

Automata and Formal Languages (9)

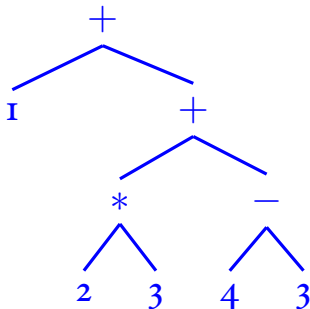
Email: christian.urban at kcl.ac.uk

Office: SI.27 (1st floor Strand Building)

Slides: KEATS (also home work is there)

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

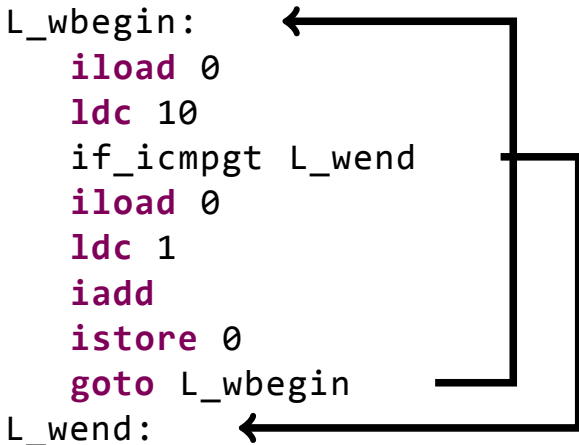
```
if 1 = 1 then x := 2 else y := 3
```

```
    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
```



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

```
1 def fib(n) = if n == 0 then 0
2             else if n == 1 then 1
3             else fib(n - 1) + fib(n - 2);
4
5 def fact(n) = if n == 0 then 1 else n * fact(n - 1);
6
7 def ack(m, n) = if m == 0 then n + 1
8                 else if n == 0 then ack(m - 1, 1)
9                 else ack(m - 1, ack(m, n - 1));
10
11 def gcd(a, b) = if b == 0 then a else gcd(b, a % b);
```


Fun Grammar

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

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

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

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

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:

- if Bexp then Exp else Exp
- Exp ; Exp
- 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

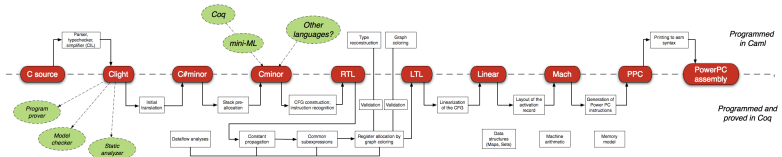
Theorem: The program is doing what it is supposed to be doing.

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.”