Review: Printing Trees into Bytecodes

To evaluate e_1*e_2 interpreter

- evaluates e_1
- evaluates e_2
- combines the result using *

Compiler for e_1*e_2 emits:

- code for e_1 that leaves result on the stack, followed by
- code for e_2 that leaves result on the stack, followed by
- arithmetic instruction that takes values from the stack and leaves the result on the stack

```
def compile(e : Expr) : List[Bytecode] = e match { // ~ postfix printer
  case Var(id) => List(ILoad(slotFor(id)))
  case Plus(e1,e2)  => compile(e1) ::: compile(e2) ::: List(IAdd())
  case Times(e1,e2) => compile(e1) ::: compile(e2) ::: List(IMul())
  ... }
```

Shorthand Notation for Translation

[$e_1 + e_2$] =

[e_1]

[e_2]

iadd

[$e_1 * e_2$] =

[e_1]

[e_2]

imul

Code Generation for Control Structures

Sequential Composition

How to compile statement sequence?

s1; s2; … ; sN

- Concatenate byte codes for each statement!

```
def compileStmt(e : Stmt) : List[Bytecode] = e match {
  …
  case Sequence(sts) =>
    for { st <- sts;  bcode <- compileStmt(st) }
      yield bcode
}
```

i.e. sts **flatMap** compileStmt

semantically: (sts **map** compileStmt) **flatten**

Compiling Control: Example

```
static void count(int from,
                  int to,
                  int step) {
  int counter = from;
  while (counter < to) {
    counter = counter + step;
  }
}
```

```
0:  iload_0
1:  istore_3
2:  iload_3
3:  iload_1
4:  if_icmpge     14
7:  iload_3
8:  iload_2
9:  iadd
10: istore_3
11: goto   2
14: return
```

We need to see how to:

- translate boolean expressions
- generate jumps for control

Representing Booleans

Java bytecode verifier does not make hard distinction between booleans and ints

- can pass one as another in some cases if we hack .class files

As when compiling to assembly, we need to choose how to represent truth values

We adopt a **convention** in our code generation for JVM:

The generated code uses 'int' to represent boolean values in: **local variables**, **parameters**, and intermediate **stack values**.

In such cases, the code ensures that these int variables always either

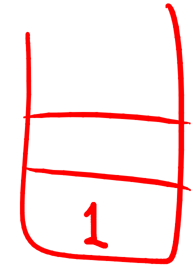
0, representing false, or

1, representing true

Truth Values for Relations: Example

```
static boolean test(int x, int y){
  return (x < y);
}
```

```
0:   iload_0
1:   iload_1
2:   if_icmpge      9
5:   iconst_1
6:   goto    10
9:   iconst_0
10:  ireturn
```



if_icmpge instruction from spec

if_icmp<cond>

Branch if int comparison succeeds

format: if_icmp<cond>
branchbyte1
branchbyte2

if_icmpeq = 159 (0x9f)

if_icmpne = 160 (0xa0)

if_icmplt = 161 (0xa1)

if_icmpge = 162 (0xa2)

if_icmpgt = 163 (0xa3)

if_icmple = 164 (0xa4)

Operand Stack:

..., value1, value2 → ...

Both value1 and value2 must be of type int. They are both popped from the operand stack and compared. All comparisons are signed.

The results of the comparison are as follows:

- if_icmpeq succeeds if and only if value1 = value2
- if_icmpne succeeds if and only if value1 ≠ value2
- if_icmplt succeeds if and only if value1 < value2
- if_icmple succeeds if and only if value1 ≤ value2
- if_icmpgt succeeds if and only if value1 > value2
- if_icmpge succeeds if and only if value1 ≥ value2

If the comparison succeeds, the unsigned branchbyte1 and branchbyte2 are used to construct a signed 16-bit offset, where the offset is calculated to be (branchbyte1 << 8) | branchbyte2. Execution then proceeds at that offset from the address of the opcode of this if_icmp<cond> instruction. The target address must be that of an opcode of an instruction within the method that contains this if_icmp<cond> instruction.

Otherwise, execution proceeds at the address of the instruction following this if_icmp<cond> instruction.

