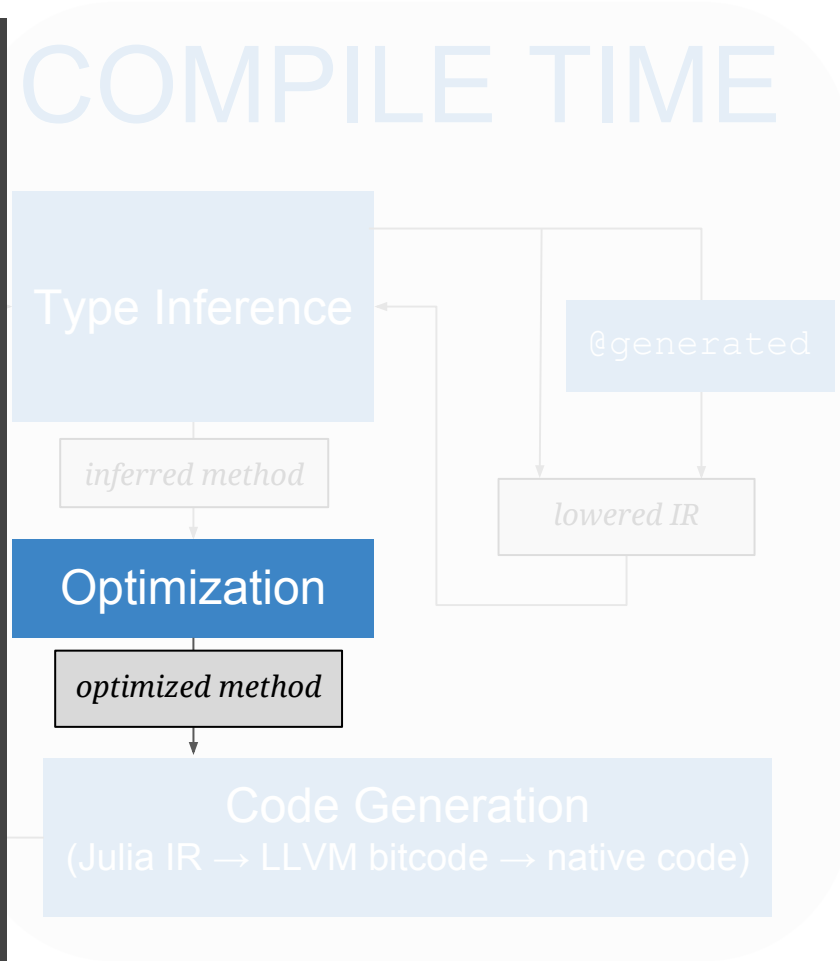
Generation

(Julia IR → LLVM bitcode → native code)




```
julia> code_typed(hypotmul, (Vector{Float64},Int,Float64), optimize=false)[]
CodeInfo(:(begin
nothing
SSAValue(0) = Base.Broadcast.materialize
SSAValue(1) = Base.Broadcast.broadcasted
SSAValue(2) = (Core._apply)(Main.hypot, args)::Float64
SSAValue(3) = (Core.typeassert)(SSAValue(2), $(Expr(:static_parameter, 1)))::Float64
SSAValue(4) = (SSAValue(1))(Main.:*, x, SSAValue(3))::Base.Broadcast.Broadcasted…
SSAValue(5) = (SSAValue(0))(SSAValue(4))::Array{Float64,1}
return SSAValue(5)
end)) => Array{Float64,1}
```

```
julia> code_typed(hypotmul, (Vector{Float64},Int,Float64),
                  optimize=true)[]
CodeInfo(:(begin
(getfield)(args, 1)::Int64
(getfield)(args, 2)::Float64
(Base.sitofp)(Float64, SSAValue(1))::Float64
$(Expr(:invoke, MethodInstance for hypot(::Float64…
⋮
$(Expr(:foreigncall, :(:jl_alloc_array_1d), Array{Float64,1},…
(Base.arraysize)(SSAValue(12), 1)::Int64
⋮
(SSAValue(17) === false)::Bool
unless SSAValue(18) goto 21
goto 22
Core.PhiNode(Any[20, 21], Any[false, true])
goto 24
unless SSAValue(22) goto 111
unless false goto 26
Core.PiNode(false, Bool)
unless SSAValue(26) goto 29
nothing
(SSAValue(12) === x)::Bool
unless SSAValue(29) goto 32
goto 45
$(Expr(:foreigncall, :(:jl_array_ptr), Ptr{Float64},
svec(Any),…
⋮
return SSAValue(12)
end)) => Array{Float64,1}
```



