Lecture 8

CS131: COMPILERS

Announcements

- HW3: LLVM lite

See llvm.org

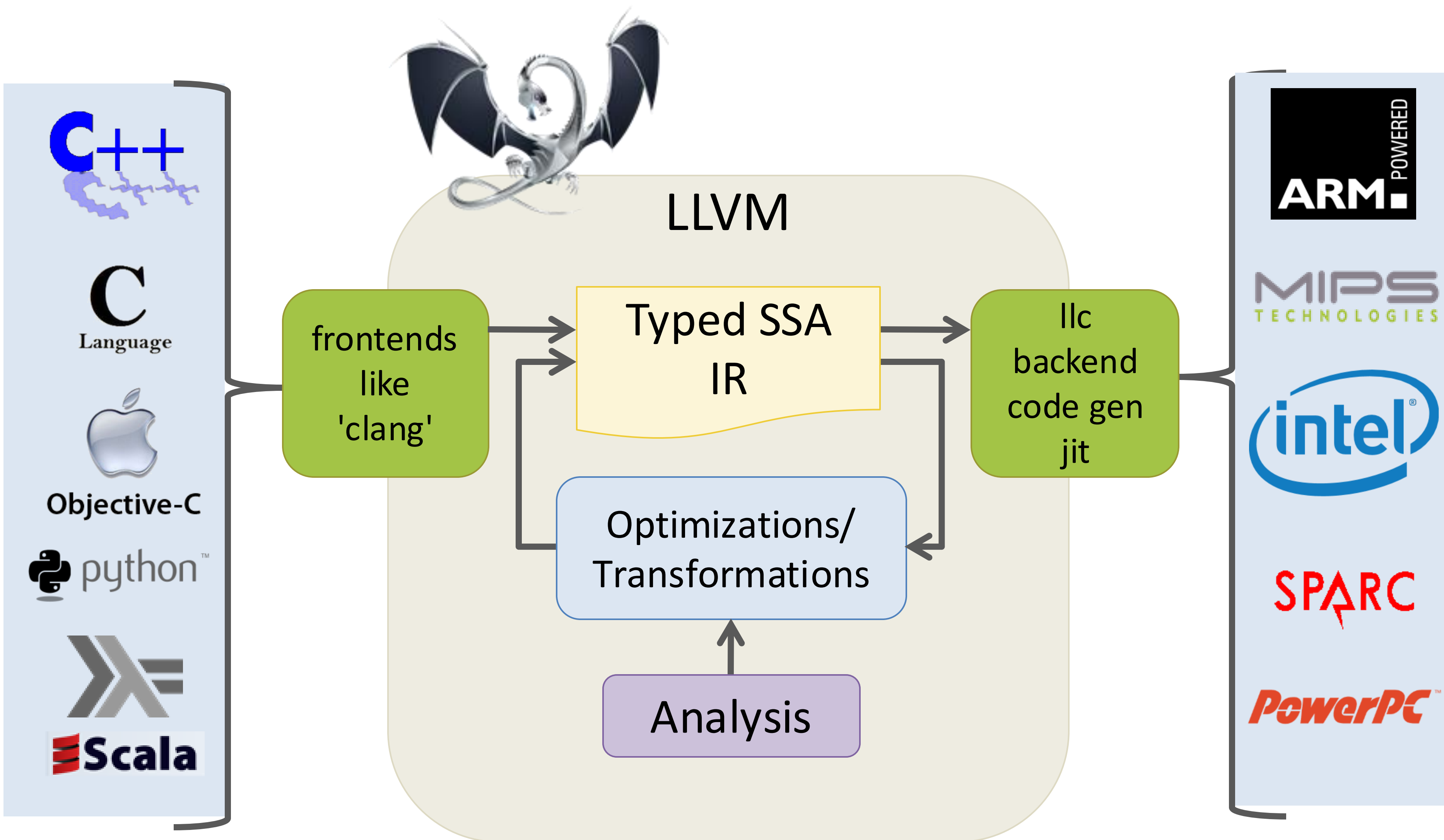
LLVM

Low-Level Virtual Machine (LLVM)

