

Automata and Formal Languages (9)

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Slides: KEATS (also home work is there)

Imagine the following situation: You talk to somebody and you find out that she/he has implemented a compiler.

What is your reaction? Check all that apply.

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What is your reaction? Check all that apply.

- You think she/he is God
- Überhacker
- superhuman
- wizard
- supremo

While-Language

Stmt → skip
| *Id* := *AExp*
| if *BExp* then *Block* else *Block*
| while *BExp* do *Block*
| write *Id*

Stmts → *Stmt* ; *Stmts*
| *Stmt*

Block → {*Stmts*}
| *Stmt*

AExp → ...

BExp → ...

Fibonacci Numbers

```
1  /* Fibonacci Program
2     input: n
3     output: fib_res */
4
5  n := 90;
6  minus1 := 0;
7  minus2 := 1;
8  temp := 0;
9  while n > 0 do {
10     temp := minus2;
11     minus2 := minus1 + minus2;
12     minus1 := temp;
13     n := n - 1
14 };
15 fib_res := minus2;
16 write fib_res
```

Interpreter

$\text{eval}(n, E)$	$\stackrel{\text{def}}{=} n$
$\text{eval}(x, E)$	$\stackrel{\text{def}}{=} E(x)$ lookup x in E
$\text{eval}(a_1 + a_2, E)$	$\stackrel{\text{def}}{=} \text{eval}(a_1, E) + \text{eval}(a_2, E)$
$\text{eval}(a_1 - a_2, E)$	$\stackrel{\text{def}}{=} \text{eval}(a_1, E) - \text{eval}(a_2, E)$
$\text{eval}(a_1 * a_2, E)$	$\stackrel{\text{def}}{=} \text{eval}(a_1, E) * \text{eval}(a_2, E)$
$\text{eval}(a_1 = a_2, E)$	$\stackrel{\text{def}}{=} \text{eval}(a_1, E) = \text{eval}(a_2, E)$
$\text{eval}(a_1 \neq a_2, E)$	$\stackrel{\text{def}}{=} \neg(\text{eval}(a_1, E) = \text{eval}(a_2, E))$
$\text{eval}(a_1 < a_2, E)$	$\stackrel{\text{def}}{=} \text{eval}(a_1, E) < \text{eval}(a_2, E)$

Interpreter (2)

$$\text{eval}(\text{skip}, E) \stackrel{\text{def}}{=} E$$

$$\text{eval}(x := a, E) \stackrel{\text{def}}{=} E(x \mapsto \text{eval}(a, E))$$

$$\begin{aligned} \text{eval}(\text{if } b \text{ then } cs_1 \text{ else } cs_2, E) &\stackrel{\text{def}}{=} \\ &\text{if } \text{eval}(b, E) \text{ then } \text{eval}(cs_1, E) \\ &\text{else } \text{eval}(cs_2, E) \end{aligned}$$

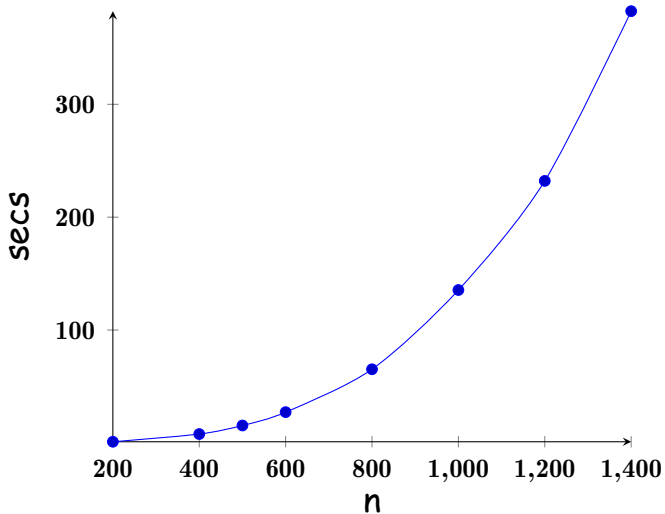
$$\begin{aligned} \text{eval}(\text{while } b \text{ do } cs, E) &\stackrel{\text{def}}{=} \\ &\text{if } \text{eval}(b, E) \\ &\text{then } \text{eval}(\text{while } b \text{ do } cs, \text{eval}(cs, E)) \\ &\text{else } E \end{aligned}$$

$$\text{eval}(\text{write } x, E) \stackrel{\text{def}}{=} \{ \text{println}(E(x)) ; E \}$$

Test Program

```
1 start := 1000;
2 x := start;
3 y := start;
4 z := start;
5 while 0 < x do {
6   while 0 < y do {
7     while 0 < z do {
8       z := z - 1
9     };
10    z := start;
11    y := y - 1
12  };
13  y := start;
14  x := x - 1
15 };
16 write x;
17 write y;
18 write z
```


Interpreted Code



Java Virtual Machine

- introduced in 1995
- is a stack-based VM (like Postscript, CLR of .Net)
- contains a JIT compiler
- many languages take advantage of JVM's infrastructure (JRE)
- languages compiled to the JVM: Scala, Clojure...
- is garbage collected \Rightarrow no buffer overflows

Compiling AExps

1 + 2

ldc 1

ldc 2

iadd

Compiling AExps

1 + 2 + 3

ldc 1

ldc 2

iadd

ldc 3

iadd

Compiling AExps

1 + (2 + 3)

ldc 1

ldc 2

ldc 3

iadd

iadd

Compiling AExps

1 + (2 + 3)

ldc 1

ldc 2

ldc 3

iadd

iadd

dadd, fadd, ladd, ...

