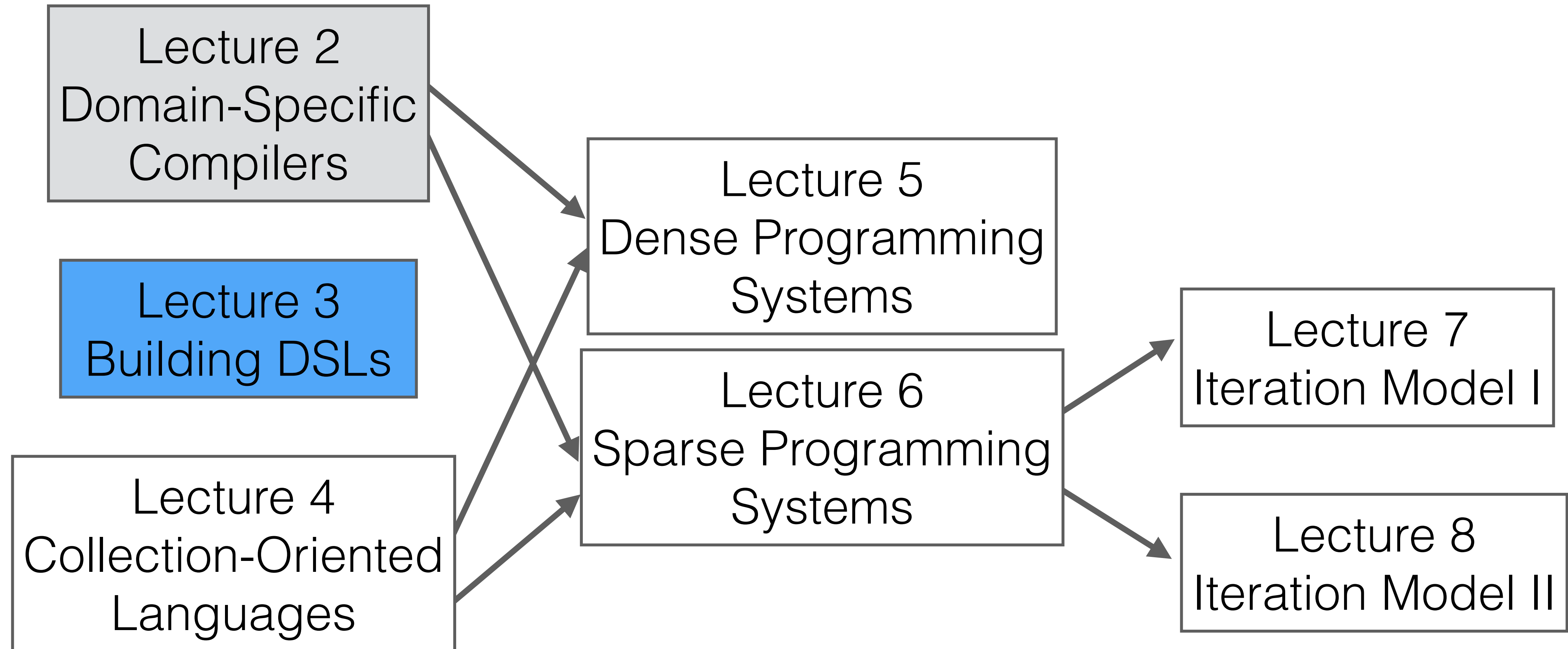


Lecture 3 — Building DSLs

