CS443: Compiler Construction

Lecture 5: LLVM

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Based on lecture material by Steve Chong, Steve Zdancewic and Greg Morrisett

LLVM is a very general compiler framework

- 2003, University of Illinois Urbana-Champaign
  - Chris Lattner, Vikram Adve
- Originally: “Low-Level Virtual Machine”
  - Now: not really relevant, no longer an acronym
- Based around LLVM IR

Features of LLVM IR

- Compiler/language-independent
- Typed(!)
- Static Single Assignment
  - Briefly: every variable can be assigned to only once.
  - (Yes, this is a big restriction; we have a whole lecture on it later)

In this lecture/class: LLVM 10.0.0 (Mar 24, 2020)

Variables

- Can be global (start with @) or local (start with %)
- (Won't be using globals much)
- Locals defined with instructions of the form `%x = …`
  - Can't be redefined (like `let x = …` in OCaml)

Types

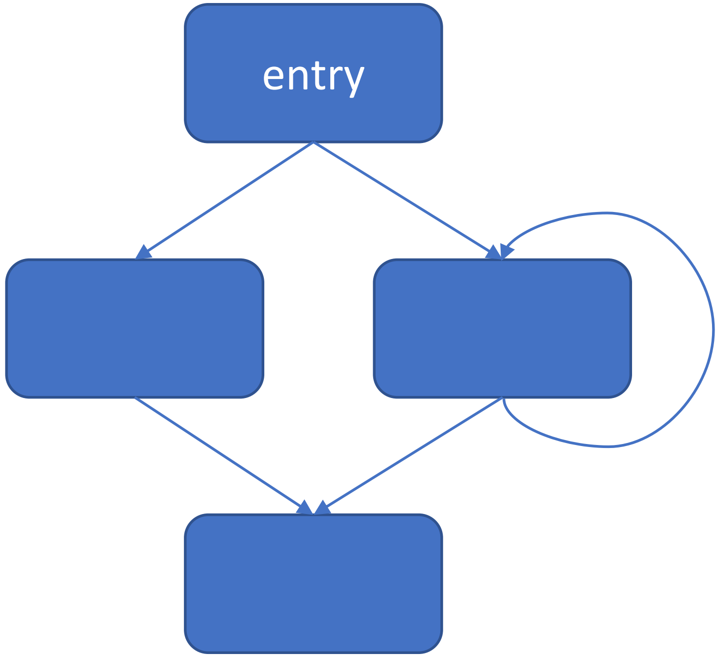
- Void (`void`)
- Integers (`iN`)
  - N specifies the number of bits in the integer
  - i1, i8, i16, i32, i64, …
- A bunch of other “first class types” (floats, etc.)
- Pointers to a type (t*)
- Functions (e.g, `i32(i32, i1)`)
- Labels (i.e., code addresses) (`label`)

Structured as *functions* consisting of a number of *basic blocks*

```
define i32 myfunc (i32 %myarg) {
 …
}
```

Basic blocks are sequences of *instructions* that execute starting at the beginning

- (i.e., can't jump to the middle of a basic block)
- Flat structure



Structured as *functions* consisting of a number of *basic blocks*

```
define i32 myfunc (i32 %myarg) {
  myfunc__entry:
     …
  block1:
     …
  block2:
     …
}
```

Instructions perform one operation

- General types: terminators, arithmetic operations, memory operations, type conversions
- Basic blocks must end with a terminator (doesn't usually return a value, jumps somewhere else)
- Most other instructions return a value
- General form: `%dest = <opcode> <ty1> <op1>, <ty2> <op2>, …`

Instructions perform one operation (e.g. arithmetic operations)

- `<var> = add <ty> <op1> <op2>`

opcode   type of operands (and result)   values (variables or integer constants)

- ex. `%dest = add i32 %x 1`
- (Declares `%dest as i32`)
- Similar: `sub, mul, udiv, sdiv, …`

Instructions perform one operation (e.g. comparison operations)

- <dest> = icmp <cond> <ty> <op1> <op2>

condition   type of operands (and result)   values (variables or integer constants)

- Conditions: eq, ne, (u/s)gt, (u/s)ge, (u/s)lt, (u/s)le
- Result type: i1

Terminators

- `ret void`
- `ret <ty> <op>`
- Return from the current function

- `br label <dest>`
- Jump to the label
- `br i1 <op>, label <truedest>, label <falsedest>`
- Jump to either label depending on the value of the condition

