HARVARD
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CS153: Compilers
Lecture 7:
Structured Data in LLVM IR

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https://www.seas.harvard.edu/courses/cs153

Contains content from lecture notes by Steve Zdancewic and Greg Morrisett

Announcements

- CS Nights: Tuesdays 8pm-10pm, MD119
  - Combined OH for CS153, CS61, CS121
  - Pizza and community!
- Homework 2: X86lite
  - Due today
- Homework 3: LLVMlite
  - Will be released today
  - Due in three weeks
  - Start early!!!
    - Challenging assignment; HW4 will be released in 2 weeks

Today

- Arrays
- Tagged datatypes (and switches)
- Datatypes in LLVM
- Brief tour of HW3

Arrays

```
void foo() {
  char buf[27];

  buf[0] = 'a';
  buf[1] = 'b';
  ...
  buf[25] = 'z';
  buf[26] = 0;
}
```

```
void foo() {
  char buf[27];

  *(buf) = 'a';
  *(buf+1) = 'b';
  ...
  *(buf+25) = 'z';
  *(buf+26) = 0;
}
```

- Space is allocated on the stack for `buf`
  - Note: without ability to allocate stack space dynamically (C's `alloca` function) need to know size of `buf` at compile time…
- `buf[i]` is really just: (base_of_array) + i * elt_size

Multi-dimensional Arrays

- In C `int m[4][3]` yields an array with 4 rows and 3 columns.
  - Laid out in row-major order:
  - `m[0][0]`, `m[0][1]`, `m[0][2]`, `m[1][0]`, `m[1][1]`, …

m[0][0]	m[0][1]	m[0][2]
m[1][0]	m[1][1]	m[1][2]
m[2][0]	m[2][1]	m[2][2]
m[3][0]	m[3][1]	m[3][2]

Multi-dimensional Arrays

- In C `int m[4][3]` yields an array with 4 rows and 3 columns.
  - Laid out in row-major order:
  - `m[0][0]`, `m[0][1]`, `m[0][2]`, `m[1][0]`, `m[1][1]`, …

m[0][0]	m[0][1]	m[0][2]	m[1][0]	m[1][1]	m[1][2]	m[2][0]	m[2][1]	m[2

- So `m[i][j]` is located where?
  - (base address of `m`) + (`i` * 3 * `sizeof(int)`) + `j` * `sizeof(int)`

Multi-dimensional Arrays

- In Fortran, arrays are laid out in column major order

m[0][0]	m[0][1]	m[0][2]
m[1][0]	m[1][1]	m[1][2]
m[2][0]	m[2][1]	m[2][2]
m[3][0]	m[3][1]	m[3][2]

- In ML, there are no multi-dimensional arrays
  - (int array) array is represented as an array of pointers to arrays of ints
- Why is knowing the memory layout strategy importan?

Multi-dimensional Arrays

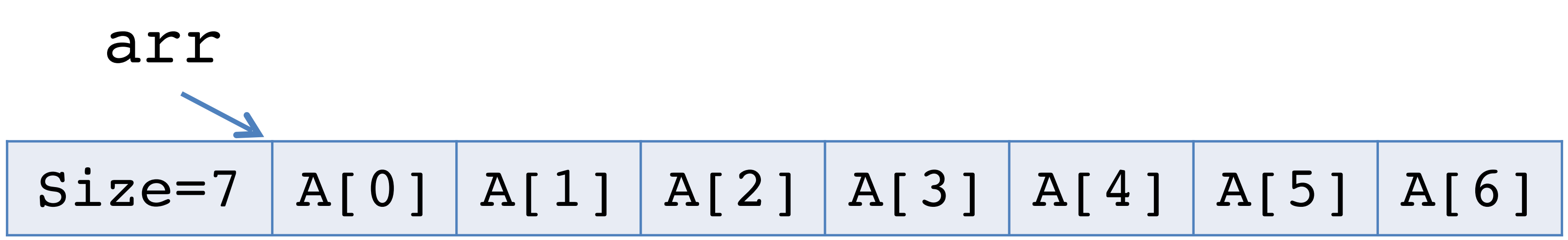
- In Fortran, arrays are laid out in column major order

m[0][0]	m[1][0]	m[2][0]	m[3][0]	m[0][1]	m[1][1]	m[2][1]	m[3][1]	m[0

- In ML, there are no multi-dimensional arrays
    - (int array) array is represented as an array of pointers to arrays of ints
- Why is knowing the memory layout strategy importan?