Compiling AExps

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

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

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

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

Compiling AExps

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

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

Compiling AExps

1 + 2 * 3 + (4 - 3)

ldc 1

ldc 2

ldc 3

imul

ldc 4

ldc 3

isub

iadd

iadd

Variables

$x := 5 + y * 2$

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- lookup: *iload number*
- store: *istore number*

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during compilation we have to maintain a map between our identifiers and the Java bytecode numbers

$$\text{compile}(a, E)$$

Compiling AExps

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

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

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

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

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

Compiling AExps

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

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

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

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

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

Compiling Statements

We return a list of instructions and an environment for the variables

$$\text{compile}(\text{skip}, E) \stackrel{\text{def}}{=} (\text{Nil}, E)$$

$$\text{compile}(x := a, E) \stackrel{\text{def}}{=} (\text{compile}(a, E) @ \text{istore } \textit{index}, E(x \mapsto \textit{index}))$$

where *index* is $E(x)$ if it is already defined, or if it is not then the largest index not yet seen

Compiling AExps

$x := x + 1$

iload n_x

ldc 1

iadd

istore n_x

where n_x is the number corresponding to the variable x

Compiling Ifs

if b else cs_1 then cs_2

code of b

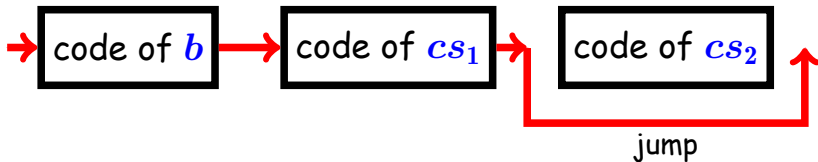
code of cs_1

code of cs_2

Compiling Ifs

if b else cs_1 then cs_2

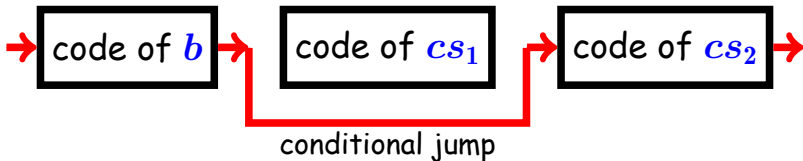
Case True:



Compiling Ifs

if b else cs_1 then cs_2

Case False:



Conditional Jumps

- `if_icmpeq label` if two ints are equal, then jump
- `if_icmpne label` if two ints aren't equal, then jump
- `if_icmpge label` if one int is greater or equal then another, then jump
- ...

Conditional Jumps

- `if_icmpeq label` if two ints are equal, then jump
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...

```
L1:  
    if_icmpeq L2  
    iload 1  
    ldc 1  
    iadd  
    if_icmpeq L1  
L2:
```

Conditional Jumps

- `if_icmpeq label` if two ints are equal, then jump
- `if_icmpne label` if two ints aren't equal, then jump
- `if_icmpge label` if one int is greater or equal then another, then jump

...

L_1 :

`if_icmpeq L_2`

`iload 1`

`ldc 1`

`iadd`

`if_icmpeq L_1`

L_2 :

labels must
be unique

Compiling BExps

$a_1 = a_2$

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

Compiling Ifs

if b then cs_1 else cs_2

compile(if b then cs_1 else cs_2 , E) $\stackrel{\text{def}}{=}$

l_{ifelse} (fresh label)

l_{ifend} (fresh label)

$(is_1, E') = \text{compile}(cs_1, E)$

$(is_2, E'') = \text{compile}(cs_2, E')$

$(\text{compile}(b, E, l_{ifelse})$

@ is_1

@ goto l_{ifend}

@ l_{ifelse} :

@ is_2

@ l_{ifend} :, E'')

Compiling Whiles

while *b* do *cs*

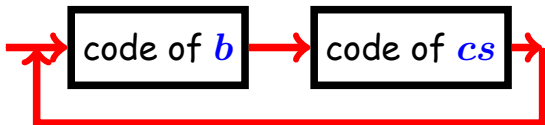
code of *b*

code of *cs*

Compiling Whiles

`while b do cs`

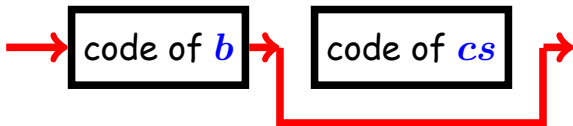
Case True:



Compiling Whiles

`while b do cs`

Case False:



Compiling Whiles

while b do cs

$\text{compile}(\text{while } b \text{ do } cs, E) \stackrel{\text{def}}{=} \\ l_{wbegin} \text{ (fresh label)} \\ l_{wend} \text{ (fresh label)} \\ (is, E') = \text{compile}(cs_1, E) \\ (l_{wbegin} : \\ @ \text{ compile}(b, E, l_{wend}) \\ @ is \\ @ \text{ goto } l_{wbegin} \\ @ l_{wend} :, E'')$

Compiling Writes

write x

```
.method public static write(I)V
  .limit locals 5
  .limit stack 5
  iload 0
  getstatic java/lang/System/out Ljava/io/PrintStream;
  swap
  invokevirtual java/io/PrintStream/println(I)V
  return
.end method
```

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

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

```
.method public <init>()V  
  aload_0  
  invokenonvirtual 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)

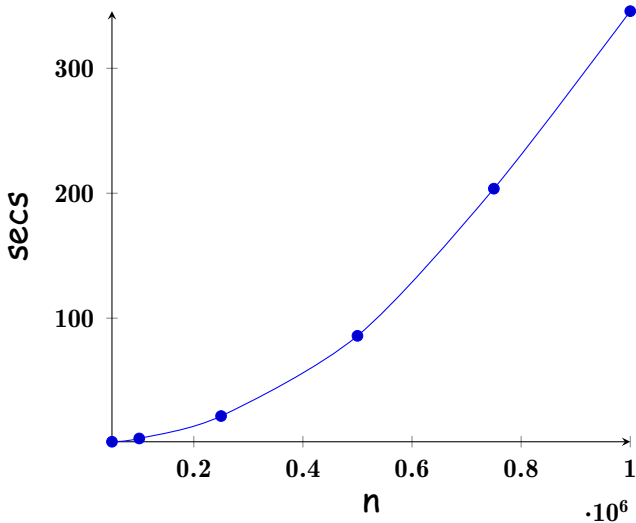
```
  return  
.end method
```

Next Compiler Phases

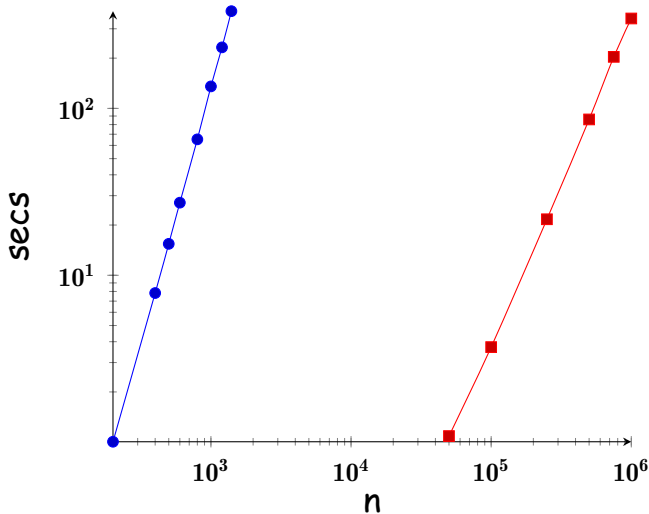
- assembly \Rightarrow byte code (class file)
- labels \Rightarrow absolute or relative jumps

- `javap` is a disassembler for class files

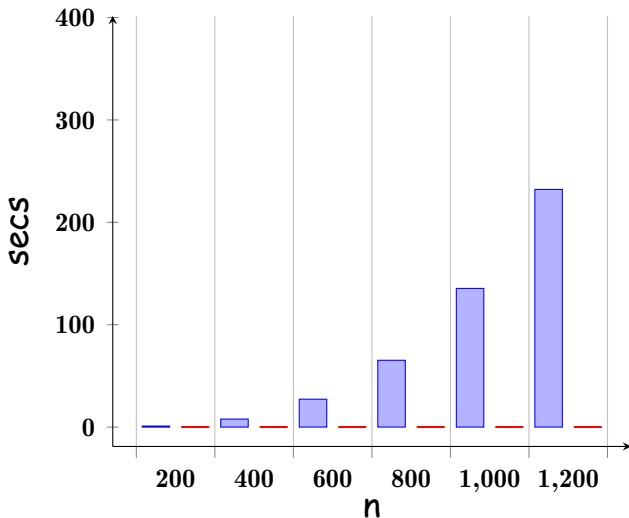
Compiled Code



Compiled vs. Interpreted Code



Compiled vs. Interpreted Code



What Next

- register spilling
- dead code removal
- loop optimisations
- instruction selection
- type checking
- concurrency
- fuzzy testing
- verification

- *GCC, LLVM, tracing JITs*