Parsing

Part I

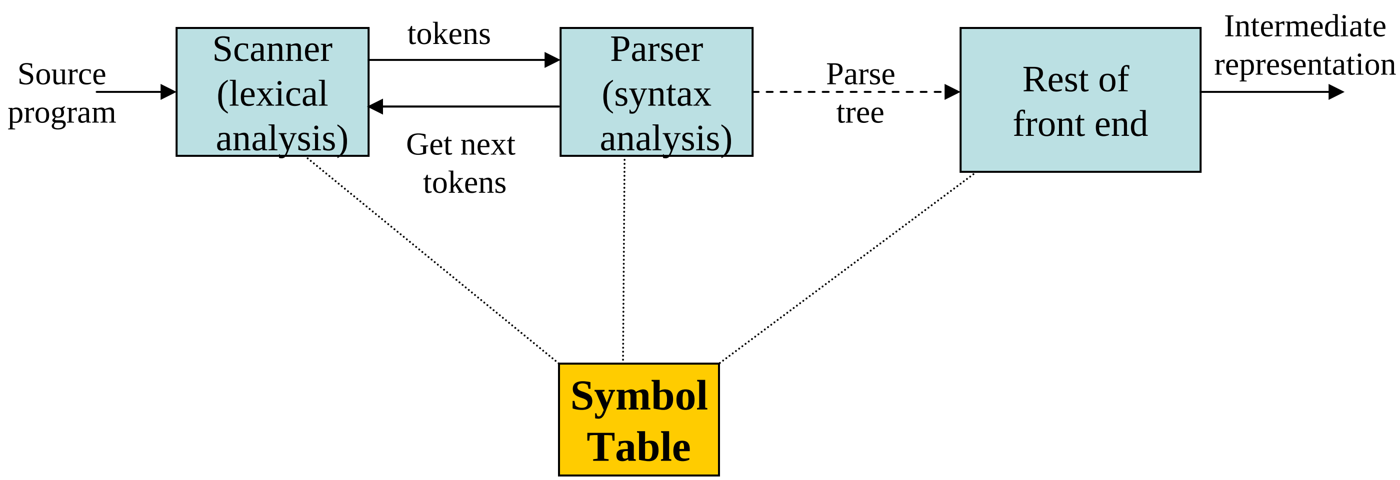
Language and Grammars

- Every (programming) language has precise rules
  - In English:
    - Subject Verb Object
  - In C
    - programs are made of functions
      - » Functions are made of statements etc.

Parsing

- A.K.A. Syntax Analysis
  - Recognize sentences in a language.
  - Discover the structure of a document/program.
  - Construct (implicitly or explicitly) a tree (called as a parse tree) to represent the structure.
  - The above tree is used later to guide translation.

Role of the parser



- Verifies if the string of token can be generated from the grammar
- Error?
    - Report with a good descriptive, helpful message
    - Recover and continue parsing!
- Build a parse tree !!

Rest of Front End

- Collecting token information
- Type checking
- Intermediate code generation

Errors in Programs

- **Lexical**

  if x<1 thenn y = 5:

  “Typos”

- **Syntactic**

  if ((x<1) & (y>5))) ...

  { ... { ... _ ... }

- **Semantic**

  if (x+5) then ...

  Type Errors

  Undefined IDs, etc.

- **Logical Errors**

  if (i<9) then ...

  Should be <= not <

  Bugs

  Compiler cannot detect Logical Errors

Error Detection

- Much responsibility on Parser
  - Many errors are syntactic in nature
  - Precision/ efficiency of modern parsing method
  - Detect the error as soon as possible

- Challenges for error handler in Parser
  - Report error clearly and accurately
  - Recover from error and continue..
  - Should be efficient in processing

- Good news is
  - Simple mechanism can catch most common errors

- Errors don’t occur that frequently!!
    - 60% programs are syntactically and semantically correct
    - 80% erroneous statements have only 1 error, 13% have 2
    - Most error are trivial : 90% single token error
    - 60% punctuation, 20% operator, 15% keyword, 5% other error

Adequate Error Reporting is Not a Trivial Task

- Difficult to generate clear and accurate error messages.

