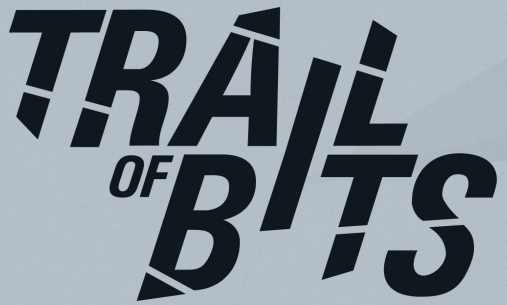

MLIR is the future of program analysis

Qualcomm Product Security Summit

May 18th, 2023

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I have returned

Peter Goodman

- **Staff engineer at Trail of Bits**
  - Email: peter@trailofbits.com
  - Twitter: @peter_a_goodman
  - Mastodon: https://infosec.exchange/@pag
- **Talk to me about:**
  - **Static or dynamic binary translation**
    - Remill, Anvill, McSema, GRR, microx, Granary, DynamoRIO, etc.
  - **Static or dynamic program analysis**
    - PASTA, Magnifier, DeepState, KLEE-native, Datalog compilers
  - **LLVM, MLIR**
    - Rellic, VAST
- **Last time at QPSS (2019):**
  - **PowerFL: Fuzzing VxWorks embedded systems (slides)**

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The last 15 years of program analysis focused on LLVM; the next 15 will not

We are where we are today because of LLVM

- **2003: LLVM created by Chris Lattner**
  - LLVM's intermediate representation (IR) makes low-level transformations and optimizations easy
- **2007: Clang frontend**
  - Makes LLVM IR *relevant*: can get it from C, C++
  - GCC-compatible command-line options
  - **Beginning of 15 years of continuous innovation**
- **2014-2018: Windows support**
  - Chrome compiles on Windows with `clang-cl`
- **2023: Clang and LLVM are everywhere**
  - Primary compiler used by Apple, Meta, Google
  - Primary IR used for academic research

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Clang / LLVM made the important things easy

- **Clang makes it easy to get LLVM IR from C and C++ code**
  - **Primary analysis substrate of source code was LLVM IR by proxy**
  - Can generally handle GNU- and MSVC-specific extensions
  - Easy to extract LLVM IR from Clang (option `-emit-llvm`)
- **LLVM's APIs make analyzing and transforming LLVM IR *really* easy**
  - `IRBuilder` for convenient construction and injection of new instructions
  - `val->replaceAllUsesWith(other_val)`
  - `val->uses()` to find something is easy
    - `Use::get()` to get back `val`
    - `Use::set(new_val)` to change `val` in the user
    - `Use::getUser()` to get the user of `val`
- **Key takeaways: LLVM is a productivity multiplier for transforming code**

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Eking out better results will require access to more information

Bug-finding has reached “peak LLVM”

- **LLVM has been *the* driving force in compiler-based bug-finding tools**
  - **Runtime sanitizers**: Address, Memory, Thread, Undefined, Data flow
  - **Fuzzing**: libFuzzer, AFL++
  - **Symbolic execution**: KLEE, S^2E, Sys
  - **Model checking**: DIVINE, LLBMC
  - **Static analysis**: Pagai, cclyzer / cclyzer++, PhASAR
  - **Translation validation**: Alive, Alive2
  - **Binary lifting**: McSema, Remill, Anvill, Rev.ng, RetDec, *etc.*
- **LLVM designed for optimization, *not bug-finding***
  - LLVM-based bug-finding tools are stuck in a **local maximum**

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Intent of source code is lost in translation

C source code	LLVM IR	Machine code
`int, unsigned, time_t, pid_t`	`i32`	DWARF debug info, if lucky
`struct point { int x, y; }` as a function parameter	`i64` (x86-64, ARMv8) `i32, i32` (x86, MIPS) `[2 x i32]` (ARMv7)	DWARF debug info, if lucky
Implicit downcast, explicit downcast	`trunc i64 %val to i32`	Read low order bytes, sub-register, or mask
	`and i64 %val, i64 0xffffffff`	
Local variables	`alloca` (unspecified ordering)	Stack memory (hardcoded ordering)
	SSA values (e.g. `%foo.scev.sroa.1.1.3`)	Registers
		Stack memory (spill/fill slots)
		Return address, callee-saved registers

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LLVM bug-finding suffers the streetlight effect

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Type names and signedness in high-level code can be load-bearing, and have *implied* semantics. This is lost in translation to LLVM.

