

Compilers and Formal Languages (5)

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Survey: Thanks!

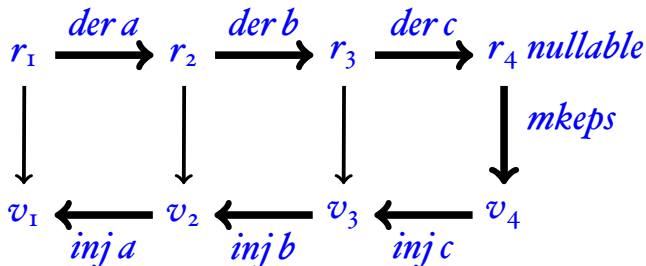
- **My Voice** “could be a bit louder”
- **Writing** “sometimes a bit difficult to read”
- **Recording** “video caps of blackboard”
- “It’s all great”

Last Week

Regexes and Values

Regular expressions and their corresponding values:

$r ::=$	0	$v ::=$	<i>Empty</i>
	1		<i>Char</i> (c)
	c		<i>Seq</i> (v_1, v_2)
	$r_1 \cdot r_2$		<i>Left</i> (v)
	$r_1 + r_2$		<i>Right</i> (v)
	r^*		$[v_1, \dots, v_n]$

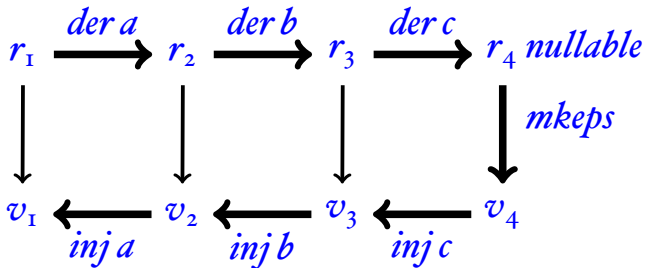
$$\begin{aligned}
 r_1: & a \cdot (b \cdot c) \\
 r_2: & \mathbf{I} \cdot (b \cdot c) \\
 r_3: & (\mathbf{O} \cdot (b \cdot c)) + (\mathbf{I} \cdot c) \\
 r_4: & (\mathbf{O} \cdot (b \cdot c)) + ((\mathbf{O} \cdot c) + \mathbf{I})
 \end{aligned}$$


$$\begin{aligned}
 v_1: & \text{Seq}(\text{Char}(a), \text{Seq}(\text{Char}(b), \text{Char}(c))) \\
 v_2: & \text{Seq}(\text{Empty}, \text{Seq}(\text{Char}(b), \text{Char}(c))) \\
 v_3: & \text{Right}(\text{Seq}(\text{Empty}, \text{Char}(c))) \\
 v_4: & \text{Right}(\text{Right}(\text{Empty}))
 \end{aligned}$$

$$\begin{aligned}
 |v_1|: & abc \\
 |v_2|: & bc \\
 |v_3|: & c \\
 |v_4|: & []
 \end{aligned}$$

Simplification

- If we simplify after the derivative, then we are building the value for the simplified regular expression, but *not* for the original regular expression.



$$(b \cdot c) + (\mathbf{0} + \mathbf{1}) \mapsto (b \cdot c) + \mathbf{1}$$

$$(b \cdot c) + (\mathbf{0} + \mathbf{I}) \mapsto (b \cdot c) + \mathbf{I}$$

$$(\underline{b \cdot c}) + (\underline{\mathbf{0} + \mathbf{I}}) \mapsto (b \cdot c) + \mathbf{I}$$

$$(\underline{b \cdot c}) + (\underline{\mathbf{0} + \mathbf{I}}) \mapsto (b \cdot c) + \mathbf{I}$$

$$f_{s1} = \lambda v.v$$

$$f_{s2} = \lambda v.Right(v)$$

$$\underline{(b \cdot c) + (\mathbf{0} + \mathbf{1})} \mapsto (b \cdot c) + \mathbf{1}$$

$$\begin{aligned} f_{s_1} &= \lambda v. v \\ f_{s_2} &= \lambda v. \mathit{Right}(v) \end{aligned}$$

$$\begin{aligned} f_{alt}(f_{s_1}, f_{s_2}) &\stackrel{\text{def}}{=} \\ &\lambda v. \text{ case } v = \mathit{Left}(v') : \text{ return } \mathit{Left}(f_{s_1}(v')) \\ &\quad \text{ case } v = \mathit{Right}(v') : \text{ return } \mathit{Right}(f_{s_2}(v')) \end{aligned}$$

$$\underline{(b \cdot c) + (\mathbf{0} + \mathbf{I})} \mapsto (b \cdot c) + \mathbf{I}$$

$$\begin{aligned} f_{s1} &= \lambda v.v \\ f_{s2} &= \lambda v.Right(v) \end{aligned}$$

