

# Compilers and Formal Languages (9)

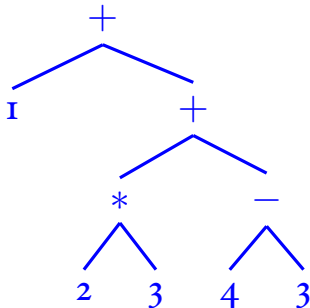
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# Compiling AExps

For example  $1 + ((2 * 3) + (4 - 3))$ :



**ldc** 1

**ldc** 2

**ldc** 3

**imul**

**ldc** 4

**ldc** 3

**isub**

**iadd**

**iadd**

Traverse tree in post-order  $\Rightarrow$  code for stack-machine

# Compiling AExps

$compile(n, E) \stackrel{\text{def}}{=} ldc\ n$

$compile(a_1 + a_2, E) \stackrel{\text{def}}{=} compile(a_1, E) @ compile(a_2, E) @ iadd$

$compile(a_1 - a_2, E) \stackrel{\text{def}}{=} compile(a_1, E) @ compile(a_2, E) @ isub$

$compile(a_1 * a_2, E) \stackrel{\text{def}}{=} compile(a_1, E) @ compile(a_2, E) @ imul$

$compile(a_1 \setminus a_2, E) \stackrel{\text{def}}{=} compile(a_1, E) @ compile(a_2, E) @ idiv$

$compile(x, E) \stackrel{\text{def}}{=} iload\ E(x)$

# Compiling Ifs

For example

```
if 1 = 1 then x := 2 else y := 3
```

```
ldc 1
```

```
ldc 1
```

```
if_icmpne L_ifelse
```

```
ldc 2
```

```
istore 0
```

```
goto L_ifend
```

```
L_ifelse:
```

```
ldc 3
```

```
istore 1
```

```
L_ifend:
```

# Compiling Whiles

For example

```
while x <= 10 do x := x + 1
```

```
L_wbegin:
```

```
  iload 0
```

```
  ldc 10
```

```
  if_icmpgt L_wend
```

```
  iload 0
```

```
  ldc 1
```

```
  iadd
```

```
  istore 0
```

```
  goto L_wbegin
```

```
L_wend:
```

# Compiling Writes

```
.method public static write(I)V
  .limit locals 1
  .limit stack 2
  getstatic java/lang/System/out
                                     Ljava/io/PrintStream;
  iload 0
  invokevirtual java/io/PrintStream/println(I)V
  return
.end method
```

```
iload  $E(x)$ 
invokestatic XXX/XXX/write(I)V
```

# Compiling Main

```
.class public XXX.XXX
.super java/lang/Object

.method public <init>()V
    aload_0
    invokevirtual java/lang/Object/<init>()V
    return
.end method

.method public static main([Ljava/lang/String;)V
    .limit locals 200
    .limit stack 200

    ...here comes the compiled code...

    return
.end method
```

# Functional Programming

```
def fib(n) = if n == 0 then 0
             else if n == 1 then 1
                 else fib(n - 1) + fib(n - 2);
```

```
def fact(n) = if n == 0 then 1 else n * fact(n - 1);
```

```
def ack(m, n) = if m == 0 then n + 1
                 else if n == 0 then ack(m - 1, 1)
                     else ack(m - 1, ack(m, n - 1));
```

```
def gcd(a, b) = if b == 0 then a else gcd(b, a % b);
```



# Fun Grammar

$\langle Exp \rangle ::= \langle Var \rangle \mid \langle Num \rangle$   
|  $\langle Exp \rangle + \langle Exp \rangle \mid \dots \mid (\langle Exp \rangle)$   
| **if**  $\langle BExp \rangle$  **then**  $\langle Exp \rangle$  **else**  $\langle Exp \rangle$   
| **write**  $\langle Exp \rangle$   
|  $\langle Exp \rangle ; \langle Exp \rangle$   
|  $FunName (\langle Exp \rangle, \dots, \langle Exp \rangle)$

$\langle BExp \rangle ::= \dots$

$\langle Decl \rangle ::= \langle Def \rangle ; \langle Decl \rangle \mid \langle Exp \rangle$

$\langle Def \rangle ::= \mathbf{def} \textit{FunName} (x_1, \dots, x_n) = \langle Exp \rangle$

# Abstract Syntax Trees

```
abstract class Exp
```

```
abstract class BExp
```

```
abstract class Decl
```

```
case class Var(s: String) extends Exp
```

```
case class Num(i: Int) extends Exp
```

```
case class Aop(o: String, a1: Exp, a2: Exp) extends Exp
```

```
case class If(a: BExp, e1: Exp, e2: Exp) extends Exp
```

```
case class Write(e: Exp) extends Exp
```

```
case class Sequ(e1: Exp, e2: Exp) extends Exp
```

```
case class Call(name: String, args: List[Exp]) extends Exp
```

```
case class Bop(o: String, a1: Exp, a2: Exp) extends BExp
```

```
case class Def(name: String,  
              args: List[String],  
              body: Exp) extends Decl
```

```
case class Main(e: Exp) extends Decl
```

# Sequences

Compiling `exp1 ; exp2`:

```
compile(exp1)
```

```
pop
```

```
compile(exp2)
```

# Write

Compiling call to `write(1+2)`:

```
compile(1+2)
```

```
dup
```

```
invokestatic XXX/XXX/write(I)V
```

needs the helper method

```
.method public static write(I)V
```

```
  .limit locals 1
```

```
  .limit stack 2
```

```
  getstatic java/lang/System/out Ljava/io/PrintStream;
```

```
  iload 0
```

```
  invokevirtual java/io/PrintStream/println(I)V
```

```
  return
```

```
.end method
```