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		Stack memory (hardcoded ordering)
		Registers
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Hard to report bugs related to types and values that cannot be easily related back to source code.

Ideally, want consistent representations so that analyses generalize to different architectures.

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Implicit downcast, explicit downcast	`trunc i64 %val to i32` `and i64 %val, i64 0xffffffff`	Read low order bytes, sub-register, or mask
Local variables	ified ordering)	Stack memory (hardcoded ordering) slots) saved registers

Un/signed conversions are bread and butter of buffer overflows. Can't distinguish implicit vs. explicit conversion, or signed to unsigned conversions in LLVM

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Intent of source code is lost in translation

Knowing how data is stored on the stack would help diagnose the severity of stack-based buffer overflows.

Need full-stack visibility to distinguish intra- from inter-structure overflows.

		Machine code
		DWARF debug info, if lucky
	ARMv8) PS)	DWARF debug info, if lucky
Implicit downcast, explicit downcast	and i6 l, i64 0xffffffff	Read low order bytes, sub-register, or mask
Local variables	`alloca` (unspecified ordering)	Stack memory (hardcoded ordering)
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Bugs span the semantic gap, bug-finding should too

Different IRs are good for different things

Level	Pros	Cons
High	• Close to bug-finder domain • Explicit abstractions (data structures) • Explicit intra-object boundaries	• Verbose, not efficiently analyzable • Missing implicit behaviors (e.g. C++ destructor calls)
Medium	• Explicit control-flow, data-flow	• Semantic types (e.g. `time_t`) elided
Low	• Efficiently analyzable • Explicit inter-object boundaries	• Tenuous connection back to source code • ABI-specific data representation, inlining, folding, propagation, has destroyed data
Binary	• Bug-exploiter domain • Blurred object boundaries (easier to evaluate buffer overflows) • Succinct	• Blurred object boundaries (hard to analyze) • Unreliability of debug info, symbols • Tight coupling of control-flow, type, variable recovery

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Ideally, we want the efficiency of LLVM IR and expressivity of source

LLVM IR: A blessing and a curse

Blessings

- **Trust**
  - **Analyze the same representation used by the compiler to generate machine code**
- **Broad compatibility**
  - GNU and MSVC option and extension support
- **Permissive open-source license**
  - Academic and industry *momentum*
- **Easy and scalable to analyze**
  - Not that many kinds of instructions
  - Close-ish to C
- **Debug information**
  - Points back to source code
  - DWARF-like types

Curses

- **Many unspecified LLVM dialects**
  - -O0 *vs.* -O1 *vs.* -O2 *vs.* -O3
  - ABI-specific intrinsics, ABI lowering of types
- **Very low level**
  - **Inlined mechanics of abstractions** (e.g. C++ standard library containers)
  - **Optimized for target, not for analyzer**
- **LLVM values are meaningless**
  - **Not related to bug-finder's domain: source**
  - `%foo.1.scev.sroa.1.1.3` 🤣
- **API evolution causes tool churn**
  - Many tools stuck on LLVM 3.x, 4.x, 5.x, *etc.*
  - Many tools will never work with opaque `ptrs`
- **Debug information is unreliable**

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Curses

- Many unspecified LLVM dialects
- Debug information is unreliable

It turns out that if you pray for ~~forgiveness~~ a better IR then Chris Lattner will deliver one.

MLIR, the multi-level intermediate representation, looks like the future of domain-specific compiler technology, and is well-suited for full-stack bug-finding.

