Lecture 3 — Building DSLs

Stanford CS343D (Winter 2025)
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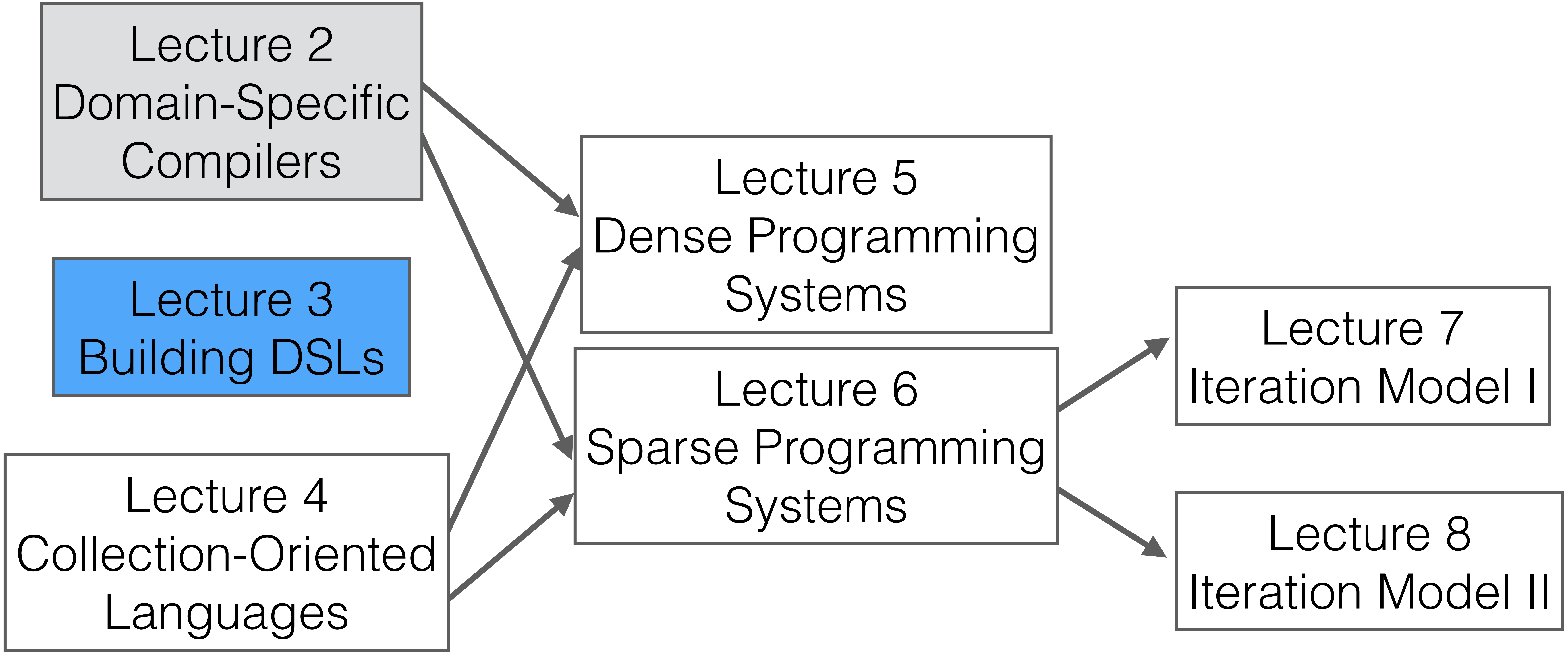
Slides based on lecture by Pat Hanrahan in CS343D Fall 2020


