Modular

Mojo Debugging

Extending MLIR & LLDB for new languages

Agenda

01	Mojo 🔥
02	Extending LLDB
03	DebugInfo in MLIR

01

Mojo 🔥

Mojo 🔥 at a glance

Pythonic system programming language

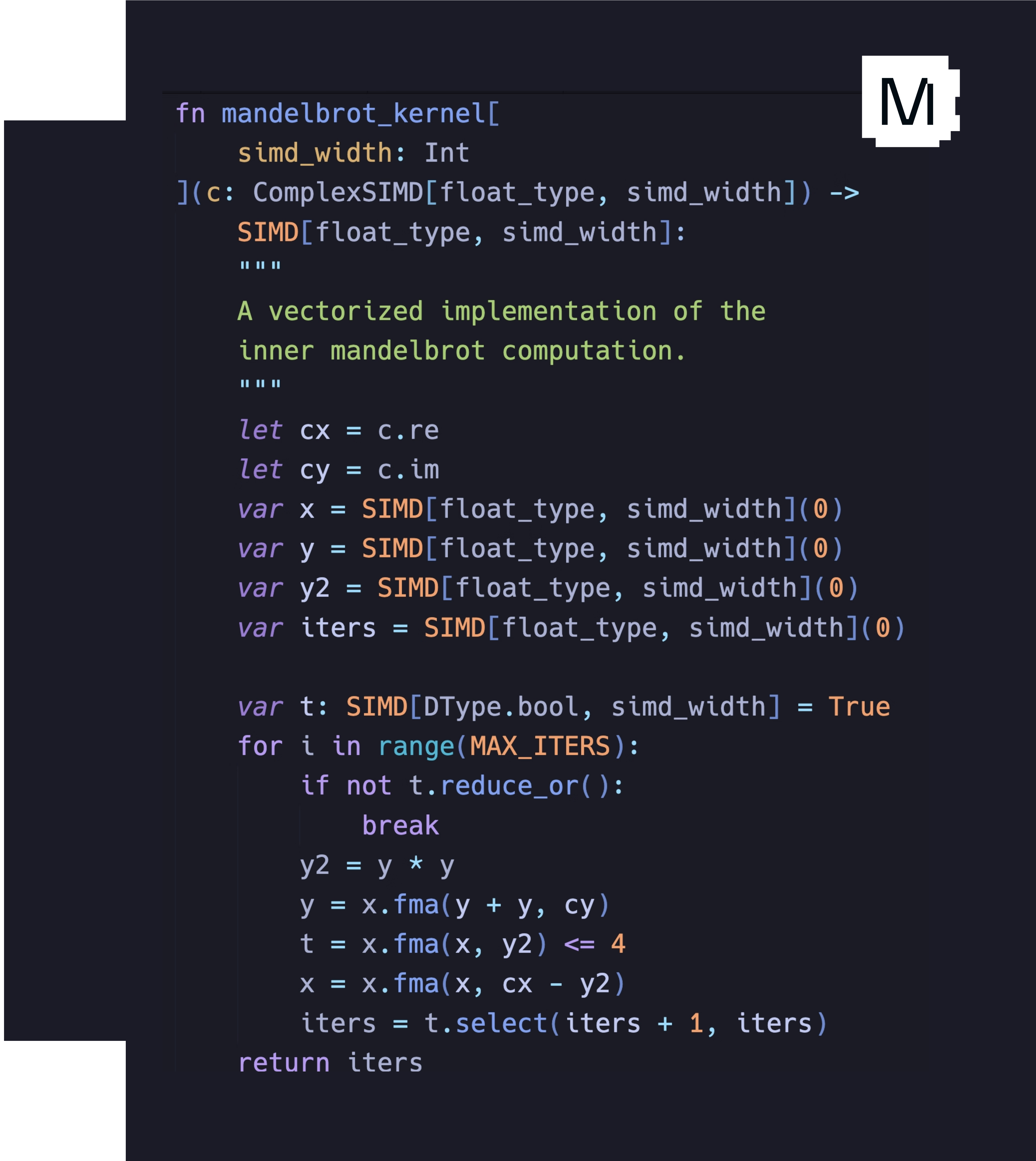
- Driving SoTA in compiler and language design
- Forget everything you know about Python! :-)

One year old and still in development

- Freely available on Linux, Mac and Windows
- Full LLVM-based toolchain + VSCode LSP support
- Powers CPU and GPU AI programs written in the same language

