CS 516: COMPILERS

Lecture 8

Topics

- Data structures in LLVM
- LLVMlite and Homework 4

Materials

- lec08.zip

DATATYPES IN THE LLVM IR

Structured Data in LLVM

- LLVM's IR uses types to describe the structure of data.

```
t ::=
    void
    i1 | i8 | i64                  N-bit integers
    [<#elts> x t]                  arrays
    fty                            function types
    {t1, t2, … , tn}               structures
    t*                             pointers
    %Tident                        named (identified) type

fty ::=             Function Types
    t (t1, .., tn)                 return, argument types
```

- <#elts> is an integer constant >= 0
- Structure types can be named at the top level:

```
%T1 = type {t1, t2, … , tn}
```

  – Such structure types can be recursive

Example LL Types

- An array of 516 integers: `[ 516 x i64]`

- A two-dimensional array of integers: `[ 3 x [ 4 x i64 ] ]`

- Structure for representing arrays with their length:

  ```
  { i64 , [0 x i64] }
  ```

  – There is no array-bounds check; the static type information is only used for calculating pointer offsets.

- C-style linked lists (declared at the top level):

  ```
  %Node = type { i64, %Node*}
  ```

- Structs from the C program shown earlier:

  ```
  %Rect = { %Point, %Point, %Point, %Point }
  %Point = { i64, i64 }
  ```

IR for types

Source:

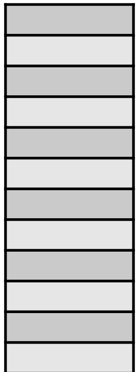
```
struct point { int x; int y; }
struct rect { point ll; point lr; point ul; point ur }
…
myR.ul.x = 42;
int t = myR.ur.y;
```

IR:

```
%Rect = { %Point, %Point, %Point, %Point }
%Point = { i64, i64 }
…
(something) = 42;   // store a new ul.x
…
%13 = (something) ; // load the ur y
```

X86:

```
…
Mov $42, (X86 address)
Mov (X86 address), %eax
```



getelementptr

- LLVM provides the `getelementptr` instruction to compute pointer values
  - Given a pointer and a "path" through the structured data pointed to by that pointer, `getelementptr` computes an address
  - `getelementptr` ***does not access memory***.
  - This is the abstract analog of the X86 LEA (load effective address).
  - It is a "type indexed" operation, since the size computations depend on the type

```
insn ::= …
      |   getelementptr t* %val, t1 idx1, t2 idx2 ,…
```

- Example: access the x component of the first point of a rectangle:

```
%tmp1 = getelementptr %Rect* %square, i32 0, i32 0
%tmp2 = getelementptr %Point* %tmp1, i32 0, i32 0
```

GEP Example*

```
struct RT {
     int A;
     int B[10][20];
     int C;
}
struct ST {
     struct RT X;
     int Y;
     struct RT Z;
}
int *foo(struct ST *s) {
  return &s[1].Z.B[5][13];
}
```

```
%RT = type { i32, [10 x [20 x i32]], i32 }
%ST = type { %RT, i32, %RT }
define i32* @foo(%ST* %s) {
entry:
     %arrayidx = getelementptr %ST* %s, i32 1, i32 2, i32 1, i32 5, i32 13
     ret i32* %arrayidx
}
```


*adapted from the LLVM documentaion: see http://llvm.org/docs/LangRef.html#getelementptr-instruction

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5. Index into the 2d array.

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```

Final answer: ADDR + `size_ty(%ST) + size_ty(%RT) + size_ty(i32)`
`+ size_ty(i32) + 5*20*size_ty(i32) + 13*size_ty(i32)`

*adapted from the LLVM documentaion: see http://llvm.org/docs/LangRef.html#getelementptr-instruction

getelementptr

- GEP *never* dereferences the address it's calculating:
  - GEP only produces pointers by doing arithmetic
  - It doesn't actually traverse the links of a datastructure

