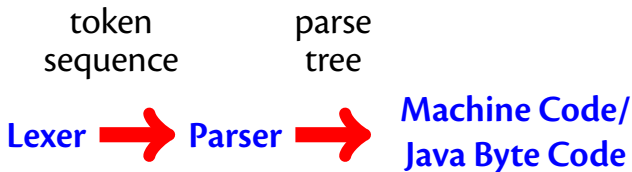


Compilers and Formal Languages (7)

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Slides & Progs: KEATS (also homework is there)

Bird's Eye View



CW3

Atomic parsers for tokens

$T_Num(123) :: rest \Rightarrow \{(T_Num(123), rest)\}$

- you consume one or more token from the input (stream)
- $T_NUM(1)$, $T_OP(+)$, $T_NUM(2)$
- a good starting point would be `comb2.scala`

JVM Code

Jasmin Krakatau ASM lib

```
ldc 1000
istore 0
iload 0
istore 1
iload 0
istore 2
iload 0
istore 3
```

```
Loop_begin_0:
```

```
ldc 0
iload 1
if_icmpge Loop_end_1
```

```
Loop_begin_2:
```

```
ldc 0
iload 2
if_icmpge Loop_end_3
```

```
Loop_begin_4:
```

```
ldc 0
iload 3
```

```
if_icmpge Loop_end_5
iload 3
ldc 1
isub
istore 3
goto Loop_begin_4
```

```
Loop_end_5:
```

```
iload 0
istore 3
iload 2
ldc 1
isub
istore 2
goto Loop_begin_2
```

```
Loop_end_3:
```

```
iload 0
istore 2
iload 1
ldc 1
isub
istore 1
goto Loop_begin_0
```

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

Stmts ::= *Stmt* ; *Stmts*
| *Stmt*

Block ::= { *Stmts* }
| *Stmt*

AExp ::= ...

BExp ::= ...

Fibonacci Numbers

```
write "Fib";  
read n;  
minus1 := 0;  
minus2 := 1;  
while n > 0 do {  
    temp := minus2;  
    minus2 := minus1 + minus2;  
    minus1 := temp;  
    n := n - 1  
};  
write "Result";  
write minus2
```

Interpreter

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

Interpreter (2)

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

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

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

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

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

Test Program

```
start := 1000;
x := start;
y := start;
z := start;
while 0 < x do {
  while 0 < y do {
    while 0 < z do { z := z - 1 };
    z := start;
    y := y - 1
  };
  y := start;
  x := x - 1
}
```

```
ldc 1000
istore 0
iload 0
istore 1
iload 0
istore 2
iload 0
istore 3
```

```
Loop_begin_0:
```

```
ldc 0
iload 1
if_icmpge Loop_end_1
```

```
Loop_begin_2:
```

```
ldc 0
iload 2
if_icmpge Loop_end_3
```

```
Loop_begin_4:
```

```
ldc 0
iload 3
```

```
if_icmpge Loop_end_5
iload 3
ldc 1
isub
istore 3
goto Loop_begin_4
```

```
Loop_end_5:
```

```
iload 0
istore 3
iload 2
ldc 1
isub
istore 2
goto Loop_begin_2
```

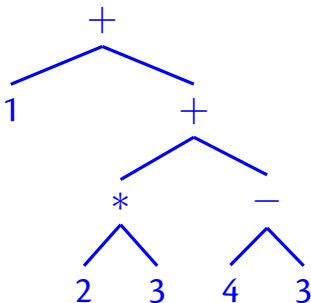
```
Loop_end_3:
```

```
iload 0
istore 2
iload 1
ldc 1
isub
istore 1
goto Loop_begin_0
```

```
Loop_end_1:
```

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

$(1 + 2) + 3$

```
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

$1 + 2 * 3 + (4 - 3)$

ldc 1

ldc 2

ldc 3

imul

ldc 4

ldc 3

isub

iadd

iadd

Variables

$x := 5 + y * 2$

Variables

$x := 5 + y * 2$

- lookup: **iload** *index*
- store: **istore** *index*

Variables

$x := 5 + y * 2$

- lookup: **iload** *index*
- store: **istore** *index*

while compiling we have to maintain a map between our identifiers and the Java bytecode indices

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

Compiling AExps

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

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

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

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

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

Mathematical Functions

Compilation of some mathematical functions:

`Aop("+", a1, a2) ⇒ ...iadd`

`Aop("-", a1, a2) ⇒ ...isub`

`Aop("*", a1, a2) ⇒ ...imul`

`Aop("/", a1, a2) ⇒ ...idiv`

`Aop("%", a1, a2) ⇒ ...irem`

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 Assignments

$x := x + 1$

