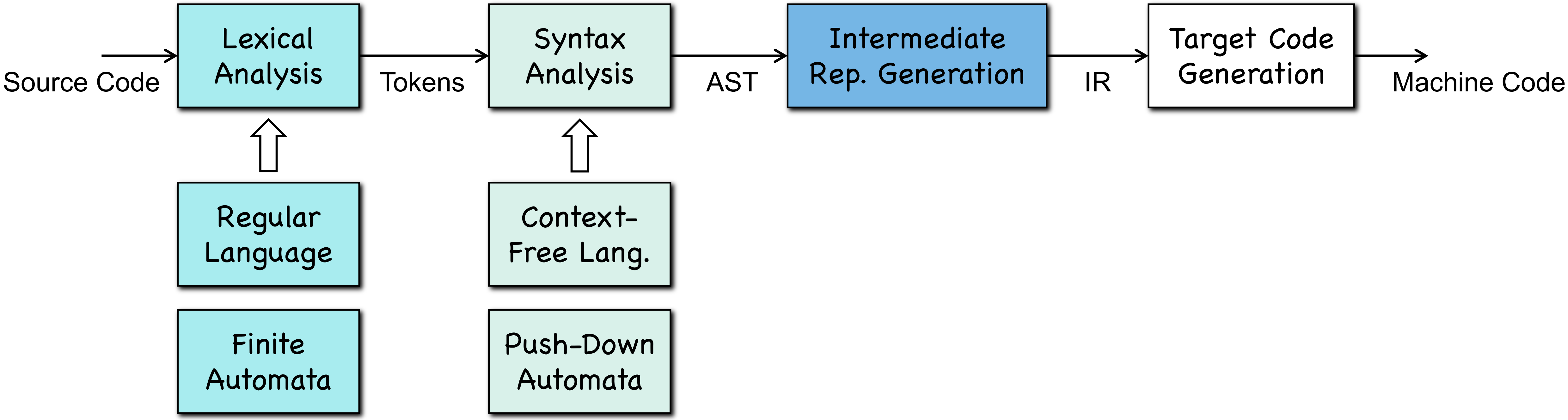
Recap-1
The Compilers’ Front End

Front End of Compilers



PART I: Regex → NFA → (Min) DFA

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- **Example:** $(a|b)^* c$

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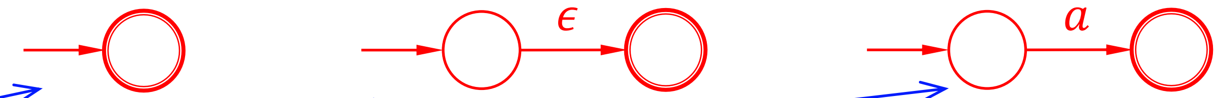

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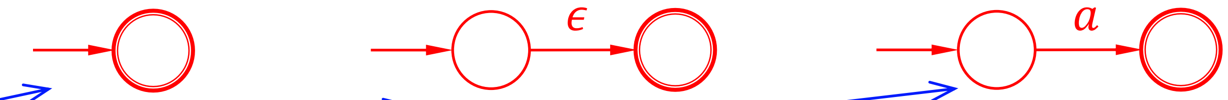

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- Build the NFA for the regex:$(a|b)^*c$
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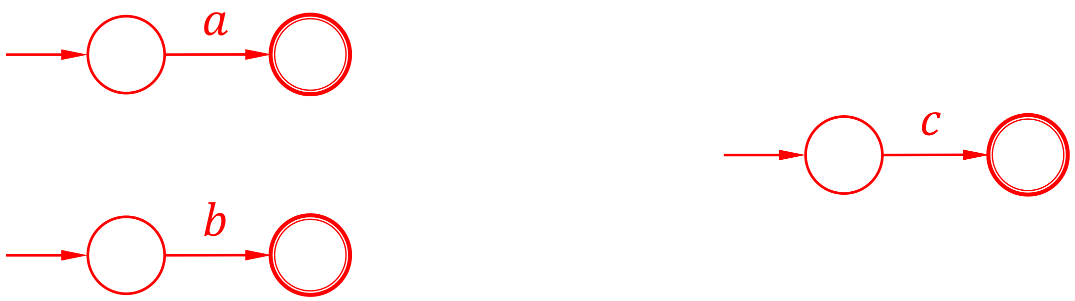