Lecture 2
Domain-Specific
Compilers
Lecture 3
Building DSLs
Lecture 4
Collection-Oriented
Languages
Lecture 5
Dense Programming
Systems
Lecture 6
Sparse Programming
Systems
Lecture 7
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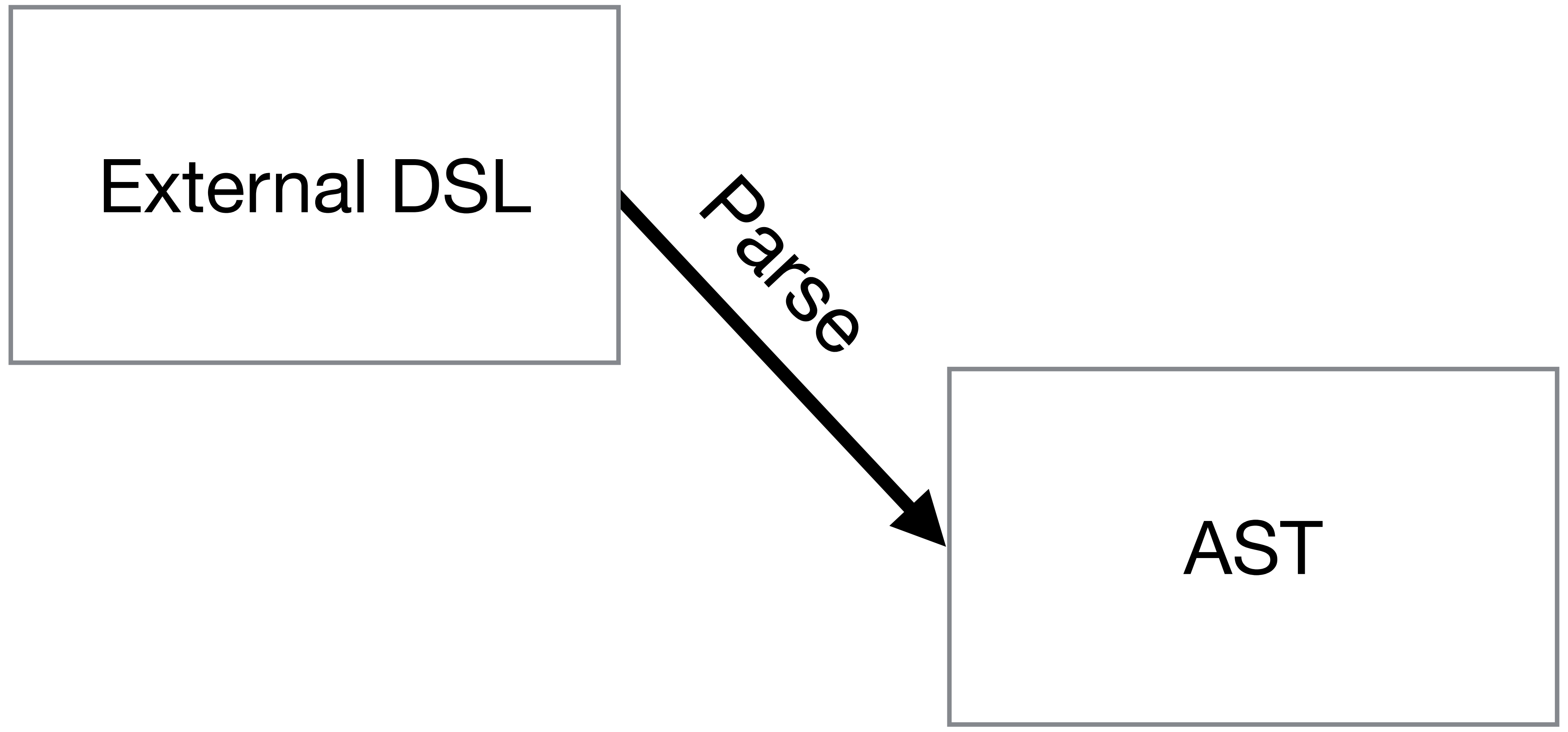
Lecture 8
Iteration Model II