Array Bounds Checks

- Safe languages (e.g. Java, C#, ML but not C, C++) check array indices to ensure that they are in bounds.
  - Compiler generates code to test that the computed offset is legal
- Needs to know the size of the array… where to store it?
  - One answer: Store the size **before** the array contents.



- Other possibilities:
  - Store size and a pointer to array data
  - Pascal: only permit statically known array sizes (very unwieldy in practice)
  - What about multi-dimensional arrays?

Array Bounds Checks (Implementation)

- Example: Assume `%rax` holds the base pointer (`arr`) and `%ecx` holds the array index `i`. To read a value from the array `arr[i]`:

```
    movq -8(%rax) %rdx          // load size into rdx
    cmpq %rdx %rcx              // compare index to bound
    j l __ok                    // jump if  0 <= i < size
    callq __err_oob             // test failed, call the error handler
__ok:
    movq (%rax, %rcx, 8) dest   // do the load from the array access
```

- Clearly more expensive: adds move, comparison & jump
  - More memory traffic
  - These overheads are particularly bad in an inner loop
  - Compiler optimizations can help remove the overhead
  - e.g. In a for loop, if bound on index is known, only do the test once
- Hardware support can improve performance: executing instructions in parallel, branch prediction
  - But speculative execution is behind the Spectre/Meltdown vulnerabilities...

C-style Strings

- A string constant "foo" is represented as global data:

```
_string42: 0x66 0x6F 0x6F 0x00
```

- C uses null-terminated strings
- Strings are usually placed in the text segment so they are read only.
    - allows all copies of the same string to be shared.
- Rookie mistake (in C): write to a string constant.

```
char *p = "foo”;
p[0] = 'b’;
```

- Instead, must allocate space on the heap:

```
char *p = (char *)malloc(4 * sizeof(char));
strncpy(p, “foo”, 4);   /* include the null byte */
p[0] = 'b’;
```

Tagged Datatypes

C-style Enumerations / ML-style datatypes

- In C:

```
enum Day {sun, mon, tue, wed, thu, fri, sat} today;
```

- In ML:

```
type day = Sun | Mon | Tue | Wed | Thu | Fri | Sat
```

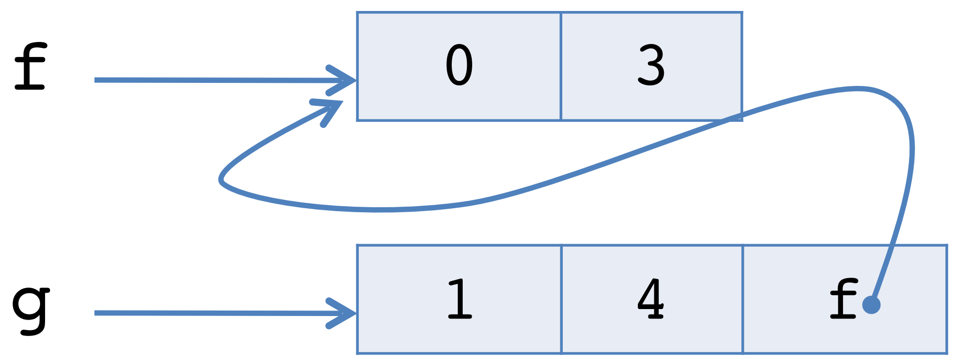
- Associate an integer **tag** with each case: `sun` = 0, `mon` = 1, …
  - C lets programmers choose the tags
- ML datatypes can also carry data:

```
type foo = Bar of int | Baz of int * foo
```

- Representation: a `foo` value is a pointer to a pair: (tag, data)
- Example: tag(`Bar`) = 0, tag(`Baz`) = 1

⟦`let f = Bar(3)`⟧ =

⟦`let g = Baz(4, f)`⟧ =



Switch Compilation

- Consider the C statement:

```
switch (e) {
  case sun: s1; break;
  case mon: s2; break;
  …
  case sat: s3; break;
}
```

- How to compile this?
  - What happens if some of the break statements are omitted? (Control falls through to the next branch.)

