Compiler construction 2012

Lecture 5

Code generation for LLVM

LLVM modules

A LLVM compilation unit (a module) consists of a sequence of

- type definitions.
- global variable definitions.
- function definitions.
- (external) function declarations.

Also global variables may be declared, rather than defined.

This is not necessary for Javalette; the only use of global variables is for naming string literals (as arguments to `printString`).

Basic blocks in LLVM

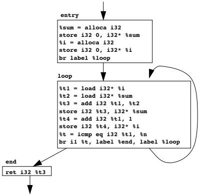
Recall

A basic block starts with a label and ends with a terminating instruction (`ret` or `br`).

Thus one cannot "fall through" the end of a block into the next; an explicit branch to (the label of) the next instruction is necessary.

Consequence

The basic blocks of a LLVM function definition can be reordered arbitrarily; a function body is a graph of basic blocks (the **control flow graph**).



Compilation to LLVM

General observations

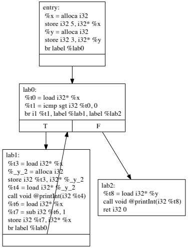
- Compilation schemes described for JVM often easily modified.
- Idea with two different codegen functions for expressions useful also here (one function for test expressions in control structures, one for Boolean expressions in assignments and as parameters).
- Local variables and parameters should be treated as memory locations (`alloca`/`load`/`store` instructions). These will be removed by `opt`
  (and new memory references maybe introduced during register allocation).

Code generation for variables, 1

There are no nested scopes in LLVM. Thus Javalette variables may need to be renamed.

Example

```
int main () {
  int x = 5;
  int y = 3;
  while (x>0) {
    int y = x;
    printInt(y);
    x--;
  }
  printInt(y);
  return 0;
}
```



Optimizing code from previous slide

```
$ opt -std-compile-opts a.ll | llvm-dis
; ModuleID = '<stdin>'

declare void @printInt(i32)

define i32 @main() {
entry:
  tail call void @printInt(i32 5)
  tail call void @printInt(i32 4)
  tail call void @printInt(i32 3)
  tail call void @printInt(i32 2)
  tail call void @printInt(i32 1)
  tail call void @printInt(i32 3)
  ret i32 0
}
```


Code generation for variables, 2

- When a variable declaration is seen, generate a (possibly) new name, generate `alloca` instruction and save (Javalette name, LLVM name) pair in lookup table in the code generator.
- Keep track of scope in lookup table.
- In assignment statement, `store` value of RHS using the LLVM name.
- When a variable is seen (in an expression), `load` from memory using the LLVM name.
- Similar considerations for parameters.

Types of local and global variables

Local variables

The instruction

```
%x = alloca i32
```

introduces a new variable `%x` of type `i32*`;
`%x` is a **pointer to** a newly allocated memory location.

Global variables

The instruction

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

introduces a global name `@hw` of type `[ 13 x i8 ]*`;
`@hw` is a pointer to a byte array.

Treatment of labels

Labels are not instructions in LLVM

But it may be convenient for you to treat them as if they were!

Basic blocks without instructions are illegal

Depending on your compilation schemes, you may find yourself in the situation that a label has just been emitted and the function ends without further instructions.

The situation can then be saved by emitting the terminator instruction `unreachable`.

The `getelementptr` instruction

From reference manual

The `getelementptr` instruction is used to get the address of a subelement of an aggregate data structure. It performs address calculation only and does **not** access memory.

Instruction arguments

First argument is always a pointer to the beginning of the structure; the following are integers specifying the subelement.

Example type

```
%T = type
    { i32,
      { [ 4 x i32 ],
        [ 8 x i32 ]
      }
    }*
```

Example use

```
define i32 @f (%T %x) {
  %p = getelementptr %T %x,
       i32 0, i32 1, i32 1, i32 7
  %res = load i32* %p
  ret i32 %res
}
```


Another `getelementptr` example

```
@mat = global [3 x [4 x i32]]
              [[4 x i32] [i32 1, i32 2, i32 3, i32 4],
               [4 x i32] [i32 5, i32 6, i32 7, i32 8],
               [4 x i32] [i32 9, i32 10, i32 11, i32 12]]
declare void @printInt(i32)

define i32 @main () {
  %t1 = getelementptr [3 x [4 x i32]]* @mat,
             i32 0, i32 1, i32 2
  %t2 = load i32* %t1
  call void @printInt(i32 %t2)
  ret i32 0
}
```

Executing this program prints 7. Note type of `@mat`.