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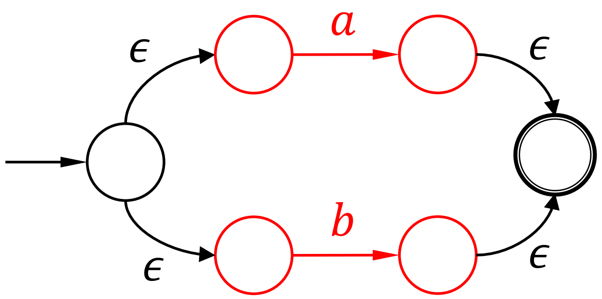

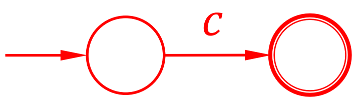

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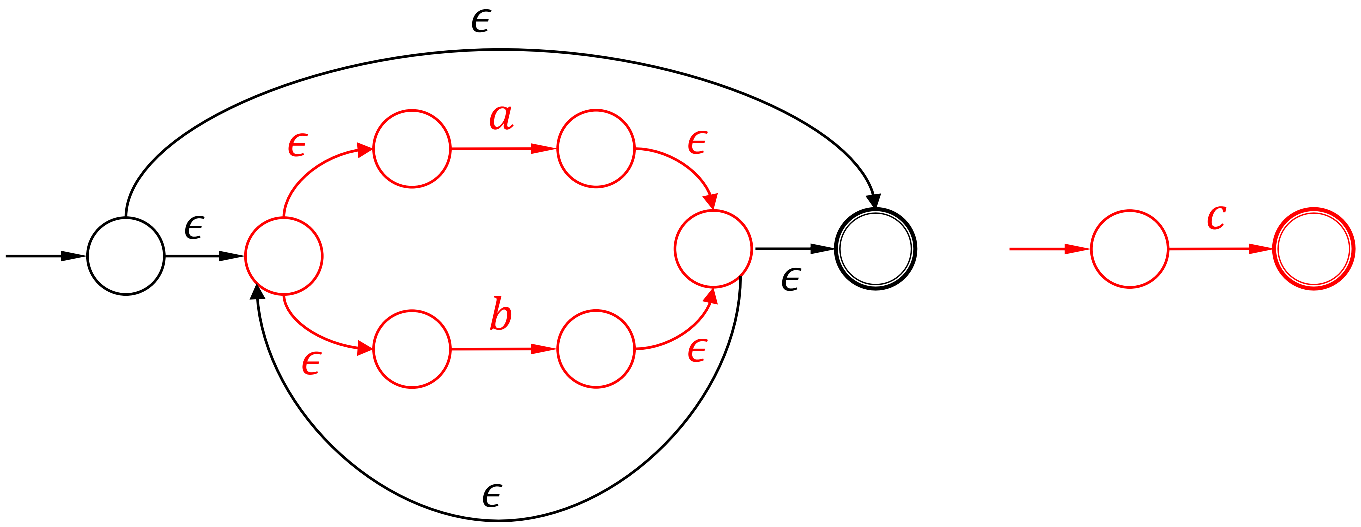