- To index into a deeply nested structure, need to "follow the pointer" by loadingfrom the computed pointer
  - See list.ll from HW4

```
%node = type { i64, %node* }

@hd = global %node { i64 1, %node* @md }
@md = global %node { i64 2, %node* @tl }
@tl = global %node { i64 3, %node* null }

define i64 @main(i64 %argc, i8** %arcv) {
  %head = getelementptr %node, %node* @hd, i32 0, i32 0
  %link = getelementptr %node, %node* @hd, i32 0, i32 1
  %next = load %node*, %node** %link
  %val = getelementptr %node, %node* %next, i32 0, i32 0
  %link2 = getelementptr %node, %node* %next, i32 0, i32 1
  %next2 = load %node*, %node** %link2
  %val2 = getelementptr %node, %node* %next2, i32 0, i32 0
  %1 = load i64, i64* %val2
  ret i64 %1
}
```

hw4/llprograms/list1.ll

Compiling Datastructures via LLVM

1. Translate high level language ***types*** into an *LLVM type*.
   - For some languages (e.g. C) this process is straight forward
     - The translation simply uses platform-specific alignment and padding
   - For other languages, (e.g. OO languages) there might be a fairly complex elaboration.
     - e.g. for Ocaml, arrays types might be translated to pointers to length-indexed structs.

       ```
       ⟦int array⟧ = { i32, [0 x i32]}*
       ```
2. Translate ***accesses*** of the data into *getelementptr* operations:
   - e.g. for Ocaml array size access:
     ⟦length a⟧ =
     ```
     %1 = getelementptr {i32, [0xi32]}* %a, i32 0, i32 0
     ```

see HW4: lib/ll/ll.ml

LLVMLITE SPECIFICATION

LLVMlite notes

- Real LLVM requires that constants appearing in getelementptr be declared with type i32:

```
%struct = type { i64, [5 x i64], i64}

@gbl = global %struct {i64 1,
   [5 x i64] [i64 2, i64 3, i64 4, i64 5, i64 6], i64 7}



define void @foo() {
  %1 = getelementptr %struct* @gbl, i32 0, i32 0
  …
}
```

- LLVMlite ignores the i32 annotation and treats these as i64 values
  - we keep the i32 annotation in the syntax to retain compatibility with the clang compiler

COMPILING LLVMLITE TO X86

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  - Map each %uid to a x86 register
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  - Map each %uid to a stack-allocated space
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  - Simple to implement

- For HW3 we will follow Option 2

Compiling LLVMlite Types to X86

- ⟦`i1`⟧, ⟦`i64`⟧, ⟦`t*`⟧ = quad word (8 bytes, 8-byte aligned)
- raw `i8` values are not allowed (they must be manipulated via `i8*`)
- array and struct types are laid out sequentially in memory

- getelementptr computations must be relative to the LLVMlite size definitions
  - i.e. ⟦i1⟧ = quad

Other LLVMlite Features

- Calls
  - Follow x64 AMD ABI calling conventions
  - Should interoperate with C programs