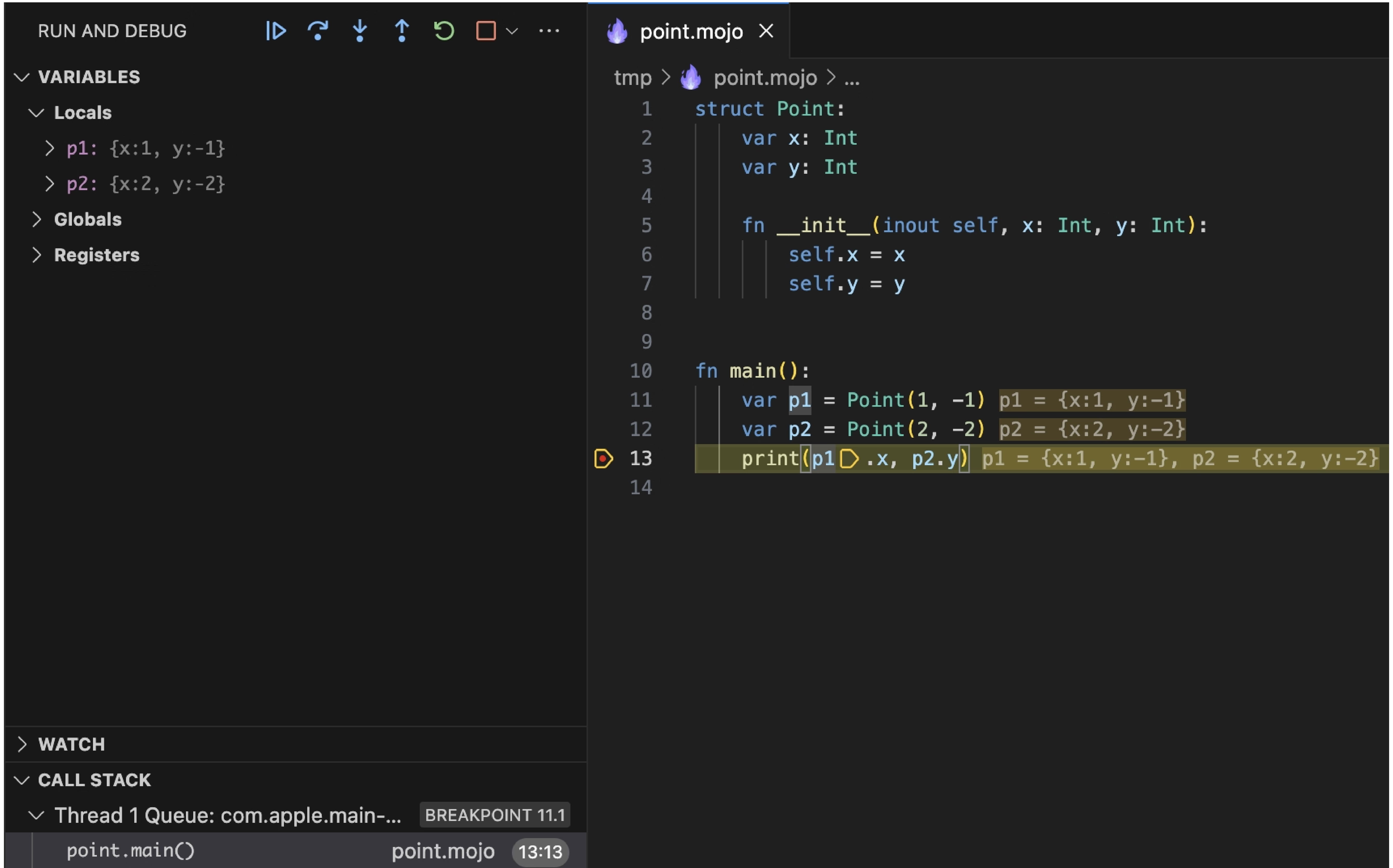
Available now

- modular.com



```
fn mandelbrot_kernel[
    simd_width: Int
](c: ComplexSIMD[float_type, simd_width]) ->
    SIMD[float_type, simd_width]:
    """
    A vectorized implementation of the
    inner mandelbrot computation.
    """
    let cx = c.re
    let cy = c.im
    var x = SIMD[float_type, simd_width](0)
    var y = SIMD[float_type, simd_width](0)
    var y2 = SIMD[float_type, simd_width](0)
    var iters = SIMD[float_type, simd_width](0)

    var t: SIMD[DType.bool, simd_width] = True
    for i in range(MAX_ITERS):
        if not t.reduce_or():
            break
        y2 = y * y
        y = x.fma(y + y, cy)
        t = x.fma(x, y2) <= 4
        x = x.fma(x, cx - y2)
        iters = t.select(iters + 1, iters)
    return iters
```