$\lambda v.$ case $v = Left(v')$: return $Left(v')$
case $v = Right(v')$: return $Right(Right(v'))$

$$\underline{(b \cdot c) + (\mathbf{0} + \mathbf{I})} \mapsto (b \cdot c) + \mathbf{I}$$

$$\begin{aligned} f_{s1} &= \lambda v.v \\ f_{s2} &= \lambda v.Right(v) \end{aligned}$$

$\lambda v.$ case $v = Left(v')$: return $Left(v')$
case $v = Right(v')$: return $Right(Right(v'))$

mkeps simplified case: $Right(Empty)$
rectified case: $Right(Right(Empty))$

Records

- new regex: $(x : r)$ new value: $Rec(x, v)$
- $nullable(x : r) \stackrel{\text{def}}{=} nullable(r)$
- $der\ c(x : r) \stackrel{\text{def}}{=} (x : der\ c\ r)$
- $mkeps(x : r) \stackrel{\text{def}}{=} Rec(x, mkeps(r))$
- $inj(x : r)\ c\ v \stackrel{\text{def}}{=} Rec(x, inj\ r\ c\ v)$

for extracting subpatterns $(z : ((x : ab) + (y : ba)))$

Environments

Obtaining the “recorded” parts of a value:

$env(Empty)$	$\stackrel{\text{def}}{=}$	$[]$
$env(Char(c))$	$\stackrel{\text{def}}{=}$	$[]$
$env(Left(v))$	$\stackrel{\text{def}}{=}$	$env(v)$
$env(Right(v))$	$\stackrel{\text{def}}{=}$	$env(v)$
$env(Seq(v_1, v_2))$	$\stackrel{\text{def}}{=}$	$env(v_1) @ env(v_2)$
$env([v_1, \dots, v_n])$	$\stackrel{\text{def}}{=}$	$env(v_1) @ \dots @ env(v_n)$
$env(Rec(x : v))$	$\stackrel{\text{def}}{=}$	$(x : v) :: env(v)$

While Tokens

WHILE_REGS $\stackrel{\text{def}}{=} (($ "k" : KEYWORD) +
("i" : ID) +
("o" : OP) +
("n" : NUM) +
("s" : SEMI) +
("p" : (LPAREN + RPAREN)) +
("b" : (BEGIN + END)) +
("w" : WHITESPACE))*

”if true then then 42 else +”

KEYWORD(if),
WHITESPACE,
IDENT(true),
WHITESPACE,
KEYWORD(then),
WHITESPACE,
KEYWORD(then),
WHITESPACE,
NUM(42),
WHITESPACE,
KEYWORD(else),
WHITESPACE,
OP(+)

”if true then then 42 else +”

KEYWORD(if),
IDENT(true),
KEYWORD(then),
KEYWORD(then),
NUM(42),
KEYWORD(else),
OP(+)

Two Rules

- Longest match rule (“maximal munch rule”): The longest initial substring matched by any regular expression is taken as next token.
- Rule priority: For a particular longest initial substring, the first regular expression that can match determines the token.