- Open-Source Compiler Infrastructure
  - see llvm.org for full documentation
- Created by Chris Lattner (advised by Vikram Adve) at UIUC
  - LLVM: An infrastructure for Mult-stage Optimization, 2002
  - LLVM: A Compilation Framework for Lifelong Program Analysis and Transformation, 2004
- 2005: Adopted by Apple for XCode 3.1
- Front ends:
  - llvm-gcc (drop-in replacement for gcc)
  - Clang: C, objective C, C++ compiler supported by Apple
  - various languages: Swift, ADA, Scala, Haskell, …
- Back ends:
  - x86 / Arm / Power / etc.
- Used in many academic/research projects

LLVM Compiler Infrastructure

[Lattner et al.]



IR3/4/5 vs. LLVM

- “let - in” and
  OCaml-style identifiers:

let tmp1 = add 3L 4L in

- OCaml-style “let-rec”
  and functions for blocks:

```
let rec entry () =
  let tmp1 = …
and foo () =
  let tmp2 = …
```

- OCaml-style global variables:
  let varX = ref 0L

- Omits let/in and prefixes local identifiers with %:

%tmp1 = add i64 3, i64 4

- Uses lighter-weight colon notation:

```
entry:
  %tmp1 = …
foo:
  %tmp2 = …
```

- Prefixes globals with @
  define @X = i64 0

Example LLVM Code

- LLVM offers a textual representation of its IR
  - files ending in .ll

factorial64.c

```c
#include <stdio.h>
#include <stdint.h>

int64_t factorial(int64_t n) {
  int64_t acc = 1;
  while (n > 0) {
    acc = acc * n;
    n = n - 1;
  }
  return acc;
}
```

factorial-pretty.ll

```llvm
define @factorial(%n) {
  %1 = alloca
  %acc = alloca
  store %n,  %1
  store 1,  %acc
  br label %start

start:
  %3 = load %1
  %4 = icmp sgt %3, 0
  br %4, label %then, label %else

then:
  %6 = load %acc
  %7 = load %1
  %8 = mul %6, %7
  store %8, %acc
  %9 = load %1
  %10 = sub %9, 1
  store %10, %1
  br label %start

else:
  %12 = load %acc
  ret %12
}
```