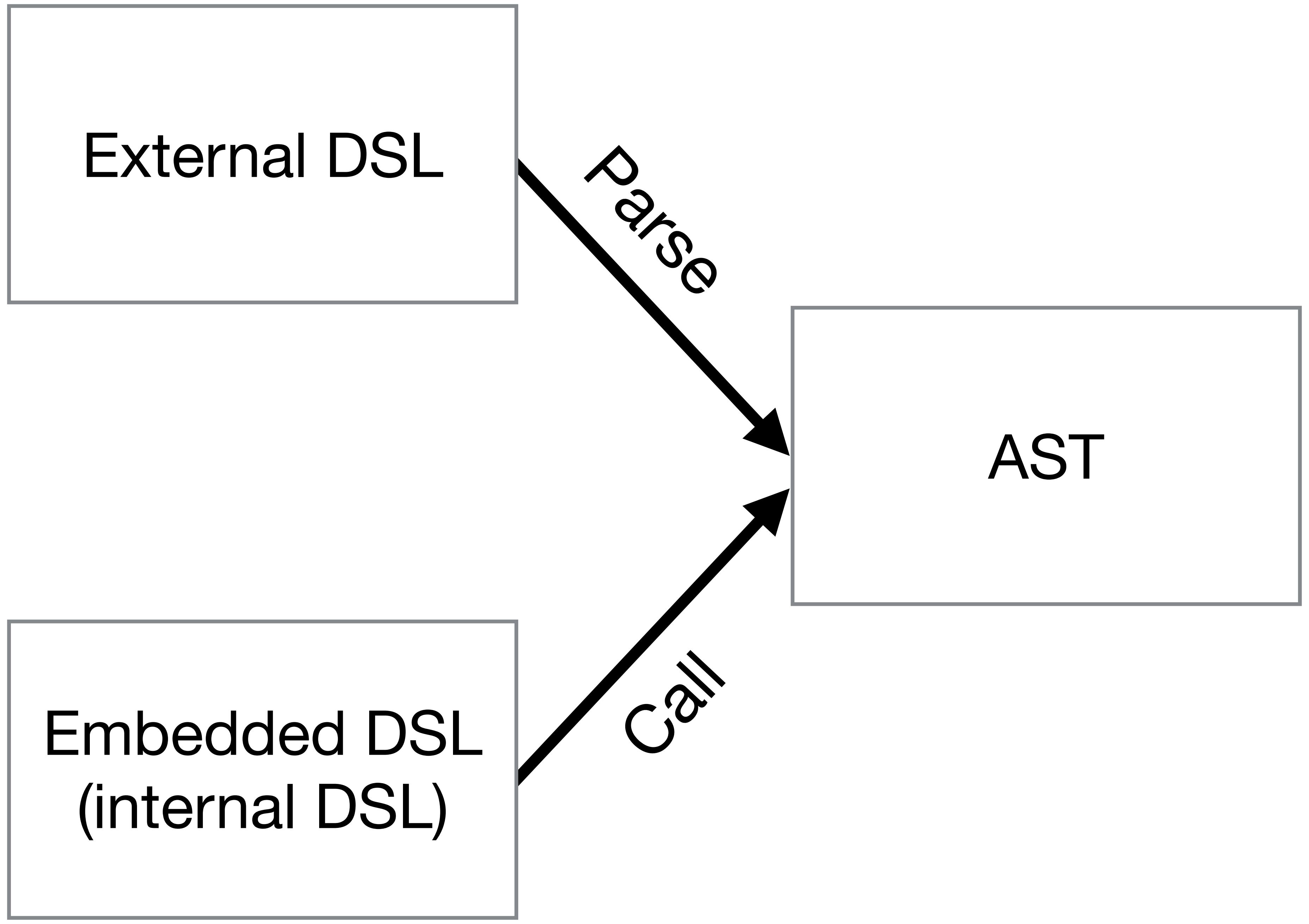
Types of DSLs — languages or libraries?

Implemented as standalone language



Types of DSLs — languages or libraries?

