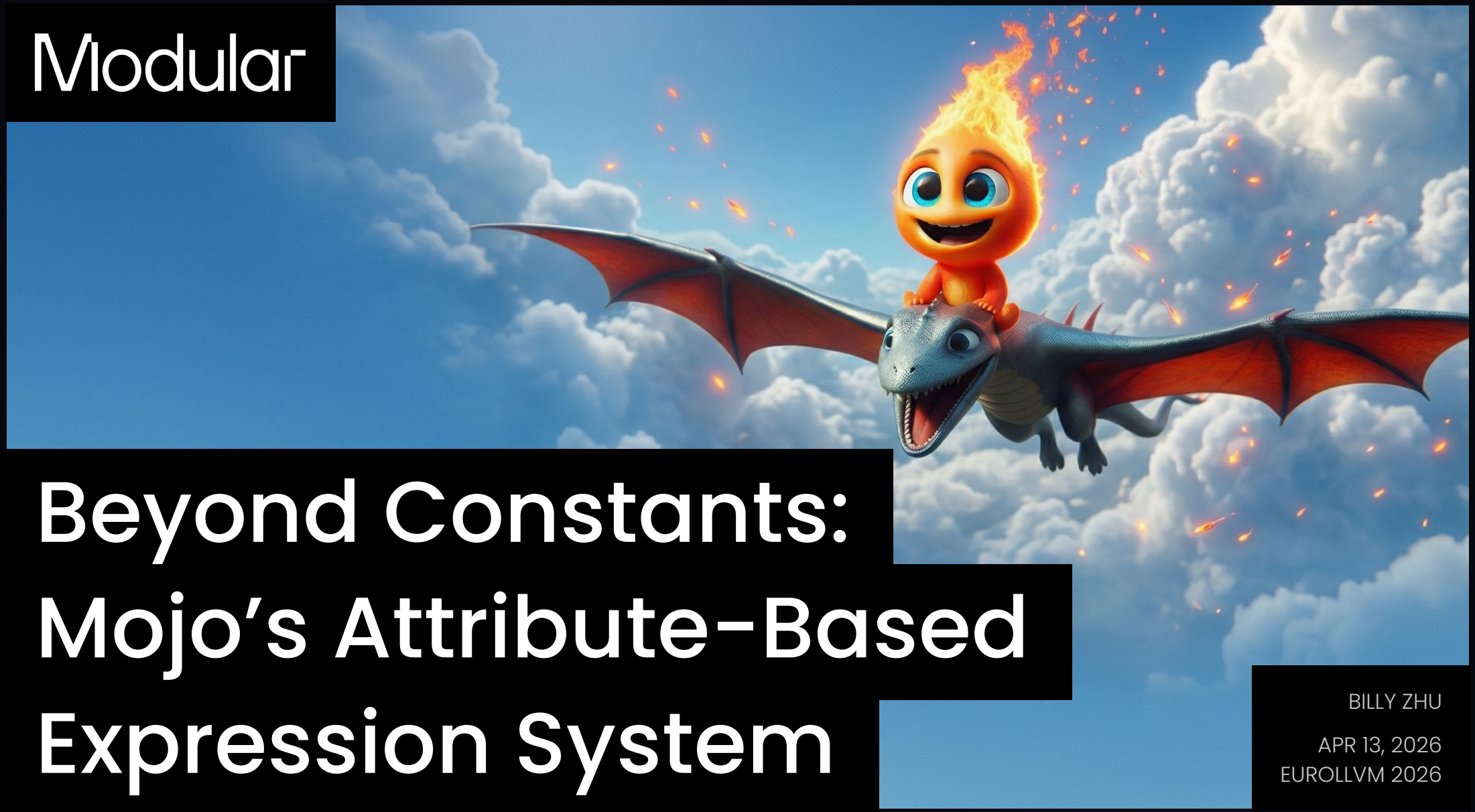
Modular



Beyond Constants: Mojo's Attribute-Based Expression System

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Agenda

01 Brief Mojo Primer

02 The Attribute Language

03 Expression Evaluation

04 How Well Does it Work?

Brief Mojo Primer

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Why Mojo?