And now it has a debugger! 🔥

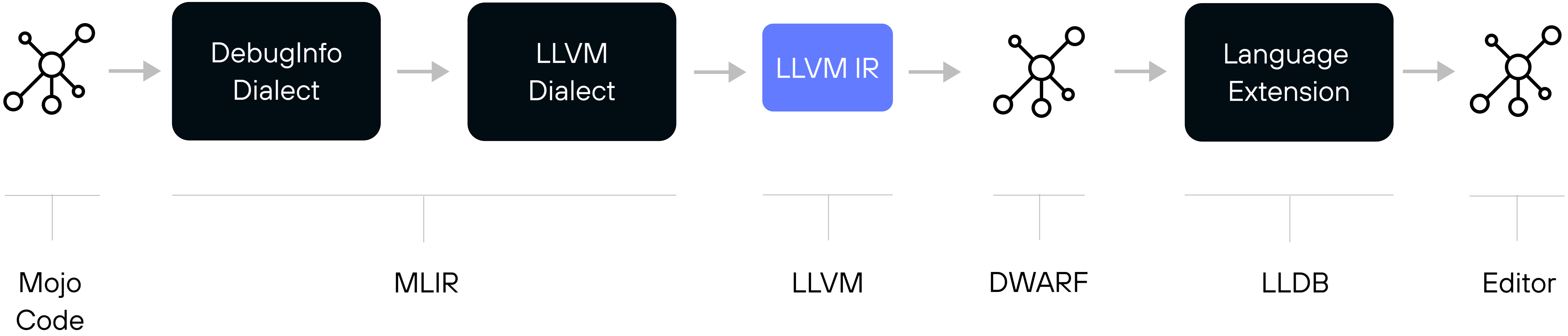


```
p1: {x:1, y:-1}
p2: {x:2, y:-2}
```

```
Thread 1 Queue: com.apple.main-...   BREAKPOINT 11.1
point.main()   point.mojo   13:13
```

```
struct Point:
    var x: Int
    var y: Int

    fn __init__(inout self, x: Int, y: Int):
        self.x = x
        self.y = y


fn main():
    var p1 = Point(1, -1) p1 = {x:1, y:-1}
    var p2 = Point(2, -2) p2 = {x:2, y:-2}
    print(p1.x, p2.y) p1 = {x:1, y:-1}, p2 = {x:2, y:-2}

```

Mojo Debugging



DebugInfo Dialect

LLVM Dialect

LLVM IR

Language Extension

Mojo Code

MLIR

LLVM

DWARF

LLDB

Editor

02

Extending LLDB

Supporting Mojo in LLDB

- LLDB doesn't have first class support for non-clang based languages.

Supporting Mojo in LLDB

- Some previous experiences:

    - Fork LLDB (e.g. swift)
        - Maintenance pain
        - Compiler integration
            - Expr eval
            - Conditional breakpoints
            - IR-based features

Supporting Mojo in LLDB

- Some previous experiences:

    - Pretend to be C++ (e.g. go-lldb)
        - Very buggy experience...

Supporting Mojo in LLDB

- Some previous experiences:

  - Limit to pretty printing (e.g. rust-lldb)
    - No compiler integration
    - Very limited expr eval
    - No cool features

Full compiler integration via a runtime plugin

Vanilla LLDB

- `> plugin load libMojoLLDB.so`

Full compiler integration via a runtime plugin

Problems:

- LLDB didn't export all internal symbols
  - Needed by our DWARF parser
- Core LLDB assumed all languages are clang-based

Full compiler integration via a runtime plugin

Major upstream changes

- Namespaced internal plugin symbols
    - E.g. lldb_plugin::dwarf
- Selective export of private symbols via CMake (PR 68013)
- Removed assumptions on clang
    - Arbitrary typesystems

Current status of the debugger

Linux + MacOS
JIT + AOT debugging
Variable printing
Stepping
Breakpoints
REPL / Jupyter Notebooks

Coming soon:
Expression evaluation
REPL debugging
Windows support
Smart formatters
Better inline support