Implemented as standalone language

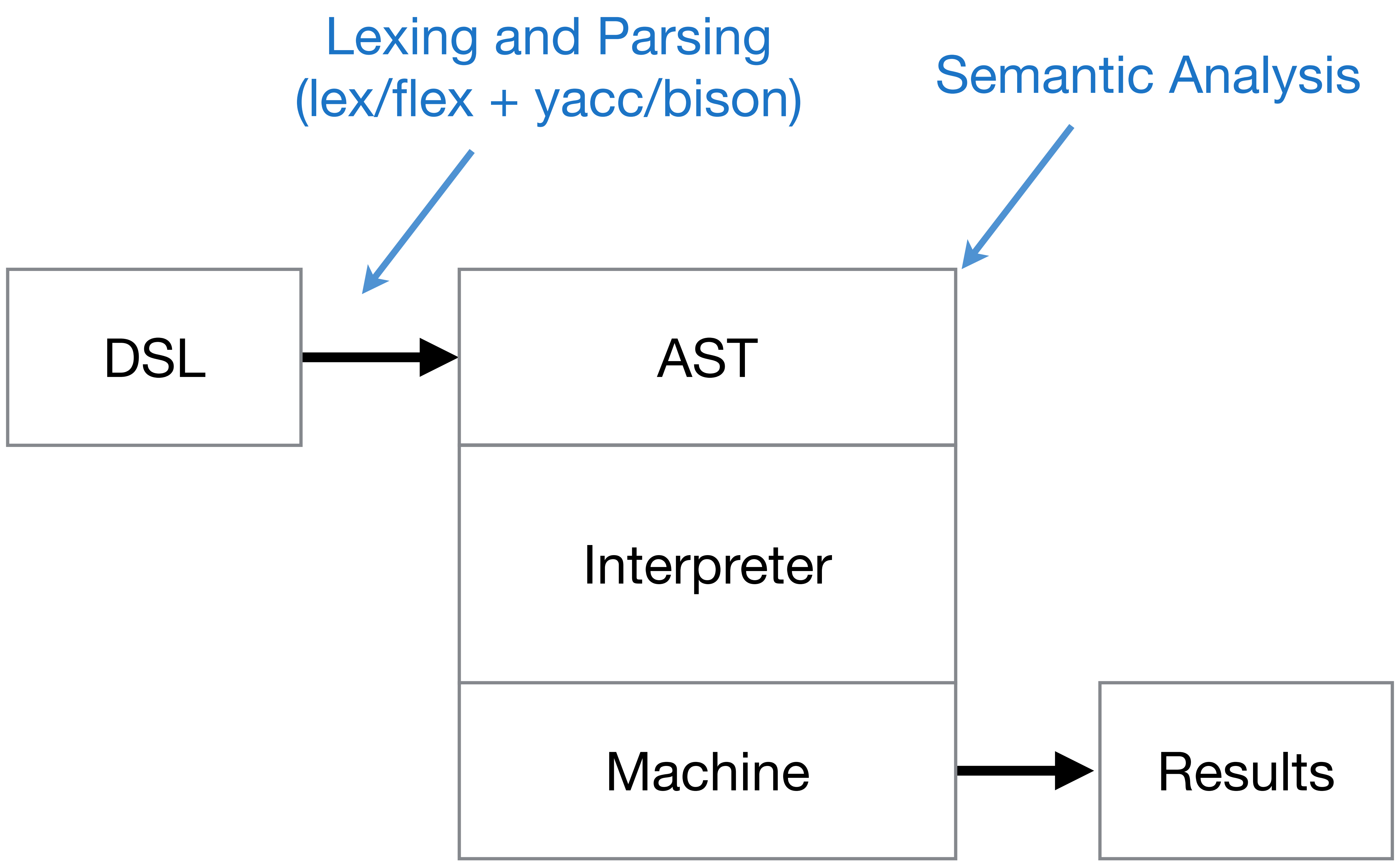


Embedded inside another language.
Ideally the host language has features to make it easy to embed DSLs.

External DSLs

That is, DSLs as textual languages

External DSLs — Implementation



External DSLs — Demo

calc1.py
calc2.py

lexical analysis
syntactic analysis
interpretation
ASTs

External DSLs — Advantages and Disadvantages

Advantages

+ Flexibility (syntax and semantics)
+ Easy to make a small textual language

Disadvantages

- Yet another programming language
- Syntactic cacophony
- Slippery slope towards generality
- Hard to interoperate with other languages
- No tool chain: IDE, debuggers, profilers

Embedded DSLs

That is, DSLs as a library

Embedded DSL — Language implemented as a library

OpenGL

```
glMatrixMode(GL_PROJECTION);
glPerspective(45.0);

for(;;) {
    glBegin(TRIANGLES);
        glVertex(…);
        glVertex(…);
        …
    glEnd();
}

glSwapBuffers();
```

Fluent Interfaces — Composable API calls with method chaining

html

```
<ul>
  <li>One</li>
  <li>Two</li>
  <li>Three</li>
</ul>
```

jquery

```
// turn first element green
$("li:first").css("color", "green");
```

Sophisticated data rendering with embedded DSL

https://www.d3-graph-gallery.com/graph/density_basic.html

http://d3js.org/

Sparse Tensor Algebra DSL in C++ (taco)

```
Format dv({dense});
Format csr({dense,compressed});

Tensor<double> a({m},   dv);
Tensor<double> c({n},   dv);
Tensor<double> B({m,n}, csr);

// Load data

IndexVar i,j,i1,i2;
a(i) = sum(j, B(i,j) * c(j));

a.split(i, i1, i2, Down, 32);
 .parallelize(i1, CPUThread, NoRaces);

std::cout << a << std::endl;
```

C-like DSL (Pochi) embedded in C++ for online code generation

```
Function* regexfn = codegen(“ab.d*e”);
using Regexs = int(*)(vector<string>*);
auto [regexs, inputs] = newFunction<Regexs>(“regexs”);
auto result = regexs.newVariable<int>();
auto it = regexs.newVariable<vector<string>::iterator>();
regexs.setBody(
  Declare(result, 0),
  For(Declare(it, inputs->begin()),
      it != inputs->end(),
      it++
  ).Do(
    result += StaticCast<int>(
       Call<RegexFn>(regexfn, it->c_str()))
  ),
  Return(result)
);

vector<string> input {“abcde”, “abcdde”,  // good input
                      “abde” , “abcdef”}; // bad input
buildModule();
Regexs match = getFunction<Regexs>(“regexs”);
assert(match(&input) == 2);
```

Pochi loop iterates over a C++ STL iterator

```
using RegexFn = bool(*)(char* /*input*/);
Function* codegen(const char* regex) {
  auto [regexfn, input] = newFunction<RegexFn>();
  if (regex[0] == ‘\0’) {
    regexfn.setBody(
      Return(*input == ‘\0’)
    );
  } else if (regex[1] == ‘*’) {
    regexfn.setBody(
      While(*input == regex[0]).Do(
        input++,
        If (Call<RegexFn>(codegen(regex+2), input)).Then(
          Return(true)
        )
      ),
      Return(false)
    );
  } else if (regex[0] == ‘.’) {
    regexfn.setBody(
      Return(*input != ‘\0’ &&
             Call<RegexFn>(codegen(regex+1), input+1))
    );
  } else {
    regexfn.setBody(
      Return(*input == *regex &&
             Call<RegexFn>(codegen(regex+1), input+1))
    );
  }
  return regexfn;
}
```