RUN TIME

```
julia> @code_llvm hypotmul([3.4], 2, 2.7)

; Function hypotmul
; Location: REPL[1]:1
define nonnull %jl_value_t addrspace(10)* @julia_hypotmul…
top:
  %gcframe = alloca %jl_value_t addrspace(10)*, i32 3
  %3 = bitcast %jl_value_t addrspace(10)** %gcframe to i8*
  call void @llvm.memset.p0i8.i32(i8* %3, i8 0, i32 24, i32…
  %4 = alloca i64, align 8
  %5 = call %jl_value_t*** inttoptr (i64 4480712320 to…
⋮
```

cached native code

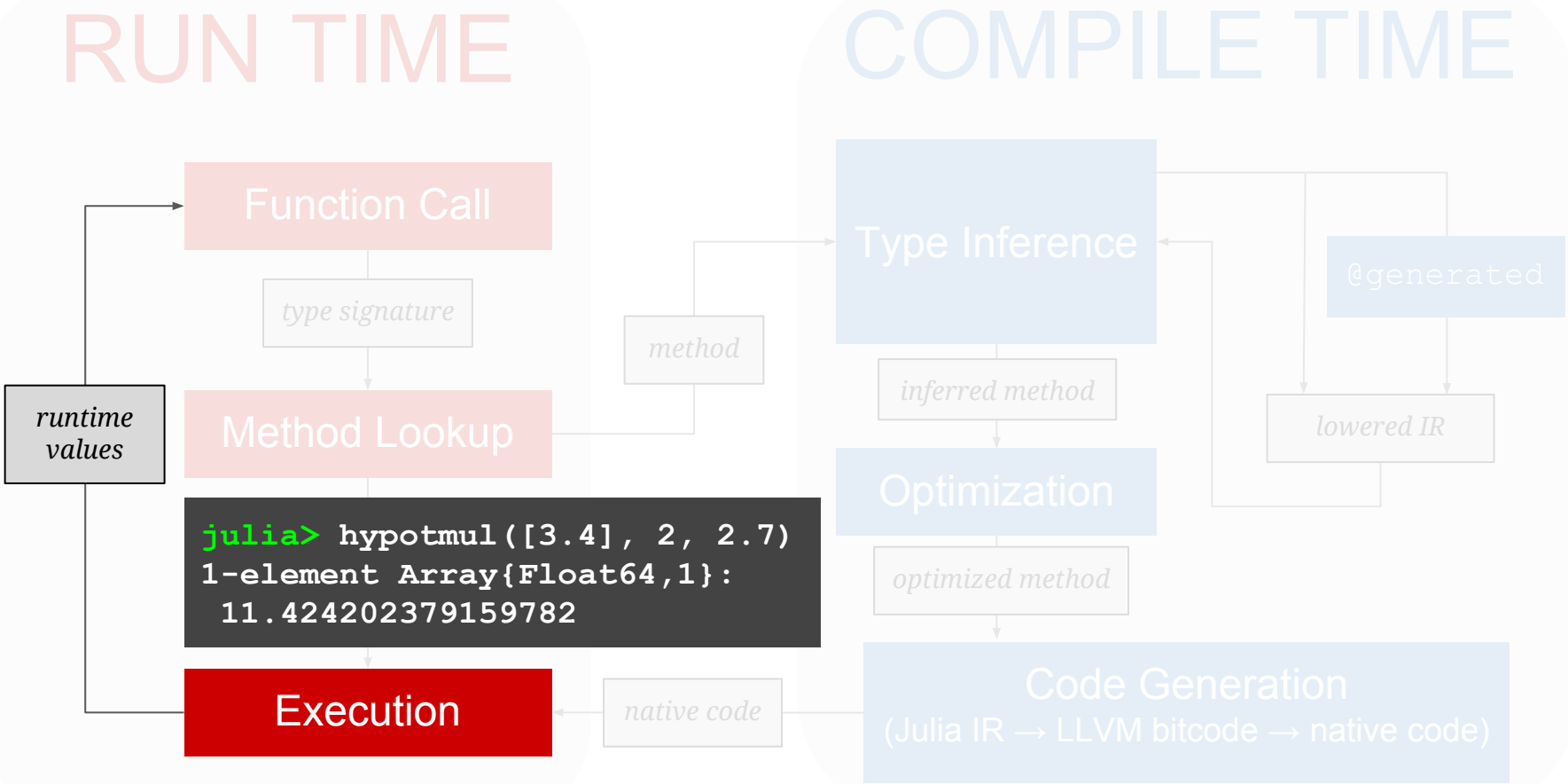
Execution

native code

```
julia> @code_native hypotmul([3.4], 2, 2.7)
        .section        __TEXT,__text,regular …
; Location: REPL[1]:1
        pushq   %rbp
        pushq   %r15
        pushq   %r14
        pushq   %r13
        pushq   %r12
        pushq   %rbx
        subq    $72, %rsp
        vmovsd  %xmm0, 32(%rsp)
        movq    %rsi, %r15
        movq    %rdi, %r12
        movabsq $jl_alloc_array_1d, %r13
        vxorps  %xmm0, %xmm0, %xmm0
        vmovaps %xmm0, (%rsp)
        movq    $0, 16(%rsp)
        leaq    153440(%r13), %rax

⋮
```

optimized method

Code Generation
(Julia IR → LLVM bitcode → native code)


RUN TIME
COMPILE TIME
Function Call
type signature
Method Lookup
runtime values
julia> hypotmul([3.4], 2, 2.7)
1-element Array{Float64,1}:
11.424202379159782
Execution
native code
method
Type Inference
@generated
inferred method
lowered IR
Optimization
optimized method
Code Generation
(Julia IR → LLVM bitcode → native code)

