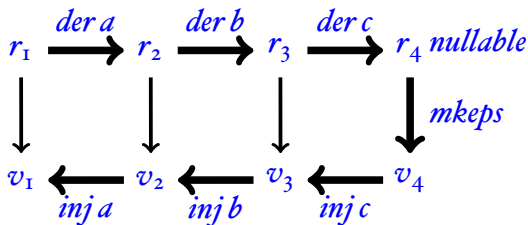


Compilers and Formal Languages (6)

Email: christian.urban at kcl.ac.uk

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

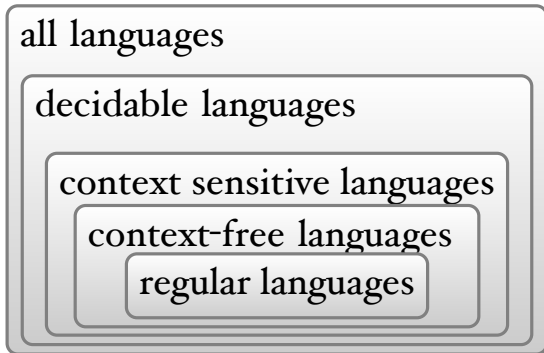
Slides: KEATS (also home work is there)



$$\begin{array}{ll}
 \text{inj}(c) \text{ c Empty} & \stackrel{\text{def}}{=} \text{Char } c \\
 \text{inj}(r_1 + r_2) \text{ c Left}(v) & \stackrel{\text{def}}{=} \text{Left}(\text{inj } r_1 \text{ c } v) \\
 \text{inj}(r_1 + r_2) \text{ c Right}(v) & \stackrel{\text{def}}{=} \text{Right}(\text{inj } r_2 \text{ c } v) \\
 \text{inj}(r_1 \cdot r_2) \text{ c Seq}(v_1, v_2) & \stackrel{\text{def}}{=} \text{Seq}(\text{inj } r_1 \text{ c } v_1, v_2) \\
 \text{inj}(r_1 \cdot r_2) \text{ c Left}(\text{Seq}(v_1, v_2)) & \stackrel{\text{def}}{=} \text{Seq}(\text{inj } r_1 \text{ c } v_1, v_2) \\
 \text{inj}(r_1 \cdot r_2) \text{ c Right}(v) & \stackrel{\text{def}}{=} \text{Seq}(\text{mkeps}(r_1), \text{inj } r_2 \text{ c } v) \\
 \text{inj}(r^*) \text{ c Seq}(v, vs) & \stackrel{\text{def}}{=} \text{inj } r \text{ c } v :: vs
 \end{array}$$

Hierarchy of Languages

Recall that languages are sets of strings.



Two Grammars

Which languages are recognised by the following two grammars?

$$S \rightarrow \begin{array}{l} I \cdot S \cdot S \\ | \\ \epsilon \end{array}$$

$$U \rightarrow \begin{array}{l} I \cdot U \\ | \\ \epsilon \end{array}$$

Atomic parsers, for example

$$I :: \textit{rest} \Rightarrow \{(I, \textit{rest})\}$$

- you consume one or more token from the input (stream)
- also works for characters and strings

Alternative parser (code $p \parallel q$)

- apply p and also q ; then combine the outputs

$$p(\text{input}) \cup q(\text{input})$$

Sequence parser (code $p \sim q$)

- apply first p producing a set of pairs
- then apply q to the unparsed parts
- then combine the results:

$((\text{output}_1, \text{output}_2), \text{unparsed part})$

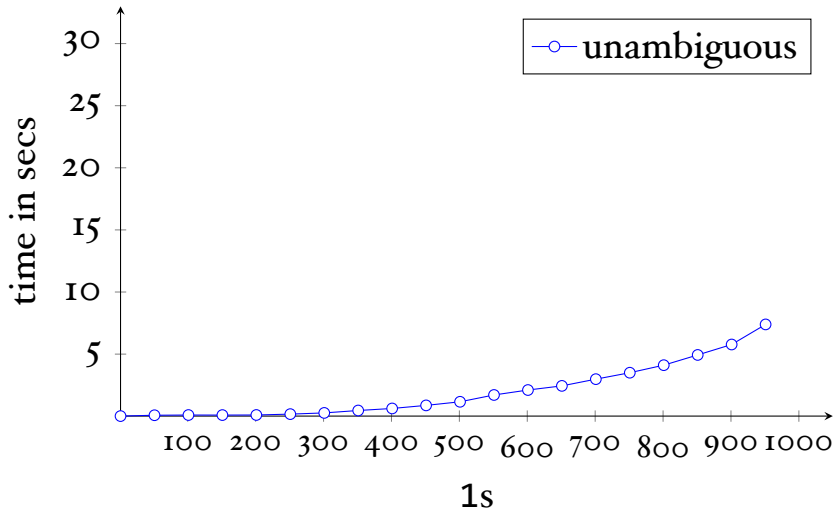
$$\{((o_1, o_2), u_2) \mid (o_1, u_1) \in p(\text{input}) \wedge (o_2, u_2) \in q(u_1)\}$$

Function parser (code $p \Rightarrow f$)

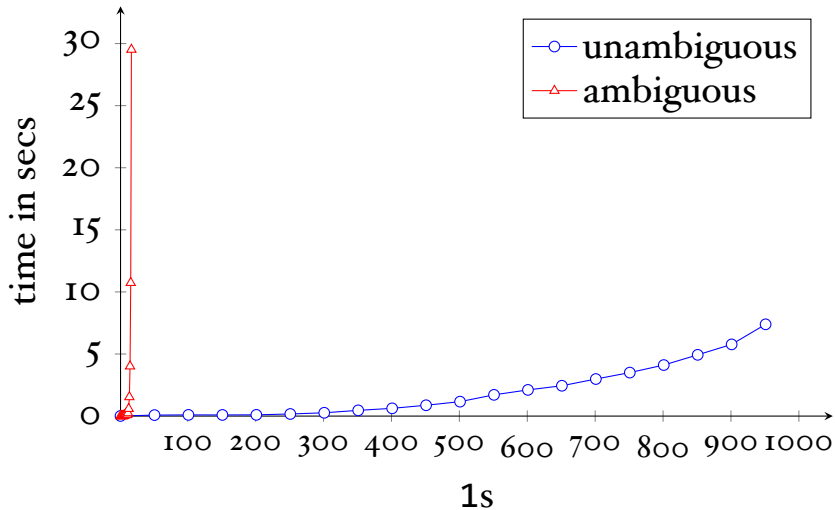
- apply p producing a set of pairs
- then apply the function f to each first component

$$\{(f(o_I), u_I) \mid (o_I, u_I) \in p(\text{input})\}$$

Ambiguous Grammars



Ambiguous Grammars



Arithmetic Expressions

A grammar for arithmetic expressions and numbers:

$$\begin{aligned} E &\rightarrow E \cdot + \cdot E \mid E \cdot * \cdot E \mid (\cdot E \cdot) \mid N \\ N &\rightarrow N \cdot N \mid 0 \mid 1 \mid \dots \mid 9 \end{aligned}$$

Unfortunately it is left-recursive (and ambiguous).

A problem for **recursive descent parsers** (e.g. parser combinators).

Arithmetic Expressions

A grammar for arithmetic expressions and numbers:

$$\begin{aligned} E &\rightarrow E \cdot + \cdot E \mid E \cdot * \cdot E \mid (\cdot E \cdot) \mid N \\ N &\rightarrow N \cdot N \mid 0 \mid 1 \mid \dots \mid 9 \end{aligned}$$

Unfortunately it is left-recursive (and ambiguous).

A problem for **recursive descent parsers** (e.g. parser combinators).