Example

```
function foo () {
...
if (...) {
...
} else {
   ...
                      Missing } here

...
}
<eof>                 Not detected until here
```

Example

```
int myVarr;
...                   Misspelled ID here
x = myVar;
...                   Not detected until here
```

Error Recovery

- After first error recovered
  - Compiler must go on!
    - Restore to some state and process the rest of the input

- **Error-Correcting Compilers**
  - Issue an error message
  - Fix the problem
  - Produce an executable

Example

```
Error on line 23: “myVarr” undefined.
“myVar” was used.
```

May not be a good Idea!!

- Guessing the programmers intention is not easy!

Error Recovery May Trigger More Errors!

- Inadequate recovery may introduce more errors
  - Those were not programmers errors

- Example:

```
int myVar flag ;
...
x := flag;
...
...
while (flag==0)
...
```

Declaration of flag is discarded

Variable flag is undefined

Variable falg is undefined

Too many Error message may be obscuring

- May bury the real message
- Remedy:
  - allow 1 message per token or per statement
  - Quit after a maximum (e.g. 100) number of errors

Error Recovery Approaches: Panic Mode

- Discard tokens until we see a “synchronizing” token.

> **Example**
>
> Skip to next occurrence of
> **`} end ;`**
> Resume by parsing the next statement

- The key...
  - Good set of synchronizing tokens
  - Knowing what to do then
- Advantage
  - Simple to implement
  - Does not go into infinite loop
  - Commonly used
- Disadvantage
  - May skip over large sections of source with some errors

Error Recovery Approaches: Phrase-Level Recovery

- Compiler corrects the program

  by deleting or inserting tokens

  ...so it can proceed to parse from where it was.

Example

while (x==4) y:= a + b

Insert do to fix the statement

- The key...

  Don't get into an infinite loop

  ...constantly inserting tokens and never scanning the actual source

- Generally used for error-repairing compilers
  - Difficulty: Point of error detection might be much later the point of error occurrence

Error Recovery Approaches: Error Productions

- Augment the CFG with “Error Productions”
- Now the CFG accepts anything!
- If “error productions” are used...

  Their actions:

  { print (“Error...”) }

- Used with...
  - LR (Bottom-up) parsing
  - Parser Generators

Error Recovery Approaches: Global Correction

- Theoretical Approach
- Find the minimum change to the source to yield a valid program
  - Insert tokens, delete tokens, swap adjacent tokens
- Global Correction Algorithm

  Input: grammatically incorrect input string x; grammar G

  Output: grammatically correct string y

  Algorithm: converts x → y using minimum number changes (insertion, deletion etc.)
- Impractical algorithms - too time consuming

Context Free Grammars (CFG)

- A **context free grammar** is a formal model that consists of:
- **Terminals**

  Keywords

  Token Classes

  Punctuation
- **Non-terminals**

  Any symbol appearing on the lefthand side of any rule
- **Start Symbol**

  Usually the non-terminal on the lefthand side of the first rule
- **Rules (or "Productions")**

  BNF: Backus-Naur Form / Backus-Normal Form

  Stmt **::= if** Expr **then** Stmt **else** Stmt

Rule Alternative Notations

$$
\begin{aligned}
E &\rightarrow E + E \\
E &\rightarrow (E) \\
E &\rightarrow - E \\
E &\rightarrow ID
\end{aligned}
$$

$$
\begin{aligned}
E &\rightarrow E + E \\
&\rightarrow (E) \\
&\rightarrow - E \\
&\rightarrow ID
\end{aligned}
$$

$$
\begin{aligned}
E &\rightarrow E + E \\
&\quad \mid (E) \\
&\quad \mid - E \\
&\quad \mid ID
\end{aligned}
$$

$$E \rightarrow E + E \mid (E) \mid - E \mid ID$$

All Notations are Equivalent

Notational Conventions

Terminals

a b c ...