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One ~~ring~~ IR to ~~rule~~ represent them all and in the ~~darkness~~ analysis bind them

Represent everything with MLIR

Multi-Level Intermediate Representation (MLIR)

- **Define new IRs, called *dialects***
  - Invent your own domain-specific language
  - Tree-structured, SSA-based
- **New dialects come batteries-included**
  - **Mutation operations, just like with LLVM**
  - Validation logic, e.g. for type checking
  - Serialization and printing logic for persistence
- **Key feature: Composition**
  - **Multiple dialects can be simultaneously used within a single module**

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MLIR looks like it will thrive in the next 15 years

- **Momentum**
  - **Captured industry and academic mindshare** (TensorFlow, OpenXLA, Flang, *etc.*)
    - Driven by unique needs of ML and hardware compilers
    - Database query optimizers / compilers hot on their heels
    - Laggards: program analysis!
- **MLIR comes with an LLVM dialect built-in**
  - Don't throw the baby out with the bathwater
  - Learns from Swift's SIL and Rust's MIR
    - Some language-specific optimizations are best applied in a higher-level IR
    - Lower to LLVM IR to benefit from battery of pre-existing optimizations
- **Open-source, permissively licensed, enthusiastically developed**
  - MLIR is a first-class LLVM subproject

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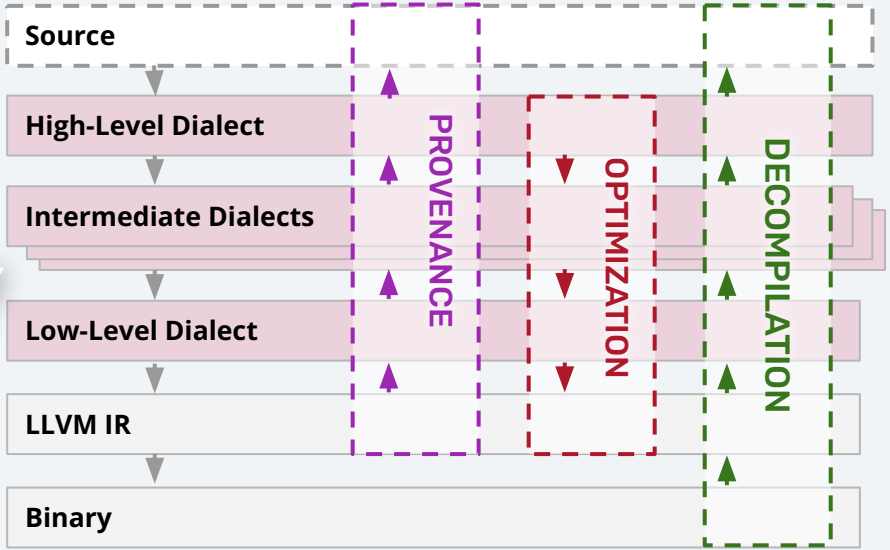
Our vision: a Tower-of-IRs

MLIR dialects can bridge the semantic gap by representing the *same* program at *different* levels of abstraction.

Provenance: higher-level dialects can be the debug information for lower-level dialects.



MLIR

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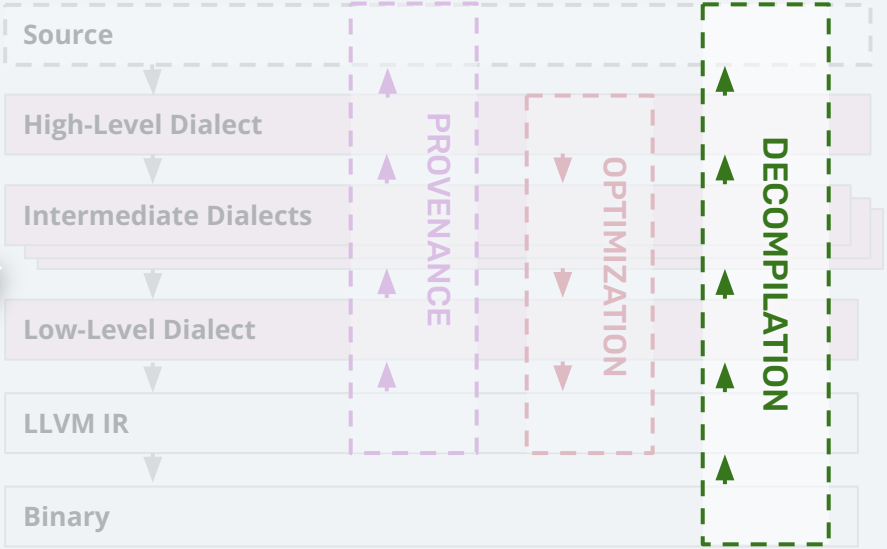
Tomorrow's vision, today

Building the tower, one brick at a time

rev.ng is building an interactive decompiler. Their MLIR dialect, `clift`, is used in their backend to accurately represent high-level C types and constructs.