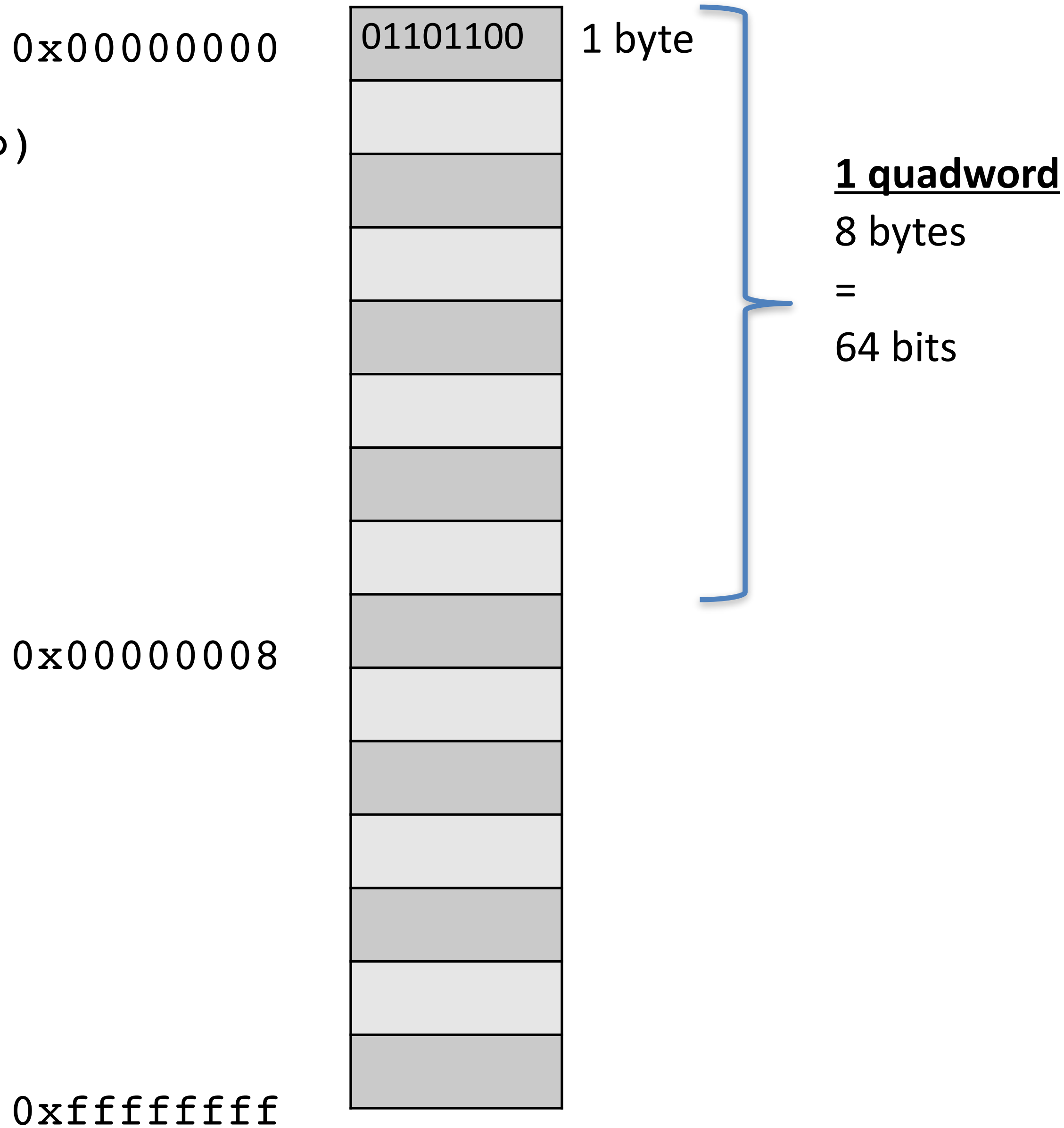
- More types: structured data records and arrays
- New instruction: getelementptr
  - LLVM IR's way of dealing with structured data
  - trickiest part of the compilation process
  - Note: you can start HW3 before understanding getelementptr
- New instruction: bitcast
  - convert between pointer types

- Globals
  - must use %rip relative addressing. See next slide…

RIP-relative global variables

```
Mov global_foo(%rip)
```

2^{64} total bytes



Announcements

- HW4: LLVM lite
  - **Goal**: "Backend" compiler from LLVMlite —> X86lite
  - **Available**: Later today on the course web pages.
  - **Due**: Thursday, March 2nd at 11:59:59pm
  - **Teams**: Teams of 2. Only one group member needs to submit

START EARLY!!

see HW4 and README

ll.ml, using oatc, clang, etc.

TOUR OF HW 4

Bitcast

- What if the LLVM IR's type system isn't expressive enough?
  - e.g. if the source language has subtyping, perhaps due to inheritance
  - e.g. if the source language has polymorphic/generic types

- LLVM IR provides a `bitcast` instruction
  - This is a form of (potentially) unsafe cast. Misuse can cause serious bugs (segmentation faults, or silent memory corruption)

```
%rect2 = type { i64, i64 }          ; two-field record
%rect3 = type { i64, i64, i64 }     ; three-field record

define @foo() {
  %1 = alloca %rect3      ; allocate a three-field record
  %2 = bitcast %rect3* %1 to %rect2*     ; safe cast
  %3 = getelementptr %rect2* %2, i32 0, i32 1  ; allowed
  …
}
```