# Function Definitions

```
.method public static write(I)V
  .limit locals 1
  .limit stack 2
  getstatic java/lang/System/out Ljava/io/PrintStream;
  iload 0
  invokevirtual java/io/PrintStream/println(I)V
  return
.end method
```

We will need for definitions, like

```
def fname (x1, ... , xn) = ...
```

```
.method public static fname (I...I)I
  .limit locals ??
  .limit stack ??
  ??
.end method
```

# Stack Estimation

$estimate(n)$	$\stackrel{\text{def}}{=} I$
$estimate(x)$	$\stackrel{\text{def}}{=} I$
$estimate(a_1 \text{ aop } a_2)$	$\stackrel{\text{def}}{=} estimate(a_1) + estimate(a_2)$
$estimate(\text{if } b \text{ then } e_1 \text{ else } e_2)$	$\stackrel{\text{def}}{=} estimate(b) +$ $max(estimate(e_1), estimate(e_2))$
$estimate(\text{write}(e))$	$\stackrel{\text{def}}{=} estimate(e) + I$
$estimate(e_1; e_2)$	$\stackrel{\text{def}}{=} max(estimate(e_1), estimate(e_2))$
$estimate(f(e_1, \dots, e_n))$	$\stackrel{\text{def}}{=} \sum_{i=1..n} estimate(e_i)$
$estimate(a_1 \text{ bop } a_2)$	$\stackrel{\text{def}}{=} estimate(a_1) + estimate(a_2)$

# Successor Function

```
.method public static suc(I)I
.limit locals 1
.limit stack 2
  iload 0
  ldc 1
  iadd
  ireturn
.end method
```

```
def suc(x) = x + 1;
```

# Addition Function

```
.method public static add(II)I
.limit locals 2
.limit stack 5
  iload 0
  ldc 0
  if_icmpne If_else
  iload 1
  goto If_end
If_else:
  iload 0
  ldc 1
  isub
  iload 1
  invokestatic XXX/XXX/add(II)I
  invokestatic XXX/XXX/suc(I)I
If_end:
  ireturn
.end method
```

```
def add(x, y) =
  if x == 0 then y
  else suc(add(x - 1, y));
```



# Factorial

```
.method public static fact(II)I
.limit locals 2
.limit stack 6
  iload 0
  ldc 0
  if_icmpne If_else_2
  iload 1
  goto If_end_3
If_else_2:
  iload 0
  ldc 1
  isub
  iload 0
  iload 1
  imul
  invokestatic fact/fact/fact(II)I
If_end_3:
  ireturn
.end method
```

```
def fact(n, acc) =
  if n == 0 then acc
  else fact(n - 1, n * acc);
```

```
.method public static fact(II)I
.limit locals 2
.limit stack 6
fact_Start:
  iload 0
  ldc 0
  if_icmpne If_else_2
  iload 1
  goto If_end_3
If_else_2:
  iload 0
  ldc 1
  isub
  iload 0
  iload 1
  imul
  istore 1
  istore 0
  goto fact_Start
If_end_3:
  ireturn
.end method
```

```
def fact(n, acc) =
  if n == 0 then acc
  else fact(n - 1, n * acc);
```

# Tail Recursion

A call to `f(args)` is usually compiled as

```
args onto stack  
invokestatic .../f
```

# Tail Recursion

A call to  $f(\text{args})$  is usually compiled as

```
args onto stack  
invokestatic .../f
```

A call is in tail position provided:

- $\text{if } B_{\text{exp}} \text{ then } \text{Exp} \text{ else } \text{Exp}$
- $\text{Exp} ; \text{Exp}$
- $\text{Exp op Exp}$

then a call  $f(\text{args})$  can be compiled as

```
prepare environment  
jump to start of function
```

# Tail Recursive Call

```
def compile_expT(a: Exp, env: Mem, name: String): Instrs =  
  ...  
  case Call(n, args) => if (name == n)  
  {  
    val stores = args.zipWithIndex.map  
      { case (x, y) => "istore " + y.toString + "\n" }  
    args.flatMap(a => compile_expT(a, env, "")) ++  
    stores.reverse ++  
    List ("goto " + n + "_Start\n")  
  }  
  else  
  {  
    val is = "I" * args.length  
    args.flatMap(a => compile_expT(a, env, "")) ++  
    List ("invokestatic XXX/XXX/" + n + "(" + is + ")I\n")  
  }
```

# Dijkstra on Testing

“Program testing can be a very effective way to show the presence of bugs, but it is hopelessly inadequate for showing their absence.”

What is good about compilers: the either seem to work, or go horribly wrong (most of the time).

# Proving Programs to be Correct

**Theorem:** There are infinitely many prime numbers.

**Proof ...**

similarly

**Theorem:** The program is doing what it is supposed to be doing.

**Long, long proof ...**

This can be a gigantic proof. The only hope is to have help from the computer. 'Program' is here to be understood to be quite general (compiler, OS, ...).

# Can This Be Done?

- in 2008, verification of a small C-compiler
  - “if my input program has a certain behaviour, then the compiled machine code has the same behaviour”
  - is as good as `gcc -O1`, but much, much less buggy



# Fuzzy Testing C-Compilers

- tested GCC, LLVM and others by randomly generating C-programs
- found more than 300 bugs in GCC and also many in LLVM (some of them highest-level critical)
- about CompCert:

“The striking thing about our CompCert results is that the middle-end bugs we found in all other compilers are absent. As of early 2011, the under-development version of CompCert is the only compiler we have tested for which Csmith cannot find wrong-code errors. This is not for lack of trying: we have devoted about six CPU-years to the task.”