They also work with Qualcomm on qemu-hexagon!



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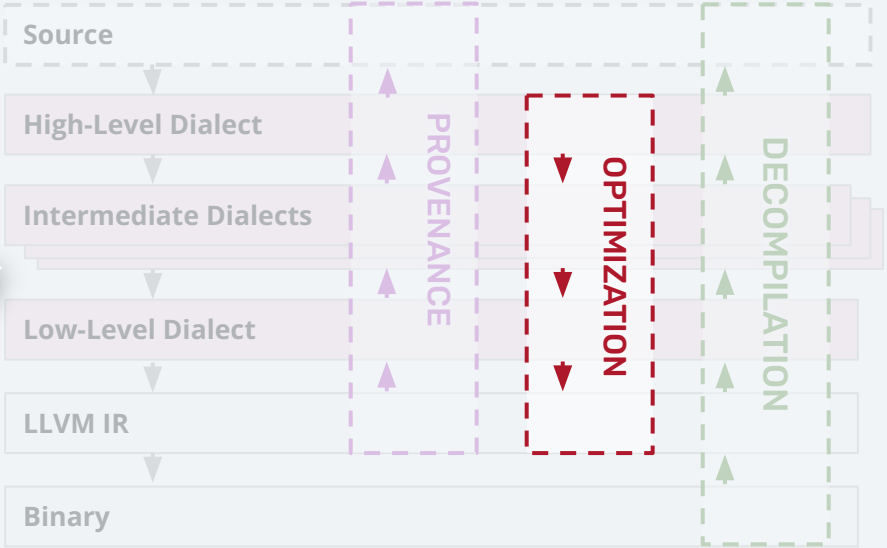
Building the tower, one brick at a time

Meta is building Clang IR (CIR) to find C++ coroutine lifetime bugs, and better optimize C++ code using coroutines.

CIR is a mid-level dialect: it mixes high-level control-flow with low-level, LLVM-like data representations.

Meta



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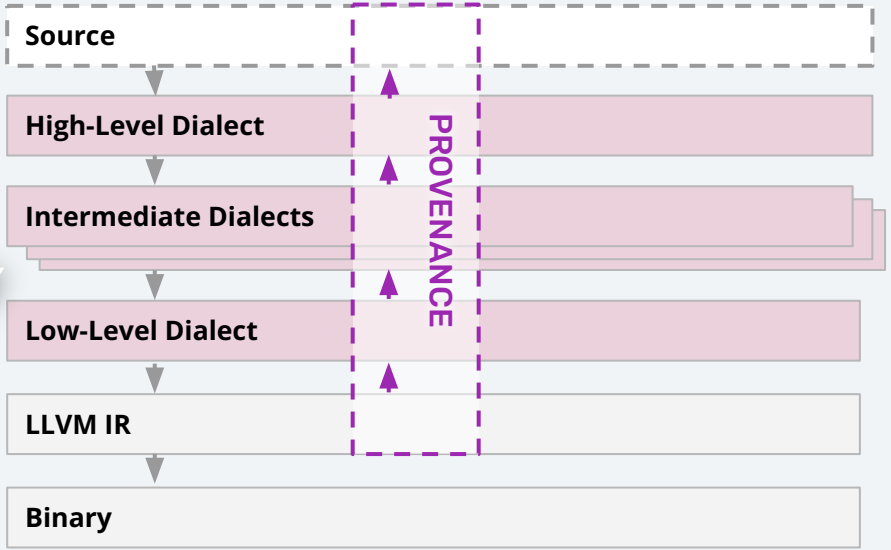
Building the tower, one brick at a time

Trail of Bits is building the *whole damn tower* with github.com/trailofbits/vast.