Real LLVM

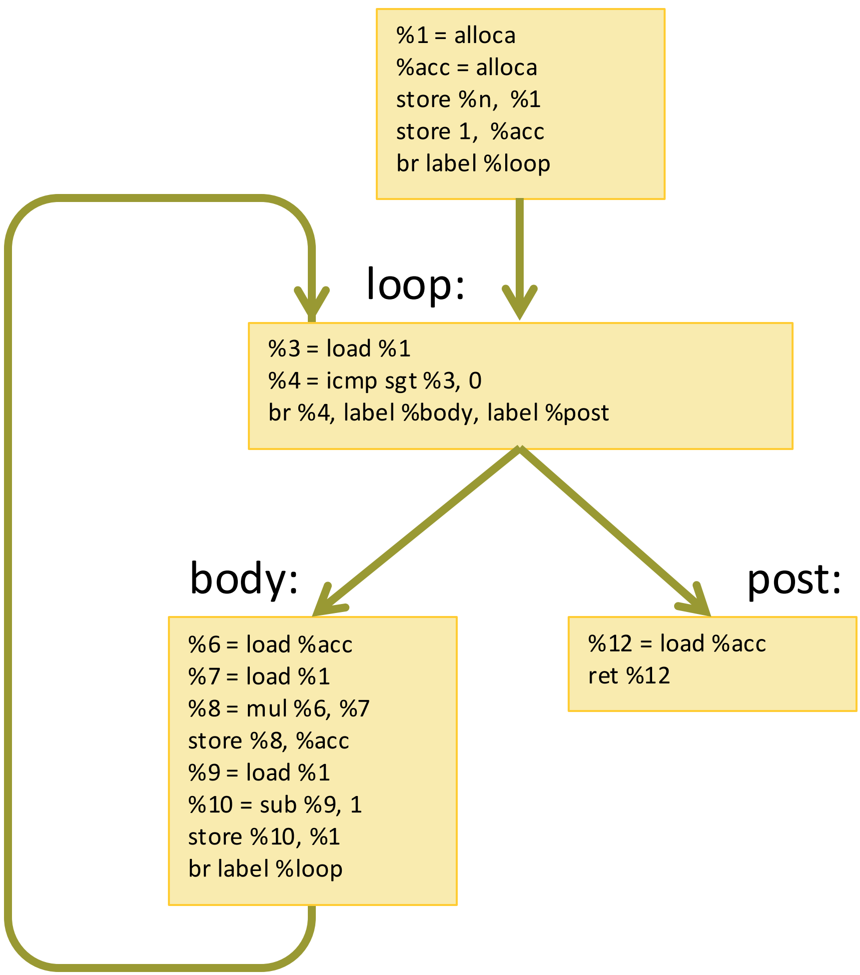
- Decorates values with type information
  i64
  i64*
  i1
- Permits numeric identifiers
- Has alignment annotations
- Keeps track of entry edges for each block:
  preds = %5, %0

factorial.ll

```
; Function Attrs: nounwind ssp
define i64 @factorial(i64 %n) #0 {
  %1 = alloca i64, align 8
  %acc = alloca i64, align 8
  store i64 %n, i64* %1, align 8
  store i64 1, i64* %acc, align 8
  br label %2

; <label>:2                          ; preds = %5, %0
  %3 = load i64* %1, align 8
  %4 = icmp sgt i64 %3, 0
  br i1 %4, label %5, label %11

; <label>:5                          ; preds = %2
  %6 = load i64* %acc, align 8
  %7 = load i64* %1, align 8
  %8 = mul nsw i64 %6, %7
  store i64 %8, i64* %acc, align 8
  %9 = load i64* %1, align 8
  %10 = sub nsw i64 %9, 1
  store i64 %10, i64* %1, align 8
  br label %2

; <label>:11                          ; preds = %2
  %12 = load i64* %acc, align 8
  ret i64 %12
}
```

Example Control-flow Graph

define @factorial(%n) {



}

LL Basic Blocks and Control-Flow Graphs

- LLVM enforces (some of) the basic block invariants syntactically.
- Representation in OCaml:

```
type block = {
    insns : (uid * insn) list;
    term  : (uid * terminator)
}
```

- A *control flow graph* is represented as a list of labeled basic blocks with these invariants:
  - No two blocks have the same label
  - All terminators mention only labels that are defined among the set of basic blocks
  - There is a distinguished, unlabeled, entry block:

```
type cfg = block * (lbl * block) list
```

LL Storage Model

- Several kinds of storage:
  - *Local* variables (or temporaries): %uid
  - *Global* declarations (*e.g.*, for string constants): @gid
  - Abstract locations: references to (stack-allocated) storage created by the alloca instruction
  - Heap-allocated structures created by external calls (*e.g.*, to malloc)

LL Storage Model: Locals

- Local variables:
  - Defined by the instructions of the form %uid = …
  - Analogous to “let %uid = e in …” in OCaml

static single assignment (SSA) invariant:

Each %uid appears on the left-hand side of an assignment ***only once*** *in the entire control flow graph.*

- The value of a %uid remains unchanged throughout its lifetime
- Intended to be an abstract version of machine registers.
- We’ll see soon how to extend SSA to allow richer use of local variables
  - ***phi nodes*** (allow "controlled mutation" of uids)