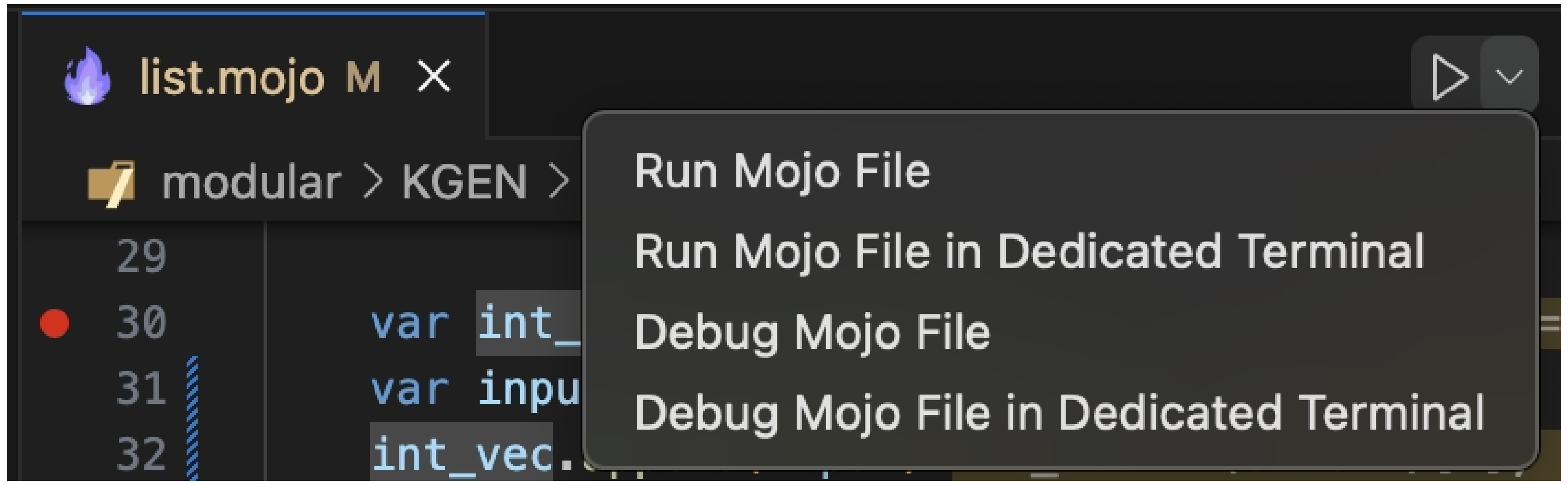
Debug adapter protocol

Modern interface for IDE integration

- VS Code, Visual Studio, Eclipse, Vim, Emacs, etc.
- lldb-dap

lldb-dap / VS Code-first

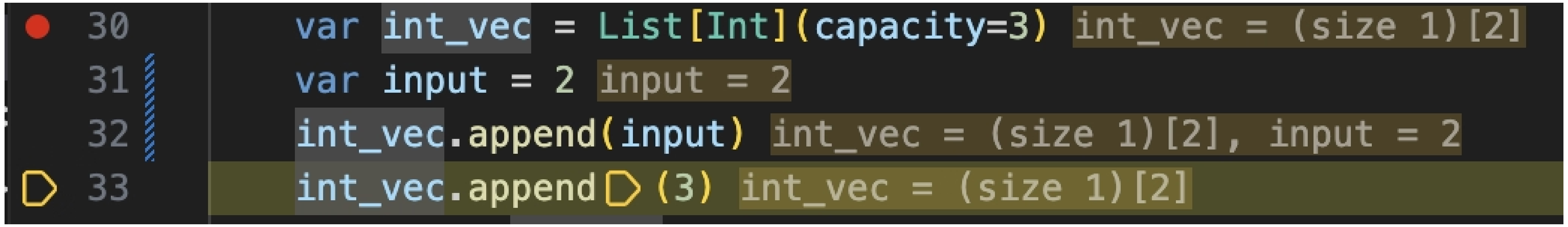
- UX focused
- Lower learning curve



Two-click JIT debugging

Extending the debug adapter protocol

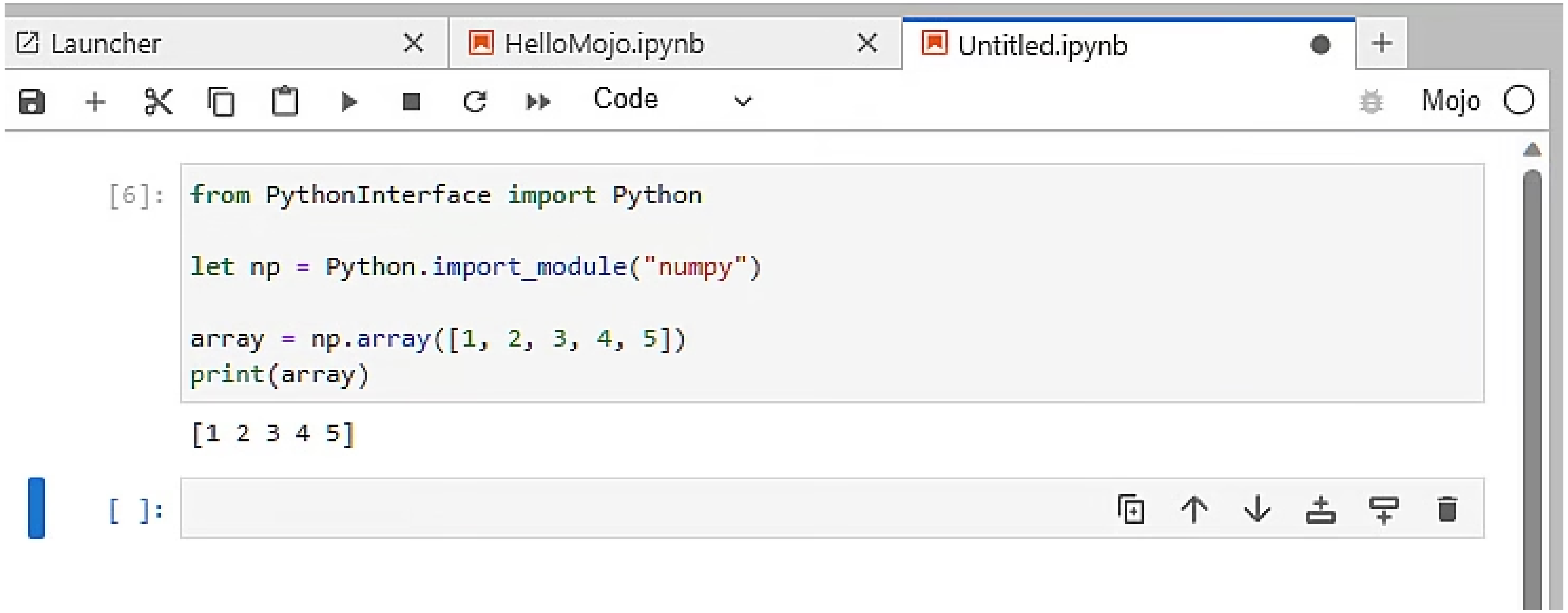
Richer variable metadata for nicer features



```
    var int_vec = List[Int](capacity=3) int_vec = (size 1)[2]
    var input = 2 input = 2
    int_vec.append(input) int_vec = (size 1)[2], input = 2
    int_vec.append(3) int_vec = (size 1)[2]
```