Pochi test on runtime regex

Embedded DSLs — Advantages and Disadvantages

Advantages

+ Familiar host language syntax
+ Can combine DSL code with host language features
+ Can interoperate with other libraries
+ Complete host language toolchain

Disadvantages

- Host language syntax can be rigid and verbose
- Hard to debug DSL with host language tools
- Hard to restrict features in DSL
- Still hard to develop

Shallow Embedding

A shallow embedding is when the expressions are interpreted in the semantics of the base language

calc1.py: direct interpretation of arithmetic

Deep Embedding

A deep embedding first builds an abstract syntax tree (AST). The abstract syntax tree is typically an algebraic data type. The AST is then evaluated with an interpreter.

calc2.py: AST represented as lists of lists

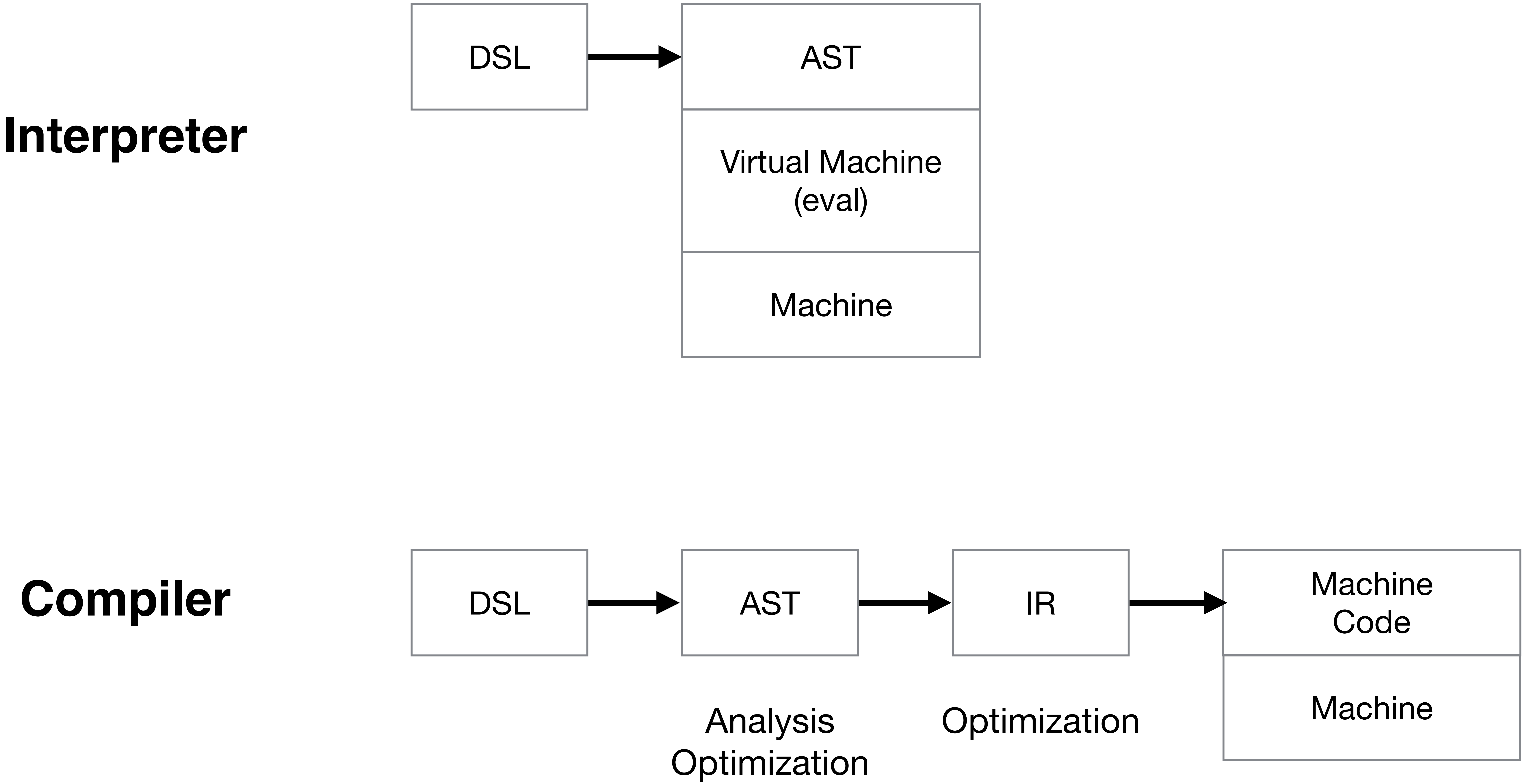
Operator Overloading

Not all “operations” can be intercepted

- Arithmetic operators
- Iteration operators
- Function definition?
- Type/class definition?
- Equality?
- Assignment?

