CSE 110A: Winter 2020

Fundamentals of Compiler Design I

Data Representation

Owen Arden

UC Santa Cruz

Based on course materials developed by Ranjit Jhala

Data Representation

Next, lets add support for

- **Multiple datatypes** (`number` and `boolean`)
- **Calling** external functions

In the process of doing so, we will learn about

- **Tagged Representations**
- **Calling Conventions**

Plan

Our plan will be to (start with `boa`) and add the following features:

- **Representing** boolean values (and numbers)
- **Arithmetic Operations**
- **Arithmetic Comparisons**
- **Dynamic Checking** (to ensure operators are well behaved)

1. Representation

Motivation: Why booleans?

In the year 2018, its a bit silly to use

- `0` for `false` and
- non-zero for `true`.

But really, `boolean` is a stepping stone to other data

- Pointers,
- Tuples,
- Structures,
- Closures.

The Key Issue

How to *distinguish* numbers from booleans?

- Need to store some *extra* information to mark values as `number` or `bool`.

Option 1: Use Two Words

First word is `1` means `bool`,
is `0` means `number`, `2` means pointer etc.

Value	Representation (HEX)
3	[0x000000000][0x00000003]
5	[0x000000000][0x00000005]
12	[0x000000000][0x0000000c]
42	[0x000000000][0x0000002a]
FALSE	[0x000000001][0x00000000]
TRUE	[0x000000001][0x00000001]

Pros

- Can have *lots* of different types, but

Cons

- Takes up *double* memory,
- Operators `+`, `-` do *two* memory reads `[eax]`, `[eax - 4]`.

In short, rather wasteful. Don't need *so many* types.

Option 2: Use a Tag Bit

Can distinguish *two* types with a *single bit*.

Least Significant Bit (LSB) is

- `0` for `number`
- `1` for `boolean`

Why not 0 for boolean and 1 for number?

Tag Bit: Numbers

So `number` is the binary representation shifted left by 1 bit

- Lowest bit is always `0`
- Remaining bits are number's binary representation

For example,

Value	Representation (Binary)	Value	Representation (HEX)
3	[0b…00000110]	3	[0x00000006]
5	[0b…00001010]	5	[0x0000000a]
12	[0b…00011000]	12	[0x00000018]
42	[0b…01010100]	42	[0x00000054]

Tag Bit: Booleans

Most Significant Bit (MSB) is

- `1` for `true`
- `0` for `false`

For example

Value	Representation (Binary)	Value	Representation (HEX)
TRUE	[0b1000…0001]	TRUE	[0x80000001]
FALSE	[0b0000…0001]	FALSE	[0x00000001]

Types

Lets extend our source types with `boolean` constants

```
data Expr a
  = ...
  | Boolean Bool a
```

Correspondingly, we extend our assembly `Arg` (values) with

```
data Arg
  = ...
  | HexConst  Int
```

So, our examples become:

Value	Representation (HEX)
`Boolean False`	`HexConst 0x00000001`
`Boolean True`	`HexConst 0x80000001`
`Number 3`	`HexConst 0x00000006`
`Number 5`	`HexConst 0x0000000a`
`Number 12`	`HexConst 0x00000018`
`Number 42`	`HexConst 0x0000002a`

Transforms

Next, lets update our implementation

`Text` $\xrightarrow{\text{Parse}}$ `BareE` $\xrightarrow{\text{Norm.}}$ `AnfE` $\xrightarrow{\text{Tag}}$ `AnfTagE` $\xrightarrow{\text{CodeGen}}$ `Asm`

The `parse`, `anf` and `tag` stages are straightforward.
Let's focus on the `compile` function.

A TypeClass for Representing Constants

Its convenient to introduce a type class describing Haskell types that can be *represented* as x86 arguments:

```
class Repr a where
  repr :: a -> Arg
```

We can now define instances for `Int` and `Bool` as:

```
instance Repr Int where
  repr n = Const (Data.Bits.shift n 1)
                 -- left-shift `n` by 1

instance Repr Bool where
  repr False = HexConst 0x00000001
  repr True  = HexConst 0x80000001
```

Immediate Values to Arguments

`Boolean b` is an *immediate* value (like `Number n`).