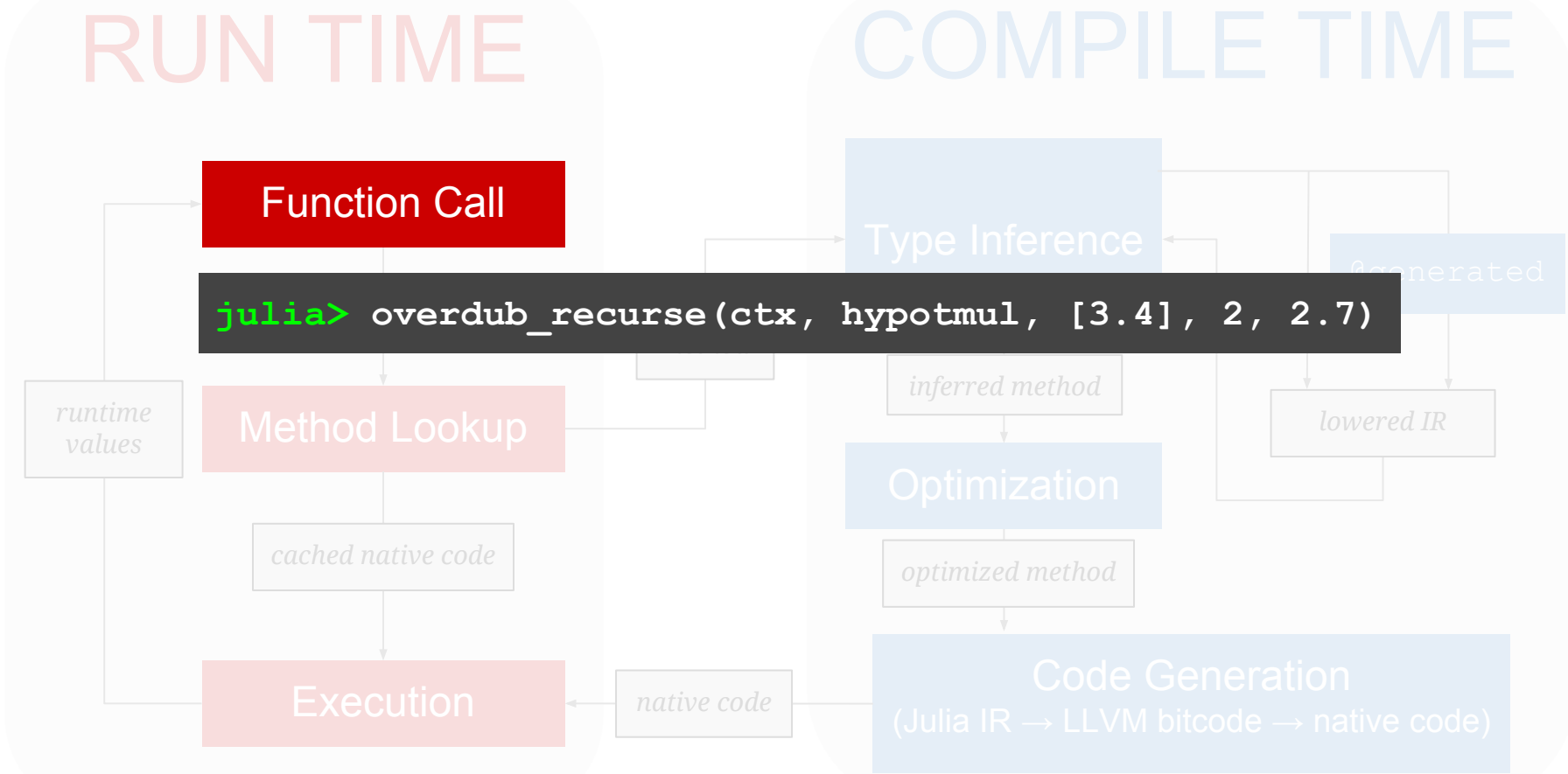
Let's "overdub" our example, and see where the cycle changes:

```
julia> using Cassette: @context, overdub_recurse

julia> @context Ctx # define a new context type

julia> ctx = Ctx();

# execute hypotmul([3.4], 2, 2.7) in our new Cassette context
julia> overdub_recurse(ctx, hypotmul, [3.4], 2, 2.7)
```

Recall our mental model for `overdub_recurse`

```
function f(x)
    T = eltype(x)
    n = length(x)
    result = zero(T)
    oneT = one(T)
    k = 100 * oneT
    for i in 1:n
        tmp1 = oneT - i
        tmp2 = k * tmp1
        result += tmp2
    end
    return result
end
```

```
function overdub_recurse(ctx, ::typeof(f), x)
    T = overdub_execute(ctx, eltype, x)
    n = overdub_execute(ctx, length, x)
    result = overdub_execute(ctx, zero, T)
    oneT = overdub_execute(ctx, one, T)
    k = overdub_execute(ctx, *, 100, oneT)
    for i in overdub_execute(ctx, :, 1, n)
        tmp1 = overdub_execute(ctx, -, oneT, i)
        tmp2 = overdub_execute(ctx, *, k, tmp1)
        result = overdub_execute(ctx, +, result, tmp2)
    end
    return result
end
```