Coursework

$nullable([c_1 c_2 \dots c_n]) \stackrel{\text{def}}{=} ?$

$nullable(r^+) \stackrel{\text{def}}{=} ?$

$nullable(r^?) \stackrel{\text{def}}{=} ?$

$nullable(r^{\{n,m\}}) \stackrel{\text{def}}{=} ?$

$nullable(\sim r) \stackrel{\text{def}}{=} ?$

$der\ c\ ([c_1 c_2 \dots c_n]) \stackrel{\text{def}}{=} ?$

$der\ c\ (r^+) \stackrel{\text{def}}{=} ?$

$der\ c\ (r^?) \stackrel{\text{def}}{=} ?$

$der\ c\ (r^{\{n,m\}}) \stackrel{\text{def}}{=} ?$

$der\ c\ (\sim r) \stackrel{\text{def}}{=} ?$

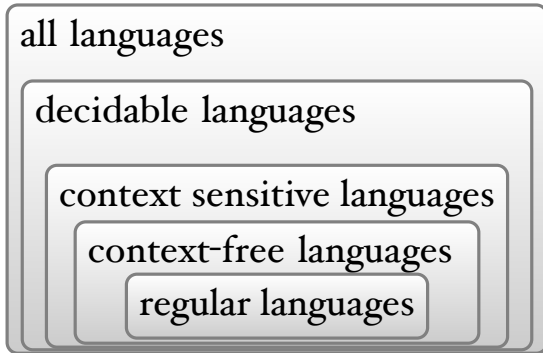
Regular Languages

While regular expressions are very useful for lexing, there is no regular expression that can recognise the language $a^n b^n$.

$((((()))))$ vs. $((((()))))$

So we cannot find out with regular expressions whether parentheses are matched or unmatched. Also regular expressions are not recursive, e.g. $(1 + 2) + 3$.

Hierarchy of Languages



CF Grammars

A **context-free grammar** G consists of

- a finite set of nonterminal symbols (\langle upper case \rangle)
- a finite terminal symbols or tokens (lower case)
- a start symbol (which must be a nonterminal)
- a set of rules

$$\langle A \rangle ::= rhs$$

where rhs are sequences involving terminals and nonterminals, including the empty sequence ϵ .

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$$\langle A \rangle ::= rhs$$

where rhs are sequences involving terminals and nonterminals, including the empty sequence ϵ .

We also allow rules

$$\langle A \rangle ::= rhs_1 | rhs_2 | \dots$$

Palindromes

A grammar for palindromes over the alphabet $\{a, b\}$:

$$\langle S \rangle ::= \epsilon$$

$$\langle S \rangle ::= a \cdot \langle S \rangle \cdot a$$

$$\langle S \rangle ::= b \cdot \langle S \rangle \cdot b$$

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or

$$\langle S \rangle ::= \epsilon \mid a \cdot \langle S \rangle \cdot a \mid b \cdot \langle S \rangle \cdot b$$

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or

$$\langle S \rangle ::= \epsilon \mid a \cdot \langle S \rangle \cdot a \mid b \cdot \langle S \rangle \cdot b$$

Can you find the grammar rules for matched parentheses?

Arithmetic Expressions

$\langle E \rangle ::= num_token$

| $\langle E \rangle \cdot + \cdot \langle E \rangle$

| $\langle E \rangle \cdot - \cdot \langle E \rangle$

| $\langle E \rangle \cdot * \cdot \langle E \rangle$

| $(\cdot \langle E \rangle \cdot)$

Arithmetic Expressions

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| $(\cdot \langle E \rangle \cdot)$

1 + 2 * 3 + 4

A CFG Derivation

- 1 Begin with a string containing only the start symbol, say $\langle S \rangle$
- 2 Replace any nonterminal $\langle X \rangle$ in the string by the right-hand side of some production $\langle X \rangle ::= rhs$
- 3 Repeat 2 until there are no nonterminals

$\langle S \rangle \rightarrow \dots \rightarrow \dots \rightarrow \dots \rightarrow \dots$

Example Derivation

$$\langle S \rangle ::= \epsilon \mid a \cdot \langle S \rangle \cdot a \mid b \cdot \langle S \rangle \cdot b$$

$$\begin{aligned} \langle S \rangle &\rightarrow a \langle S \rangle a \\ &\rightarrow ab \langle S \rangle ba \\ &\rightarrow aba \langle S \rangle aba \\ &\rightarrow abaaba \end{aligned}$$

Example Derivation

$\langle E \rangle ::= num_token$

| $\langle E \rangle \cdot + \cdot \langle E \rangle$

| $\langle E \rangle \cdot - \cdot \langle E \rangle$

| $\langle E \rangle \cdot * \cdot \langle E \rangle$

| $(\cdot \langle E \rangle \cdot)$

$\langle E \rangle \rightarrow \langle E \rangle * \langle E \rangle$
 $\rightarrow \langle E \rangle + \langle E \rangle * \langle E \rangle$
 $\rightarrow \langle E \rangle + \langle E \rangle * \langle E \rangle + \langle E \rangle$
 $\rightarrow^+ 1 + 2 * 3 + 4$