Numbers

$$N \rightarrow N \cdot N \mid 0 \mid 1 \mid \dots \mid 9$$

A non-left-recursive, non-ambiguous grammar for numbers:

$$N \rightarrow 0 \cdot N \mid 1 \cdot N \mid \dots \mid 0 \mid 1 \mid \dots \mid 9$$

Removing Left-Recursion

The rule for numbers is directly left-recursive:

$$N \rightarrow N \cdot N \mid 0 \mid 1 \quad (\dots)$$

Translate

$$\begin{array}{l} N \rightarrow N \cdot \alpha \\ \quad \mid \beta \end{array} \quad \Rightarrow \quad \begin{array}{l} N \rightarrow \beta \cdot N' \\ N' \rightarrow \alpha \cdot N' \\ \quad \mid \epsilon \end{array}$$

Removing Left-Recursion

The rule for numbers is directly left-recursive:

$$N \rightarrow N \cdot N \mid 0 \mid 1 \quad (\dots)$$

Translate

$$\begin{array}{l} N \rightarrow N \cdot \alpha \\ \quad \mid \beta \end{array} \quad \Rightarrow \quad \begin{array}{l} N \rightarrow \beta \cdot N' \\ N' \rightarrow \alpha \cdot N' \\ \quad \mid \epsilon \end{array}$$

Which means

$$\begin{array}{l} N \rightarrow 0 \cdot N' \mid 1 \cdot N' \\ N' \rightarrow N \cdot N' \mid \epsilon \end{array}$$

Operator Precedences

To disambiguate

$$E \rightarrow E \cdot + \cdot E \mid E \cdot * \cdot E \mid (\cdot E \cdot) \mid N$$

Decide on how many precedence levels, say
highest for $()$, medium for $*$, lowest for $+$

$$\begin{aligned} E_{low} &\rightarrow E_{med} \cdot + \cdot E_{low} \mid E_{med} \\ E_{med} &\rightarrow E_{hi} \cdot * \cdot E_{med} \mid E_{hi} \\ E_{hi} &\rightarrow (\cdot E_{low} \cdot) \mid N \end{aligned}$$

Operator Precedences

To disambiguate

$$E \rightarrow E \cdot + \cdot E \mid E \cdot * \cdot E \mid (\cdot E \cdot) \mid N$$

Decide on how many precedence levels, say
highest for $()$, medium for $*$, lowest for $+$

$$E_{low} \rightarrow E_{med} \cdot + \cdot E_{low} \mid E_{med}$$

$$E_{med} \rightarrow E_{hi} \cdot * \cdot E_{med} \mid E_{hi}$$

$$E_{hi} \rightarrow (\cdot E_{low} \cdot) \mid N$$

What happens with $1 + 3 + 4$?

Chomsky Normal Form

All rules must be of the form

$$A \rightarrow a$$

or

$$A \rightarrow B \cdot C$$

No rule can contain ϵ .

ϵ -Removal

- 1 If $A \rightarrow \alpha \cdot B \cdot \beta$ and $B \rightarrow \epsilon$ are in the grammar, then add $A \rightarrow \alpha \cdot \beta$ (iterate if necessary).
- 2 Throw out all $B \rightarrow \epsilon$.

$$N \rightarrow 0 \cdot N' \mid 1 \cdot N'$$
$$N' \rightarrow N \cdot N' \mid \epsilon$$

$$N \rightarrow 0 \cdot N' \mid 1 \cdot N' \mid 0 \mid 1$$
$$N' \rightarrow N \cdot N' \mid N \mid \epsilon$$

$$N \rightarrow 0 \cdot N' \mid 1 \cdot N' \mid 0 \mid 1$$
$$N' \rightarrow N \cdot N' \mid N$$

ϵ -Removal

- 1 If $A \rightarrow \alpha \cdot B \cdot \beta$ and $B \rightarrow \epsilon$ are in the grammar, then add $A \rightarrow \alpha \cdot \beta$ (iterate if necessary).
- 2 Throw out all $B \rightarrow \epsilon$.

