Compiler construction 2014

Lecture 3

- Introduction to LLVM.
- LLVM language and tools.

Register machines

Fast but scarce

Registers are places for data inside the CPU.

+ up to 10 times faster access than to main memory.
- expensive; typically just 32 of them in a 32-bit CPU.

Typically, arithmetic operations, conditional jumps etc operate on values stored in registers.

Most modern assembly languages use registers, which correspond closely to the machine registers.

LLVM (the Low Level Virtual Machine)

LLVM is a virtual machine:
it has an unbounded number of registers.

A later step does register allocation, mapping virtual registers to real machine registers.

The LLVM project

The LLVM Infrastructure

A collection of (C++) software libraries and tools to help in building compilers, debuggers, program analysers, etc.

Tools available on Studat Linux machines.
Can also be downloaded to your own computer. Visit `llvm.org` .

History

Started as academic project at University of Illinois at Urbana-Champaign 2002.

Now a large open source project with many contributors. Growing user base.

Related projects

- Clang. C/C++ front end; aims to replace `gcc`.
- VMKit. Implements JVM and CLI by translating to LLVM.

ACM Software Systems Award 2012 to LLVM

Last year ACM announced that LLVM is the 2012 winner of the Software Systems Award.

Previous winners include:

- VMware
- Make
- Java
- Spin
- Apache
- WWW
- TCP/IP
- Postscript
- TEX
- Unix

The LLVM language

Characteristic features

- Three adress-code: two source registers and one destination register:
  `%t2 = add i32 %t0, %t1`
- One source can be a value:
  `%t5 = add i32 %t3, 7`
- Instructions are typed:
  ```
  %t8 = fadd double %t6, %t7
  store i32 %t5 , i32* %r
  ```
- New register for each result (Static Single Assignment form).

Hello world in LLVM

```
@hw = internal constant [13 x i8] c"hello world\0A\00"
declare i32 @puts(i8*)

define i32 @main () {
entry: %t1 = bitcast [13 x i8]* @hw to i8*
       %t2 = call i32 @puts(i8* %t1)
       ret i32 %t2
}
```

Comments

- String is named `@hw`, a global constant (global names start with `@`). Note escape sequences!
- Library function `@puts` is declared, giving type signature.
- `@hw` is cast to type of argument to `puts`.
  Note: Better (type-safe) solution later!

An illegal LLVM program

```
declare void @printInt(i32 %n)
define i32 @main() {
entry: %t1 = call i32 @sum(i32 100)
       call void  @printInt(i32 %t1)
       ret i32 0
}
define i32 @sum (i32 %n) {
entry: %sum = i32 0
       %i = i32 0
       br label %lab1
lab1:  %i = add i32 %i, 1
       %sum = add i32 %sum, %i
       %t = icmp eq i32 %i, %n
       br i1 %t, label %end, label %lab1
end:   ret i32 %sum
}
```

Reasons

- Important reason: Not SSA form: Two assignments to `%i` and `%sum`.
- Trivial reason: There is no *reg = val* instruction.

Corrected program

```
define i32 @sum (i32 %n) {
entry: %sum = alloca i32
       store i32 0, i32* %sum
       %i = alloca i32
       store i32 0, i32* %i
       br label %lab1
lab1:  %t1 = load i32* %i
       %t2 = add i32 %t1, 1
       %t3 = load i32* %sum
       %t4 = add i32 %t2, %t3
       store i32 %t2, i32* %i
       store i32 %t4, i32* %sum
       %t5 = icmp eq i32 %t2, %n
       br i1 %t5, label %end, label %lab1
end:   ret i32 %t4
}
```

Comments

- `%i` and `%sum` are now pointers to memory locations.
- Only one assignment to any register.

Problem

This program has a lot more memory traffic!

What can LLVM's optimizer do about that?

Optimizing @sum

```
> opt -mem2reg sum.ll > sumreg.bc
> llvm-dis sumreg.bc
> less sumreg.ll
define i32 @sum(i32 %n) {
entry:
  br label %lab1
lab1:
  %i.0 = phi i32 [ 0, %entry ], [ %t2, %lab1 ]
  %sum.0 = phi i32 [ 0, %entry ], [ %t4, %lab1 ]
  %t2 = add i32 %i.0, 1
  %t4 = add i32 %t2, %sum.0
  %t5 = icmp eq i32 %t2, %n
  br i1 %t5, label %end, label %lab1
end:
  ret i32 %t4
}
```


Φ "functions"

SSA form

- Only one assignment in the program text to each variable. (But dynamically, this assignment can be executed many times).
- Many (static) stores to a memory location are allowed.
- Also, Φ (`phi`) instructions can be used, in the beginning of a basic block.
  Value is one of the arguments, depending on from which block control came to this block.
  Register allocation tries to keep these variables in same real register.

Why SSA form?

Many code optimizations can be done more efficiently (later).

Optimizing the program further

Many optimization passes

`opt` implements many code analysis and improvement methods.
To get a default selection, give command line arg `-std-compile-opts`.

Result, part 1

```
; ModuleID = '<stdin>'

declare void @printInt(i32)

define i32 @main() {
entry:
  tail call void @printInt(i32 5050)
  ret i32 0
}
```


Optimizing sum further

Result after `opt -std-compile-opts`

```
define i32 @sum(i32 %n) nounwind readnone {
entry:
  %0 = shl i32 %n, 1
  %1 = add i32 %n, -1
  %2 = zext i32 %1 to i33
  %3 = add i32 %n, -2
  %4 = zext i32 %3 to i33
  %5 = mul i33 %2, %4
  %6 = lshr i33 %5, 1
  %7 = trunc i33 %6 to i32
  %8 = add i32 %0, %7
  %9 = add i32 %8, -1
  ret i32 %9
}
```

Analysis of optimized code for `@sum`

- Previous loop with execution time $O(n)$ has been optimized to code without loop, running in constant time.
- Recall $1 + 2 + \ldots + n = n(n+1)/2$.
  Check that optimized code computes this.
- Why extensions/truncations to and from 33 bits?
- What happens when n is negative?

