Data Representation

Next, lets add support for

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

01-adder scores out

03-cobra due 4/29.

In the process of doing so, we will learn about

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

Static
Haskell
Java

dynamic
Python (mypy)
JavaScript → ~~Elm~~ → TypeScript

Plan

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

1. **Representing** boolean values (and numbers)
2. **Arithmetic Operations**
3. **Arithmetic Comparisons** $e_1 < e_2$, $e_1 \&\& e_2$, not e
4. **Dynamic Checking** (to ensure operators are well behaved)

2 + true ✗   3 < false ✗

1. Representation

Motivation: Why booleans?

In the year 2021, its a bit silly to use

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

"avoid confusion", improve readability
support for &&, ||

int → int + bool

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

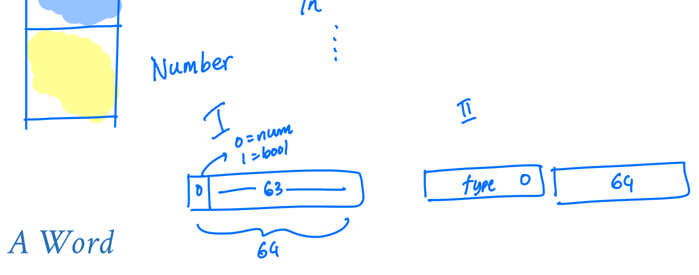
- Pointers
- Tuples
- Structures
- Closures

The Key Issue

in X86

How to *distinguish* numbers from booleans?

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



A Word

(A reminder for me, since I always get mixed up)

- A *Bit* is 1-bit
- A *Byte* is 8-bits
- A *Word* is 2-bytes = 16 bits
- A *Double Word* is 2-words = 4-bytes = 32 bits
- A *Quad Word* is 4-words = 8-bytes = 64 bits

We are working in `x86_64` where the *default* size is a `qword`

- Registers are 64-bits
- Arithmetic is 64-bits
- Stack slots should be 64-bits
- etc.

Option 1: Use Two (Quad-)Words

How to *distinguish* numbers from booleans?

> *Need extra information to mark values as `number` or `bool`.*

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

Value	Representation (HEX)
0	[0x0 - - - - - 0][0x0 —— 0]
3	`[0x000000000][0x00000003]`
5	`[0x000000000][0x00000005]`
12	`[0x000000000][0x0000000c]`
42	`[0x000000000][0x0000002a]`
`false`	`[0x000000001][0x00000000]` — false
`true`	`[0x000000001][0x00000001]` — true

bool

Pros
- 64-bits

Cons
- use 64-bits which is too much!
- duplic instr (but fancy HW solves)

Pros

- Can have *lots* of different types, but

Cons

- Takes up *double* memory,
- Operators `+` , `-` require *two* memory reads.

In short, rather wasteful! We don't need **so many** types.

Int   Integer

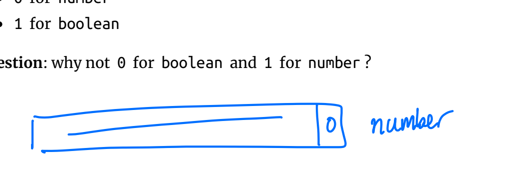
Option 2: Use a Tag Bit

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

Least Significant Bit (LSB) is

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

Question: 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, in binary:

Value	Representation (Binary)
3	`[0b00000110]`
5	`[0b00001010]`
12	`[0b00011000]`
42	`[0b01010100]`

32 16 8 4 2 1

Or in hexadecimal:

Value	Representation (HEX)
3	`[0x06]`
5	`[0x0a]`
12	`[0x18]`
42	`[0x54]`

Tag Bit: Booleans

Most Significant Bit (MSB) is

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

For example

Value	Representation (Binary)
`true`	`[0b10000000000000000000000000000001]`
`false`	`[0b00000000000000000000000000000001]`

Or, in HEX

Value	Representation (HEX)
`true`	`[0x80000001]`
`false`	`[0x00000001]`

(eliding the 32/8 zeros in the "most-significant" `DWORD`)