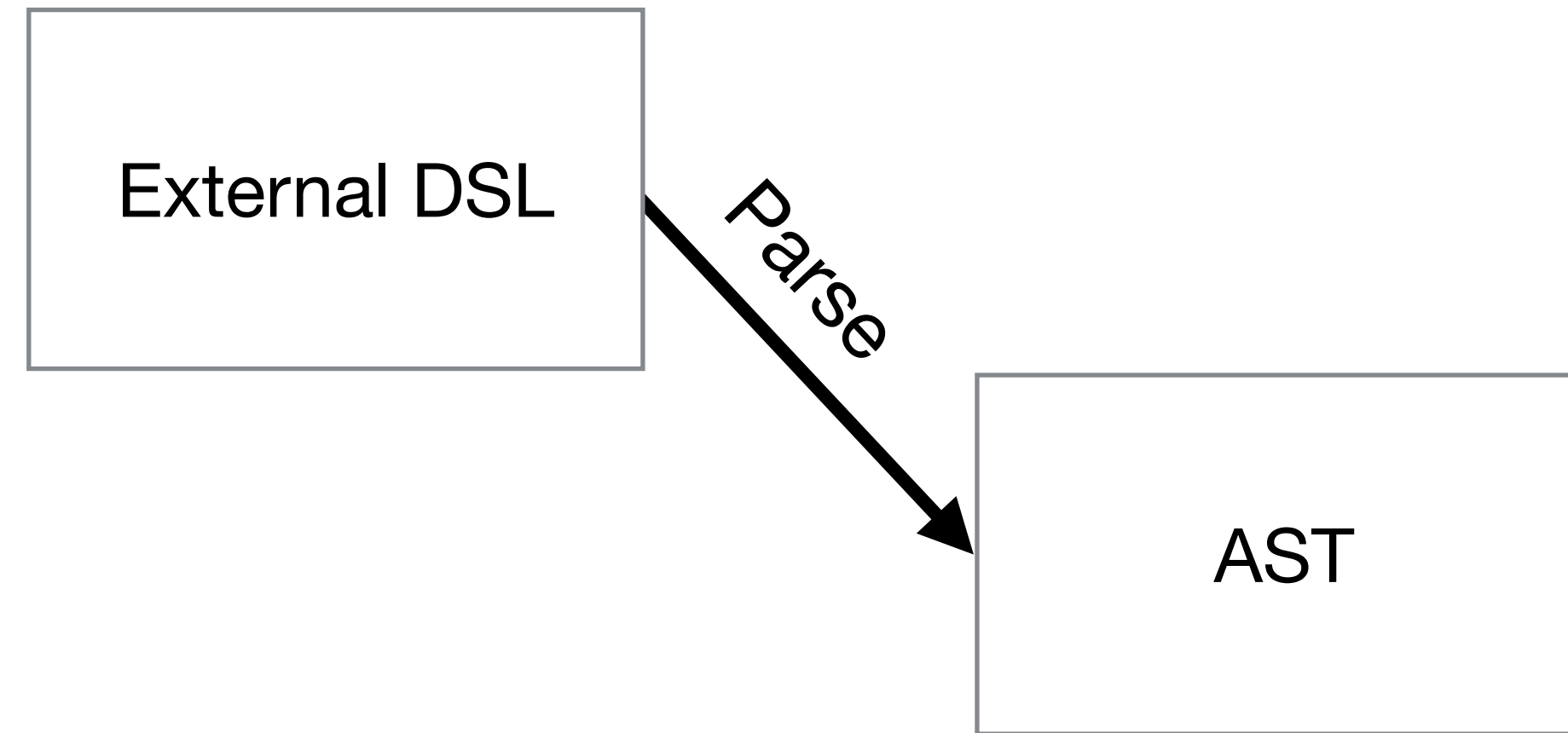
Stanford CS343D (Winter 2026)
Fred Kjolstad