Inline variables: talking to the LSP

Future work - notebook debugging



```
from PythonInterface import Python

let np = Python.import_module("numpy")

array = np.array([1, 2, 3, 4, 5])
print(array)
```

```
[1 2 3 4 5]
```

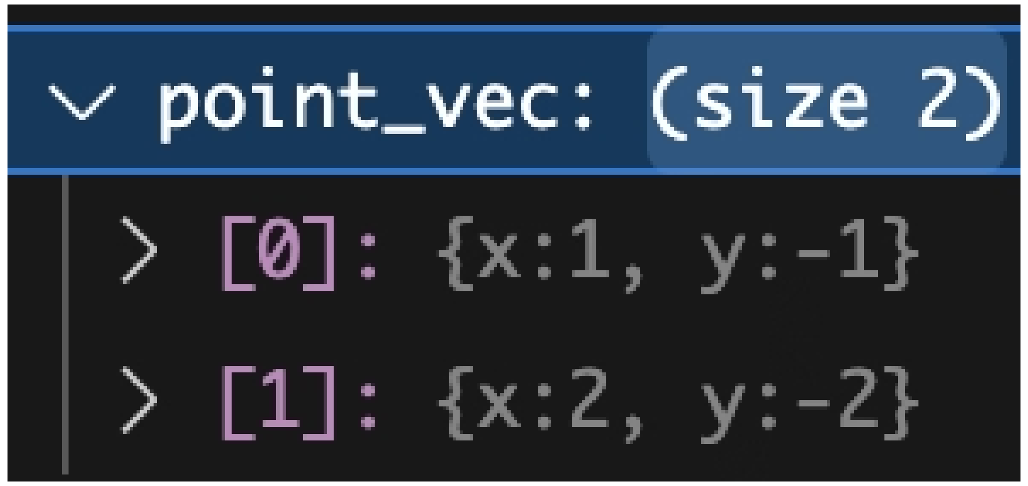
- Used very much!
- New debugging interface
  - Need to enable REPL debugging within an editor
- Python-interop in Mojo
  - debugging and variable printing

Future work
Mojo-based formatters

Decorator-based formatters

- Based on common archetypes

```
@lldb_formatter_list
struct List[T]:
    var data: AnyPointer[T]
    var size: Int
    var capacity: Int
```



```
⌄ point_vec: (size 2)
  › [0]: {x:1, y:-1}
  › [1]: {x:2, y:-2}
```

Future work
Mojo-based formatters

Function-based summary providers

- Matches python experience
- Requires interpretation

```
struct URL:
    fn __repr__(self) -> String:
      …
```

```
> url: http://localhost/Index.html
```

03

DebugInfo in MLIR

Debug Info

Infrastructure for keeping track of **source level concepts in the IR** across **transformations**.

Debug Info in LLVM

Source Level Debugging with LLVM

Debug metadata on instructions

- E.g. DILocation
- Source location & scope

Debug intrinsics

- E.g. dbg.declare, dbg.value
- Keep track of the location / value of source variables

```
%i.addr = alloca i32, align 4, !dbg !3
call void @llvm.dbg.declare(
  metadata ptr %i.addr,
  metadata !1,
  metadata !DIExpression())


!1 = !DILocalVariable(name: "i", ...)
!2 = !DISubprogram(name: "main", ...)
!3 = !DILocation(scope: !2, line: 2, ...)
```

Debug Info in the LLVM Dialect

Lowering target for **custom debug info constructs** in MLIR for **codegen via LLVM**.

Direct LLVM Mappings

Scoped location tracking with DIScopeAttrs

Variable value tracking with DbgValueOp & DbgDeclareOp

Two-way translation to/from LLVM IR

```
%0 = llvm.mlir.constant(1 : i32) : i32
%1 = llvm.alloca %0 x i32
       : (i32) -> !llvm.ptr
llvm.intr.dbg.declare #var = %1
       : !llvm.ptr loc(#loc1)


#loc  = loc("test.mlir":2:4)
#loc1 = loc(fused<#di_subprogram>[#loc])
#main = #llvm.di_subprogram<
           name = "main", ...>
#var  = #llvm.di_local_variable<
           scope = #main, name = "i", ...>
```

DebugInfo Dialect

Exploration of a generic MLIR solution for keeping track of source level information.

