COS320: Compiling Techniques

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March 9, 2019

Compiling data types

Structures

```c
struct Point { long x; long y; };

struct Rect  { struct Point tl, br; };

struct Rect mk_square(struct Point top_left, long len) {
  struct Rect square;
  square.tl = top_left;
  square.br.x = top_left.x + len;
  square.br.y = top_left.y - len;
  return square;
}
```

How do we compile these structures?

```
struct Rect mk_square(struct Point top_left, long len)
```

- cdecl convention:
    - Parameter 1 in `rdi`
    - Parameter 2 in `rsi`
    - Return in `rax`

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- cdecl convention:
  - Parameter 1 in `rdi`
  - Parameter 2 in `rsi`
  - Return in `rax`
- Parameter 1 doesn't fit into `rdi`, and return doesn't fit into `rax`
- Straightforward solution: pass & return pointers to values that don't fit into registers (Java, OCaml)
- C has copy-in/copy out semantics ("call by value")
  - If we call `mk_square(p,5)` and `mk_square` writes to `top_left.x`, the value of `p.x` does not change from the perspective of the caller

Copy-in/Copy-out

- Solution: use additional parameters for structs

```
struct Rect mk_square(long top_left_x, long top_right_y, long len)
```

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```
struct Rect mk_square(long top_left_x, long top_right_y, long len)
```

- ~~Solution~~ for return:

```
struct Rect* mk_square(long top_left_x, long top_right_x, long len) {
  struct Rect result;
  ...
  return &result;
}
```

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  ...
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}
```

  - Unsafe!

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```

- Solution for return:

```
struct Rect* mk_square(long top_left_x, long top_right_x, long len) {
  struct Rect *result = malloc(sizeof(struct Rect));
  ...
  return result;
}
```

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struct Rect mk_square(long top_left_x, long top_right_y, long len)
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- Solution for return:

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  struct Rect *result = malloc(sizeof(struct Rect));
  ...
  return result;
}
```

  - Protocol: caller must de-allocate space
  - Heap allocation is slow

Copy-in/Copy-out

- Solution: use additional parameters for structs

```
struct Rect mk_square(long top_left_x, long top_right_y, long len)
```

- Solution for return:

```
void mk_square(struct Rect *result,
               long top_left_x, long top_right_x, long len) {
  ...
  return;
}
```

  - Callee is responsible for allocating space for return value

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Structures in memory

- What *is* a pointer to a structure?

Structures in memory

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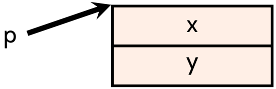
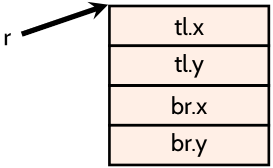
  - Address of the start of a block of memory large enough to store the struct

```
struct Point { long x, y; };
struct Point* p = malloc(sizeof(struct Point));
```



Structures in memory

- What *is* a pointer to a structure?
  - Address of the start of a block of memory large enough to store the struct
  - Nested structs: `struct Rect { struct Point tl, br; };`
    `struct Rect* r = malloc(sizeof(struct Rect));`



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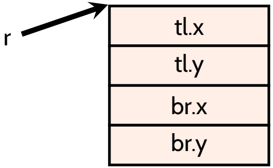
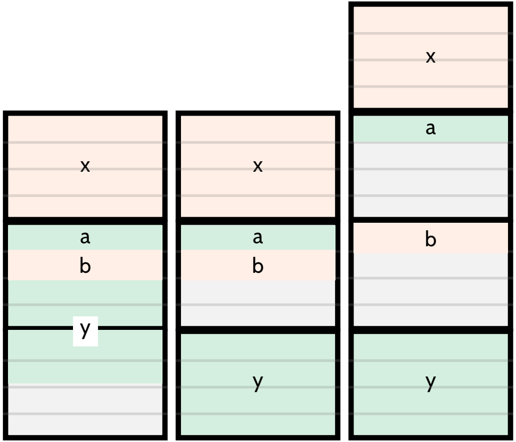


- Compiler needs to know:
  - Size of the struct so that it can allocate storage
  - Shape of the struct so that it can index into the structure

Padding & Alignment

- Memory accesses need to be aligned
  - E.g., in x86lite, memory addresses are divisible by 8
  - Need to insert *padding*: unused space so that pointers align with addressable boundaries
- How do we lay out storage?

```
struct Example {
  int x;
  char a;
  char b;
  int y;
};
```



Structures in LLVM

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

define void @mk_square(%Rect* noalias sret %result, i64 %top_left_x, i64 %top_left_y, i64 %len) {
  %square = alloca %Rect
  ; %square.tl = top_left
  %square_tl_x = getelementptr %Rect, %Rect* %square, i32 0, i32 0, i32 0
  %square_tl_y = getelementptr %Rect, %Rect* %square, i32 0, i32 0, i32 1
  store i64 %top_left_x, i64* %square_tl_x
  store i64 %top_left_y, i64* %square_tl_y

  ; %square.br.x = top_left + len
  %square_br_x = getelementptr %Rect, %Rect* %square, i32 0, i32 1, i32 0
  %t1 = add i64 %top_left_x, %len
  store i64 %t1, i64* %square_br_x

  ; %square.br.y = top_left - len
  %square_br_y = getelementptr %Rect, %Rect* %square, i32 0, i32 1, i32 1
  %t2 = sub i64 %top_left_y, %len
  store i64 %t2, i64* %square_br_y

  ; return square
  %result_tl_x = getelementptr %Rect, %Rect* %result, i32 0, i32 0, i32 0
  %result_tl_y = getelementptr %Rect, %Rect* %result, i32 0, i32 0, i32 1  ...
  %t3 = load i64, i64* %square_tl_x
  %t4 = load i64, i64* %square_tl_y ...
  store i64 %t3, i64* %result_tl_x
  store i64 %t4, i64* %result_tl_y ...
  ret void
}
```

getelementpointer

- The `getelementpointer` instruction handles indexing into tuple, array, and pointer types
  - Given a type, a pointer p of that type, and a *path* q consisting of a sequence of indices, `getelementpointer` computes the address of p->q
- Does *not* access memory (like x86 `lea`)