Compiling Relational Expressions

```
def compile(e : Expr) : List[Bytecode] = e match { ...
  case Times(e1,e2) => compile(e1) ::: compile(e2) ::: List(IMul())
  case Comparison(e1, op, e2) => {
    val nFalse = getFreshLabel(); val nAfter =  getFreshLabel()
      compile(e1)
     :::compile(e2)
     :::List(     if_icmp_instruction(converse(op), nFalse),
                  IConst1,
                  goto_instruction(nAfter),
label(nFalse), IConst0,
label(nAfter))       // result: 0 or 1 added to stack
  }
}
```

is there a **dual** translation?

A separate pass resolves labels before emitting class file

ifeq instruction from spec

if<cond>

Branch if int comparison with zero succeeds

if<cond>

branchbyte1

branchbyte2

ifeq = 153 (0x99)

ifne = 154 (0x9a)

iflt = 155 (0x9b)

ifge = 156 (0x9c)

ifgt = 157 (0x9d)

ifle = 158 (0x9e)

Operand Stack

..., value →...

The value must be of type int. It is popped from the operand stack and compared against zero. All comparisons are signed.

The results of the comparisons are as follows:

ifeq succeeds if and only if value = 0

ifne succeeds if and only if value ≠ 0

iflt succeeds if and only if value < 0

ifle succeeds if and only if value ≤ 0

ifgt succeeds if and only if value > 0

ifge succeeds if and only if value ≥ 0

If the comparison succeeds, the unsigned branchbyte1 and branchbyte2 are used to construct a signed 16-bit offset, where the offset is calculated to be (branchbyte1 << 8) | branchbyte2. Execution then proceeds at that offset from the address of the opcode of this if<cond> instruction. The target address must be that of an opcode of an instruction within the method that contains this if<cond> instruction.

Otherwise, execution proceeds at the address of the instruction following this if<cond> instruction.

Compiling **If Statement** using compilation of 0/1 for condition

```
def compileStmt(e : Stmt) : List[Bytecode] = e match {  ...
  case If(cond,tStmt,eStmt) => {
      val nElse = getFreshLabel(); val nAfter = getFreshLabel()
      compile(cond)
    :::List(Ifeq(nElse))
    :::compileStmt(tStmt)
    :::List(goto(nAfter))
    :::List(label(nElse))
    :::compileStmt(eStmt)
    :::List(label(nAfter))
  }
}
```

Compiling If Statement using compilation of 0/1 for condition

Shorthand math notation for the previous function:

[if (cond**)** tStmt **else** eStmt **]** =

[cond **]**
Ifeq(nElse)
[tStmt **]**
goto(**nAfter**)
nElse: **[** eStmt **]**
nAfter:

[cond]
If neq (nTrue)
[eStmt]
goto nAfter
nTrue: [tStmt]
nAfter:

Compiling While Statement using compilation of 0/1 for condition

[while (cond) stmt **]** =

nStart: **[** cond **]**
Ifeq(**nExit**)
[stmt **]**
goto(**nStart**)
nExit:

goto test
body: [stmt]
test: [cond]
Ifneq body

give a translation with only one jump during loop

Example result for **while** loop

```
static boolean condition(int n)
{ ... }
static void work(int n) { ... }
static void test() {
  int n = 100;
  while (condition(n)) {
    n = n - 11;
    work(n);
  }
}
```

```
0:   bipush  100
2:   istore_0
3:   iload_0
4:   invokestatic #4;// condition:(I)Z
7:   ifeq    22
10:  iload_0
11:  bipush  11
13:  isub
14:  istore_0
15:  iload_0
16:  invokestatic    #5; work:(I)V
19:  goto    3
22:  return
```

Exercise: LOOP with EXIT IF

Oberon-2 has a statement

```
LOOP
  code1
  EXIT IF cond
  code2
END
```

which executes a loop and exits when the condition is met. This generalizes 'while' and 'do … while'

Give a translation scheme for the LOOP construct.