Let's extend `immArg` that transforms an immediate expression to an x86 argument.

```
immArg :: Env -> ImmTag -> Arg
immArg (Var     x _)  = ...
immArg (Number n _)  = repr n
immArg (Boolean b _) = repr b
```


Compiling Constants

Finally, we can easily update the `compile` function as:

```
compileEnv :: Env -> AnfTagE -> Asm
compileEnv _ e@(Number _ _)  = [IMov (Reg EAX) (immArg env e)]
compileEnv _ e@(Boolean _ _) = [IMov (Reg EAX) (immArg env e)]
```

(The other cases remain unchanged.)
Let's run some tests to double check.

Output Representation

Say what?! Ah. Need to update our run-time printer in `main.c`

```
void print(int val){
  if (val == CONST_TRUE)
    printf("true");
  else if (val == CONST_FALSE)
    printf("false");
  else // should be a number!
    printf("%d", val >> 1);  // shift right to remove tag bit.
}
```

Can you think of some other tests we should write?

2. Arithmetic Operations

Constants like `2`, `29`, `false` are only useful if we can perform computations with them.

First let's see what happens with our arithmetic operators.

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Shifted Representation and Addition

We are *representing* a number `n` by **shifting it left by 1.** `n` **has the machine representation** `2*n`

Thus, our *source values* have the following representations:

Source Value	Representation (DEC)
`3`	`6`
`5`	`10`
`3 + 5 = 8`	`6 + 10 = 16`
`n1 + n2`	`2*n1 + 2*n2 = 2*(n1 + n2)`

That is, *addition* (and similarly, *subtraction*) works *as is* with the shifted representation.

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Shifted Representation and Multiplication

We are *representing* a number `n` by **shifting it left by 1** `n` ***has the machine representation*** `2*n`

Thus, our *source values* have the following representations:

Source Value	Representation (DEC)
`3`	`6`
`5`	`10`
`3 * 5 = 15`	`6 * 10 = 60`
`n1 * n2`	`2*n1 * 2*n2 = 4*(n1 * n2)`

Thus, multiplication ends up accumulating the factor of 2. The result is *two times* the desired one.

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Strategy

Thus, our strategy for compiling arithmetic operations is simply:

- Addition and Subtraction "just work" as before, as shifting "cancels out",
- Multiplication result must be "adjusted" by dividing-by-two
  - i.e. **right shifting by 1**

Types

The *source* language does not change at all, for the `Asm` lets add a "right shift" instruction (`shr`):

```
data Instruction
  = ...
  | IShr    Arg   Arg
```


Transforms

We need only modify `compileEnv` to account for the "fixing up"

```
compileEnv :: Env -> AnfTagE -> [Instruction]
compileEnv env (Prim2 o v1 v2 _) =
                   compilePrim2 env o v1 v2
```

where the helper `compilePrim2` works for `Prim2` (binary) operators and *immediate arguments*:

Transforms

```
compilePrim2 :: Env -> Prim2 -> ImmE -> ImmE -> [Instruction]
compilePrim2 env Plus v1 v2   = [ IMov (Reg EAX) (immArg env v1)
                                , IAdd (Reg EAX) (immArg env v2)
                                ]
compilePrim2 env Minus v1 v2  = [ IMov (Reg EAX) (immArg env v1)
                                , ISub (Reg EAX) (immArg env v2)
                                ]
compilePrim2 env Times v1 v2  = [ IMov (Reg EAX) (immArg env v1)
                                , IMul (Reg EAX) (immArg env v2)
                                , IShr (Reg EAX) (Const 1)
                                ]
```


Tests

Let's take it out for a drive.

What does `"2 * (-1)"` evaluate to?

`2147483644`

Whoa?!

Well, its easy to figure out if you look at the generated assembly:

```
mov eax, 4
imul eax, -2
shr eax, 1
ret
```


Tests

The trouble is that the **negative** result of the multiplication is saved in **twos-complement** format, and when we shift that right by one bit, we get the wierd value (**does not "divide by two"**)

Decimal	Hexadecimal	Binary
-8	FFFFFFF8	0b11111111111111111111111111111000
2147483644	7FFFFFFC	0b01111111111111111111111111111100

Solution: Signed/Arithmetic Shift

The instruction `sar` shift arithmetic right does what we want, namely:

- preserves the sign-bit when shifting
- i.e. doesn't introduce a `0` by default

Transforms Revisited

Lets add `sar` to our target:

```
data Instruction
  = ...
  | ISar Arg Arg
```

and use it to fix the post-multiplication adjustment

- i.e. use `ISar` instead of `IShr`

```
compilePrim2 env Times v1 v2  = [ IMov (Reg EAX) (immArg env v1)
                                , IMul (Reg EAX) (immArg env v2)
                                , ISar (Reg EAX) (Const 1)
                                ]
```

After which all is well:

```
"2 * (-1)"
```

produces

```
-2
```


3. Arithmetic Comparisons

Next, lets try to implement comparisons:

Many ways to do this:

- branches `jne, jl, jg` or
- bit-twiddling.

Comparisons via Bit-Twiddling

Key idea: negative number's most significant bit is 1

To implement `arg1 < arg2`, compute `arg1 - arg2`

- * When result is negative, MSB is `1`, ensure `eax` set to `0x80000001`
- * When result is non-negative, MSB is `0`, ensure `eax` set to `0x00000001`
- Can **extract msb** by bitwise `and` with `0x80000000`.
- Can **set tag bit** by bitwise `or` with `0x00000001`

So compilation strategy is:

```
mov eax, arg1
sub eax, arg2
and eax, 0x80000000   ; mask out "sign" bit (msb)
or  eax, 0x00000001   ; set tag bit to bool
```

Comparisons: Implementation

Lets go and extend:

- The `Instruction` type

```
data Instruction
  = ...
  | IAnd    Arg   Arg
  | IOr     Arg   Arg
```

- The `instrAsm` converter

```
instrAsm :: Instruction -> Text
instrAsm (IAnd a1 a2) = ...
instrAsm (IOr  a1 a2) = …
```

- The actual `compilePrim2` function

Exercise: Comparisons via Bit-Twiddling

- Can compute `arg1 > arg2` by computing `arg2 < arg1`.
- Can compute `arg1 != arg2` by computing `arg1 < arg2 || arg2 < arg1`
- Can compute `arg1 = arg2` by computing `! (arg1 != arg2)`

For the above, can you figure out how to implement:

- Boolean `!` ?
- Boolean `||` ?
- Boolean `&&` ?

You may find these instructions useful

4. Dynamic Checking

We've added support for `Number` and `Boolean` but we have no way to ensure that we don't write gibberish programs like:

```
2 + true
```

or

```
7 < false
```

In fact, lets try to see what happens with our code on the above:

```
ghci> exec "2 + true"
```

Oops.

Checking Tags at Run-Time

Later, we will look into adding a *static* type system. For now, let's see how to *abort execution* when the wrong *types of operands* are found when the code is *executing*.

Operation	Op-1	Op-2
`+`	`int`	`int`
`-`	`int`	`int`
`*`	`int`	`int`
`<`	`int`	`int`
`>`	`int`	`int`
`&&`	`bool`	`bool`
`||`	`bool`	`bool`
`!`	`bool`	
`if`	`bool`	
`=`	`int` or `bool`	`int` or `bool`

Strategy

Let's check that the data in `eax` is an `int`:

- Suffices to check that the LSB is `0`
- If not, jump to special `error_non_int` label

For example, to check if `arg` is a `Number`

```
mov eax, arg
mov ebx, eax            ; copy into ebx register
and ebx, 0x00000001     ; extract lsb
cmp ebx, 0              ; check if lsb equals 0
jne error_non_number
...
```

at `error_non_number` we can call into a `C` function:

```
error_non_number:
  push eax              ; pass erroneous value
  push 0                ; pass error code
  call error            ; call run-time "error" function
```


Strategy

Finally, the `error` function is part of the *run-time* and looks like:

```
void error(int code, int v){
   if (code == 0) {
     fprintf(stderr, "Error: expected a number but got %#010x\n", v);
   }
   else if (code == 1) {
     // print out message for errorcode 1 ...
   }
   else if (code == 2) {
     // print out message for errorcode 2 ...
   } ...
   exit(1);
 }
```

Strategy By Example

Lets implement the above in a simple file `tests/output/int-check.s`

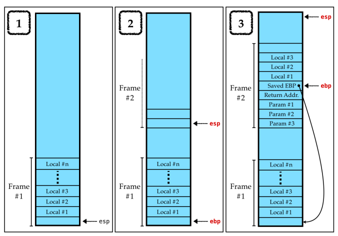
```
section .text
extern error
extern print
global our_code_starts_here
our_code_starts_here:
  mov eax, 1                ; not a valid number
  mov ebx, eax              ; copy into ebx register
  and ebx, 0x00000001       ; extract lsb
  cmp ebx, 0                ; check if lsb equals 0
  jne error_non_number
error_non_number:
  push eax
  push 0
  call error
```

```
make tests/output/int-check.result
... segmentation fault ...
```

What happened ?