LL Storage Model: alloca

- alloca instruction allocates stack space and returns a reference to it.
  - The returned reference is stored in local:

    %ptr = alloca type
  - The amount of space allocated is determined by the type

- The contents of the slot are accessed via the load and store instructions:

```
%acc = alloca i64                  ; allocate a storage slot
store i64 3410, i64* %acc          ; store the integer value 3410
%x = load i64, i64* %acc           ; load the value 3410 into %x
```

- Gives an abstract version of stack slots see HW3 lib/ll/ll.ml

LLVMLITE SPECIFICATION

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

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
  (see today's lecture)

Other LLVMlite Features

- Globals
  - must use %rip relative addressing

- 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

STRUCTURED DATA

Compiling Structured Data

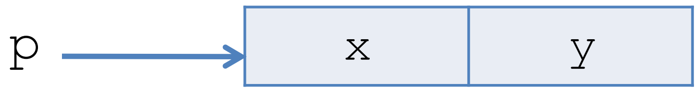
- Consider C-style structures like those below.
- How do we represent `Point` and `Rect` values?

```
struct Point { int x; int y; };

struct Rect  { struct Point ll, lr, ul, ur };

struct Rect mk_square(struct Point ll, int len) {
  struct Rect square;
  square.ll = square.lr = square.ul = square.ur = ll;
  square.lr.x += len;
  square.ul.y += len;
  square.ur.x += len;
  square.ur.y += len;
  return square;
}
```

Representing Structs

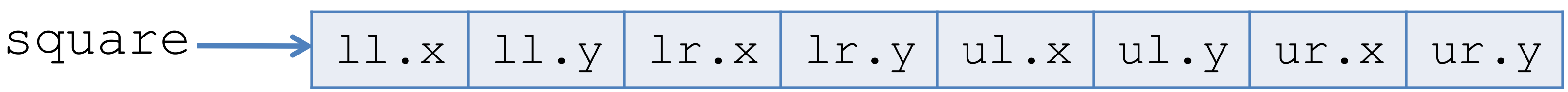
```
struct Point { int x; int y;};
```

- Store the data using two contiguous words of memory.
- Represent a `Point` value `p` as the address of the first word.




```
struct Rect  { struct Point ll, lr, ul, ur };
```

- Store the data using 8 contiguous words of memory.



- Compiler needs to know the *size* of the struct at compile time to allocate the needed storage space.
- Compiler needs to know the *shape* of the struct at compile time to index into the structure.

Assembly-level Member Access

square →

ll.x	ll.y	lr.x	lr.y	ul.x	ul.y	ur.x	ur.y

```
struct Point { int x; int y; };

struct Rect  { struct Point ll, lr, ul, ur };
```

- Consider: ⟦`square.ul.y`⟧ = (x86.operand, x86.insns)