Example Derivation

$$\langle E \rangle ::= \textit{num_token}$$
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$$| \langle E \rangle \cdot - \cdot \langle E \rangle$$
$$| \langle E \rangle \cdot * \cdot \langle E \rangle$$
$$| (\cdot \langle E \rangle \cdot)$$
$$\begin{aligned} \langle E \rangle &\rightarrow \langle E \rangle * \langle E \rangle \\ &\rightarrow \langle E \rangle + \langle E \rangle * \langle E \rangle \\ &\rightarrow \langle E \rangle + \langle E \rangle * \langle E \rangle + \langle E \rangle \\ &\rightarrow^+ 1 + 2 * 3 + 4 \end{aligned}$$
$$\begin{aligned} \langle E \rangle &\rightarrow \langle E \rangle + \langle E \rangle \\ &\rightarrow \langle E \rangle + \langle E \rangle + \langle E \rangle \\ &\rightarrow \langle E \rangle + \langle E \rangle * \langle E \rangle + \langle E \rangle \\ &\rightarrow^+ 1 + 2 * 3 + 4 \end{aligned}$$

Context Sensitive Grammars

It is much harder to find out whether a string is parsed by a context sensitive grammar:

$$\langle S \rangle ::= b \langle S \rangle \langle A \rangle \langle A \rangle \mid \epsilon$$

$$\langle A \rangle ::= a$$

$$b \langle A \rangle ::= \langle A \rangle b$$

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$$\langle S \rangle \rightarrow \dots \rightarrow? ababaa$$

Language of a CFG

Let G be a context-free grammar with start symbol $\langle S \rangle$. Then the language $L(G)$ is:

$$\{c_1 \dots c_n \mid \forall i. c_i \in T \wedge \langle S \rangle \rightarrow^* c_1 \dots c_n\}$$

Language of a CFG

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- Terminals, because there are no rules for replacing them.
- Once generated, terminals are “permanent”.
- Terminals ought to be tokens of the language (but can also be strings).

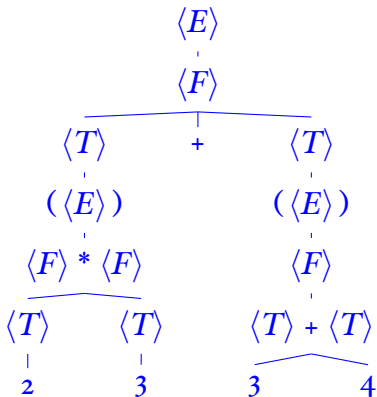
Parse Trees

$\langle E \rangle ::= \langle F \rangle \mid \langle F \rangle \cdot * \cdot \langle F \rangle$

$\langle F \rangle ::= \langle T \rangle \mid \langle T \rangle \cdot + \cdot \langle T \rangle \mid \langle T \rangle \cdot - \cdot \langle T \rangle$

$\langle T \rangle ::= \textit{num_token} \mid (\cdot \langle E \rangle \cdot)$

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



Arithmetic Expressions

$\langle E \rangle ::= \textit{num_token}$

| $\langle E \rangle \cdot + \cdot \langle E \rangle$

| $\langle E \rangle \cdot - \cdot \langle E \rangle$

| $\langle E \rangle \cdot * \cdot \langle E \rangle$

| $(\cdot \langle E \rangle \cdot)$

Arithmetic Expressions

$$\begin{aligned}\langle E \rangle &::= \textit{num_token} \\ &| \langle E \rangle \cdot + \cdot \langle E \rangle \\ &| \langle E \rangle \cdot - \cdot \langle E \rangle \\ &| \langle E \rangle \cdot * \cdot \langle E \rangle \\ &| (\cdot \langle E \rangle \cdot)\end{aligned}$$

A CFG is **left-recursive** if it has a nonterminal $\langle E \rangle$ such that $\langle E \rangle \rightarrow^+ \langle E \rangle \cdot \dots$

Ambiguous Grammars

A grammar is **ambiguous** if there is a string that has at least two different parse trees.

$$\begin{aligned}\langle E \rangle &::= \textit{num_token} \\ &| \langle E \rangle \cdot + \cdot \langle E \rangle \\ &| \langle E \rangle \cdot - \cdot \langle E \rangle \\ &| \langle E \rangle \cdot * \cdot \langle E \rangle \\ &| (\cdot \langle E \rangle \cdot)\end{aligned}$$