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
```

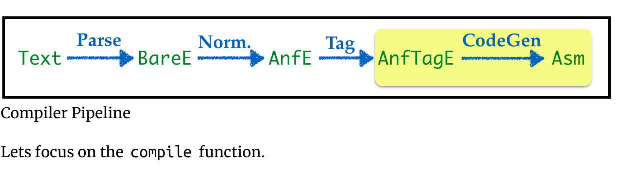
So, our examples become:

Value	Representation (HEX)
`Boolean False`	`HexConst 0x00000001`
`Boolean True`	`HexConst 0x80000001`
`Number 3`	`HexConst 0x00000006`
`Number 5`	`HexConst 0x0000000a`
`Number 12`	`HexConst 0x0000000c`
`Number 42`	`HexConst 0x0000002a`

Transforms

Next, lets update our implementation

The `parse` , `anf` and `tag` stages are straightforward.



Compiler Pipeline

Lets 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`).

Lets 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 RAX) (immArg env e)]
compileEnv _ e@(Boolean _ _) = [IMov (Reg RAX) (immArg env e)]
```

(The other cases remain unchanged.)

Lets run some tests to double check.

QUIZ

What is the result of:

```
ghci> exec "15"
```

A. Error

B. `0`

C. `15`

D. `30`

Output Representation

Say what?! 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", d >> 1);  // shift right to remove tag bit.
}
```

and now we get:

```
ghci> exec "15"
15
```

Can you think of some other tests we should write?

QUIZ

What is the result of

```
ghci> exec "let x = 15 in x"
```

A. Error

B. `0`

C. `15`

D. `30`

QUIZ

What is the result of

```
>>> exec "if 3: 12 else: 49"
```
A / C

```
>>> exec "if 0: 12 else: 49"
```
A / D

```
>>> exec "if true: 12 else: 49"
```
A/C

```
>>> exec "if false: 12 else: 49"
```
C/D

A. Error

B. `0`

C. `12`

D. `49`

Lets go and fix the code so the above do the right thing!

2. Arithmetic Operations

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

First lets see what happens with our arithmetic operators.

QUIZ: Addition

What will be the result of:

```
ghci> exec "12 + 4"
```

A. Does not compile

B. Run-time error (e.g. segmentation fault)

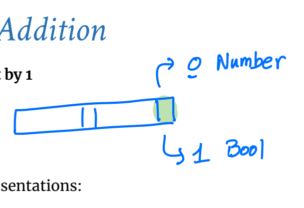
C. `16`

D. `32`

E. `0`

Shifted Representation and Addition

We are *representing* a number `n` by **shifting it left by 1**

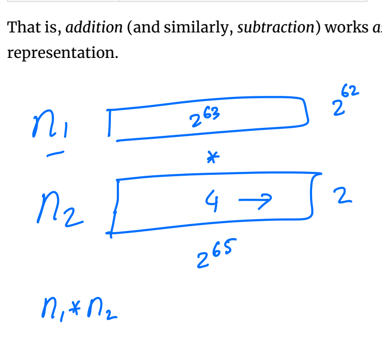


> *n has the machine representation 2*n*

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.



QUIZ: Multiplication

What will be the result (using our code so far) of:

```
ghci> exec "12 * 4"
```

A. Does not compile

B. Run-time error (e.g. segmentation fault)

C. `24`

D. `48`

E. `96`

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.

- Result is *two times* the desired one.

Strategy

Thus, our strategy for compiling arithmetic operations is:

Addition and Subtraction "just work" - 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*:

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

Tests

Lets take it out for a drive.

```
ghci> exec' "2 * (0 - 1)"
4611686018427387902
```

Whoa?!

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

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

Two's Complement

The **negative** result is in **twos-complement** format.

When we shift that right-by-one, we get the odd value

- **does not "divide by two"**

Decimal	Hexadecimal
-8	0xFFFFFFFFFFFFFFF8
2147483644	0x7FFFFFFFFFFFFFFC

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:

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

and use it to fix the post-multiplication adjustment

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

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

After which all is well:

```
ghci> exec' "2 * (-1)"
-2
```

3. Arithmetic Comparisons

Next, lets try to implement comparisons:

```
ghci> exec "1 < 2"
...
boa: lib/Language/Boa/Compiler.hs:(104,1)-(106,43): Non-exhaustive p
atterns in function compilePrim2
```

Oops. Need to implement it first!

$v_1 < v_2$

① sub, comp with 0
issue = overflow
mov rax, v1
sub rax, v2
cmp rax, 0
jl magic
mov rax, <false>
jmp done
magic:
mov rax, <true> ; v1-v2<0
done:

② builtin "cmp" + jump
mov rax, v1
cmp rax, v2
jl magic
mov rax, <false>
jmp done
magic:
mov rax, <true> ; v1-v2<0
done:

(<
mov rax, v1
cmp rax, v2
mov rax, <false>
cmovl rax, <true>

How to implement comparisons?

Many ways to do this:

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

Option 1: Comparisons via Branches

Key Idea:

> *Use the machine comparisons and branch*

To implement `arg1 < arg2`