```
iload  $n_x$ 
```

```
ldc 1
```

```
iadd
```

```
istore  $n_x$ 
```

where n_x is the index corresponding to the variable x

Compiling Ifs

if b then cs_1 else cs_2

code of b

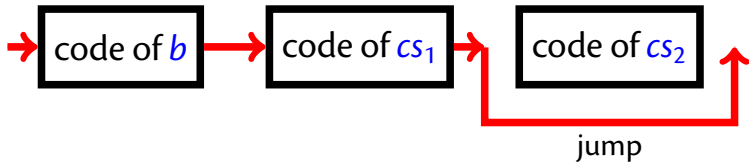
code of cs_1

code of cs_2

Compiling Ifs

if b then cs_1 else cs_2

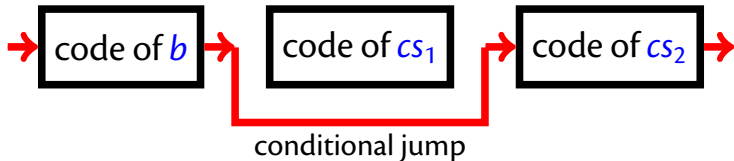
Case True:



Compiling Ifs

if b then cs_1 else 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 than another, then jump
- ...

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

...

```
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

...

`L1:`

`if_icmpeq L2`

`iload 1`

`ldc 1`

`iadd`

`if_icmpeq L1`

`L2:`

labels must be
unique

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: ←
```

```
graph TD
    A[ldc 1] --> B[ldc 1]
    B --> C[if_icmpne L_ifelse]
    C --> D[ldc 2]
    C --> E[L_ifend]
    D --> F[istore 0]
    F --> G[goto L_ifend]
    G --> E
    H[L_ifelse] --> I[istore 1]
    I --> E
    J[L_ifend] --> K[L_ifend]
```

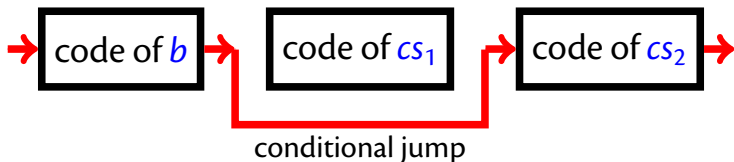
Compiling BExps

$a_1 = a_2$

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

Boolean Expressions

Compilation of boolean expressions:



`Bop("==", a1, a2) ⇒ ...if_icmpne...`

`Bop("!=", a1, a2) ⇒ ...if_icmpeq...`

`Bop("<", a1, a2) ⇒ ...if_icmpge...`

`Bop("<=", a1, a2) ⇒ ...if_icmpgt...`

Compiling Ifs

if b then cs_1 else cs_2

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

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*

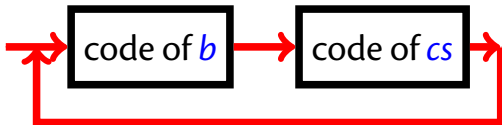
code of *b*

code of *cs*

Compiling Whiles

while *b* do *cs*

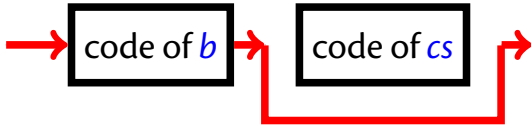
Case True:



Compiling Whiles

while *b* do *cs*

Case **False**:



Compiling Whiles

while b do cs

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

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...

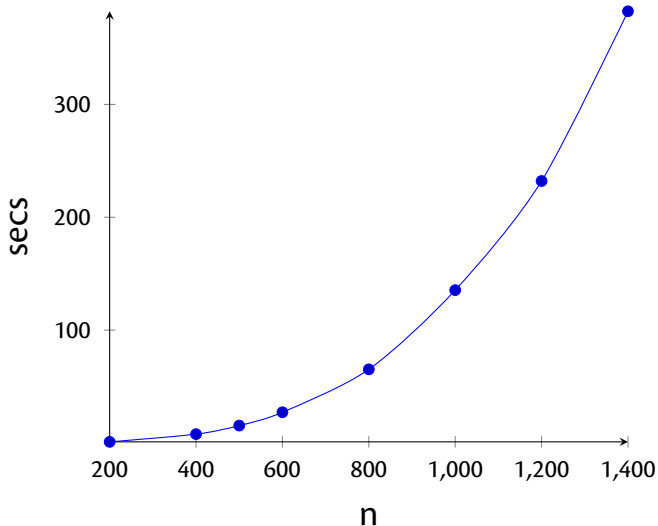
    return
.end method
```