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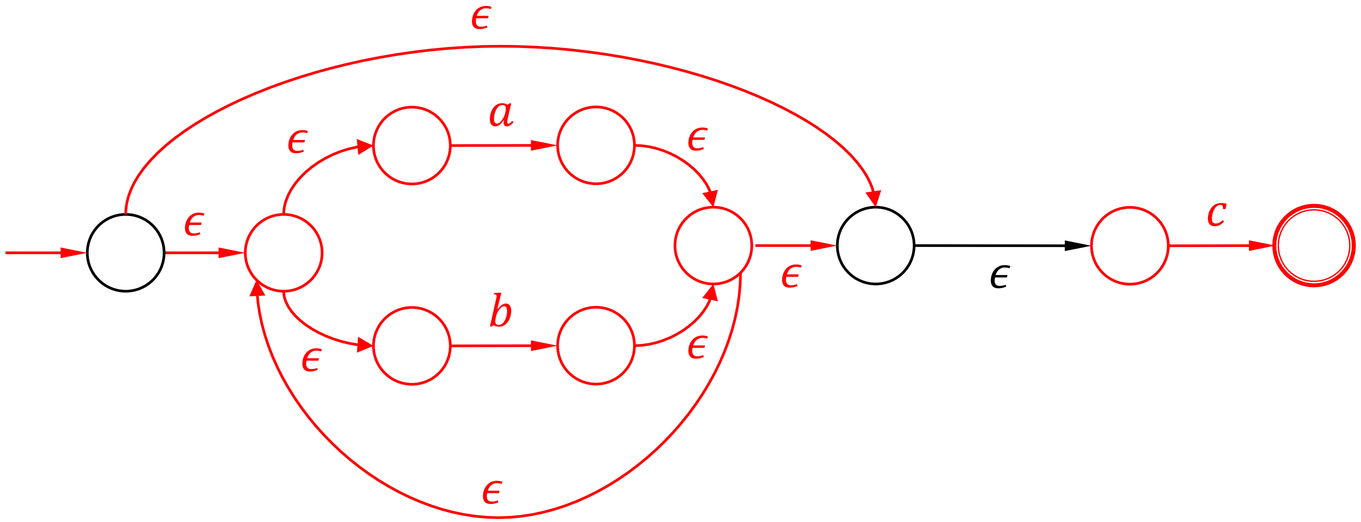
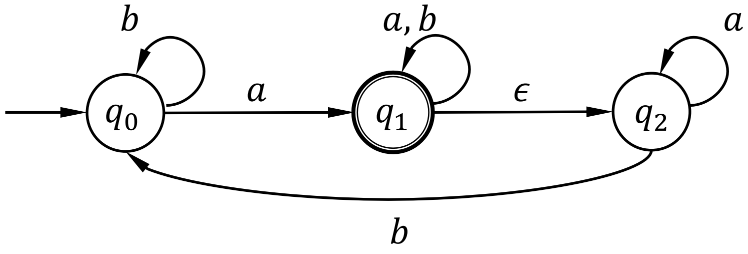
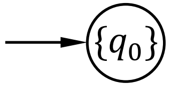


From NFA to DFA

- **Subset Construction**
- A subset of NFA states is a DFA state

From NFA to DFA





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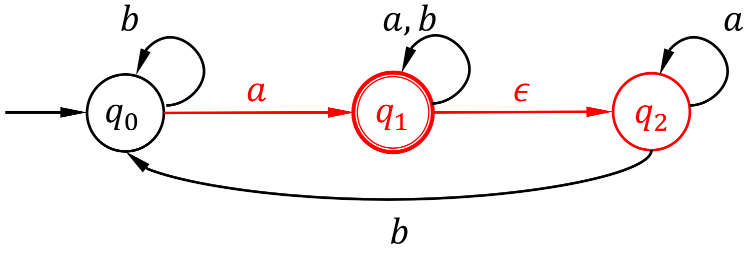

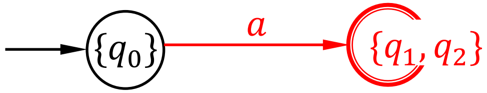

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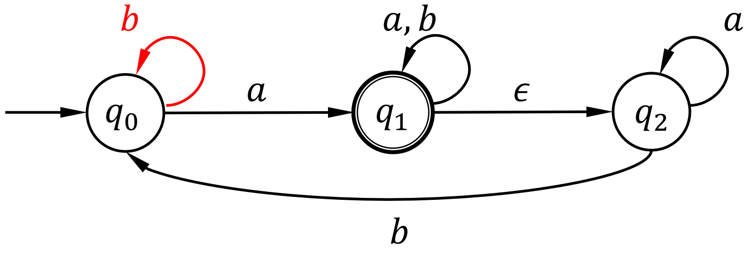