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```

```
%square_tl_x = getelementptr %Rect, %Rect* %square, i32 0, i32 0, i32 0
```

`&(%square[0])`

`&(%square[0].tl)`

`&(%square[0].tl.x)`

computes `%square + 0*sizeof(struct Rect) + 0 + 0`

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- `getelementptr %Rect, %Rect* %square, i32 0` → `&(%square[0])`
- `getelementptr %Rect, %Rect* %square, i32 0, i32 0` → `&(%square[0].tl)`
- `getelementptr %Rect, %Rect* %square, i32 0, i32 0, i32 1` → `&(%square[0].tl.y)`

computes `%square + 0*sizeof(struct Rect) + 0 + sizeof(i64)`

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%Point = type { i64, i64 }
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%square_br_y = getelementptr %Rect, %Rect* %square, i32 0, i32 1, i32 1
```

- `getelementptr %Rect, %Rect* %square, i32 0` — `&(%square[0])`
- `getelementptr %Rect, %Rect* %square, i32 0, i32 1` — `&(%square[0].br)`
- `getelementptr %Rect, %Rect* %square, i32 0, i32 1, i32 1` — `&(%square[0].br.y)`

computes `%square + 0*sizeof(struct Rect) + sizeof(struct Point) + sizeof(i64)`

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

$$\%squar6\_br\_y = \underbrace{\underbrace{\underbrace{\texttt{getelementptr \%Rect, \%Rect* \%square, i32 6}}_{\texttt{\&(\%square[0])}}\texttt{, i32 1}}_{\texttt{\&(\%square[6].tl)}}\texttt{, i32 1}}_{\texttt{\&(\%square[0].tl.y)}}$$

computes `%square + 6*sizeof(struct Rect) + sizeof(struct Point) + sizeof(i64)`

Arrays

Single-dimensional arrays

- In C: essentially the same as tuples
  - Array is stored as a contiguous chunk of memory
  - Index into position of `i` of an array `a` of `t`s with `a + sizeof(t)*i`

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- Memory-safe languages (e.g, OCaml & Java) must check that an array access is within bounds before accessing
  - Compiler must generate array access checking code
  - Store array length before array contents, or in a pair

    `type bytes = char array` → `%bytes = type { i64, [0 x i8] }*`

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    `type bytes = char array` → `%bytes = type { i64, [0 x i8] }*`

    or `%bytes = type { i64, i8* }*`
  - Example: suppose we want to load `a[i]` into `%rax`; suppose `%rbx` holds a pointer to `a` and `%rcx` holds an index.

```
movq (%rbx) %rdx               // load size into rdx
cmpq %rdx %rcx                 // compare index to bound
j l __ok                       // jump if i < a.size
callq __err_oob                // test failed, call the error handler
__ok:
movq 8(%rbx, %rcx, 8) %rax     // load a[i]
```

Multi-dimensional arrays

- In C: row-major order
  - 3x2 array: `m[0][0], m[0][1], m[1][0], m[1][1], m[2][0], m[2][1]`
- In Fortran: column-major order
  - 3x2 array: `m[0][0], m[1][0], m[2][0], m[0][1], m[1][1], m[2][1]`
- In OCaml & Java: no multi-dimensional arrays
  - 2-dimensional array is an array of arrays

```
type mat = int array array → %mat = type { i64, { i64, i64* }*] }
```

Strings

- Null-terminated arrays of characters
- String constants are kept in the text segment
  - LLVM: `@str = constant [18 x i8] c"Factorial is %ld\0A\00"`
  - X86: `str: .string "Factorial is %d\n"`
  - In the text segment $\Rightarrow$ immutable

Variant types

Enumerations

- `type color = Red | Green | Blue` $\rightarrow$ `i8`
    - Red $\rightarrow$ 0
    - Green $\rightarrow$ 1
    - Blue $\rightarrow$ 2

Enumerations

- `type color = Red | Green | Blue` → `i8`
  - Red → 0
  - Green → 1
  - Blue → 2
- Compiling `switch`:
  1. Nested if statements
  2. Jump tables (for dense switches):

```
switch(color) {
  case Red:
    ...
  case Green:
    ...
  case Blue:
    ...
}
```

→

```
  #color in %rax
  jmp (table, %rax, 8)
LabelRed:
  ...
LabelGreen:
  ...
LabelBlue:
  ...
table:
  .quad LabelRed, LabelGreen, LabelBlue
```

Algebraic data types

- Algebraic data types hold data, and can pattern match on constructor
- `type expr = Add of expr * expr | Var of string`
  - Easy way: quadword tag + payload. Must store a pointer if more space is needed.
    - `type %expr = { i64, i64* }`
    - (use `bitcast` to convert i64* pointer to `{ %expr*, %expr* }*` or `{ i64, [0 x i8] }*` after pattern matching)
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- Nested pattern matching → unnested pattern matching at AST level