“Monkey patching” like this can be dangerous

Interpretation vs. Compilation



Mini-APL Assignment

- Implement simple array processing language in C++
- We provide recursive descent parser that builds an AST
- Lower the AST to LLVM; use LLVM to generate machine code!
- The LLVM Kaleidoscope tutorial contains most of what you need to know: https://llvm.org/docs/tutorial/MyFirstLanguageFrontend/LangImpl03.html
- Assignment released today and due January 30th

LLVM Tutorial

Christophe Gyurgyik

The O.G. Paper

LLVM: A Compilation Framework for Lifelong Program Analysis & Transformation

Chris Lattner Vikram Adve
University of Illinois at Urbana-Champaign
{lattner,vadve}@cs.uiuc.edu
http://llvm.cs.uiuc.edu/

“This paper describes LLVM (Low Level Virtual Machine), a compiler framework designed to support transparent, lifelong program analysis and transformation for arbitrary programs, by providing high-level information to compiler transformations at compile-time, link-time, run-time, and in idle time between runs.”

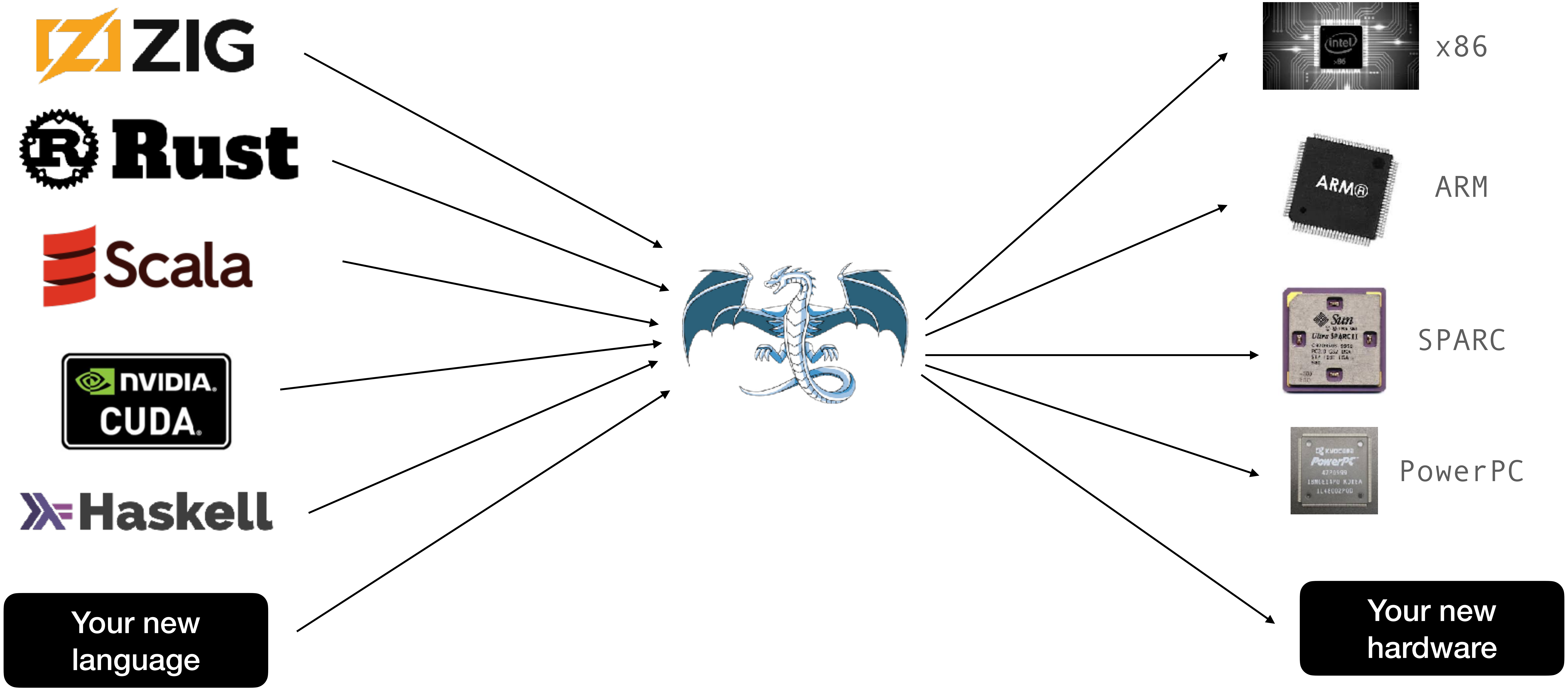
Relevance

	2014	2024
# Contributors	**336**	**2,138**
Lines of Code	**5M**	**36M**

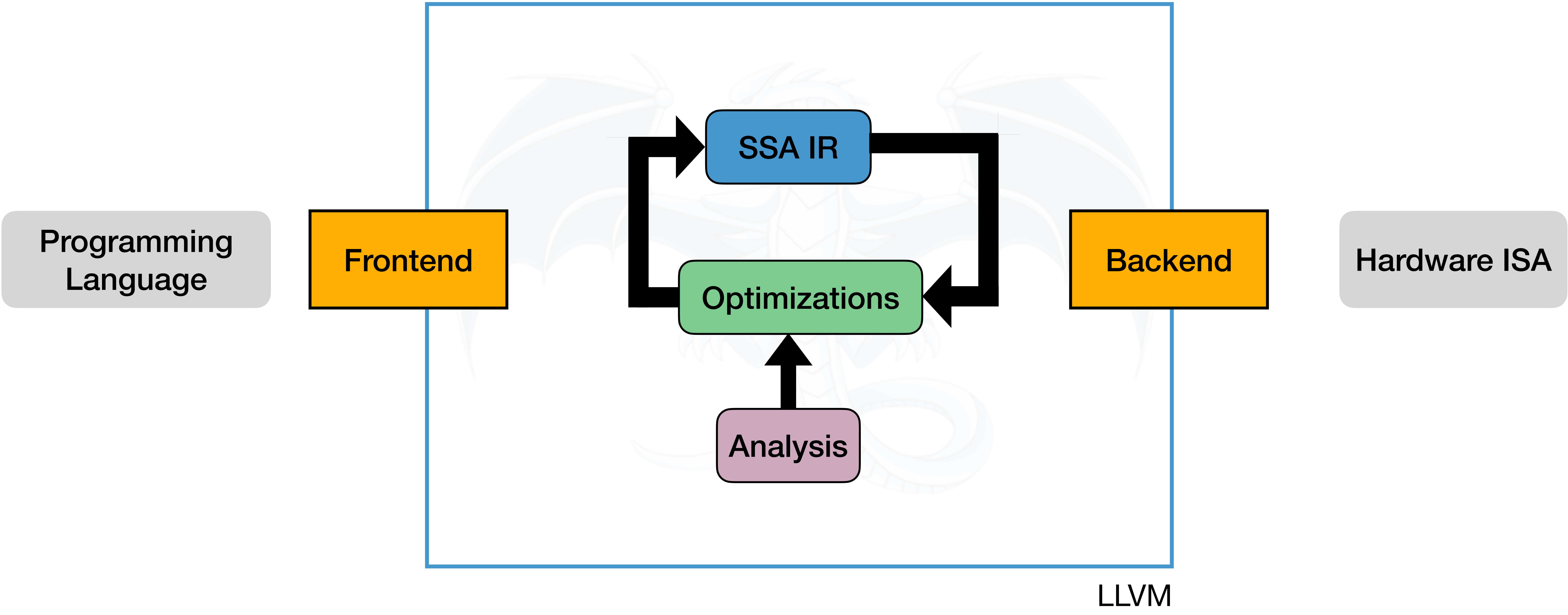
"In 2024 there were 37,486 commits to the LLVM repository... Roughly inline with the 37.4~37.5k commits seen in 2022 and 2023. Those 37.4k commits added 9,339,334 lines of code while removing 5,591,115 lines."