RUN TIME
COMPILE TIME
Function Call
julia> overdub_recurse(ctx, hypotmul, [3.4], 2, 2.7)
Type Inference
generated
inferred method
lowered IR
runtime values
Method Lookup
Optimization
cached native code
optimized method
Execution
native code
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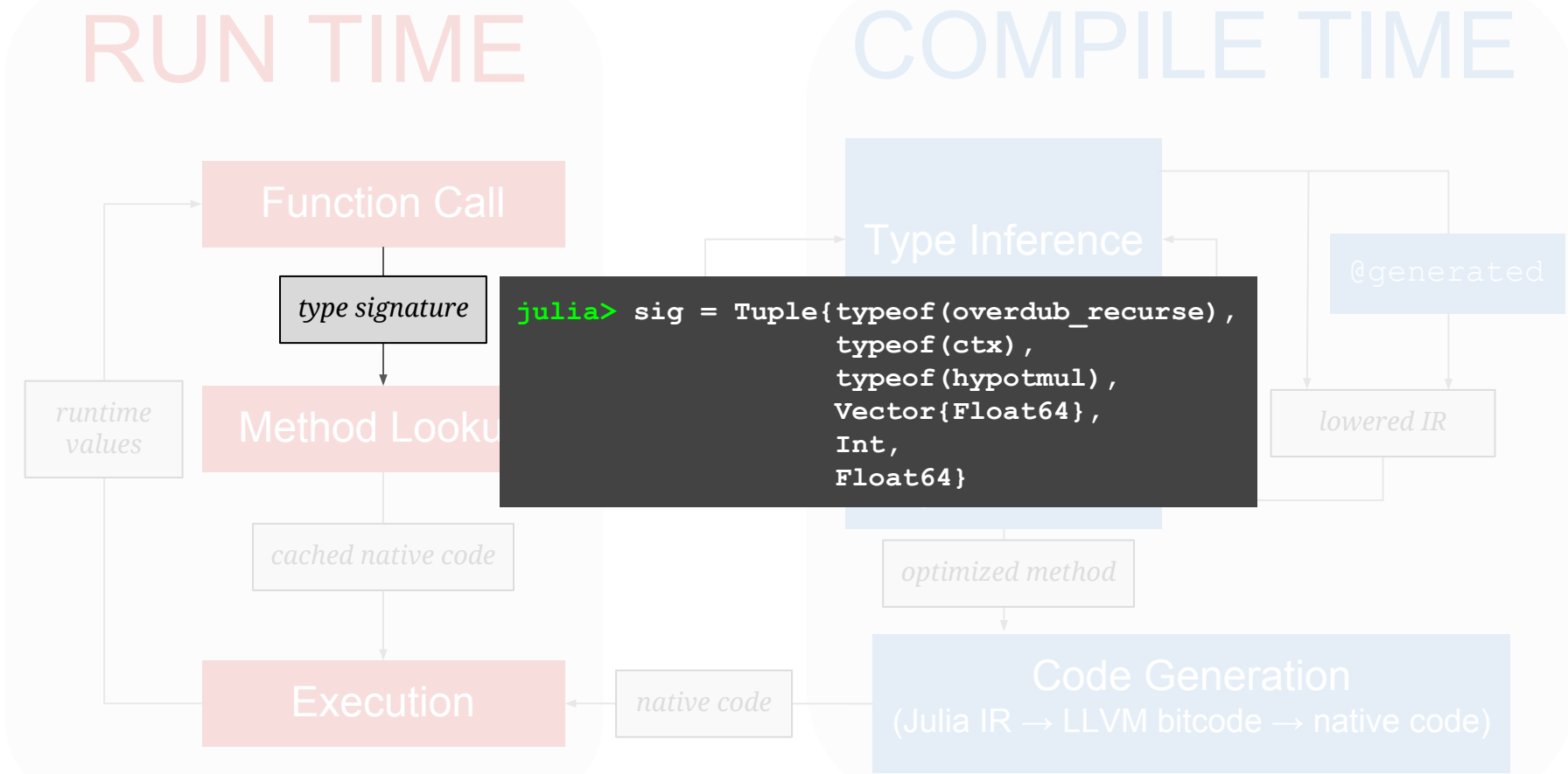