1 + 2 * 3 + 4

Dangling Else

Another ambiguous grammar:

$$\begin{array}{l} E \rightarrow \text{if } E \text{ then } E \\ \quad | \text{if } E \text{ then } E \text{ else } E \\ \quad | \dots \end{array}$$

if a then if x then y else c

Parser Combinators

One of the simplest ways to implement a parser,
see <https://vimeo.com/142341803>

Parser combinators:

$\underbrace{\text{list of tokens}}_{\text{input}} \Rightarrow \underbrace{\text{set of (parsed input, unparsed input)}}_{\text{output}}$

- atomic parsers
- sequencing
- alternative
- semantic action

Atomic parsers, for example, number tokens

$$\text{Num}(123) :: \text{rest} \Rightarrow \{(\text{Num}(123), \text{rest})\}$$

- 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

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

Function parser (code $p \Rightarrow f$)

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

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

f is the semantic action (“what to do with the parsed input”)

Semantic Actions

Addition

$$T \sim + \sim E \Rightarrow \underbrace{f((x, y), z)}_{\text{semantic action}} \Rightarrow x + z$$

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Multiplication

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Multiplication

$$F \sim * \sim T \Rightarrow f((x, y), z) \Rightarrow x * z$$

Parenthesis

$$(\sim E \sim) \Rightarrow f((x, y), z) \Rightarrow y$$

Types of Parsers

- **Sequencing:** if p returns results of type T , and q returns results of type S , then $p \sim q$ returns results of type

$$T \times S$$

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$$T$$

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$$T \times S$$

- **Alternative:** if p returns results of type T then q **must** also have results of type T , and $p \parallel q$ returns results of type

$$T$$

- **Semantic Action:** if p returns results of type T and f is a function from T to S , then $p \Rightarrow f$ returns results of type

$$S$$

Input Types of Parsers

- input: **token list**
- output: set of (output_type, **token list**)

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- input: **token list**
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actually it can be any input type as long as it is a kind of sequence (for example a string)

Scannerless Parsers

- input: **string**
- output: set of (output_type, **string**)

but lexers are better when whitespaces or comments need to be filtered out; then input is a sequence of tokens

Successful Parses

- input: string
- output: **set of** (output_type, string)

a parse is successful whenever the input has been fully “consumed” (that is the second component is empty)

Abstract Parser Class

```
abstract class Parser[I, T] {  
  def parse(ts: I): Set[(T, I)]  
  
  def parse_all(ts: I) : Set[T] =  
    for ((head, tail) <- parse(ts);  
         if (tail.isEmpty)) yield head  
}
```

```

class AltParser[I, T](p: => Parser[I, T],
                    q: => Parser[I, T])
    extends Parser[I, T] {
  def parse(sb: I) = p.parse(sb) ++ q.parse(sb)
}

class SeqParser[I, T, S](p: => Parser[I, T],
                       q: => Parser[I, S])
    extends Parser[I, (T, S)] {
  def parse(sb: I) =
    for ((head1, tail1) <- p.parse(sb);
         (head2, tail2) <- q.parse(tail1))
      yield ((head1, head2), tail2)
}

class FunParser[I, T, S](p: => Parser[I, T], f: T => S)
    extends Parser[I, S] {
  def parse(sb: I) =
    for ((head, tail) <- p.parse(sb))
      yield (f(head), tail)
}

```

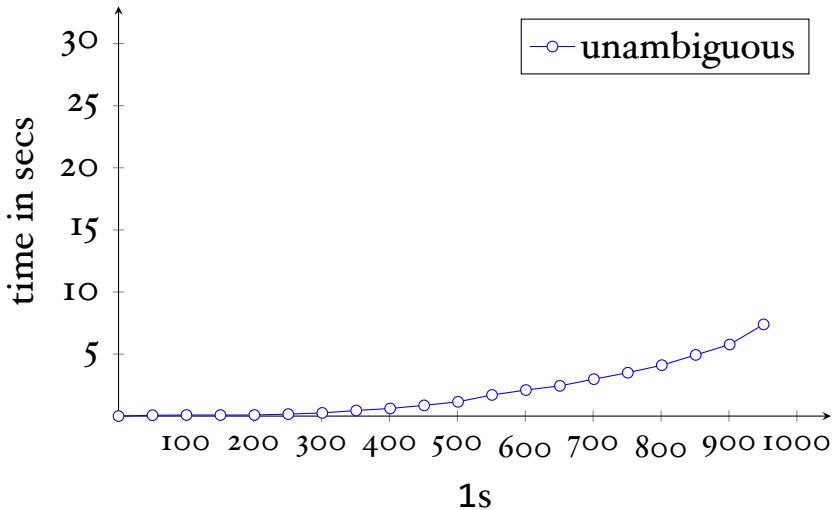
Two Grammars

Which languages are recognised by the following two grammars?