Keeping track of source level concepts in IR across transformations

DebugInfo Dialect

01

Scope-Based Locations

Augments MLIR's native Location tracking with source scopes.

02

Source Variable Tracking

Tracks value / location of source variables, and their lifetimes.

03

Transformation Hooks

Utilities to incentivize maintaining debuginfo across transformations.

Conversions into LLVM dialect.

Scoped Locations

MLIR has operation locations

- Missing source scope information

DebugInfo provides attributes for describing scopes

- DICompileUnit
- DIFile
- DISubprogram

Scope is fused onto operation locations

```
#subprogram = #debuginfo.subprogram<
  compileUnit = #compile_unit,
  scope = #file,
  name = #main_name,
  linkageName = "main()",
  file = #file,
  line = 1,
  scopeLine = 1,
  subprogramFlags = Definition
> : !subroutine
#loc0 = loc("test.mojo":2:5)
#loc1 = loc(fused<#subprogram>[#loc0])
```

Variable Tracking

Tracks the value / location of a source variable starting from a program point.

In-line operation `debuginfo.value`

- Relates an IR Value with a variable in the source program
- Similar to the LLVM intrinsic `dbg.value` (with subtle semantic differences)

```
%0 = ...
debuginfo.value #var = %0 : index
%1 = ...
debuginfo.value #var = %1 : index


#var = #debuginfo.local_variable<
  scope = #subprogram,
  name = "x",
  file = #file,
  line = 2
> : !debuginfo.unresolved<index>
```

DI Expressions

A high-level counterpart to DWARF expressions.

Models the transformations needed to map the IR value to a source variable.

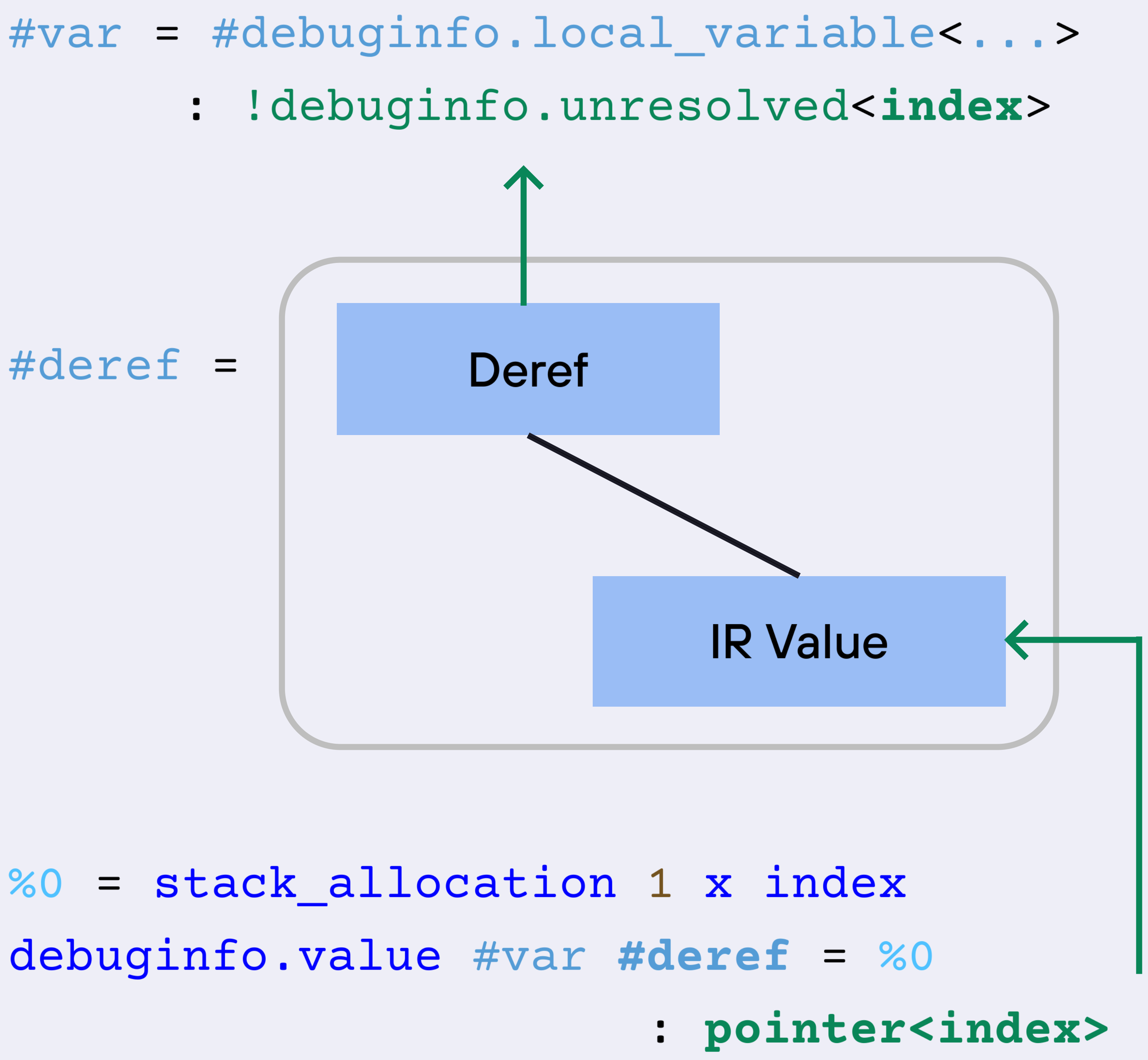
```
// Mojo
var x: Int = 42


// MLIR
%index42 = kgen.param.constant = <42>
debuginfo.value #var = %index42 : index

#var = #debuginfo.local_variable<
  scope = #foo,
  name = "x",
  file = #file,
  line = 2
> : !debuginfo.unresolved<index>
```