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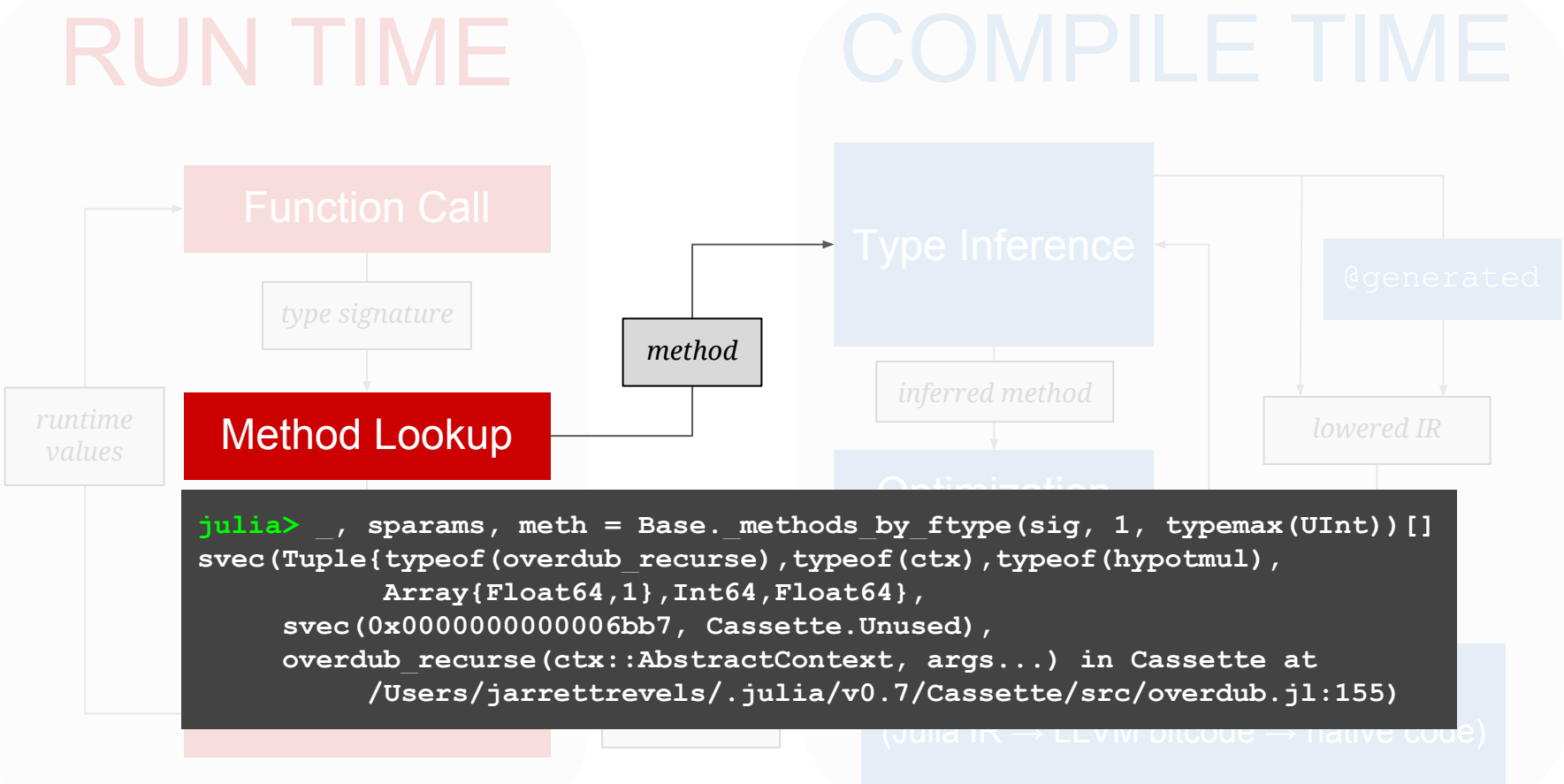
Code Generation
(Julia IR → LLVM bitcode → native code)
julia> sig = Tuple{typeof(overdub_recurse),
typeof(ctx),
typeof(hypotmul),
Vector{Float64},
Int,
Float64}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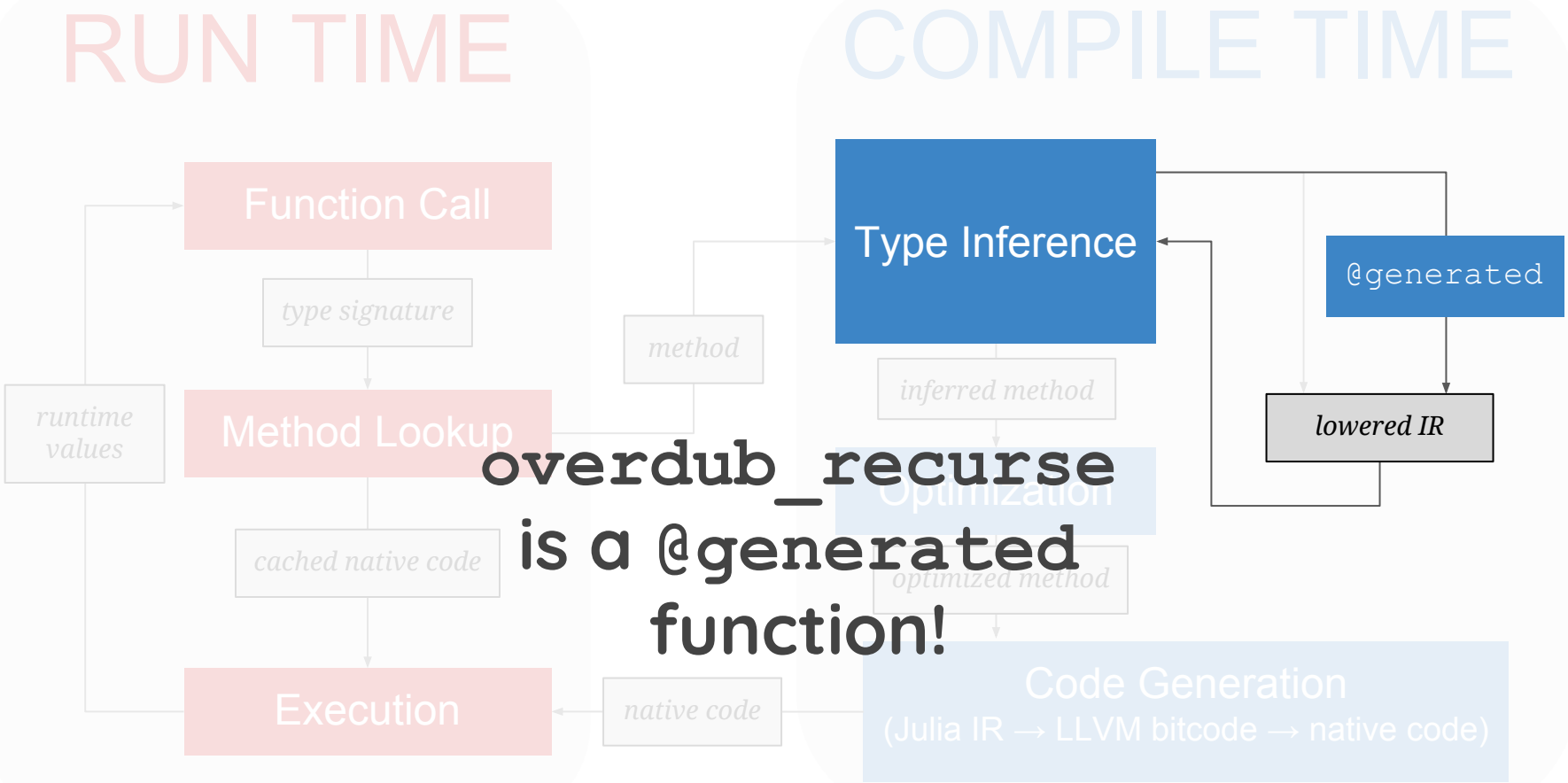
method
Type Inference
inferred method
@generated
lowered IR