```
IF
  arg1 < arg2

THEN
  rax := <true>

ELSE
  rax := <false>
```

```
mov rax, <arg1>
cmp rax, <arg2>        # flags are set with comparison
jg false_label         # if cmp-greater then false else true
  mov rax, <true>      # assign to RAX := true
jmp exit_label
false_label:
  mov rax, <false>     # assign to RAX := false
exit_label:
```

Option 2: Comparisons via Bit-Twiddling

Key idea:

> *A negative number's **most significant bit** is 1*

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

- When result is negative, MSB is `1`, ensure `rax` set to `0x80000001`
- When result is non-negative, MSB is `0`, ensure `rax` set to `0x00000001`

1. Can **extract msb** by bitwise `and` with `0x8000000000000000`.
2. Can **shift msb** to 32-position with `shr`
3. Can **set tag bit** by bitwise `or` with `0x00000001`

So compilation strategy is:

```
mov rax, arg1
sub rax, arg2
and rax, 0x8000000000000000    ; mask out "sign" bit (msb)
shr rax, 32                    ; shift "sign" bit (msb) by 32
or  rax, 0x00000001            ; set tag bit to bool
```

Comparisons: Implementation

Lets go and extend:

1. The `Instruction` type

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

2. The `instrAsm` converter

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

3. The actual `compilePrim2` function

Do in class

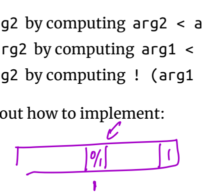
$v_1 \leq v_2$ $\quad v_1 < v_2 \;||\; v_1 = v_2$

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:

1. Boolean `!` ?
2. Boolean `||` ?
3. 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.

Static vs. Dynamic Type Checking

Later we will add a *static* type system

- that rejects meaningless programs at *compile* time.

Now lets add a *dynamic* system

- that *aborts execution* with wrong *operands* at *run* time.

Checking Tags at Run-Time

Here are the **allowed** types of operands for each primitive operation.

Operation	Op-1	Op-2
+	int	int
-	int	int
*	int	int
<	int	int
>	int	int
&&	bool	bool
||	bool	bool

"pattern match"

$v_1 + v_2$

is int ?

!	bool	
if	bool	
=	int or bool	int or bool

handler

assertInt v

test

simplifies and compl

```
mov rax, <v>
and rax, 0x1
// if v isInt, rax==0
cmp rax, 0
jne yikes_non_number
```

assert Bool v

```
mov rax, <v>
and rax, 0x1
// if v isBool, rax==1
cmp rax, 1
jne yikes_non_bool
```

Strategy: Asserting a Type

To check if `arg` is a `number`

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

For example

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

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

```
error_non_number:
  mov rdi, 0              ; pass error code
  mov rsi, rax            ; pass erroneous value
  call error              ; call run-time "error" function
```

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

```
void error(long code, long 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);
 }
```

−3 * 4

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 rax, 1              ; not a valid number
  mov rbx, rax            ; copy into rbx register
  and rbx, 0x00000001     ; extract lsb
  cmp rbx, 0              ; check if lsb equals 0
  jne error_non_number
error_non_number:
  mov rdi, 0
  mov rsi, rax
  call error
```

RSP

caller

RBP

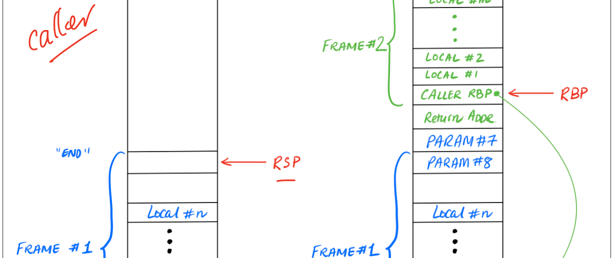
Alas

```
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



Stack Layout

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 `rbp`,
3. The *start* of the *next* frame is saved in register `rsp`.

Calling Convention

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

In the Callee

At the **start** of the function

```
push rbp           ; SAVE (previous) caller's base-pointer on stack
mov rbp, rsp       ; set our base-pointer using the current stack-poi
nter
sub rsp, 8*N       ; ALLOCATE space for N local variables
```

At the **end** of the function