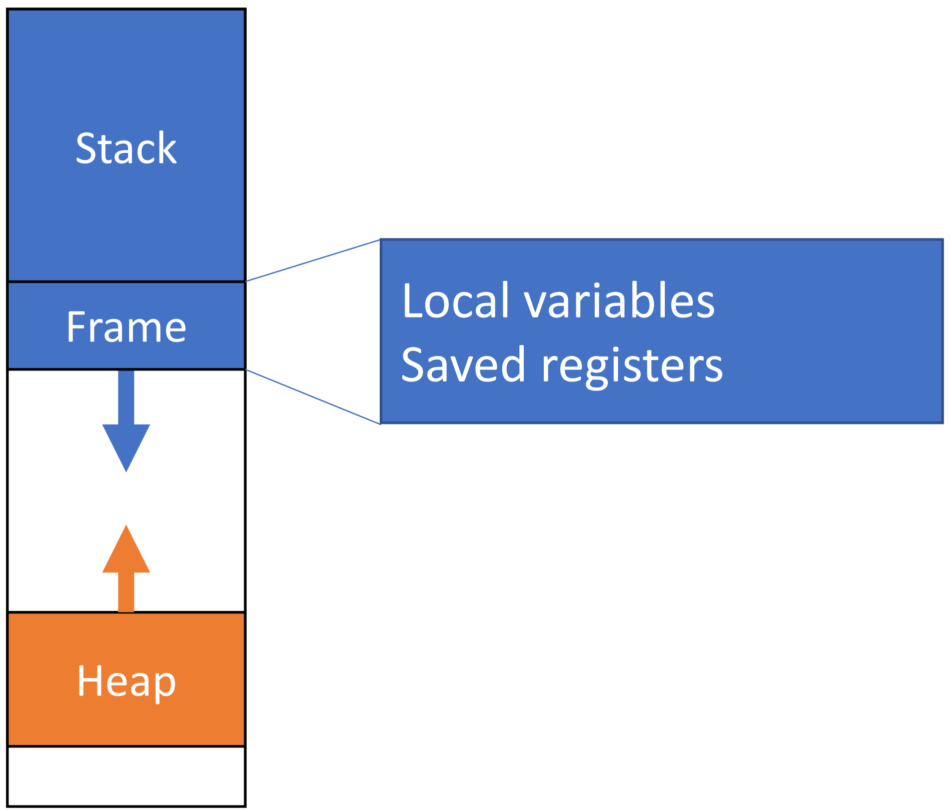
Terminators (cont'd)

- ```
  switch <ty> <val> label <default>
  [<ty> <val1>, label <label1>
   <ty> <val2>, label <label2> …
  ]
  ```

Must all be ints (of the same size?)

Actual syntax, not optional arguments
  ```

LLVM Memory Model




```
void foo () {
  int a = 1;
  int b = 2;
  return 3 + bar(a, b);
}

void bar(int a, int b) {
  return a + b;
}
```

LLVM Memory Model

- `%ptr = alloca <ty>, <intty> <num>`
- Allocates **stack** space for <num> elements of type <ty>
- Returns type `<ty>*` - the **stack address** of the allocated memory
- Access memory with `load, store`
  - ```
    %ptr = alloca i64
    store i64 443, i64* %ptr
    %bestclass = load i64, i64* %ptr
    ```
- (`Load, store`) work the same for heap but allocate using malloc
    ```

Type conversions

- <dest> = trunc <ty1> <value> to <ty2> Truncate
- <dest> = zext <ty1> <value> to <ty2> Zero-extend

- <dest> = bitcast <ty1> <value> to <ty2>
  Bitwise conversion (doesn’t change value at all)

- <dest> = inttoptr <intty> <value> to <ptrty>
- <dest> = ptrtoint <ptrty> <value> to <intty>

Example

```c
int factorial (int n) {
  int result = 1;
  while (n > 1) {
    result = result * n;
  }
  return result;
}
```

```llvm
define i32 @factorial(i32 %0) {
  %n = alloca i32
  %result = alloca i32
  store i32 %0, i32* %n
  store i32 1, i32* %result
  br label %4
```

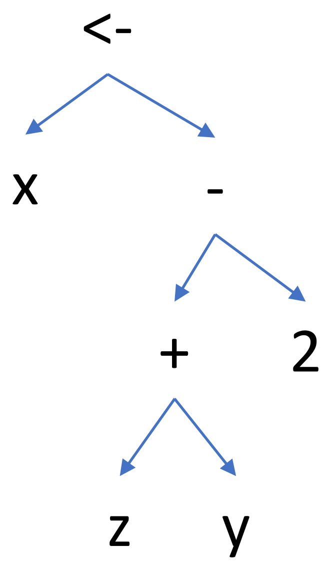
```llvm
4:
  %n1 = load i32, i32* %n
  %temp1 = icmp sgt i32 %n1, 1
  br i1 %temp1, label %7, label %11

7:
  %result1 = load i32, i32* %result
  %n2 = load i32, i32* %n
  %temp2 = mul i32 %result1, %n2
  store i32 %temp2, i32* %result
  br label %4

11:
  %temp3 = load i32, i32* %result
  ret i32 %temp3
}
```