DI Expression Representation

DWARF & LLVM DI Expressions are modeled with a stack machine

DebugInfo uses a typed attribute tree

- An "inner" operator is parameterized on other DIExpressions
- A "leaf" operator models constants or inputs (e.g. `debuinfo.expr.irvalue`)



```
#var = #debuginfo.local_variable<...>
      : !debuginfo.unresolved<index>
```

```
#deref =
```

```
%0 = stack_allocation 1 x index
debuginfo.value #var #deref = %0
                       : pointer<index>
```

Example: DeRef

Value may become stack allocated

- Source type is still `index`
- IR type is now a pointer type

DI Expression helps reconcile this difference

- Encodes the "inverse" operation to get back the source representation

```
#var = #debuginfo.local_variable<...>
      : !debuginfo.unresolved<index>


#deref = #debuginfo.expr.deref<#irValue>
  : !debuginfo.unresolved<index>
#irValue = #debuginfo.expr.irvalue
  : !debuginfo.ti.ptr<
      !debuginfo.unresolved<index>>


%0 = stack_allocation 1 x index
debuginfo.value #var #deref = %0
                            : pointer<index>
```

Incentivizing DebugInfo Update

Handle representational changes.

Type-checked `debuginfo.value`

- Operand matches `expr.irvalue` type

Leaf-replacer utility

- Register the "opposite" logic of the pass using DI Expression operators
- Cached & type-checked

```
DebugInfo::DIExprAttr
stackAllocLeafConversion(
  DebugInfo::DIType irType) {
  // newIRType is a pointer to `irType`.
  // New leaf (expr.irvalue) has newIRType.
  // Wrap with operator opposite of stack
  // allocation (expr.deref) & return.
}

DebugInfo::DIExprLeafReplacer
  leafReplacer(stackAllocLeafConversion);

leafReplacer.apply(
  debugValueOp.getConversionExpr())
```

Lifetime Tracking

Mojo eager destruction

- Value is destroyed after last use
- Can no longer rely on scopes for local variable lifetime

In-line operation `debuginfo.kill`

- A special kind of `debuginfo.value` denoting a dead value
- Lowers into "killed" DbgValueOp in LLVM

```
fn main():
    var text = "Hello World"
    print(text)
    # `text` destroyed here.
    # `debuginfo.kill` inserted.
    foo()
```