VAST converts Clang ASTs into a high-level dialect, then progressively lowers it down to Clang-compatible LLVM IR. We will target CIR for C++ support.



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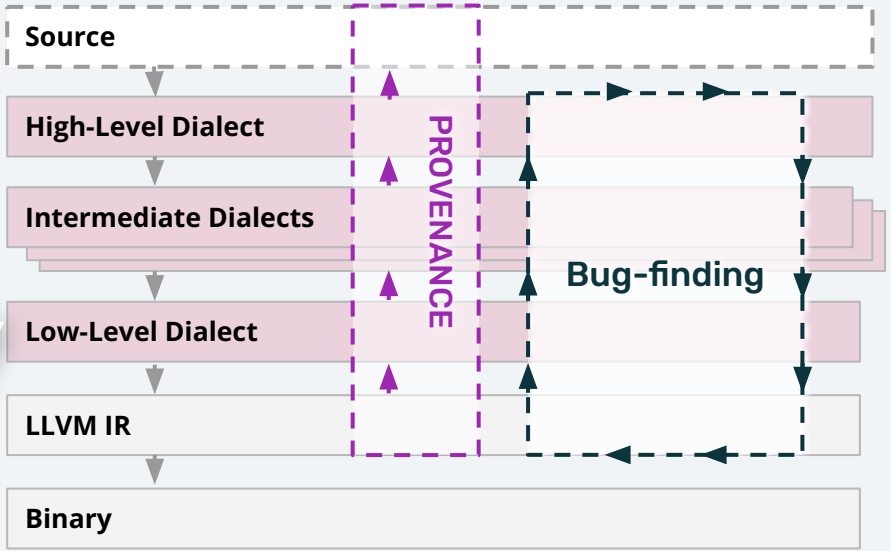
Full-stack bug-finding

A tower-of-IRs gives your analysis *visibility*, from high to low.

MLIR lets you *specialize* the tower to your analysis needs: bring your own dialects!

Stay *productive* and skip format shifting: your analyses can live in one address space.



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State of MLIR

- **MLIR *usage* is fractured**
  - Mix of in-tree and out-of-tree, forked versions, etc.
  - Hard to compose independent projects, as they're often on slightly different MLIR versions
    - Fast pace of MLIR core development means high API churn, similar to early LLVM
- **Almost (but not yet) easy to use**
  - Steep learning curve
  - Defining a new dialect requires using the evil TableGen system
  - There's hope: IRDL and xDSL will make dialect definition/extension substantially simpler
- **High level of effort**
  - A new code generator doesn't materialize overnight
  - Lot's still to do to support C end-to-end

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Actually finding bugs with MLIR

- **CVE-2021-33909, *aka* Sequoia, is a Linux kernel privilege escalation bug**
  - Implicit downcast of a `size_t` to an `int`
  - Integral types (e.g. `i64`, `i32`) in LLVM IR don't know their signedness
  - `trunc` operations in LLVM IR don't know if they were generated from explicit or implicit casts
- **Marek Surovič created vast-checker for finding Sequoia**
  - VAST's high-level MLIR dialect distinguishes integer signedness, implicit and explicit casts
  - Blog post coming soon!
- **Lessons learned**
  - Need ability to connect across translation units, e.g. integrate with Clang Static Analyzer

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I'm looking forward to the future

MLIR is the future of program analysis

- **The last 15 years of program analysis focused on LLVM**
  - Clang made LLVM relevant, LLVM made transformation easy
  - Eking out better results will require access to more information
  - Intent of source code is lost in translation
- **Bugs span the semantic gap, bug-finding should too**
  - Represent everything with MLIR, using a ***tower-of-IRs***
  - We want the efficiency of LLVM IR and expressivity of source
  - Avoid format shifting
- **State of MLIR**
  - High momentum, high investment
  - High churn, steep learning curve
- **Want MLIR for C *today*? Try VAST (github.com/trailofbits/vast)**
  - vast-checker is our first experiment with MLIR-based bug-finding