julia> _, sparams, meth = Base._methods_by_ftype(sig, 1, typemax(UInt))[]
svec(Tuple{typeof(overdub_recurse),typeof(ctx),typeof(hypotmul),
Array{Float64,1},Int64,Float64},
svec(0x0000000000006bb7, Cassette.Unused),
overdub_recurse(ctx::AbstractContext, args...) in Cassette at
/Users/jarrettrevels/.julia/v0.7/Cassette/src/overdub.jl:155)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Function Call
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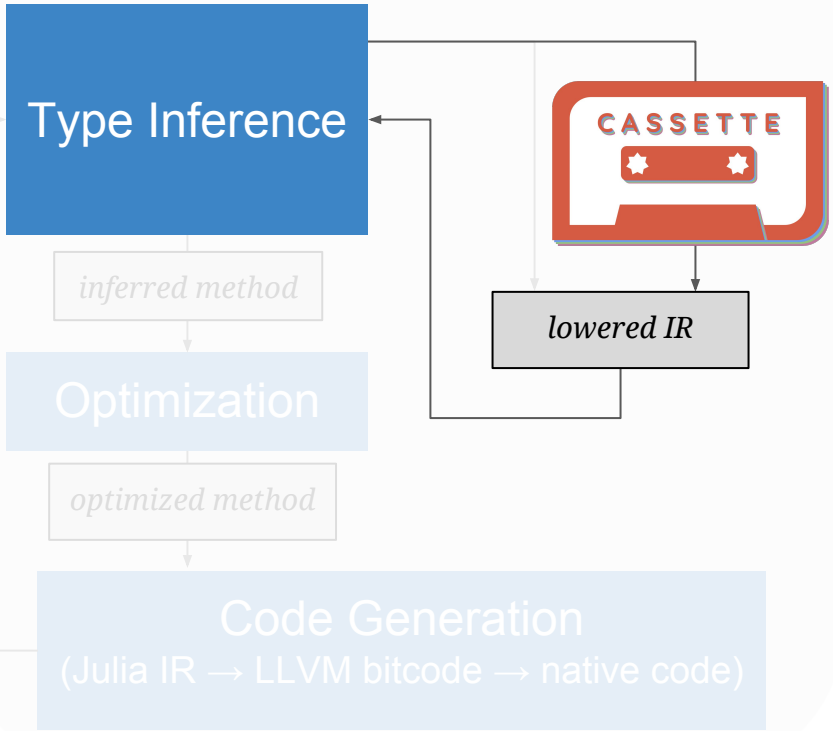
cached native code
Execution
runtime values
method
native code
Type Inference
inferred method
Optimization
optimized method
Code Generation
(Julia IR → LLVM bitcode → native code)
@generated
lowered IR
overdub_recurse is a @generated function!