Cascading `if`s and Jumps

⟦`switch(e) {case tag1: s1; break; case tag2 s2; …}`⟧ =

- Each `$tag1…$tagN` is just a constant int tag value.
- Note: ⟦`break;`⟧ (within the switch branches) is:
  `br %merge`

```
     %tag = ⟦e⟧;
     br label %l1
l1:  %cmp1 = icmp eq %tag, $tag1
     br %cmp1 label %b1, label %l2
b1:  ⟦s1⟧
     br label %merge

l2:  %cmp2 = icmp eq %tag, $tag2
     br %cmp2 label %b2, label %l3
b2:  ⟦s2⟧
     br label %l3
…
lN:  %cmpN = icmp eq %tag, $tagN
     br %cmpN label %bN, label %merge
bN:  ⟦sN⟧
     br label %merge

merge:
```

Alternatives for Switch Compilation

- Nested if-then-else works OK in practice if # of branches is small
  - (e.g. < 16 or so).
- For more branches, use better datastructures to organize the jumps:
  - Create a table of pairs (v1, branch_label) and loop through
  - Or, do binary search rather than linear search
  - Or, use a hash table rather than binary search

- One common case: the tags are dense in some range [min…max]
  - Let N = max – min
  - Create a branch table Branches[N] where Branches[i] = branch_label for tag i.
  - Compute tag = ⟦e⟧ and then do an **indirect jump**: J Branches[tag]
- Common to use heuristics to combine these techniques.

ML-style Pattern Matching

- ML-style match statements are like C's switch statements except:
  - Patterns can bind variables
  - Patterns can nest

```
match e with
| Bar(z) -> e1
| Baz(y, Bar(w)) -> e2
| _ -> e3
```

```
match e with
| Bar(z) -> e1
| Baz(y, tmp) ->
    (match tmp with
         | Bar(w) -> e2
         | Baz(_, _) -> e3)
```

- Compilation strategy:
  - "Flatten" nested patterns into matches against one constructor at a time.
  - Compile the match against the tags of the datatype as for C-style switches.
  - Code for each branch additionally must copy data from ⟦e⟧ to the variables bound in the patterns.
- There are many opportunities for optimization, many papers about "pattern-match compilation"
  - Many of these transformations can be done at the AST level

Datatypes in the LLVM IR

Structured Data in LLVM

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

`t ::=`	*Types*
`void`	
`i1 | i8 | i64`	*N-bit integers*
`[<#elts> x t]`	*arrays*
fty	*function types*
$\{t_1, t_2, \ldots, t_n\}$	*structures*
`t*`	*pointers*
`%Tident`	*named (identified) type*
`fty ::=`	*Function Types*
$t\ (t_1, .., t_n)$	*return, argument types*

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

`%T1 = type` $\{t_1, t_2, \ldots, t_n\}$

  - Such structure types can be recursive

Example LL Types

- An array of 341 integers: `[ 341 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 }
```

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
  - This is the abstract analog of the X86 LEA (load effective address). It does not access memory.
  - 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];
}
```

1. `%s` is a pointer to an (array of) `%ST` structs, suppose the pointer value is ADDR
2. Compute the index of the 1st element by adding `size_ty(%ST)`.
3. Compute the index of the `Z` field by adding `size_ty(%RT) + size_ty(i32)` to skip past `X` and `Y`.
4. Compute the index of the `B` field by adding `size_ty(i32)` to skip past `A`.
5. Index into the 2d array.

```
%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
}
```

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 documentation: see https://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 loading from the computed pointer
  - See list.ll from HW3

Compiling Data Structures via LLVM

- 1. Translate high level language types into an LLVM representation 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) might be 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
    ```

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
  …
}
```

LLVMlite Specification

- see HW3

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

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

Compiling LLVM locals

- How do we manage storage for each %uid defined by an LLVM instruction?
- Option 1:
  - Map each %uid to a x86 register
  - Efficient!
  - Difficult to do effectively: many %uid values, only 16 registers
  - We will see how to do this later in the semester
- Option 2:
  - Map each %uid to a stack-allocated space
  - Less efficient!
  - Simple to implement

- For HW3 we will follow Option 2

Other LLVMlite Features

- Globals
  - must use %rip relative addressing
- Calls
  - Follow x64 AMD ABI calling conventions
  - Should interoperate with C programs
- `getelementptr`
  - trickiest part