Requirement: Needed a **portable systems** programming language for **heterogeneous compute**

Goal: Unlock the full power of the hardware by giving **programmers**:

- low level control
- zero-cost abstractions
- safety guarantees

How: Powerful, type-safe **meta-programming**

🔥Mojo

```
def mandelbrot_kernel[
    width: Int  # SIMD Width
](c: ComplexSIMD[float, width]) ->
    SIMD[int, width]:
    z = ComplexSIMD[float, width](0, 0)
    iters = SIMD[DType.index, width](0)
    for i in range(MAX_ITERS):
        mask = z.squared_norm() <= 4
        iters = mask.select(iters + 1, iters)
        z = z.squared_add(c)
    return iters
```

Meta-Programming

Typed-Checked Generics:
- Write once, checked once

Dependent Types: Parameterize anything
- Parameterize functions, types, and even arbitrary expressions
- Parameterize on types and user-defined structures

Enables powerful **user-defined libraries**:
- Very important for GPU Programming

Simplifies and unifies the language:
- Types are just comptime values
- Removes many special case features in other languages

🔥Mojo

```
# Complex custom datatype
struct Layout:
  var shape: List[Int] # has malloc
  var stride: List[Int]

  @staticmethod
  def col_major(shape: List[Int]) -> Layout:
    return ...

struct LayoutTensor[
  dtype: DType,
  layout: Layout, # Used at comptime
]:

  # Methods can add more parameters too
  def load[width: Int](self, *idx: Int)
      -> SIMD[dtype, width]:
    return ...
```

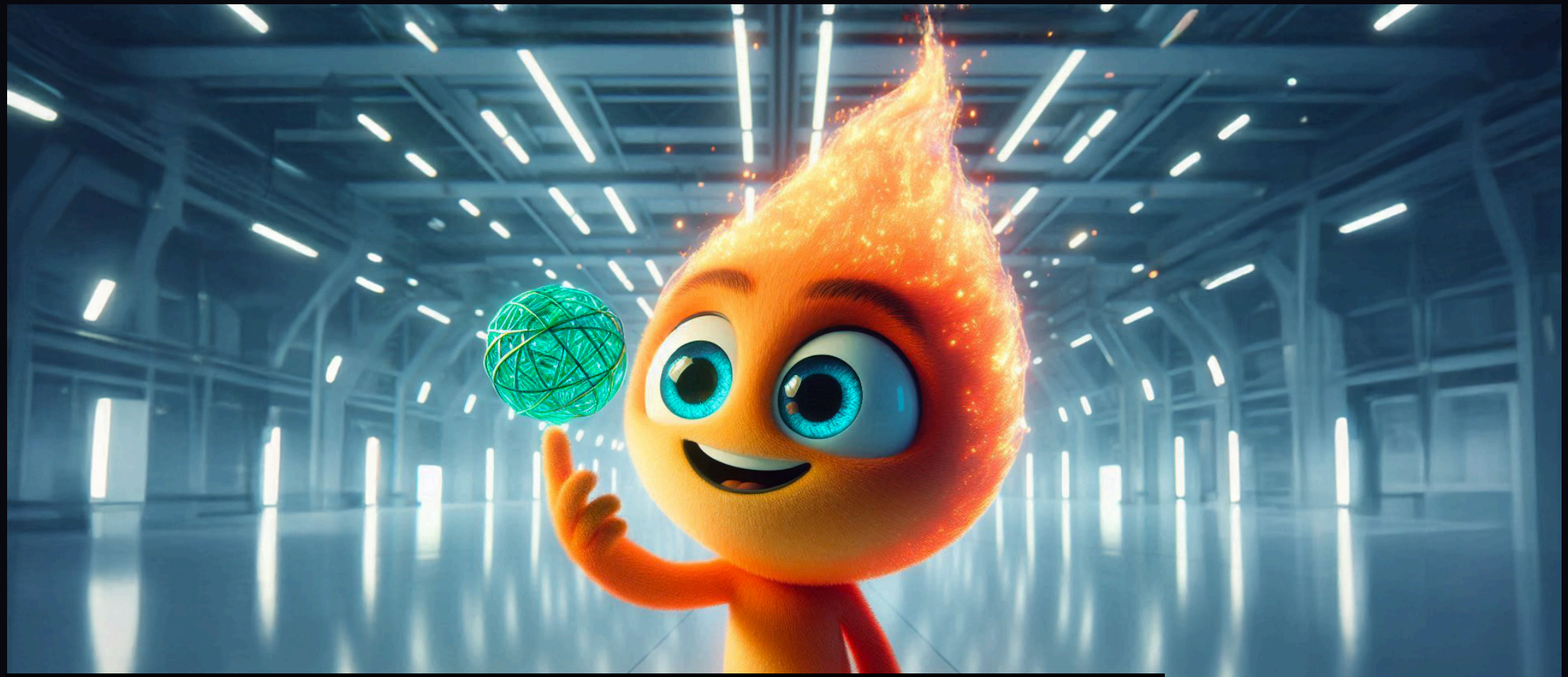
Parametric MLIR

Two-layer Parametric IR in MLIR:

- **Base Layer**: Operations with typed-holes
  - Part of the “execution-time” logic
- **Meta Layer**: Typed-Expressions for filling holes
  - Used to “configure” some base IR operation

Parametric IR

```
lit.fn @simd_sum
  <size: @Int, dtype: @DType>
  (%value: @SIMD<size, dtype>)
    -> @SIMD<1, dtype> {
  ...
  kgen.param.for iter in ... {
    ...
    kgen.param.call @other_fn<size>()
    ...
    kgen.param.if iter {
      ...
      my.param.op { dt = dtype }
      ...
    }
    kgen.deferred {
      name = “hw.specific”,
      attrs = {...} }
  }
  %c = kgen.param.constant = <size>
  ...
}
```



The Attribute Language

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MLIR Attributes

> "Attributes are the mechanism for specifying **constant data on operations** in places where a variable is never allowed - e.g. the comparison predicate of a cmpi operation."
>
> — MLIR LangRef

MLIR Operations defined as parametric "templates"

- E.g. The `cmpi` op is parameterized by an attribute that represents the predicate to use

Definition

TableGen

```
def Arith_CmpIOp
    : Arith_CompareOp<"cmpi", ...> {
  let summary = "integer comparison";
  ...
  let arguments = (ins
    Arith_CmpIPredicateAttr:$predicate,
    SignlessIntegerOrIndexLike:$lhs,
    SignlessIntegerOrIndexLike:$rhs);
}
```

Example

MLIR

```
%x = arith.cmpi eq, %lhs, %rhs
       : vector<4xi64>
```

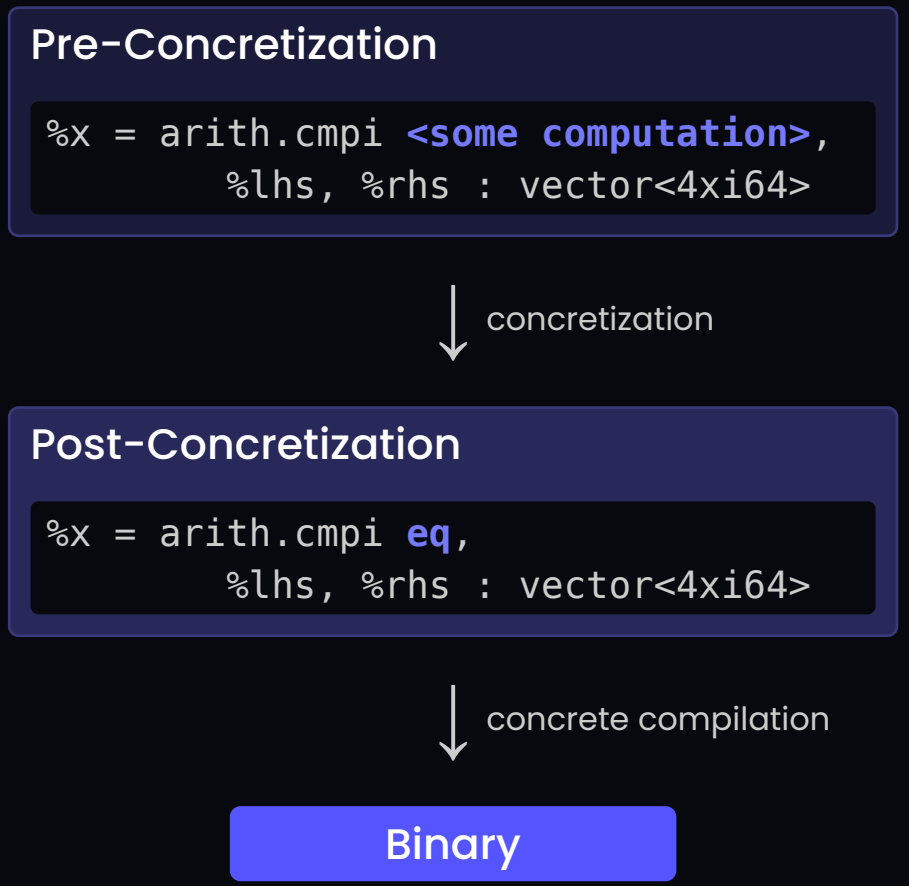
Eventually Constant Attributes

The missing piece:

- Specify the attribute not with a “constant” attribute, but with **some computation** that results in such an attribute

Solution: An expression language that produces attributes for parameterized MLIR Ops

- Not “immediately” constant data, but “eventually” constant data
- Becomes constant over the course of compilation



Mojo's Attribute Language

Attributes can themselves be parameterized by Attributes

Use Attributes to express computation "nodes"

Components:
- Types
- Abstractions
- Extensions

Source

```
(4 - 2) * 3
```

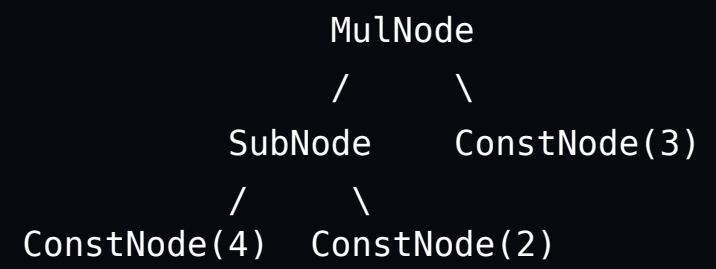
🔥Mojo

Op Repr.

```
%0 = index.constant 4 : index
%1 = index.constant 2 : index
%2 = index.constant 3 : index
%3 = index.sub %0, %1 : index
%4 = index.mul %3, %2 : index
```

MLIR

Attribute Repr.



Typed Expressions

All nodes are typed:

- `TypedAttr` MLIR interface provides `Type getType()`

Types enforce expression well-formedness:

- A leaf attr defines its type intrinsically
- An operator attr defines:
  - Its operand types
  - Its own type
    - May or may not depend on its operands

Operand types are checked via Attribute verifier on construction

Already powerful enough to define grammar rules for a programming language

TableGen

```
def MyStringAttr
    : MyDialect_Attr<"string"> {
  let parameters = (ins
    StringRefParameter<"">:$value);

  let extraClassDeclaration =
    [{ Type getType() const; }];
}

def MyStringConcatAttr
    : MyDialect_Attr<"string.concat"> {
  let parameters = (ins
    "TypedAttr":$lhs,
    "TypedAttr":$rhs);

  let extraClassDeclaration =
    [{ Type getType() const; }];

  let genVerifyDecl = 1;
}
```

Abstractions

`GeneratorType`

- The type of lambdas $(A \to B)$
- … with:
  - Multiple arguments $(A_0, A_1, A_2 \to B)$
  - Dependent abstractions $(\Pi_{x:A} B(x))$

Specify:

- Input parameter types
  - Later parameter types can depend on earlier parameter values
- Result type
  - Can depend on input parameters

```
comptime incr[x: Int] = x + 1
# type: !gen<[x: Int] Int>


comptime add[x: Int, y: Int] = x + y
# type: !gen<[x: Int, y: Int] Int>


comptime id[T: AnyType, x: T] = x
# type: !gen<[T: AnyType, x: T] T>
```

Binders

Inside a `GeneratorType`, reference arguments via De Bruijn indices

`ParamIndexRefAttr`:

- depth: size_t
- index: size_t
- type: Type

Unique representation: Avoid variable naming problems

```
comptime incr[x: Int] = x + 1
# type: !gen<[Int] Int>


comptime add[x: Int, y: Int] = x + y
# type: !gen<[Int, Int] Int>


comptime id[T: AnyType, x: T] = x
# type: !gen<[AnyType, *(0,0)] *(0,0)>
```

Binder Depths

Inside a `GeneratorType`, reference arguments via De Bruijn indices

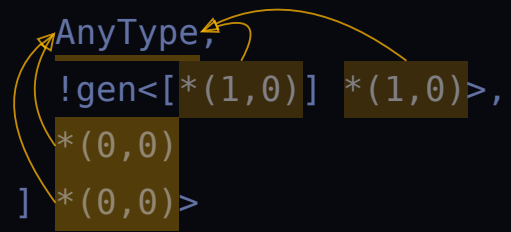
`ParamIndexRefAttr`:

- depth: size_t
- index: size_t
- type: Type

Unique representation: Avoid variable naming problems

```mojo
comptime id[T: AnyType, x: T] = x
# type: !gen<[AnyType, *(0,0)] *(0,0)>

comptime id2[
  T: AnyType,
  f: type_of(id[T]),
  v: T
]: T = f[v]
# type: !gen<[
#         AnyType,
#         !gen<[*(1,0)] *(1,0)>,
#         *(0,0)
#       ] *(0,0)>
```



Abstractions

`GeneratorAttr`

- A constructor of `GeneratorType`

Specify:

- Input parameter types
- Result type
- Body attribute

```
comptime incr[x: Int] = x + 1
# type : !gen<[Int] Int>
# value: #gen<add<*(0,0), 1>>

comptime add[x: Int, y: Int] = x + y
# type : !gen<[Int, Int] Int>
# value: #gen<add<*(0,0), *(0,1)>>

comptime id[T: AnyType, x: T] = x
# type : !gen<[AnyType, *(0,0)] *(0,0)>

# value: #gen<*(0,0)>
```

Leveraging MLIR Extensibility

Expand our core calculus with extensions, organized by MLIR dialects

A dialect can define:
- Custom Types
- Type constructors/eliminators as Attributes

Examples:
- From upstream:
  - `index` Type
  - `IntegerAttr`: constants for `index`
- Locally:
  - `simd` Type
  - `SIMDAttr`: constants for `simd`
  - `SIMDCmpAttr`: `(simd<dtype, size>, simd<dtype, size>) -> simd<bool, size>`

Expression Evaluation

Modular

Evaluation Exercise

Fold:

- `1 + (2 * 3)`
- `add<1, mul<2, 3>>`

Want to reduce it into the constant attribute `7`

Evaluation Exercise

Fold:

- `1 + (2 * 3)`
- `add<1, mul<2, 3>>`

Want to reduce it into the constant attribute `7`

Rewrite rule in the constructors

- If both operands are constants, emit a constant attribute instead of an operator attribute

Evaluation Exercise 2

Given:

- `comptime add_gen[x: index, y: index] = x + y`
- `#add_gen: !gen<<index, index> index> = #gen<add<*(0,0), *(0,1)>>`

Fold:

- `add_gen[2, 3]`
- `#bind_params<#add_gen, 2, 3>`

Evaluation Exercise 2

Given:

- `comptime add_gen[x: index, y: index] = x + y`
- `#add_gen: !gen<<index, index> index> = #gen<add<*(0,0), *(0,1)>>`

Fold:

- `add_gen[2, 3]`
- `#bind_params<#add_gen, 2, 3>`

Reach for the AttrTypeReplacer:

- On `ParamIndexRefAttr`, replace with the corresponding input attribute
- The `add` attribute constructor will automatically kick in

All good?

Depth-Aware

AttrTypeReplacer:
- Powerful: Generic over all attributes
- Efficient: Caches replacements

Problem: Binder replacement is context-dependent

Depth-aware walk:
- Track how many abstraction scopes we have entered
  - None: Replace `*(0, i)`
  - 2: Replace `*(2, i)`

Depth-aware replacement cache:
- Key on walk depth

~30% attr/types hit the cache

Context-Aware

Context external to the attribute expression

Symbol lookup:

- Symbol references are also just attributes

Use cases:

- Invoke a function op
- Lookup witness table for a type's conformance to a trait

MLIR

```
// Symbol op
kgen.generator @ceildiv(
  x: Float32, y: Float32) -> Float32 {
    ...
}

// Attribute Expression
#attr = apply<@ceildiv, 5.0, 2.0>
  : scalar<f32>
```

EvaluationContext

Custom evaluation context for looking up external information

Context-Aware evaluation AttrInterface:

- `evaluateWithContext(EvaluationContext&).`

EvaluationContext interface:

- Lookup functions
- Lookup type definitions

Enables:

- More efficient repr.
- Invoke function ops (base IR) from attributes (meta IR)
  - Wednesday 11am: *Mojo Compile-time Interpreter in MLIR* - Weiwei Chen

MLIR

```
// Symbol op
kgen.generator @ceildiv(
  x: Float32, y: Float32) -> Float32 {
    ...
}

// Attribute Expression
#attr = apply<@ceildiv, 5.0, 2.0>
  : scalar<f32>
```

How Well Does it Work?

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Compile Time

Folding:

- Construction-time folding for non-leaf attrs
- Explicit folding when substituting parameters

mojo build time

Memory Footprint

Immortal Attributes & Types

max RSS


Thank You
Acknowledgement: Mojo Compiler Team @ Modular