$$N \rightarrow 0 \cdot N' \mid 1 \cdot N'$$
$$N' \rightarrow N \cdot N' \mid \epsilon$$

$$N \rightarrow 0 \cdot N' \mid 1 \cdot N' \mid 0 \mid 1$$
$$N' \rightarrow N \cdot N' \mid N \mid \epsilon$$

$$N \rightarrow 0 \cdot N' \mid 1 \cdot N' \mid 0 \mid 1$$
$$N' \rightarrow N \cdot N' \mid N$$

$$N \rightarrow 0 \cdot N \mid 1 \cdot N \mid 0 \mid 1$$

CYK Algorithm

If grammar is in Chomsky normalform ...

$S \rightarrow N \cdot P$

$P \rightarrow V \cdot N$

$N \rightarrow N \cdot N$

$N \rightarrow \text{students} \mid \text{Jeff} \mid \text{geometry} \mid \text{trains}$

$V \rightarrow \text{trains}$

Jeff trains geometry students

CYK Algorithm

- fastest possible algorithm for recognition problem
- runtime is $O(n^3)$
- grammars need to be transferred into CNF

The Goal of this Course

Write a Compiler



We have lexer and parser.

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 → ...


```
1 write "Fib";
2 read n;
3 minus1 := 0;
4 minus2 := 1;
5 while n > 0 do {
6     temp := minus2;
7     minus2 := minus1 + minus2;
8     minus1 := temp;
9     n := n - 1
10 };
11 write "Result";
12 write minus2
```

An Interpreter

```
{  
   $x := 5;$   
   $y := x * 3;$   
   $y := x * 4;$   
   $x := u * 3$   
}
```

- the interpreter has to record the value of x before assigning a value to y

An Interpreter

```
{  
   $x := 5$ ;  
   $y := x * 3$ ;  
   $y := x * 4$ ;  
   $x := u * 3$ ;  
}
```

- the interpreter has to record the value of x before assigning a value to y
- $\text{eval}(\text{stmt}, \text{env})$

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)

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

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

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

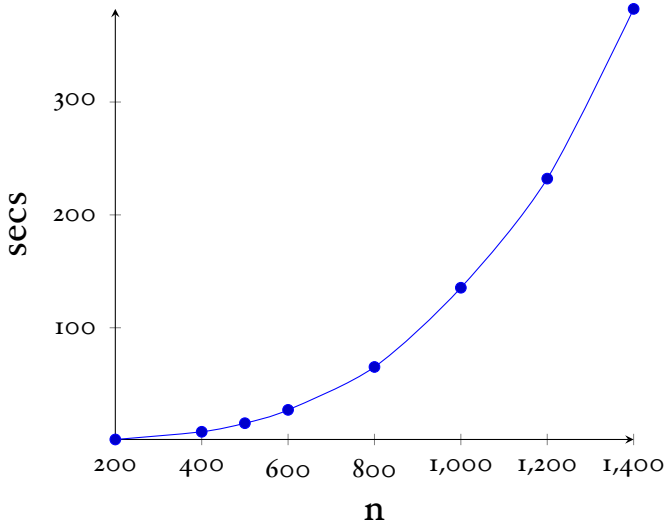
$$\begin{aligned} \text{eval}(\text{while } b \text{ do } cs, E) &\stackrel{\text{def}}{=} \\ &\text{if } \text{eval}(b, E) \\ &\text{then } \text{eval}(\text{while } b \text{ do } cs, \text{eval}(cs, E)) \\ &\text{else } E \end{aligned}$$

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

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 { z := z - 1 };
8      z := start;
9      y := y - 1
10   };
11   y := start;
12   x := x - 1
13 }
```

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)
- is garbage collected \Rightarrow no buffer overflows
- some languages compile to the JVM: Scala, Clojure...