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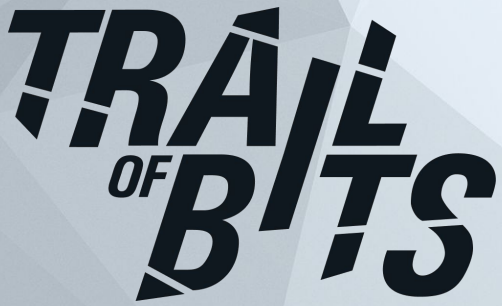

Backup slide

Multiple IRs isn't a new idea

Binary Ninja is an interactive disassembler for reverse engineering

- **Represents code using *interconnected* IRs**
  - **LLIL**: Low-level machine code instruction semantics
  - **MLIL**: Stack slots, local variables, value analysis
  - **HLIL**: High-level types, structured control-flow
- **Pros:**
  - **Start your analysis at the best-fit IR for your goal**
  - Interactive and batch mode, killer for visualization
- **Cons:**
  - **Can't extend built-in IRs**
  - Mutation via re-creation or patching machine code bytes
  - Reverse engineering focused, so not ideal if you have source

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Backup slide

Isn’t this kind of like CodeQL?

CodeQL is a semantic code analysis platform for vulnerability discovery across a broad set of languages

- **Squint and CodeQL classes kind of look like dialects**
- **Pros**:
  - **CodeQL is awesome, you should use it**
  - Sophisticated built-in analyses, e.g. taint tracking
- **Cons**:
  - **Hard to debug: what / where are the false-negatives?**
  - Re-implements compiler logic like IR generation, but is it feature- or bug-compatible with any *real* compiler?
  - Can’t go “all the way down” to executable code

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Backup slide

Analysis workflow / architecture

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VAST represents the same program at multiple abstraction levels

MLIR “dialects” as intermediate representations

High-level dialect	Close to AST, includes control-flow
Middle-level / core dialect	Propagated aliases, tuples, lazy blocks
ABI dialect	Lowers high-level typed values
Built-in MLIR-provided dialects	Standard types, arithmetic, control-flow
LLVM dialect	Executable semantics
Metadata dialect	Connects everything to Multiplier, source

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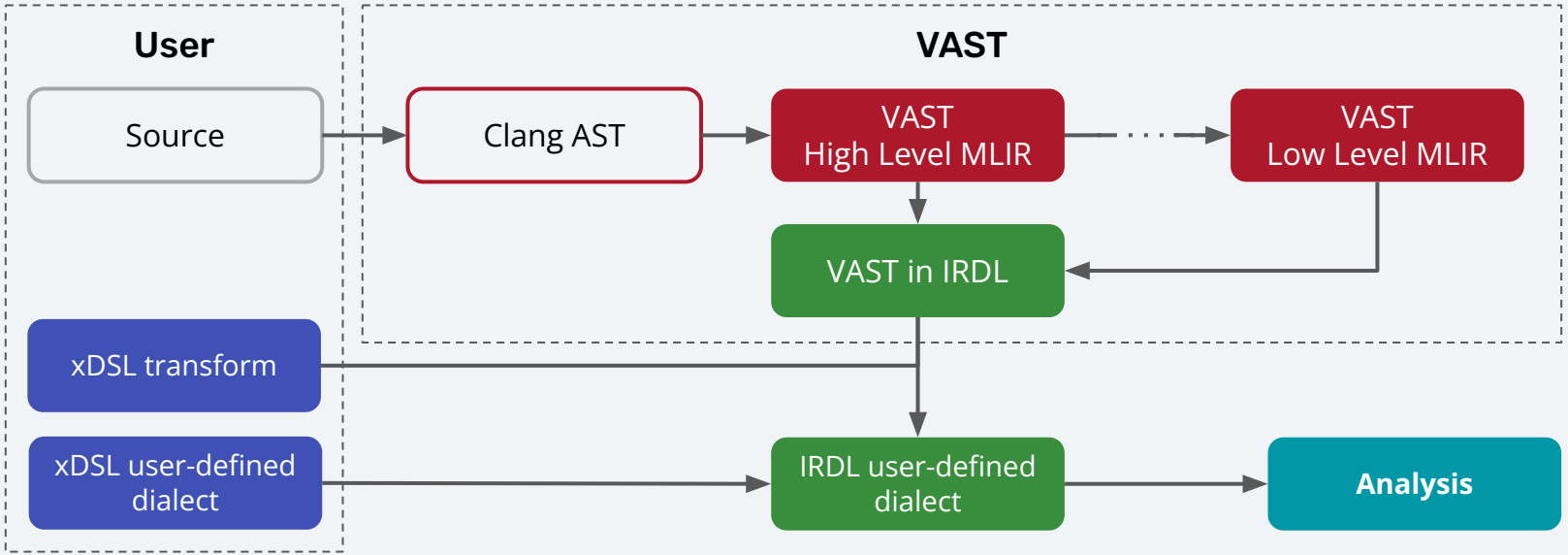
Dialects-as-abstractions workflow