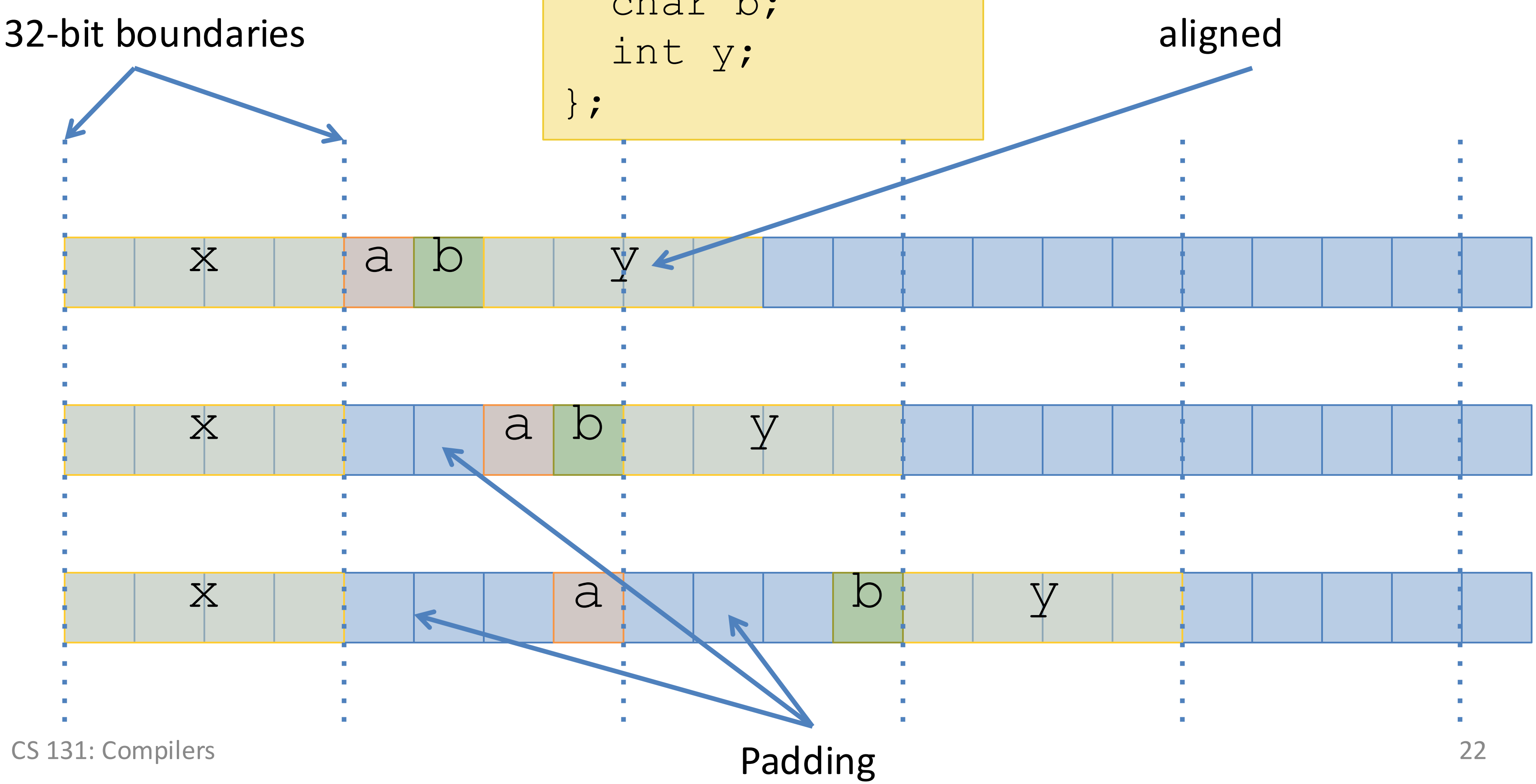
- Assume that `%rcx` holds the base address of `square`
- Calculate the offset relative to the base pointer of the data:
  - `ul` = sizeof(struct Point) + sizeof(struct Point)
  - `y` = sizeof(int)

- So: ⟦`square.ul.y`⟧ = (ans, `Movq 20(%rcx) ans`)

Padding & Alignment

- How to lay out non-homogeneous structured data?

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



Copy-in/Copy-out

When we do an assignment in C as in:

```
struct Rect mk_square(struct Point ll, int elen) {
  struct Square res;
  res.lr = ll;
   ...
```

then we copy all of the elements out of the source and put them in the target. Same as doing word-level operations:

```
struct Rect mk_square(struct Point ll, int elen) {
  struct Square res;
  res.lr.x = ll.x;
  res.lr.y = ll.x;
  ...
```

- For really large copies, the compiler uses something like `memcpy` (which is implemented using a loop in assembly).