`opt -std-compile-opts` includes many optimization passes.
Use `-time-passes` for an overview.
We will discuss some of these algorithms later.

`printInt` and other IO functions

Part of `runtime.ll`

```
@dnl = internal constant [4 x i8] c"%d\0A\00"

declare i32 @printf(i8*, ...)

define void @printInt(i32 %x) {
entry: %t0 = getelementptr [4 x i8]* @dnl, i32 0, i32 0
       call i32 (i8*, ...)* @printf(i8* %t0, i32 %x)
       ret void
}
```

We provide this file on the course web site; you just have to make sure that it is available for linking.

Linking and running the program

Linker is `llvm-ld`

```
> llvm-ld sumopt.bc runtime.bc
> ./a.out
5050
> less a.out
#!/bin/sh
exec lli a.out.bc ${1+"$@"}
```

So, linking produces two files:

- The short shellscript `a.out`.
- The linked bitcode program `a.out.bc`.

`lli` is the LLVM interpreter/JIT compiler.

What is in `a.out.bc`

Disassemble it! (Result slightly edited)

```
>cat a.out.bc | llvm-dis -
; ModuleID = 'a.out.bc'

@dnl = internal constant [4 x i8] c"%d\0A\00"

define i32 @main() {
entry:
  %t0 = getelementptr [4 x i8]* @dnl, i32 0, i32 0
  call i32 (i8*, ...)* @printf(i8* %t0, i32 5050)
  ret i32 0
}

declare i32 @printf(i8*, ...)
```

Types in LLVM

An incomplete list

Below t and t_i are types and n an integer literal.

- n bit integers: `i`n .
- `float` and `double`.
- Labels: `label`.
- The void type: `void`.
- Functions: $t(t_1, t_2, \ldots, t_n)$.
- Pointer types: t *.
- Structures: { $t_1, t_2, \ldots, t_n$ }.
- Arrays : [n x t].

Named types and type equality

Named types

One can give names to types. Examples:

```
%length = type i32
%list = type %Node*
%Node = type { i32, %Node* }

%tree = type %Node2*
%Node2 = type { %tree, i32, %tree }

%matrix = type [ 100 x [ 100 x double ] ]
```

Type equality

LLVM uses structural equality for types.
When disassembling bitcode files that contain several structurally equal types with different names, this may give confusing results.

Identifiers

Local identifiers

Registers and named types have local names, starting with `%`.

Global identifiers

Functions and global variables have global names, starting with `@`.

Javalette does not have global variables, but you will need to define global names for string literals, as in

```
@hw = internal constant [13 x i8] c"hello world\0A\00"
```

After this definition, `@hw` has type `[13 x i8]*`.

Constants

Literals

- Integer and floating-point literals are as expected.
- `true` and `false` are literals of type `i1`.
- `null` is a literal of any pointer type.

Aggregates

Constant expressions of structure and array types can be formed; not needed by Javalette.

Function definitions

Simplest form

define t *gname* ($t_1\ x_1, t_2\ x_2, \ldots, t_n\ x_n$) {
  $block_1$
  $block_2$
  ...
  $block_n$
}

where *gname* is a global name (the name of the function), the x_i are local names (the parameters) and the $\texttt{block}_i$ are basic blocks.

Basic blocks

A basic block is a label followed by a colon and a sequence of LLVM instructions, each on a separate line. The last instruction must be a terminator instruction.

Function declarations

Type-checking

The LLVM assembler does type-checking. Hence it must know the types of all external functions, i.e. functions used but not defined in the compiled unit.

Simple function declaration

The basic form is `declare` t *gname* ($t_1, t_2, \ldots t_n$)

For Javalette, this is necessary for IO functions. The compiler would typically insert in each file

```
declare void @printInt(i32)
declare void @printDouble(double)
declare void @printString(i8*)
declare i32 @readInt()
declare double @readDouble()
```


LLVM tools

- The assembler `llvm-as`. Translates to bitcode (`prog.ll` to `prog.bc`).
- The disassembler `llvm-dis`. Translates in the opposite direction.
- The interpreter/JIT compiler `lli`. Executes bitcode file containing a `main` function.
- The linker `llvm-ld`. Links together several bitcode files and produces `a.out.bc` and a small script `a.out`, which calls `lli` on `a.out.bc`.
- The compiler `llc`. Translates to native assembler.
- The optimizer `opt`. Optimizes bitcode; many options to decide on which optimizations to run. Use `-std-compile-opts` to get a default selection.
- Drop-in replacement for `gcc`: `clang`.

Use of LLVM in your compiler

Default mode

Your code generator produces assembler file (`.ll`). Then your main program uses system calls to first assemble this with `llvm-as`, optimize with `opt` and then link together with `runtime.bc`.

Other modes

More advanced; we do not recommend these for this project.

- C++ programmers can use the LLVM libraries to build in-memory representation and then output bitcode file.
- Haskell programmers can access C++ libraries via Hackage package `LLVM`.

LLVM instructions

Basic collection

Basic Javalette will only need the following instructions:

- Terminator instructions: `ret` and `br`.
- Arithmetic operations:
  - For integers `add`, `sub`, `mul`, `sdiv` and `srem`.
  - For doubles `fadd`, `fsub`, `fmul` and `fdiv`.
- Memory access: `alloca`, `load`, `getelementptr` and `store`.
- Other: `icmp`, `fcmp` and `call`.

Some of the extensions will need more.

Next time

Code generation for LLVM.