```
add rsp, 8*N0      ; FREE space for N local variables
pop rbp            ; RESTORE caller's base-pointer from stack
ret                ; return to caller
```

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 rbp                ; save caller's base-pointer
  mov rbp, rsp            ; set our base-pointer
  sub rsp, 1600           ; alloc '100' vars

  mov rax, 1              ; not a valid number
  mov rbx, rax            ; copy into rbx register
  and rbx, 0x00000001     ; extract lsb
  cmp rbx, 0              ; check if lsb equals 0
  jne error_non_number

  add rsp, 1600           ; de-alloc '100' vars
  pop rbp                 ; restore caller's base-pointer
  ret
error_non_number:
  mov rdi, 0
  mov rsi, rax
  call error
```

Aha, now the above 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, 1600` above?

Types

Lets 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:

1. Perform dynamic type checks,
2. Exit by calling `error` if a failure occurs,
3. 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 RAX) (immArg env v)
    , IMov (Reg RBX) (Reg RAX)
    , IAnd (Reg RBX) (HexConst 0x00000001)
    , ICmp (Reg RBX) (typeTag  ty)
    , IJne (TypeError ty)
    ]
```

where `typeTag` is:

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

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 RAX) (immArg env v1)
                                , IAdd (Reg RAX) (immArg env v2)
                                ]
```

2. Errors

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

```
errorHandler :: Ty -> Asm
errorHandler t =
  [ ILabel   (TypeError t)        -- the expected-number error
  ,   IMov   (Reg RDI) (ecode t)  -- set the first  "code" param,
  ,   IMov   (Reg RSI) (Reg RAX)  -- set the second "value" param fi
rst,
  ,   ICall  (Builtin "error")    -- call the run-time's "error" fun
ction.
  ]

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

3. Stack Management

Maintaining `rsp` and `rbp`

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 `rbp` and `rsp`

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

entryCode :: AnfTagE -> Asm
entryCode e = [ IPush (Reg RBP)                      -- SAVE calle
r's RBP
              , IMov  (Reg RBP) (Reg RSP)            -- SET our RBP
              , ISub  (Reg RSP) (Const (argBytes n))  -- ALLOC n loc
al-vars
              ]
  where
    n       = countVars e
```

```haskell
exitCode :: AnfTagE -> Asm
exitCode e = [ IAdd (Reg RSP) (Const (argBytes n))       -- FREE n lo
cal-vars
             , IPop (Reg RBP)                            -- RESTORE c
aller's RBP
             , IRet                                      -- RETURN to
caller
             ]
  where
    n       = countVars e
```

the rsp needs to be a multiple of 16 so:

```haskell
argBytes :: Int -> Int
argBytes n = 8 * n'
  where
    n' = if even n then n else n + 1
```

Q: But how shall we compute countVars ?

Here's a shady kludge:

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

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

4. Computing the Size of the Stack

Ok, now that everything (else) seems to work, lets work out:

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

stackSize

Finding the *exact* answer is **undecidable** in general (CSE 105), i.e. is *impossible* to compute.

However, it is easy to find an *overapproximate* heuristic, i.e.

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

As usual, lets see if we can work out a heuristic by example.

QUIZ

How many stack slots/vars are needed for the following program?

```
1 + 2
```

$V_1 \oplus V_2 \Rightarrow 0$

A. 0

B. 1

C. 2

QUIZ

How many stack slots/vars are needed for the following program?

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

ANF + compileEnv etc

what is MAX i such

MOV [RBP - 8*i]

A. 0

B. 1

C. 2

D. 3

E. 4

let x = e1 in e2 $\Rightarrow \max(\langle e_1\rangle, 1+\langle e_2\rangle)$

QUIZ

How many stack slots/vars are needed for the following program?

```
if true:
  let x = 1
    , y = 2
    , z = 3
  in
    x + y + z
else:
  0
```

if e_0: e_1 else: e_2 $\Rightarrow \max(e_0, e_1, e_2)$

A. 0

B. 1

C. 2

D. 3

E. 4

QUIZ

How many stack slots/vars are needed for the following program?

```
let x =
  let y =
    let z = 3
    in z + 1
  in y + 1
in x + 1
```

A. 0

B. 1

C. 2

D. 3

E. 4

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:

```haskell
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**

Call error

print

and in doing so, learned about

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

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

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

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