Slides based on lecture by Pat Hanrahan in CS343D Fall 2020



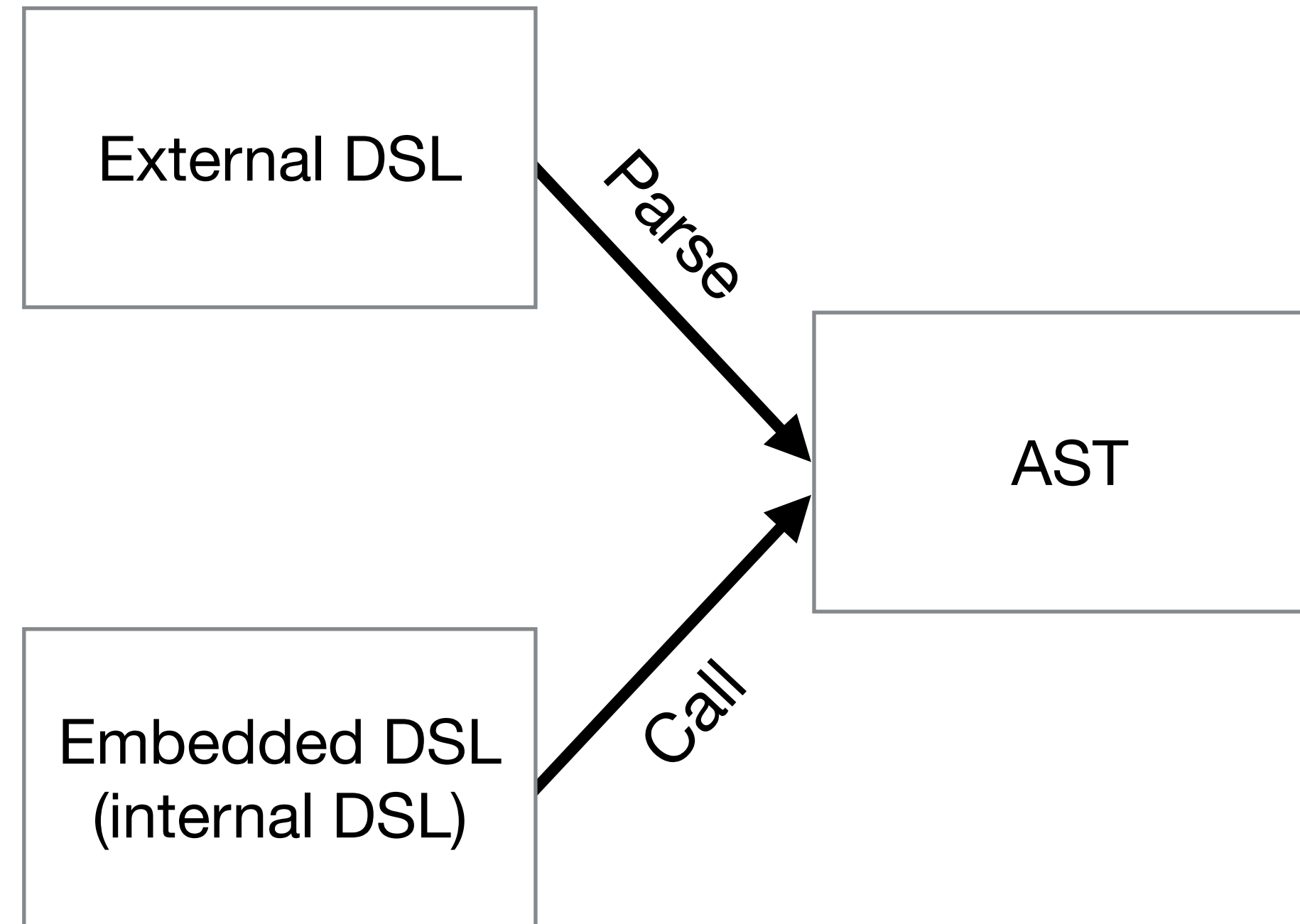
Types of DSLs — languages or libraries?

Implemented as standalone language



Types of DSLs — languages or libraries?