C Procedure Calls

- Similarly, when we call a procedure, we copy arguments in, and copy results out.
  - Caller sets aside extra space in its frame to store results that are bigger than will fit in `%rax`.
  - We do the same with scalar values such as integers or doubles.
- Sometimes, this is termed "call-by-value".
  - This is bad terminology.
  - Copy-in/copy-out is more accurate.
- Benefit: locality
- Problem: expensive for large records…

- In C: can opt to pass *pointers* to structs: "call-by-reference"

- Languages like Java and OCaml always pass non-word-sized objects by reference.

Call-by-Reference:

```
void mkSquare(struct Point *ll, int elen,
              struct Rect *res) {
  res->lr = res->ul = res->ur = res->ll = *ll;
  res->lr.x += elen;
  res->ur.x += elen;
  res->ur.y += elen;
  res->ul.y += elen;
}

void foo() {
  struct Point origin = {0,0};
  struct Square unit_sq;
  mkSquare(&origin, 1, &unit_sq);
}
```

- The caller passes in the address of the point and the address of the result (1 word each).

Stack Pointers Can Escape

- Note that returning references to stack-allocated data can cause problems…

```
int* bad() {
  int x = 3410;
  int *ptr = &x;
  return ptr;
}
```

  – see unsafestack.c

- For data that persists across a function call, we need to allocate storage in the heap…
  – in C, use the malloc library

ARRAYS

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 the ability to allocated 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[1][2]`	`M[2][0]`	…

- M[i][j] compiles to?

- 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]`	…

- In ML and Java, there are no multi-dimensional arrays:
  - (int array) array is represented as an array of pointers to arrays of ints.
- Why is knowing these memory layout strategies important?

Array Bounds Checks

- Safe languages (e.g. Java, C#, ML but not C, C++) check array indices to ensure that they're 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.

`arr`

`Size=7`	`A[0]`	`A[1]`	`A[2]`	`A[3]`	`A[4]`	`A[5]`	`A[6]`

- 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 `%rcx` 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: 102 111 111 0
```

- 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

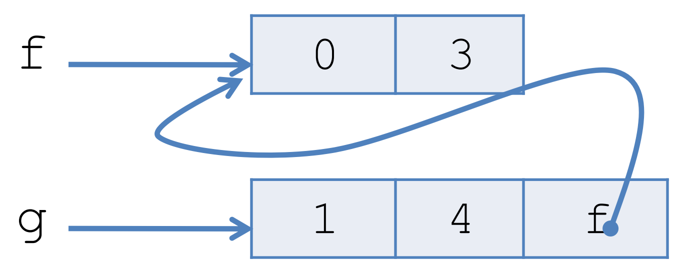
- ML datatypes can also carry data:

```
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; 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 %merge
b1: ⟦s1⟧
    br label %l2

l2: %cmp2 = icmp eq %tag, $tag2
    br %cmp2 label %b2, label %merge
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 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 3410 integers: `[ 3410 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 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 HW3

Compiling Datastructures 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) 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
     ```

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
  …
}
```

Discussion: Defining a Language

- Premise: programming languages are purely ‘formal’ objects
  - We (as language designers) get to determine the meaning of the language constructs
- Question: How do we specify that meaning?
- Question: What are the properties of a good specification?
- Examples?

Approaches to Language Specification

- Implementation
  - It does what it does!
- Social
  - Authority figure says: "it means X"
  - English prose
- Technological
  - Multiple implementations
  - Reference interpreter
  - Test cases / Examples
- Translation
  - Semantics given in terms of (hopefully better specified) target
- Mathematical
  - "Informal" specifications
  - "Formal" specifications

Less "formal": Techniques may miss problems in programs

This isn't a tradeoff… all of these methods should be used.

Even the most "formal" can still have holes:

- Did you prove the right thing?
- Do your assumptions match reality?
- Knuth. "Beware of bugs in the above code; I have only proved it correct, not tried it."

More "formal": eliminate *with certainty* as many problems as possible.

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

see HW3 and README

ll.ml, using oatc, clang, etc.

TOUR OF HW 3