Nonterminals

A B C ...
S
Expr

Grammar Symbols (Terminals or Nonterminals)

X Y Z U V W ...

Strings of Symbols

α β γ ...

A sequence of zero Or more terminals And nonterminals

Strings of Terminals

x y z u v w ...

Including ε

Examples

$A \rightarrow \alpha B$

A rule whose righthand side ends with a nonterminal

$A \rightarrow x\ \alpha$

A rule whose righthand side begins with a string of terminals (call it "x")

Derivations

1.	E	$\rightarrow$ E + E
2.		$\rightarrow$ E * E
3.		$\rightarrow$ (E)
4.		$\rightarrow$ - E
5.		$\rightarrow$ ID

A "Derivation" of "`(id*id)`"

$$E \Rightarrow (E) \Rightarrow (E*E) \Rightarrow \underbrace{(id*E)} \Rightarrow (id*id)$$

"Sentential Forms"

A sequence of terminals and nonterminals in a derivation

`(id*E)`

Derivation

If $A \rightarrow \beta$ is a rule, then we can write

$$\alpha A \gamma \Rightarrow \alpha \beta \gamma$$

Any sentential form containing a nonterminal (call it A)

... such that A matches the nonterminal in some rule.

Derives in zero-or-more steps $\Rightarrow^*$

$$E \Rightarrow^* \texttt{(id*id)}$$

If $\alpha \Rightarrow^* \beta$ and $\beta \Rightarrow \gamma$, then $\alpha \Rightarrow^* \gamma$

Derives in one-or-more steps $\Rightarrow^+$

Given

G A grammar

S The Start Symbol

Define

L(G) The language generated

$L(G) = \{ w \mid S \Rightarrow^+ w \}$

"Equivalence" of CFG's

If two CFG's generate the same language, we say they are "equivalent."

$$G_1 \approx G_2 \text{ whenever } L(G_1) = L(G_2)$$

In making a derivation...

Choose which nonterminal to expand

Choose which rule to apply

Leftmost Derivation

In a derivation... always expand the *leftmost* nonterminal.

$$\begin{aligned} & E \\ \Rightarrow\ & E+E \\ \Rightarrow\ & (E)+E \\ \Rightarrow\ & (E*E)+E \\ \Rightarrow\ & (\underline{id}*E)+E \\ \Rightarrow\ & (\underline{id}*\underline{id})+E \\ \Rightarrow\ & (\underline{id}*\underline{id})+\underline{id} \end{aligned}$$

1.	E	$\rightarrow$	E + E
2.		$\rightarrow$	E * E
3.		$\rightarrow$	(E)
4.		$\rightarrow$	- E
5.		$\rightarrow$	ID

Let $\Rightarrow_{LM}$ denote a step in a leftmost derivation ($\Rightarrow_{LM}{}^{*}$ means zero-or-more steps)

At each step in a leftmost derivation, we have

$w A \gamma \Rightarrow_{LM} w \beta \gamma$ where $A \rightarrow \beta$ is a rule

(Recall that w is a string of terminals.)

Each sentential form in a leftmost derivation is called a "left-sentential form."

If $S \Rightarrow_{LM}{}^{*} \alpha$ then we say α is a "left-sentential form."