Implemented as standalone language

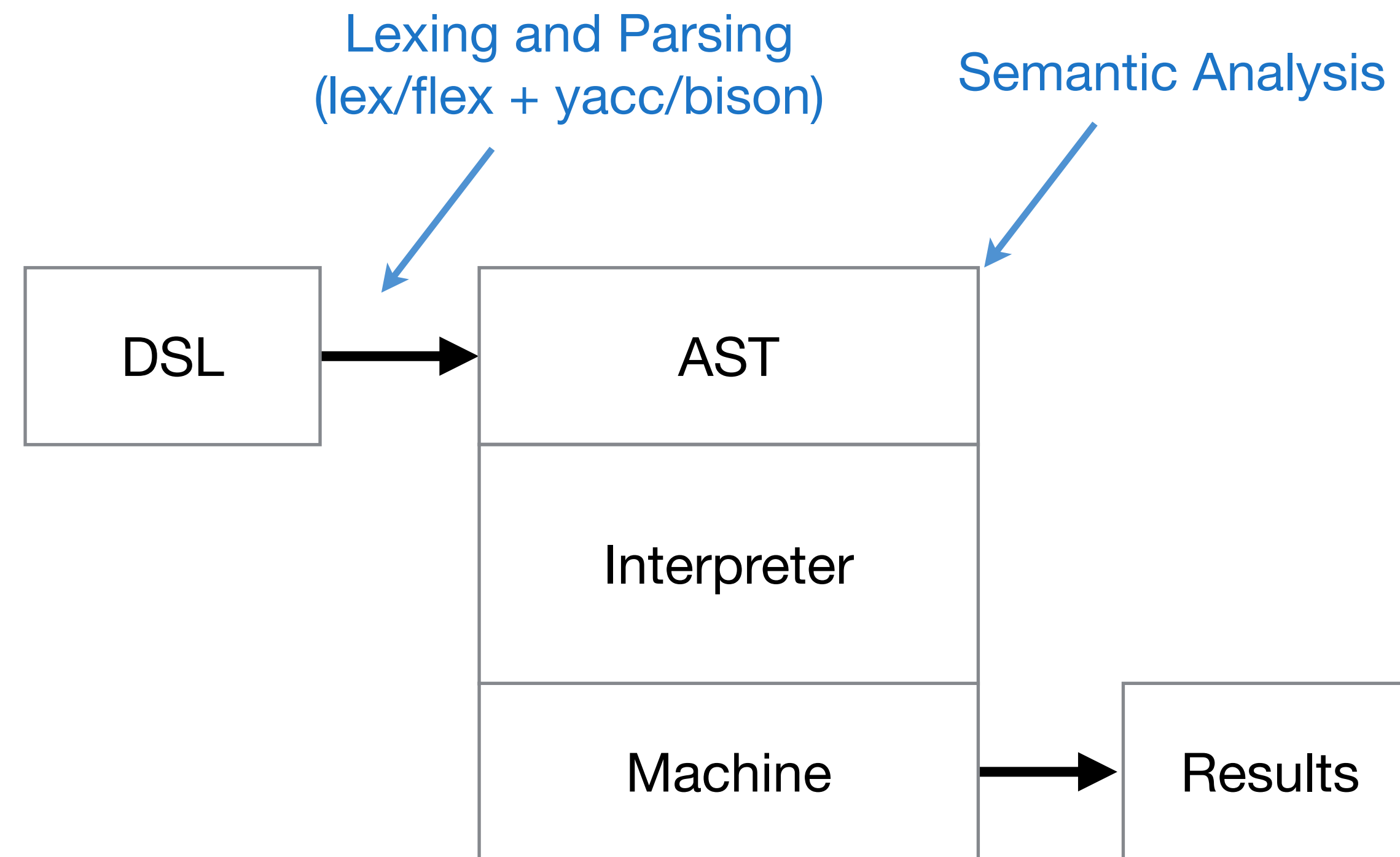


Embedded inside another language.
Ideally the host language has features to
make it easy to embed DSLs.

External DSLs

That is, DSLs as textual languages

External DSLs — Implementation



External DSLs — Demo

calc1.py

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

```
1 Function* regexfn = codegen("ab.d*e");
2 using Regexs = int(*) (vector<string>*);
3 auto [regexs, inputs] = newFunction<Regexs>("regexs");
4 auto result = regexs.newVariable<int>();
5 auto it = regexs.newVariable<vector<string>::iterator>();
6 regexs.setBody(
7     Declare(result, 0),
8     For(Declare(it, inputs->begin()),
9         it != inputs->end(),
10         it++
11     ).Do(
12         result += StaticCast<int>(
13             Call<RegexFn>(regexfn, it->c_str()))
14     ),
15     Return(result)
16 );
17
18 vector<string> input {"abcde", "abcdde", // good input
19                     "abde", "abcdef"}; // bad input
20 buildModule();
21 Regexs match = getFunction<Regexs>("regexs");
22 assert(match(&input) == 2);
```