Managing the Call Stack

To properly call into C functions (like `error`), we must play by the rules of the C calling convention



1. The *local variables* of an (executing) function are saved in its *stack frame*.
2. The *start* of the stack frame is saved in register `ebp`,
3. The *start* of the *next* frame is saved in register `esp`.

Calling Convention

We must **preserve the above invariants** as follows:

In the Callee:

At the **start** of the function

```
push ebp          ; save (previous, caller's) ebp on stack
mov ebp, esp      ; make current esp the new ebp
sub esp, 4*N      ; "allocate space" for N local variables
```

At the **end** of the function

```
mov esp, ebp      ; restore value of esp to that just before call
                  ; now, value at [esp] is caller's (saved) ebp
pop ebp           ; so: restore caller's ebp from stack [esp]
ret               ; return to caller
```

Calling Convention

We must **preserve the above invariants** as follows:

In the Caller:

To call a function `target` that takes `N` parameters:

```
push arg_N        ; push last arg first ...
...
push arg_2        ; then the second ...
push arg_1        ; finally the first
call target       ; make the call (which puts return addr on stack)
add esp, 4*N      ; now we are back: "clear" args by adding 4*numArgs
```

NOTE: If you are compiling on MacOS, you must respect the 16-Byte Stack Alignment Invariant

Fixed Strategy By Example

Lets implement the above in a simple file `tests/output/int-check.s`

```
section .text
extern error
extern print
global our_code_starts_here
our_code_starts_here:
  push ebp
  mov ebp, esp
  sub esp, 0                ; 0 local variables here
  mov eax, 1                ; not a valid number
  mov ebx, eax              ; copy into ebx register
  and ebx, 0x00000001       ; extract lsb
  cmp ebx, 0                ; check if lsb equals 0
  jne error_non_number
  mov esp, ebp
  pop ebp
  ret
error_non_number:
  push eax
  push 0
  call error
```

Aha, now the code works!

```
make tests/output/int-check.result
... expected number but got ...
```

Q: What NEW thing does our compiler need to compute?
Hint: Why do we `sub esp, 0` above?

Types

Let's implement the above strategy.

To do so, we need a new data type for run-time types:

```
data Ty = TNumber | TBoolean
```

a new `Label` for the error

```
data Label
  = ...
  | TypeError Ty        -- Type Error Labels
  | Builtin   Text      -- Functions implemented in C
```

and thats it.

Transforms

The compiler must generate code to:

- Perform dynamic type checks,
- Exit by calling `error` if a failure occurs,
- Manage the stack per the convention above.

1. Type Assertions

The key step in the implementation is to write a function

```
assertType :: Env -> IExp -> Ty -> [Instruction]
assertType env v ty
  = [ IMov (Reg EAX) (immArg env v)
    , IMov (Reg EBX) (Reg EAX)
    , IAnd (Reg EBX) (HexConst 0x00000001)
    , ICmp (Reg EBX) (typeTag  ty)
    , IJne (TypeError ty)
    ]
```

where `typeTag` is:

```
typeTag :: Ty -> Arg
typeTag TNumber  = HexConst 0x00000000
typeTag TBoolean = HexConst 0x00000001
```


1. Type Assertions

You can now splice `assertType` prior to doing the actual computations, e.g.

```
compilePrim2 :: Env -> Prim2 -> ImmE -> ImmE -> [Instruction]
compilePrim2 env Plus v1 v2   = assertType env v1 TNumber
                             ++ assertType env v2 TNumber
                             ++ [ IMov (Reg EAX) (immArg env v1)
                                , IAdd (Reg EAX) (immArg env v2)
                                ]
```

