

Compilers and Formal Languages

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```

.method public static main([Ljava/lang/String;)V
    .limit locals 200
    .limit stack 200
    invokestatic foo/foo/read()I
    istore 0
    ldc 1
    istore 1
Loop_begin_4:
    iload 0
    ldc 0
    if_icmple Loop_end_5
    iload 0
    iload 1
    imul
    istore 1
    iload 0
    ldc 1
    isub
    istore 0
    goto Loop_begin_4
Loop_end_5:
    iload 1
    invokestatic foo/foo/write(I)V
    return
.end method

```

```

.method public static main([Ljava/lang/String;)V
    .limit locals 200
    .limit stack 200
    invokestatic foo/foo/read()I
    istore 0          ; n
    ldc 1
    istore 1          ; res
Loop_begin_4:
    iload 0           ; n
    ldc 0
    if_icmple Loop_end_5
    iload 0           ; n
    iload 1           ; res
    imul
    istore 1          ; res
    iload 0           ; n
    ldc 1
    isub
    istore 0          ; n
    goto Loop_begin_4
Loop_end_5:
    iload 1           ; res
    invokestatic foo/foo/write(I)V
    return
.end method

```

```

def mkeys(r: Rexp) : Val = r match {
  ...
  case PLUS(r) => Stars(List(mkeys(r)))
  case OPTIONAL(r) => Stars(Nil)
  case NTIMES(r, n) => Stars(List.fill(n)(mkeys(r)))
}

```

```

def inj(r: Rexp, c: Char, v: Val) : Val = (r, v) match {
  ...
  case (RANGE(_), Empty) => Chr(c)
  case (PLUS(r), Sequ(v1, Stars(vs))) => Stars(inj(r, c, v1)::vs)
  case (OPTIONAL(r), v) => Stars(inj(r, c, v)::Nil)
  case (NTIMES(r, n), Sequ(v1, Stars(vs))) => Stars(inj(r, c, v1)::vs)
}

```

$r? \stackrel{\text{def}}{=} r\{0..1\}$

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

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

$BExp ::= \dots$

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

$Prog ::= Def ; Prog \mid Exp ; Prog \mid Exp$

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
```

Ideas

Use separate JVM methods for each Fun-function.

Compile `exp`s such that the result of the expression is on top of the stack.

- `write(1 + 2)`
- `1 + 2; 3 + 4`

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 methods for definitions like

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

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

Stack Estimation

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

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:
```

```
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 B_{exp} 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) => i"istore $y" }  
  
    args.map(a => compile_expT(a, env, "")).mkString ++  
    stores.reverse.mkString ++  
    i"goto ${n}_Start"  
  } else {  
    val is = "I" * args.length  
    args.map(a => compile_expT(a, env, "")).mkString ++  
    i"invokestatic XXX/XXX/${n}(${is})I"  
  }
```

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

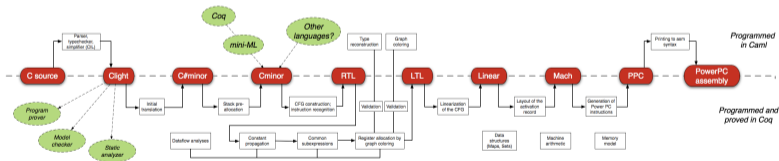
Theorem: The program is doing what it is supposed to be doing.

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.”