Pochi loop iterates over a C++ STL iterator

```
1 using RegexFn = bool(*)(char* /*input*/);
2 Function* codegen(const char* regex) {
3     auto [regexfn, input] = newFunction<RegexFn>();
4     if (regex[0] == '\\0') {
5         regexfn.setBody(
6             Return(*input == '\\0')
7         );
8     } else if (regex[1] == '*') {
9         regexfn.setBody(
10             While(*input == regex[0]).Do(
11                 input++,
12                 If (Call<RegexFn>(codegen(regex+2), input)).Then(
13                     Return(true)
14                 )
15             ),
16             Return(false)
17         );
18     } else if (regex[0] == '.') {
19         regexfn.setBody(
20             Return(*input != '\\0' &&
21                 Call<RegexFn>(codegen(regex+1), input+1))
22         );
23     } else {
24         regexfn.setBody(
25             Return(*input == *regex &&
26                 Call<RegexFn>(codegen(regex+1), input+1))
27         );
28     }
29     return regexfn;
30 }
```

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 or compiled.

`calc2.py`: AST represented as lists of lists

Operator Overloading

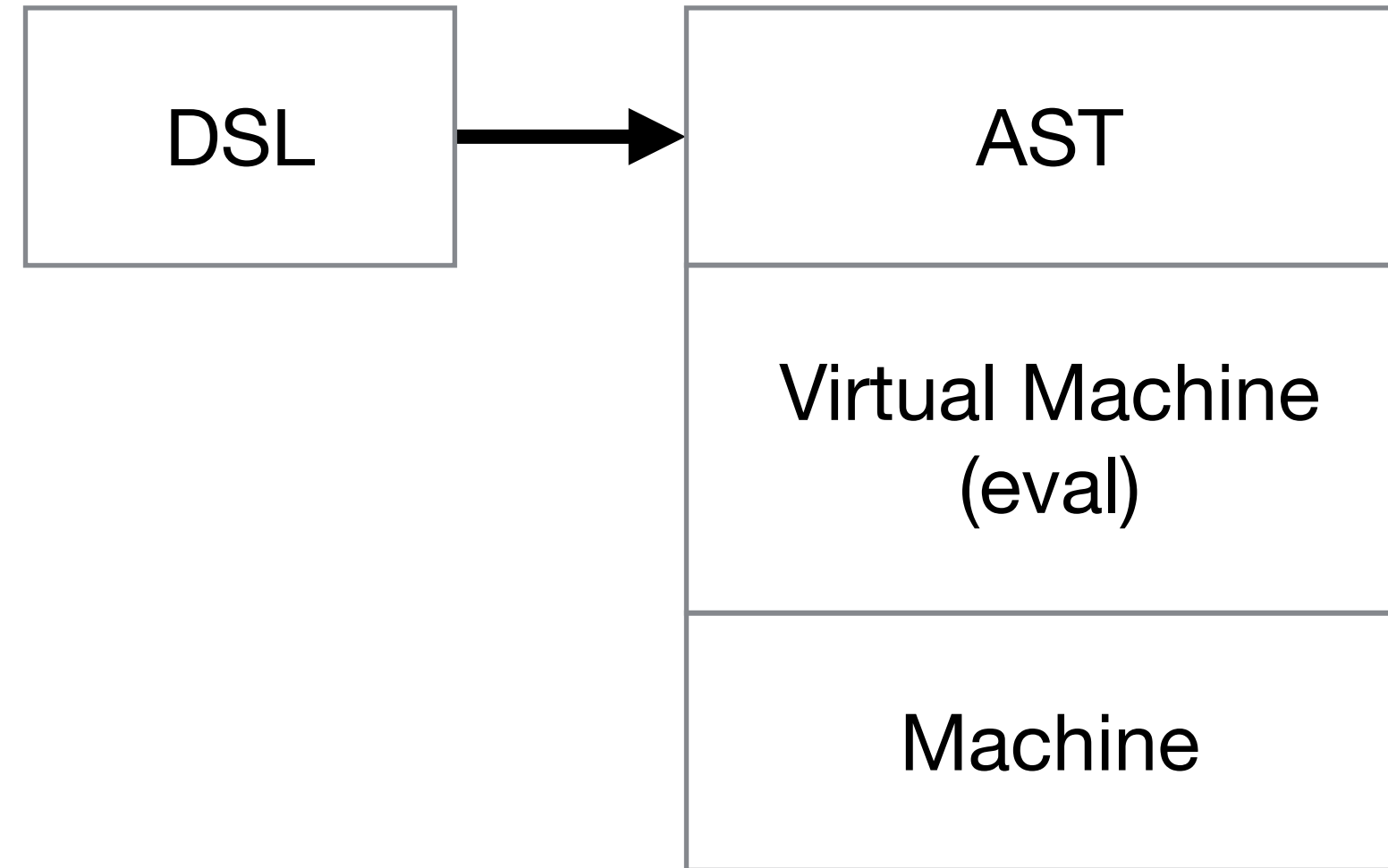
Not all “operations” can be intercepted

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

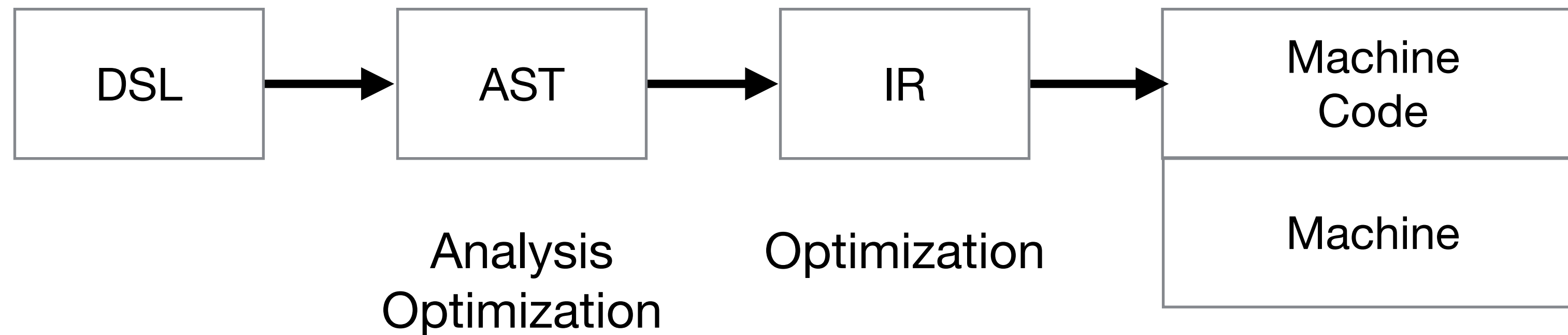
“Monkey patching” like this can be dangerous

