CMSC 430
Introduction to Compilers

Fall 2018

LLVM Compiler Framework

Overview

- We’ve focused on building a compiler, end to end

- In practice, there are a lot of tools we can leverage

- Today we’ll discuss one of the most popular: **LLVM**
  - Introduction to the framework
  - Tour of the IR
  - Using command-line tools
  - Writing optimization passes
  - Using and extending the static analyzer
  - Symbolic execution with Klee

LLVM Overview

- From http://llvm.org/: “The LLVM Project is a collection of modular and reusable compiler and toolchain technologies.”

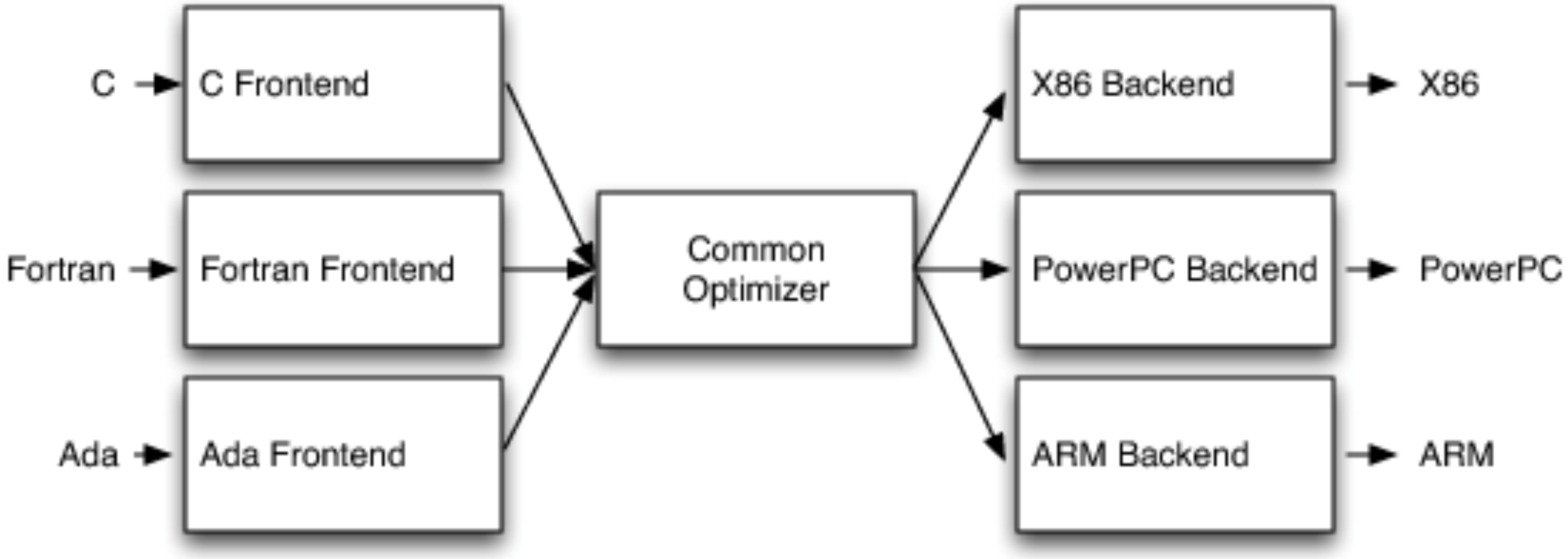
- Started in 2000 as a research project at the University of Illinois (Lattner and Adve)
  - Still actively used in compiler and PL research

- Has grown into an industrial scale collection of compilers, libraries, and tools
  - Used and supported by Apple, Adobe, Intel, etc.

- Written in C++, well-documented

Compiler architecture

- Specialized parsers (frontends) and code generators (backends), common optimizers



http://www.aosabook.org/en/llvm.html

Getting LLVM

- The project changes frequently
  - And contains a lot of code

- Typically, build from source
  - But this can take a while…

- Binary distributions are also available

- Macs ship with a subset, installed with Xcode
  - In particular, clang/clang++ (aliased as gcc)

LLVM IR

- Low-level, similar to RISC-like assembly
  - With enough structure to see high-level features
- Strongly-typed: every value has a type
  - includes support for structures
- Infinite temporary registers
- SSA -- static single assignment
  - Can only assign to each variable once
  - Simplifies program analysis

http://llvm.org/docs/LangRef.html

```
int add(int a, int b)
{
    return a + b;
}
```

```
clang -S add.c -emit-llvm -o add.ll
```

```
; Function Attrs: noinline nounwind optnone ssp uwtable
define i32 @add(i32, i32) #0 {
  %3 = alloca i32, align 4
  %4 = alloca i32, align 4
  store i32 %0, i32* %3, align 4
  store i32 %1, i32* %4, align 4
  %5 = load i32, i32* %3, align 4
  %6 = load i32, i32* %4, align 4
  %7 = add nsw i32 %5, %6
  ret i32 %7
}
```

LLVM Tools

- Three IR formats: ASCII (.ll), Bitcode (.bc), and in-memory representation
- **clang/clang++:** compile C to LLVM IR (different frontends for other high-level languages)
- **llvm-as:** translate .ll into .bc
- **llvm-dis:** convert back from .bc to .ll
- **llvm-link:** combine multiple .bc files
- **lli:** interpreter and dynamic compiler
- **llc:** .bc to native assembly (.s)
- **opt:** LLVM optimizer/analyzer

https://llvm.org/docs/CommandGuide/

opt tool

- `opt` can be used for both optimization and analysis
  - `loop.c` example: `-O3`, `-analyze -loops`
- Extensible via DLLs
  - Can write new analyses as “passes”
  - `opt -load LLVMHello.dylib -hello funcs.ll`

http://llvm.org/docs/WritingAnLLVMPass.html#quick-start-writing-hello-world

Static Analyzer

- LLVM can be used to build static analysis tools, e.g., http://clang-analyzer.llvm.org/

```
void test(int z) {
  if (z == 0) {
    int x = 1 / z;
  }
}
```

```
$ scan-build clang -c div0.c
scan-build: Using 'clang-7' for static analysis
div0.c:3:9: warning: Value stored to 'x' during its
initialization is never read
    int x = 1 / z;
        ^   ~~~~~
div0.c:3:15: warning: Division by zero
    int x = 1 / z;
            ~~^~~
2 warnings generated.
scan-build: 2 bugs found.
```

Address Sanitizer

- LLVM/clang can be used to implement runtime instrumentation for safety, performance measurement, etc.
- https://clang.llvm.org/docs/AddressSanitizer.html

```
int main(int argc, char **argv) {
  int *array = new int[100];
  delete [] array;
  return array[argc];  // BOOM
}
```

```
clang++ -O1 -g -fsanitize=address -fno-omit-frame-pointer UseAfterFree.cc
```

```
=================================================================
==65223==ERROR: AddressSanitizer: heap-use-after-free on address 0x614000000044 at pc…
READ of size 4 at 0x614000000044 thread T0
    #0 0x108d6af07 in main UseAfterFree.cc:4
    #1 0x7fff67e3a014 in start (libdyld.dylib:x86_64+0x1014)
```

Klee: Symbolic Execution

http://klee.github.io/tutorials/testing-function/