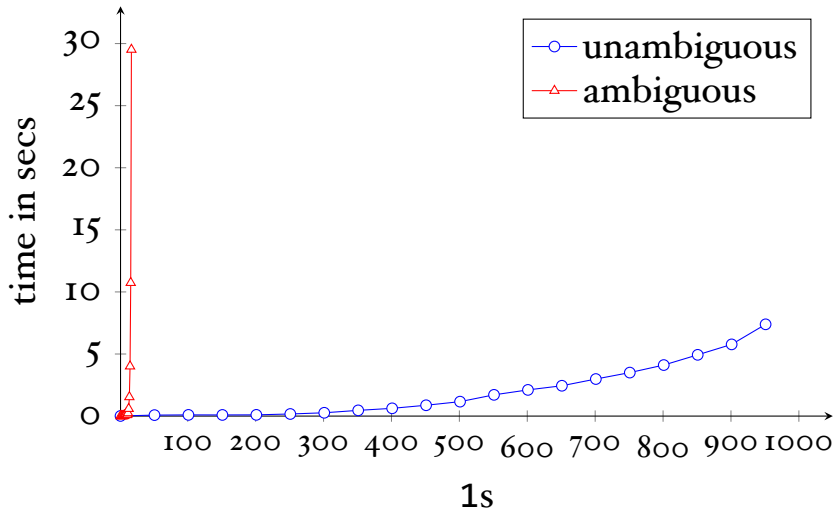
$$S \rightarrow \begin{array}{l} I \cdot S \cdot S \\ | \\ \epsilon \end{array}$$

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

Ambiguous Grammars



Ambiguous Grammars



While-Language

$\langle Stmt \rangle ::= \text{skip}$
| $\langle Id \rangle := \langle AExp \rangle$
| if $\langle BExp \rangle$ then $\langle Block \rangle$ else $\langle Block \rangle$
| while $\langle BExp \rangle$ do $\langle Block \rangle$

$\langle Stmts \rangle ::= \langle Stmt \rangle ; \langle Stmts \rangle$
| $\langle Stmt \rangle$

$\langle Block \rangle ::= \{ \langle Stmts \rangle \}$
| $\langle Stmt \rangle$

$\langle AExp \rangle ::= \dots$

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

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

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

- the interpreter has to record the value of x before assigning a value to y
- `eval(stmt, 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)

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

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

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

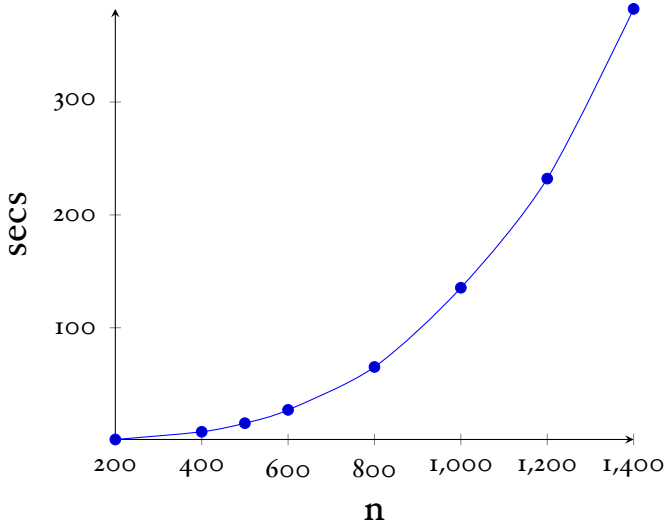
$$\begin{aligned} \text{eval}(\text{while } b \text{ do } cs, E) &\stackrel{\text{def}}{=} \\ &\text{if } \text{eval}(b, E) \\ &\text{then } \text{eval}(\text{while } b \text{ do } cs, \text{eval}(cs, E)) \\ &\text{else } E \end{aligned}$$

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

Test Program

```
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
}
```

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...