Interpretation vs. Compilation

Interpreter



Compiler



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 26th

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/`

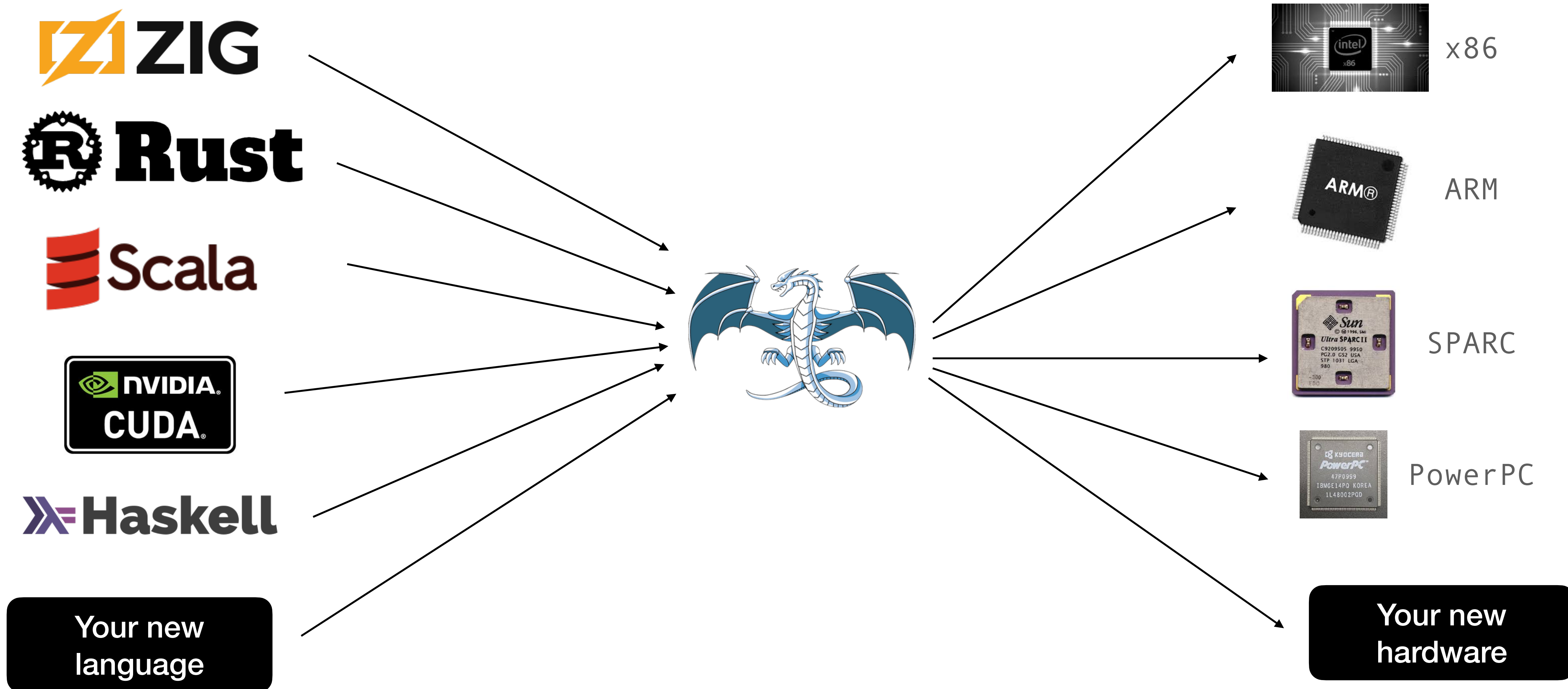
“This paper describes LLVM (Low Level Virtual Machine), a compiler framework designed to support transparent, lifelong program analysis and transformation for arbitrary programs, by providing high-level information to compiler transformations at compile-time, link-time, run-time, and in idle time between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