2. Errors

We must also add code *at* the `TypeError TNumber` and `TypeError TBoolean` labels.

```
errorHandler :: Ty -> Asm
errorHandler t =
    -- the expected-number error
  [ ILabel   (TypeError t)
    -- push the second "value" param first,
  ,   IPush  (Reg EAX)
    -- then the first  "code" param,
  ,   IPush  (ecode t)
    -- call the run-time's "error" function.
  ,   ICall  (Builtin "error")
  ]

ecode :: Ty -> Arg
ecode TNumber  = Const 0
ecode TBoolean = Const 1
```


3. Stack Management

Local Variables

First, note that the local variables live at offsets from `ebp`, so lets update

```
immArg :: Env -> ImmTag -> Arg
immArg _   (Number n _) = Const n
immArg env (Var    x _) = RegOffset EBP i
  where
    i    = fromMaybe err (lookup x env)
    err  = error (printf "Error: Variable '%s' is unbound" x)
```


3. Stack Management

Maintaining `esp` and `ebp`

We need to make sure that *all* our code respects the C calling convention..

To do so, just *wrap* the generated code, with instructions to save and restore `ebp` and `esp`

```
compileBody :: AnfTagE -> Asm
compileBody e = entryCode e
             ++ compileEnv emptyEnv e
             ++ exitCode e

entryCode :: AnfTagE -> Asm
entryCode e = [ IPush (Reg EBP)
              , IMov  (Reg EBP) (Reg ESP)
              , ISub  (Reg ESP) (Const 4 * n)
              ]
  where
    n       = countVars e

exitCode :: AnfTagE -> Asm
exitCode = [ IMove (Reg ESP) (Reg EBP)
           , IPop  (Reg EBP)
           , IRet
           ]
```

3. Stack Management

Q: But how shall we compute `countVars`?

Here's a shady kludge:

```
countVars :: AnfTagE -> Int
countVars = 100
```

Obviously a sleazy hack (*why?*), but let's use it to *test everything else*; then we can fix it.

4. Computing the Size of the Stack

Once everything (else) seems to work, let's work out:

```
countVars :: AnfTagE -> Int
```

Finding the *exact* answer is **undecidable** in general,
i.e. is *impossible* to compute.

However, it is easy to find an *over-approximate* heuristic, i.e.

- a value guaranteed to be *larger* than the than the max size,
- and which is reasonable in practice.

Strategy

Let `countVars e` be:

- The *maximum* number of let-binds in scope at any point *inside* `e`, i.e.
- The *maximum* size of the `Env` when compiling `e`

Lets work it out on a case-by-case basis:

- **Immediate values** like `Number` or `Var`
  - are compiled *without pushing* anything onto the `Env`
  - i.e. `countVars` = 0
- **Binary Operations** like `Prim2 o v1 v2` take immediate values,
  - are compiled *without pushing* anything onto the `Env`
  - i.e. `countVars` = 0
- **Branches** like `If v e1 e2` can go either way
  - can't tell at compile-time
  - i.e. worst-case is larger of `countVars e1` and `countVars e2`
- **Let-bindings** like `Let x e1 e2` require
  - evaluating `e1` and
  - *pushing* the result onto the stack and then evaluating `e2`
  - i.e. larger of `countVars e1` and `1 + countVars e2`

Implementation

We can implement the above a simple recursive function:

```
countVars :: AnfTagE -> Int
countVars (If v e1 e2)  = max (countVars e1) (countVars e2)
countVars (Let x e1 e2) = max (countVars e1) (1 + countVars e2)
countVars _             = 0
```


Naive Heuristic is Naive

The above method is quite simplistic. For example, consider the expression:

```
let x = 1
  , y = 2
  , z = 3
in
    0
```

`countVars` would tell us that we need to allocate `3` stack spaces but clearly *none* of the variables are actually used.

Will revisit this problem later, when looking at optimizations.

Recap

We just saw how to add support for

- **Multiple datatypes** (`number` and `boolean`)
- **Calling** external functions

and in doing so, learned about

- **Tagged Representations**
- **Calling Conventions**

To get some practice, in your assignment, you will add:

- Dynamic Checks for Arithmetic Overflows (see the `jo` and `jno` operations)
- A Primitive `print` operation implemented by a function in the `c` run-time.

And next, we'll see how to easily add **user-defined functions**.

Questions?