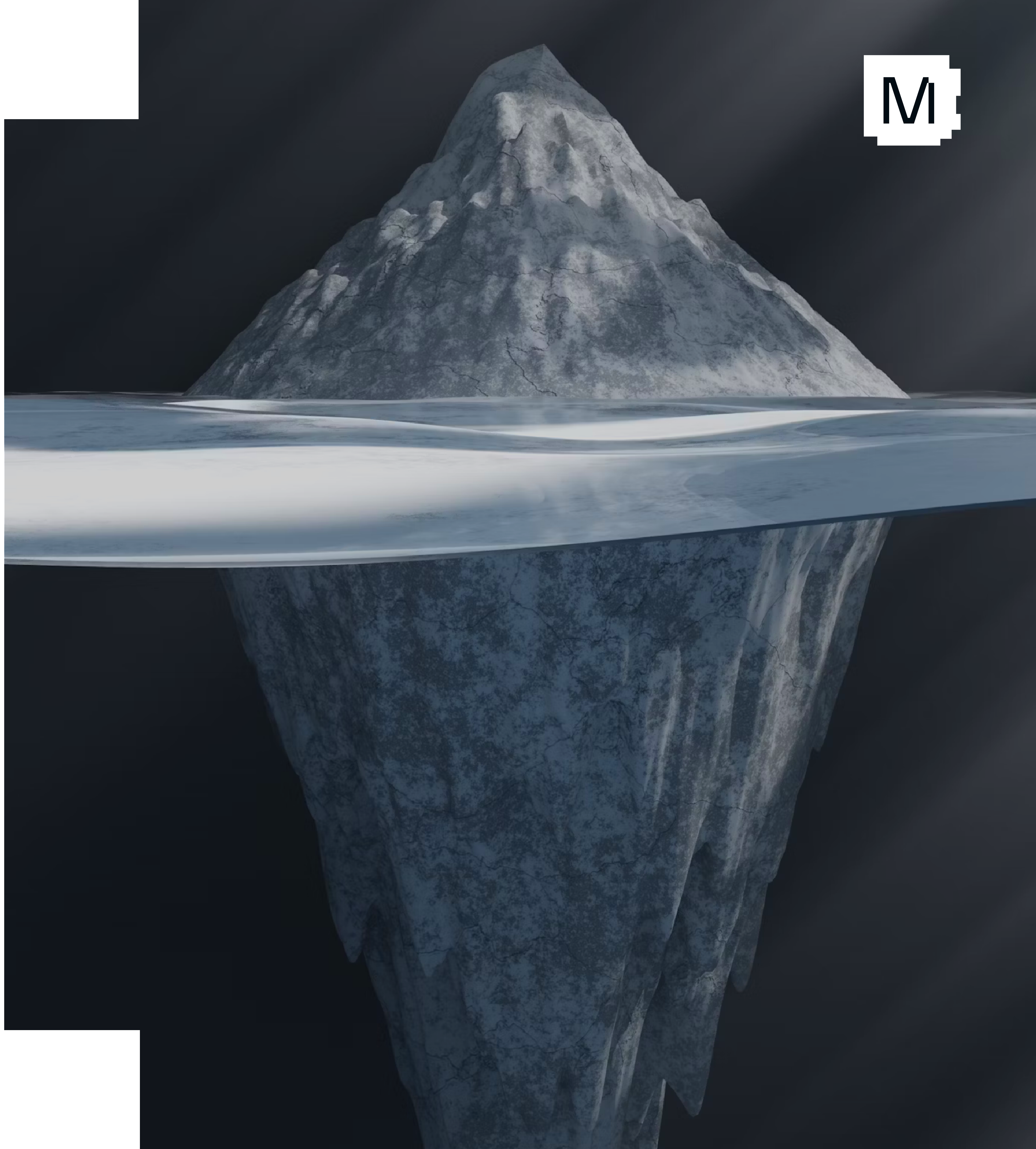
Inheriting Locations

Beware of assigning locations for derived ops (esp. merged or deduplicated ops)

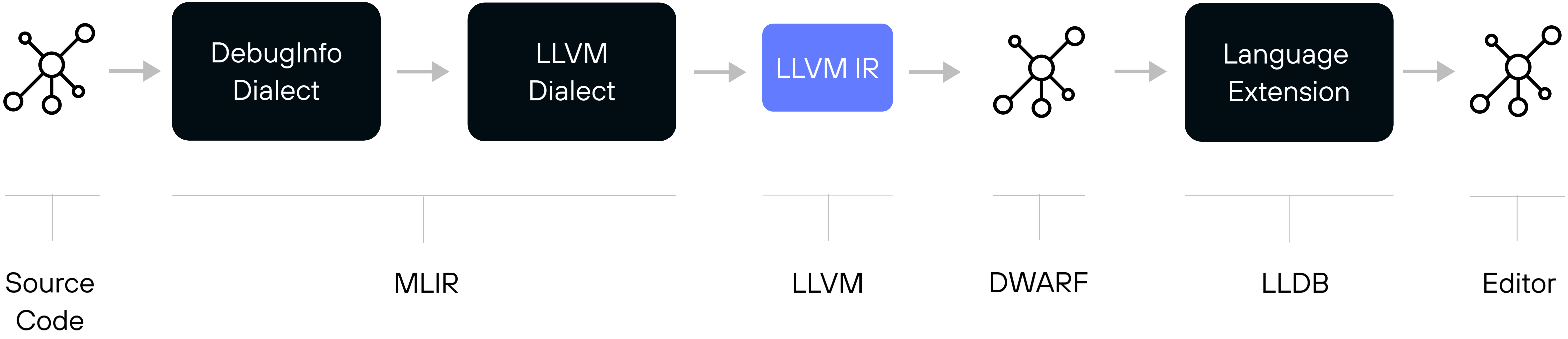
- Heavily influences stepping behavior
- E.g. changes to MLIR canonicalizer

What We Learned

- Not all debug info are preserved equally through the llvm backend
  - Stack-allocated values & DbgDeclare work best
- IR & debug info co-design for efficient transformations
  - Don't forget tests
- DebugInfo representation can still be iterated upon
  - Ongoing LLVM work too



Mojo Debugging


DebugInfo Dialect

LLVM Dialect

LLVM IR

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