Apply the translation to

```
j = i
LOOP
  j = j + 1
  EXIT IF j > 10
  s = s + j
END
z = s + j - i
```

solution

```
[ LOOP
  code1
  EXIT IF cond
  code2
END ] =
start:   [ code1 ]
         [ cond ]
         ifneq exit
         [ code2 ]
         goto start
exit:
```

How to compile complex boolean expressions expressed using &&,|| ?

Bitwise Operations

```
  10110
& 11011
= 10010

  10110
| 11011
= 11111
```

These operations always evalute both arguments.

- In contast, **&& ||** operations only evaluate their second operand if necessary!
- We must compile this correctly. It is not acceptable to emit code that always evaluates both operands of &&,||

What does this program do?

```
static boolean bigFraction(int x, int y) {
  return ((y==0) | (x/y > 100));
}
public static void main(String[] args) {
  boolean is = bigFraction(10,0);
}
```

should be **||**

Exception in thread "main" java.lang.ArithmeticException: **/ by zero**
at Test.bigFraction(Test.java:4)
at Test.main(Test.java:19)

What does this function do?

```
static int iterate() {
        int[] a = new int[10];
        int i = 0;
        int res = 0;
        while ((i < a.length) & (a[i] >= 0)) {
            i = i + 1;
            res = res + 1;
        }
        return res;
}
```

should be **&&**

```
Exception in thread "main" java.lang.ArrayIndexOutOfBoundsException: 10
        at Test.iterate(Test.java:16)
        at Test.main(Test.java:25)
```

Compiling Bitwise Operations - Easy

[e_1 **&** e_2] =
[e_1]
[e_2]
iand

[e_1 **|** e_2] =
[e_1]
[e_2]
ior

~~[e_1 **&&** e_2] =
[e_1]
[e_2]
...~~

← not allowed to evaluate e_2 if e_1 is **false**!
Also for (e1 || e2): if e1 **true**, e2 not evaluated

Conditional Expression

Scala:

if (c) t **else** e

Java, C:

c ? t : e

Meaning:

- c is evaluated
- if c is true, then t is evaluated and returned
- if c is false, then e is evaluated and returned

- Meaning of **&&**, **||**:

(p && q) ==
  if (p) q **else false**

(p **||** q) ==
  if (p) **true else** q

- To compile ||,&& transform them into 'if' **expression**

Compiling **If Expression**

- Same as for if statement, even though code for branches will leave values on the stack:

[if (cond**)** t **else** e **]** =

```
              [ cond ]
              Ifeq(nElse)
              [ t ]
              goto(nAfter)
nElse:        [ e ]
nAfter:
```

Java Example for Conditional

```
int f(boolean c, int x, int y) {
  return (c ? x : y);
}
```

```
0:  iload_1
1:  ifeq    8
4:  iload_2
5:  goto    9
8:  iload_3
9:  ireturn
```

Compiling **&&**

[if (cond**)** t **else** e **]** =

[cond **]**
Ifeq(nElse)
[t **]**
goto(**nAfter**)

nElse: **[** e **]**
nAfter:

[p **&&** q **]** =
[if (p) q **else false]** =

[p **]**
Ifeq(nElse)
[q **]**
goto(**nAfter**)

nElse: **iconst**_0
nAfter:

Compiling ||

[if (cond**)** t **else** e **]** =

[cond **]**
Ifeq(nElse)
[t **]**
goto(**nAfter**)

nElse: **[** e **]**
nAfter:

[p **||** q **]** =
[if (p) **true else** q **]** =

[p **]**
Ifeq(nElse)
iconst_1
goto(**nAfter**)

nElse: **[** q **]**
nAfter:

true, false, variables

[true] =

iconst_1

[false] =

iconst_0

for boolean variable b, for which n = slot(b)

[b **]** =

iload_n

[b = e **]** = (assignment)

[e **]**

istore_n

Example: triple **&&**

Let x,y,z be in slots 1,2,3

Show code for assignment

y = (x && y) && z

Does the sequence differ for assignment

y = x && (y && z)

```
        iload_1
        ifeq n1
        iload_2
        goto n2
n1:     iconst_0
n2:     ifeq n3
        iload_3
        goto n4
n3:     iconst_0
n4:
```