RUN TIME

COMPILE TIME

```
julia> mi = Core.Compiler.code_for_method(meth,sig,sparams,…
MethodInstance for overdub_recurse(::typeof(ctx),…

julia> mi.def.generator(typemax(UInt), …
CodeInfo(:(begin
nothing
#self#=(Core.getfield)(args, 1)
x=(Core.getfield)(args, 2)
SSAValue(6)=(Core.getfield)(args, 3)
SSAValue(7)=(Core.getfield)(args, 4)
args=(Core.tuple)(SSAValue(6), SSAValue(7))
SSAValue(0)=Base.Broadcast.materialize
SSAValue(1)=Base.Broadcast.broadcasted
SSAValue(2)=(overdub_execute)(ctx, _apply, Main.hypot, args)
SSAValue(3)=(overdub_execute)(ctx, typeassert, SSAValue(2),…
SSAValue(4)=(overdub_execute)(ctx, SSAValue(1), Main.:*, x,…
SSAValue(5)=(overdub_execute)(ctx, SSAValue(0), SSAValue(4))
return SSAValue(5)
end))
```



Defining `overdub_recurse`

```
mutable struct Reflection
    signature::DataType
    method::Method
    static_params::Vector{Any}
    code_info::CodeInfo
end


function reflect(signature::Tuple)::Union{Reflection,Nothing}
    if method_exists(signature)
        method, sparams, cinfo = get_method_and_info(signature)
        return Reflection(signature, method, sparams, cinfo)
    end
    return nothing
end
```

Defining overdub_recurse

```
@generated function overdub_recurse(ctx, args...)
    ref = reflect(args)
    if isa(ref, Reflection) # if we find a method
        pass = pass_type_from_context_type(ctx)
        if pass <: Cassette.AbstractPass # if the user gave us a valid pass
            ref.code_info = pass(ref.signature, ref.code_info)
        end
        replace_calls_with_overdub_execute!(ref)
        body = ref.code_info
    else # if we didn't find a method
        body = quote
            Cassette.execution(ctx, args...)
        end
    end
    return body
end
```

Some details I conveniently omitted

- propagating world ages as type parameters
- pass type definition actually requires overloading the generator
- spoofing inference recursion limiting heuristics

The Future

- expect a Cassette release in the Julia 1.x timeframe; hopefully before JuliaCon 2018.

- Metadata for trace values; I didn't show it off because it's not ready yet, but cool stuff is planned

- Cassette-based tools for AD, GPU transpilation, interval constraint programming

- Julia IR/compiler stdlib?

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