Rightmost Derivation

In a derivation... always expand the *rightmost* nonterminal.

$$
\begin{aligned}
& E \\
\Rightarrow\ & E+E \\
\Rightarrow\ & E+\underline{\texttt{id}} \\
\Rightarrow\ & \texttt{(}E\texttt{)}+\underline{\texttt{id}} \\
\Rightarrow\ & \texttt{(}E*E\texttt{)}+\underline{\texttt{id}} \\
\Rightarrow\ & \texttt{(}E*\underline{\texttt{id}}\texttt{)}+\underline{\texttt{id}} \\
\Rightarrow\ & \texttt{(}\underline{\texttt{id}}*\underline{\texttt{id}}\texttt{)}+\underline{\texttt{id}}
\end{aligned}
$$

1.	E	$\rightarrow$ E + E
2.		$\rightarrow$ E * E
3.		$\rightarrow$ (E)
4.		$\rightarrow$ - E
5.		$\rightarrow$ ID

Let $\Rightarrow_{RM}$ denote a step in a rightmost derivation ($\Rightarrow_{RM}^{*}$ means zero-or-more steps)

At each step in a rightmost derivation, we have

$\alpha A w \Rightarrow_{RM} \alpha\beta w$ where $A \rightarrow \beta$ is a rule

(Recall that w is a string of terminals.)

Each sentential form in a rightmost derivation is called a "right-sentential form."

If $S \Rightarrow_{RM}^{*} \alpha$ then we say α is a "right-sentential form."

Parse Tree

Two choices at each step in a derivation...

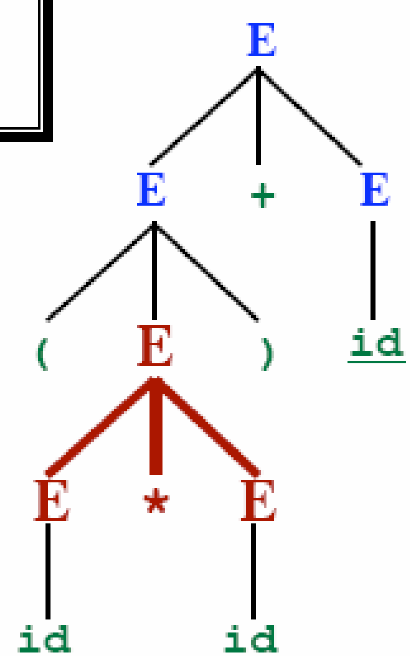
- Which non-terminal to expand
- Which rule to use in replacing it

The parse tree remembers only this

Leftmost Derivation:

E
⇒ E+E
⇒ (E)+E
⇒ (E*E)+E
⇒ (id*E)+E
⇒ (id*id)+E
⇒ (id*id)+id

1. E → E + E
2. → E * E
3. → (E)
4. → - E
5. → ID



Parse Tree

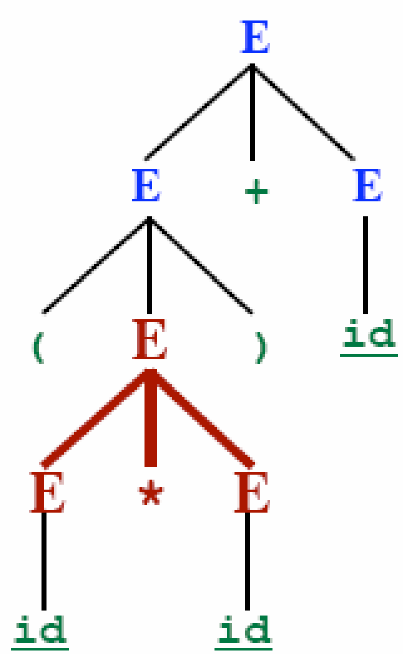
Two choices at each step in a derivation...

- Which non-terminal to expand
- Which rule to use in replacing it

The parse tree remembers only this

Rightmost Derivation:

E
$\Rightarrow E+E$
$\Rightarrow E+\underline{id}$
$\Rightarrow (E)+\underline{id}$
$\Rightarrow (E*E)+\underline{id}$
$\Rightarrow (E*\underline{id})+\underline{id}$
$\Rightarrow (\underline{id}*\underline{id})+\underline{id}$



1. $E \rightarrow E + E$
2. $\quad\rightarrow E * E$
3. $\quad\rightarrow (E)$
4. $\quad\rightarrow - E$
5. $\quad\rightarrow ID$

Parse Tree

Two choices at each step in a derivation...