Next Compiler Phases

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

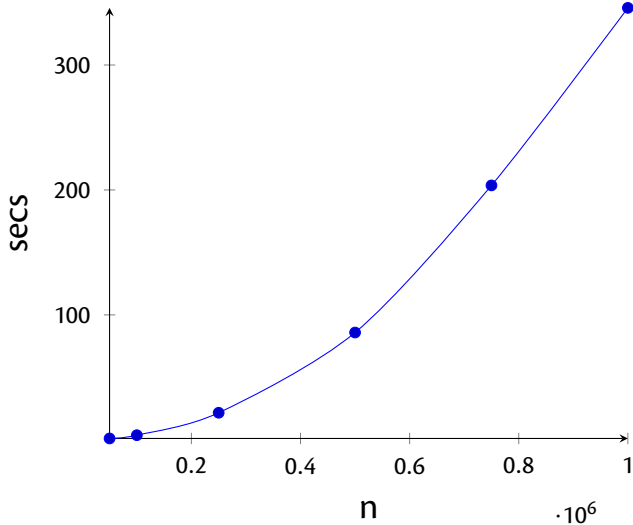
- javap is a disassembler for class files
- jasmin and krakatau are assemblers for jvm code

Recall: Interpreted Code

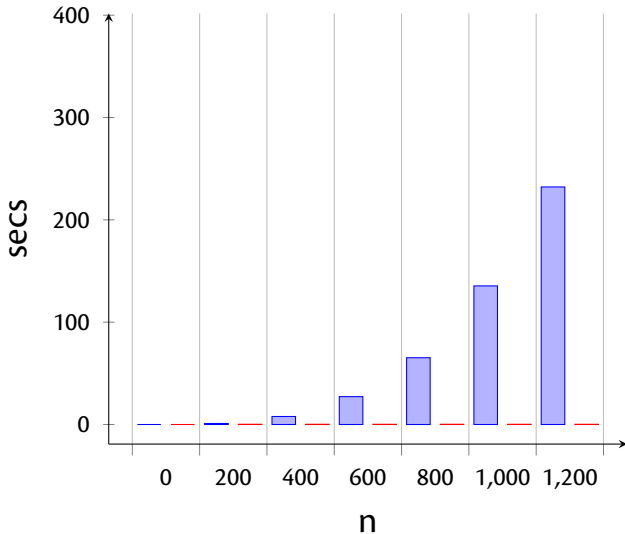


Loop program

Compiled Code



Compiler vs. Interpreter



A “Compiler” for BF*** to C

- > ⇒ ptr++
- < ⇒ ptr--
- + ⇒ (*ptr)++
- ⇒ (*ptr)--
- . ⇒ putchar(*ptr)
- , ⇒ *ptr = getchar()
- [⇒ while(*ptr){
-] ⇒ }
- ⇒ ignore everything else

```
char field[30000]
char *ptr = &field[15000]
```

BF***

we need some big array, say arr and 7 (8) instructions:

- > move ptr++
- < move ptr--
- + add arr[ptr]++
- - subtract arr[ptr]--
- . print out arr[ptr] as ASCII
- [if arr[ptr] == 0 jump just after the corresponding
]; otherwise ptr++
-] if arr[ptr] != 0 jump just after the corresponding
]; otherwise ptr++

Arrays in While

- `new arr[15000]`
- `x := 3 + arr[3 + y]`
- `arr[42 * n] := ...`

New Arrays

```
new arr[number]
```

```
ldc number
```

```
newarray int
```

```
astore loc_var
```


Array Update

```
arr[...] :=
```

```
aload loc_var
```

```
index_aexp
```

```
value_aexp
```

```
iastore
```

Array Lookup in AExp

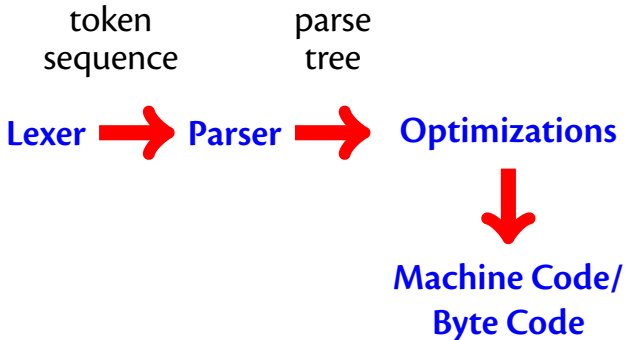
```
...arr[...]...
```

```
aload loc_var
```

```
index_aexp
```

```
iaload
```

Backend



What is Next

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

- GCC, LLVM, tracing JITs