Relevance

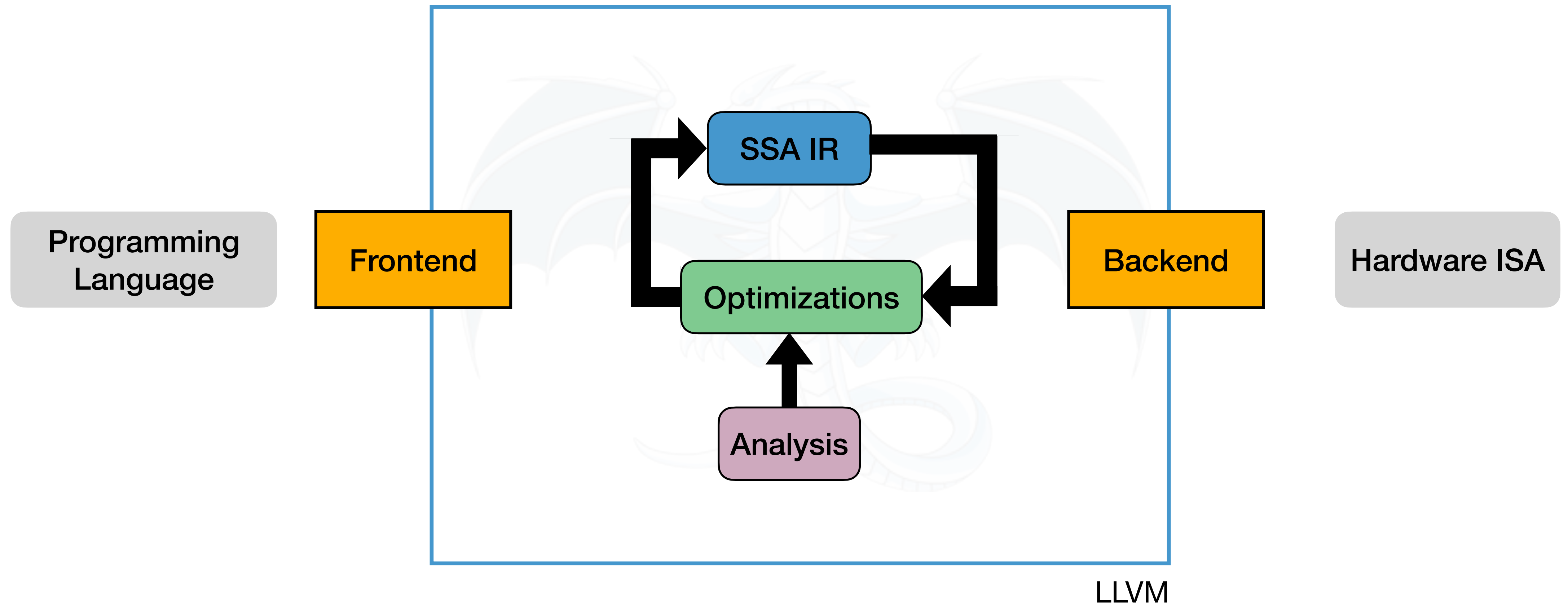


“In 2024 there were 37,486 commits to the LLVM repository... Roughly inline with the 37.4~37.5k commits seen in 2022 and 2023. Those 37.4k commits added 9,339,334 lines of code while removing 5,591,115 lines.”

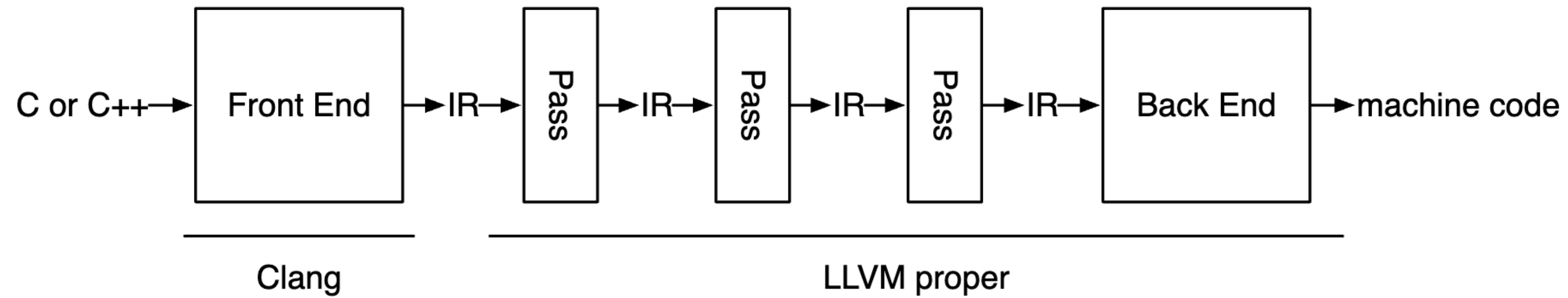
System Overview



System Overview



System Overview



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 %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.

How do you develop new language and compiler abstractions

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“Hitching our research to someone else’s driving problem, and solving those problems on the owners’ terms leads us to richer computer science research.”

— Fred Brooks

How do you develop new language and compiler abstractions

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“Like other great software, great little languages are grown, not built. Start with a solid simple design, expressed in a notation like Backus-Naur form. Before implementing the language, test your design by describing a wide variety of objects in the proposed language. After the language is up and running, iterate designs to add new features as dictated by real use.”

— Jon Bentley (Little Languages)

A process for developing DSLs

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- Study applications to find patterns in their computations
 - Best to work closely with application people
 - Empirical at first: you must see many examples

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 - Generalization must work for observed cases
 - Generalization must work for something new

A process for developing DSLs

- Study applications to find patterns in their computations
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- Then you generalize
 - Deductively from examples to a natural coherent class
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 - Generalization must work for observed cases
 - Generalization must work for something new
- Look for ways to build abstractions into the compiler
 - Lets you separately describe different concerns
 - E.g., describe data structures independently of program