- Which non-terminal to expand
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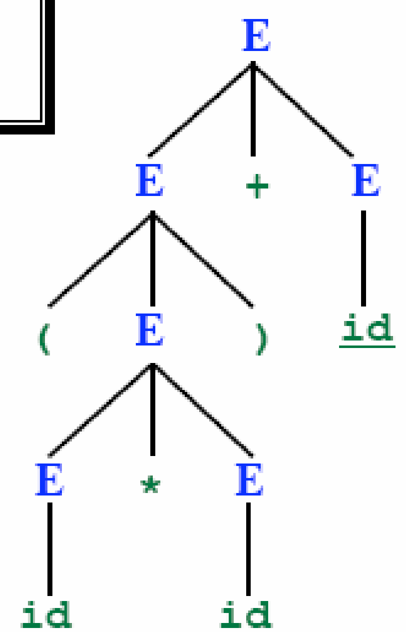
Leftmost Derivation:

E
⇒ E+E
⇒ (E)+E
⇒ (E*E)+E
⇒ (id*E)+E
⇒ (id*id)+E
⇒ (id*id)+id

Rightmost Derivation:

E
⇒ E+E
⇒ E+id
⇒ (E)+id
⇒ (E*E)+id
⇒ (E*id)+id
⇒ (id*id)+id



1. E → E + E
2. → E * E
3. → (E)
4. → - E
5. → ID

Parse Tree

Given a leftmost derivation, we can build a parse tree.
Given a rightmost derivation, we can build a parse tree.

Lefttmost Derivation of	Rightmost Derivation of
(id*id)+id	(id*id)+id

Same Parse Tree

Every parse tree corresponds to...

- A single, unique leftmost derivation
- A single, unique rightmost derivation

Ambiguity:

However, one input string may have several parse trees!!!

Therefore:

- Several leftmost derivations
- Several rightmost derivations

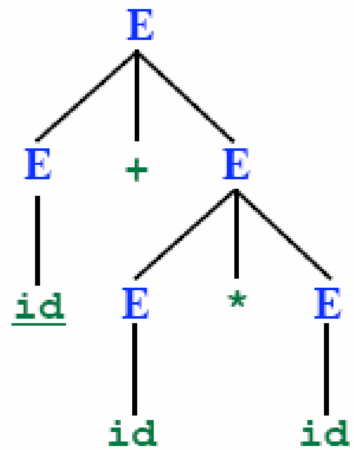
Ambiguous Grammar

1. E → E + E
2. → E * E
3. → (E)
4. → - E
5. → ID

Input: id+id*id

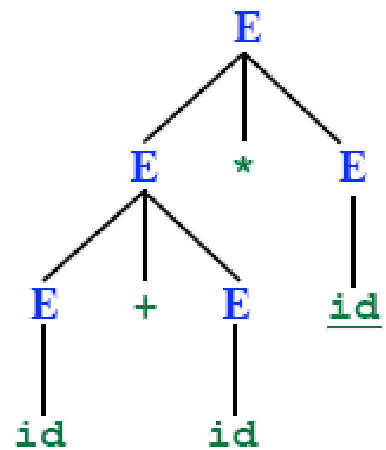
Leftmost Derivation #1

E
⇒ E+E
⇒ id+E
⇒ id+E*E
⇒ id+id*E
⇒ id+id*id



Leftmost Derivation #2

E
⇒ E*E
⇒ E+E*E
⇒ id+E*E
⇒ id+id*E
⇒ id+id*id



Ambiguous Grammar

- More than one Parse Tree for some sentence.
  - The grammar for a programming language may be ambiguous
  - Need to modify it for parsing.

- Also: Grammar may be left recursive.
- Need to modify it for parsing.