Flattening expressions

```
x <- y + z – 2  → %temp = add i32 %y %z
                     %x = sub i32 %temp 2
```



One approach: destination passing

```
let rec compile_exp (dest: var) (e: exp) : inst list =
  match e with
  | ENum n -> [dest = set n]
  | EUnop (UNeg, e1) ->
     let dest1 = new_temp () in
     (compile_exp dest1 e1) @ [dest = sub 0 dest1]
   | EAssign (EVar v, e1) ->
     (compile_exp v e1) @ (* … need to copy v to dest *)
```

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```

```
x <- y + z – 2
```

```
temp1 = set y
temp2 = set z
temp3 = add temp1
temp2
temp4 = set 2
x = sub temp3 temp4
```

Another approach

```
let rec compile_exp (e: exp) : inst list * value =
  match e with
  | ENum n -> [], n
  | EBinop (BAdd, e1, e2) ->
     let (is1, v1) = compile_exp e1 in
     let (is2, v2) = compile_exp e2 in
     let d = new_temp () in
     (is1 @ is2 @ [d = add v1 v2], d)
   | EAssign (EVar v, e1) ->
     let (is, d) = compile_exp e1 in
             (is @ [v = set d], v)
```

Another approach

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let rec compile_exp (e: exp) : inst list * value =
  match e with
  | ENum n -> [], n
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     let (is, d) = compile_exp e1 in
             (is @ [v = set d], v)
```
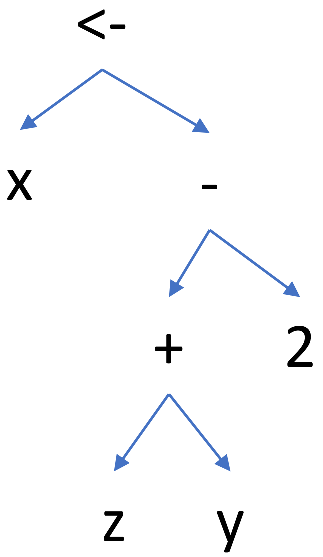
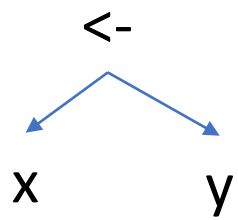

```
temp1 = add y z
temp2 = sub temp1 2
x = set temp2
```

```
x <- y + z – 2
```

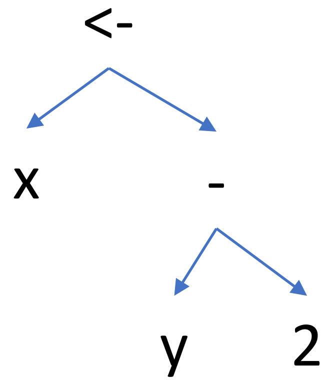
A somewhat better approach: Maximal Munch



`x = set y`



`x = sub y 2`



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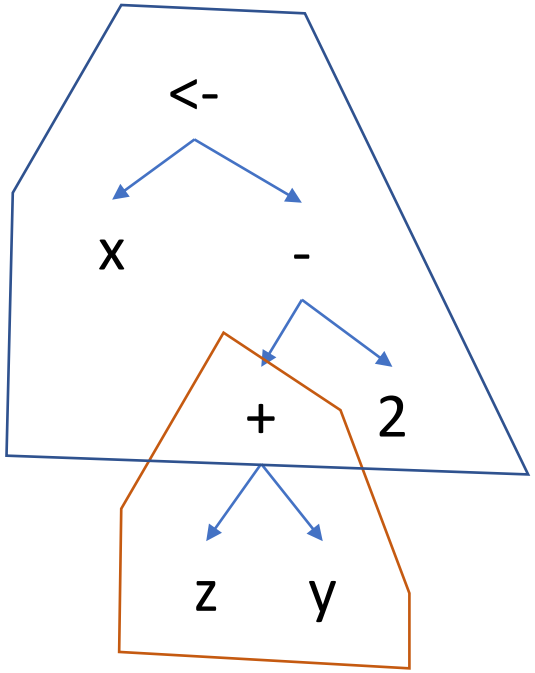


```
temp1 = add z y
x = sub temp1 2
```

(In practice, doesn’t matter a lot)

Call

- <dest> =

Structured data, getelementptr