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Backup slide

Extending MLIR from Python

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Should be easy to extend MLIR

- **How? Using the IRDL dialect definition language**
  - IRDL is a meta-dialect for defining MLIR dialects
  - Enables runtime-definable dialects

- **xDSL makes IRDL usable and extensible from Python**
  - Dialects defined using Python classes
  - Extension points defined with methods

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First-class entities can be extended with xDSL

Example: Extending operations with methods…

```
@irdl_op_definition
class IfOp(Operation):
  name = "hl.if"
  cond = OperandDef(IntegerType.from_width(1))
  true_region  = RegionDef()
  false_region = RegionDef()
  def formula(self):  # Returns an SMT representation of an if statement
    return Ite(Equals(self.cond.op.symbol(), BV(1, 1)),
               region_formula(self.true_region),
               region_formula(self.false_region))
```


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The composition of these extension methods enables convenient analysis

… lets us synthesize SMT formulas

```
int x;
if (1) {
    int a;
    x = a + 1;
} else {
    int b;
    x = b + 2;
}
```



```
((FV0 = 1_32) &
 (FV1 = 2_32) &
 (FV3 = x) &
 (FV5 = 1_1)
     ? ((FV6 = a) &
        (FV7 = (FV6 + FV0)) &
        (FV3 = FV7))

     : ((FV8 = b) &
        (FV9 = (FV8 + FV1)) &
        (FV3 = FV9))
)
```


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Backup slide

Modelling libc functions with MLIR

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Example: Modelling libc library functions as operations in a new dialect

Should be easy to define custom abstractions

- **User-defined dialects will branch off of VAST's tower of IRs like a tree**
  - **Problem**: How to introduce new abstractions, tailored to analysis needs?
  - **Solution**: Transform one of VAST's core dialects into analysis-specific dialect
- **How? Using the IRDL dialect definition language**
  - IRDL is a meta-dialect for defining MLIR dialects
  - Enables runtime-definable dialects
- **xDSL makes IRDL usable and extensible from Python**
  - Dialects defined using Python classes
  - Extension points defined with methods

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Using IRDL to specify `strcmp`

```
Dialect libc {
  Alias !string = !hl.array<!hl.char<const>>

  Operation strcmp {
    Operands (lhs: !string, rhs: !string)
    Results  (res: !hl.int)
    Format   "$lhs, $rhs"
    Summary  "Compares two null-terminated byte strings lexicographically."
  }
}
```


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Example: Modelling libc library functions as operations in a new dialect

Using xDSL to specify `strcmp`

```
@irdl_attr_definition
class StringType : HLArrayType(HLChar(const))
  name = "string"

@irdl_op_definition
class StrCmpOp(Operation):
  lhs    = OperandDef(StringType())
  rhs    = OperandDef(StringType())
  result = ResultDef(HLIntegerType())
```


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Example: Modelling libc library functions as operations in a new dialect

Transforming code with xDSL

```
@dataclass
class StrCmpRewrite(RewritePattern):
  @op_type_rewrite_pattern
  def match_and_rewrite(self, op: CallOp, rewriter: PatternRewriter):
    if op.function.name() == "strcmp":
      rewriter.replace_matched_op(StrCmpOp(op.args))
```

- **String comparisons are now a first-class entity**
- **Converting generic operations into domain-specific operations enables *composable analyses* to be implemented in Python with xDSL!**

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