LLVM Had Another Exciting Year With More Than 37k Commits, 35.5 Million Lines

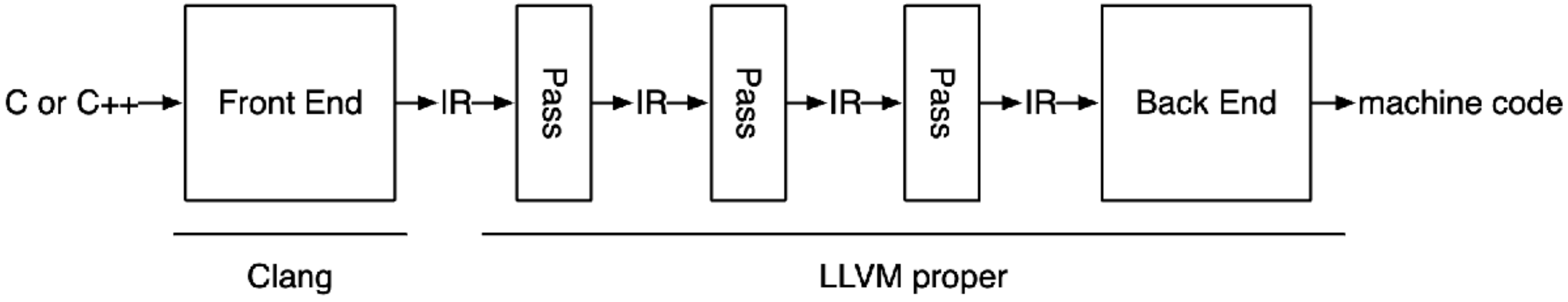
System Overview



System Overview



System Overview



credits: *LLVM for Grad Students*

Static Single Assignment (SSA)

- Type of intermediate representation (IR)
  - Typically used for imperative languages.
  - (the other popular IR for general purpose languages is *Continuation-Passing Style* (CPS), in functional languages.
- **Key ingredient**: Every variable is assigned exactly once.
  - Implication: “for every use there is *one* definition.”

Examples (whiteboard-ed in lecture)

```
%1 = constant i32 4
%2 = muli i32 %1, %1
%3 = subi i32 %2, %1
%4 = addi i32 %1, %2
ret i32 %4
```

```
define i32 @max(i32 %a, i32 %b) {
entry:
    %0 = icmp sgt i32 %a, %b
    br i1 %0, label %true, label %false
true:
    br label %exit
false:
    br label %exit
exit:
    %retval = phi i32 [%a, %true], [%b, %false]
    ret i32 %retval
}
```

LLVM IR Structure

LLVM IR

LLVM Library

LLVM IR Structure

Module

Top-level container.
Stores a list of functions, libraries, global variables, etc.

```
ModuleID = ‘module'
```

LLVM IR

```
auto context = std::make_unique<LLVMContext>();
auto module = std::make_unique<Module>(“module”, *context);
```

LLVM Library

LLVM IR Structure

Function

Function type, linkage, and list of basic blocks

```
ModuleID = ‘module'
define i32 @foo() {
}
```

LLVM IR

```
auto context = std::make_unique<LLVMContext>();
auto module = std::make_unique<Module>(“module”, *context);

Type* intType = Type::getInt32Ty(*context);
FunctionType* functionType =
  FunctionType::get(intType, /*isVarArg=*/false);

Function* fooFunction = Function::Create(
  /*FunctionType=*/functionType,
  /*LinkageTypes=*/GlobalValue::InternalLinkage,
  /*N=*/“foo”,
  /*M=*/module
);
```

LLVM Library

LLVM IR Structure

Basic Block

A list of instructions and a terminator

```
ModuleID = ‘module'
define i32 @foo() {
entry:
}
```

LLVM IR

```
auto context = std::make_unique<LLVMContext>();
auto module = std::make_unique<Module>(“module”, *context);

Function* fooFunction = Function::Create(…)

BasicBlock* entryBlock = BasicBlock::Create(
  *context,
  /*Name=*/“entry”,
  /*Parent=*/fooFunction,
  /*InsertBefore=*/nullptr
);
```

LLVM Library

LLVM IR Structure

Instruction

The smallest unit: an abstraction for machine code

```
ModuleID = ‘module'
define i32 @foo() {
entry:
  ...
  %0 = fmul double %lhs, %rhs
  %1 = call i32 @bar(%0, 42.0e+00)
  ret i32 %1
}
```

LLVM IR

```
...
BasicBlock* entryBlock = BasicBlock::Create(...);

IRBuilder<> b(*context);
b.SetInsertPoint(entryBlock);
...
Value* r0 = b.CreateFMul(lhs, rhs);
CallInst* r1 = b.CreateCall(barFunction, {r0, f42});
ReturnInst* r2 = b.CreateRet(r1);
```

LLVM Library

Can think of **%0** and and **%1** as typed registers. LLVM IR has *virtually* unlimited registers

More resources

- [IMPORTANT] **LLVM doxygen**
- **CS6120: Advanced Compilers:** compiler course by Adrian Sampson, uses a simpler version of LLVM IR (named *BRIL*)
  - aka "if you're going to work on industry compilers then you should know this"
- **Godbolt** (aka Compiler Explorer)
  - Formidable tool for exploring compilation of *many* different languages.
  - LLVM example**: max**
- **LLVM for Grad Students**: blogpost on LLVM passes (again by Adrian Sampson).
- **LLVM Weekly**
  - LLVM is always changing! Backwards compatibility is *not* a priority.