Still another `getelementptr` example

```
%T1 = type
   { i32, { [ 4 x i32 ]*, [ 8 x i32 ]* } }*

define i32 @f1 (%T1 %x) {
    %p = getelementptr %T1 %x, i32 0, i32 1, i32 1
    %p1 = load [ 8 x i32 ]** %p
    %p2 = getelementptr [ 8 x i32 ]* %p1, i32 0, i32 7
    %res = load i32* %p2
    ret i32 %res
}
```

`@f1` returns the last element of the 8-element array in `%x`.

We can **not** do this with just one `getelementptr` instruction; we need to access memory to get the pointer to the array.

Why the first 0?

```
struct Pair {
  int x, y;
};
int f(struct Pair *p) {
  return p[0].y + p[1].x;
}
```

```
%Pair = type { i32, i32 }
define i32 @f(%Pair* %p) {
entry: %t1 = getelementptr %Pair* %p, i32 0, i32 1
       %t2 = load i32* %t1
       %t3 = getelementptr %Pair* %p, i32 1, i32 0
       %t4 = load i32* %t3
       %t5 = add i32 %t2, %t4
       ret i32 %t
}
```


Computing the size of a type

Size of a variable

With the size of a type `%T`, we mean the size (in bytes) of a variable of type `%T`. For a given LLVM type `%T`, this size can vary between target architectures (e.g. pointer types differ in size). So, how does one write portable code?

LLVM does not have a correspondence to C's `sizeof` macro.

The trick

We use the `getelementptr` instruction:

```
  %p = getelementptr %T* null, i32 1
  %s = ptrtoint %T* %p to i32
```

Now, %s holds the size of `%T`. Why?

Treatment of string literals

String literals occur in Javalette only as argument to `printString`. When you encounter such a string you must introduce a definition that gives the string literal a global name.

That definition **must not** appear in the middle of the current function. (Recall hello world program.)

The type of the global variable is `[` *n* `x i8 ]*`, where *n* is the length of the string (after padding at the end).

`@printString` is called with the global variable as argument.

Quiz

What is the type of the parameter to `@printString`?

`declare void @printString( ?  )`

String literals, 2

Answer

We cannot let the parameter type be `[` *n* `x i8 ]*`, since *n* varies.
We let instead the parameter type be `i8*`, a pointer to the first byte.
How can we then call `@printString` in a type-correct way?

We use `getelementptr` to get a pointer to the first byte of the string (i.e. to the same address, but the type will change).

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

define i32 @main () {
entry: %t1 = getelementptr [ 13 x i8 ]* @hw, i32 0, i32 0
       call void @printString(i8* %t1)
       ret i32 0
}
```

State during code generation

As for JVM, we need to keep some state information during code generation. This includes **at least**

- next number for generating register names (and labels).
- definitions of global names for string literals.
- lookup table to find LLVM name for Javalette variable name.
- lookup table to find type of function.

Further properties of functions

In function definitions

- Linkage type, e.g. `private`, `internal`.
- Attributes, e.g. `readnone`, `readonly`, `nounwind`.
- Calling convention, e.g. `ccc`, `fastcc`.

In function calls

- Tail call indication.
- Attributes.
- Calling convention.

Final example

Javalette code

```
boolean even(int n) {
  if (n==0)
     return true;
  else
     return odd (n-1);
}
boolean odd(int n) {
  if (n==0)
     return false;
  else
     return even (n-1);
}
```

Javalette code

```
int main () {
  if (even (20))
     printString("Even!");
  else
     printString("Odd!");
  return 0;
}
```

To be done in class

- Write naive LLVM code.
- Send it through `opt` to get better code.

What next?

- Finish submission A at the latest April 22.
- Submit also incomplete solutions or ask for extension **before** the deadline.
- Late solutions will not get credit for extensions unless the reasons are **very** good.