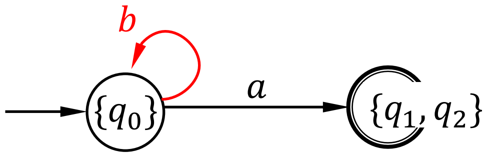

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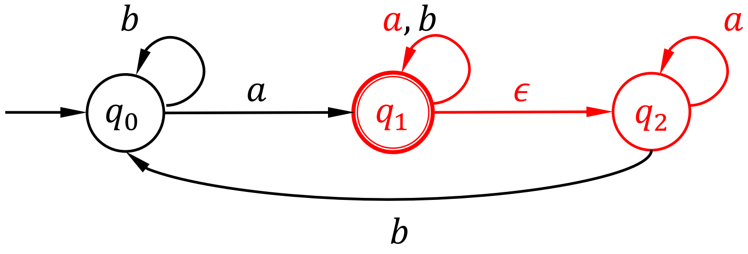

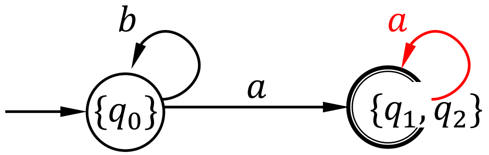

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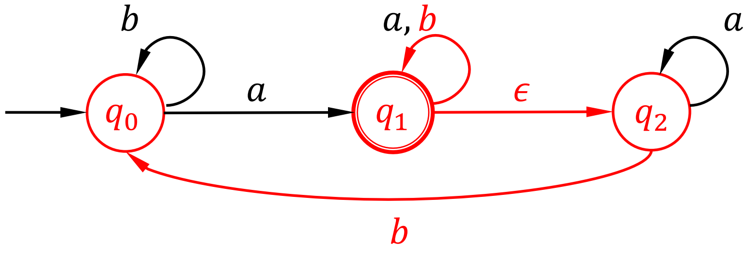

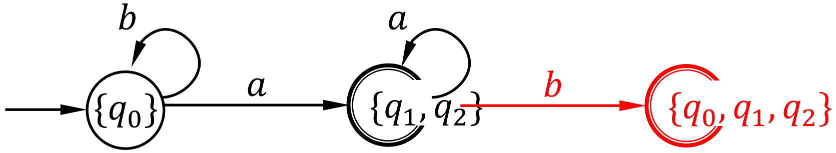

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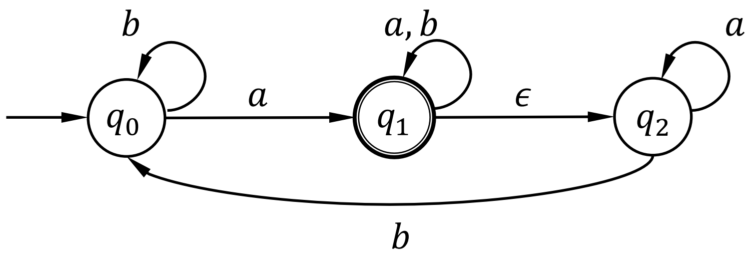

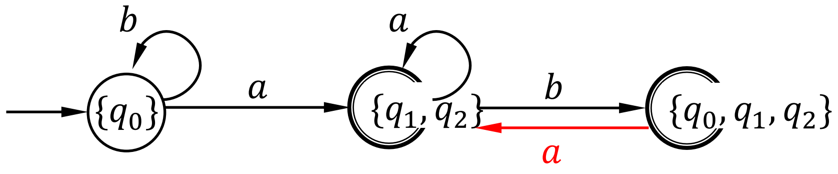

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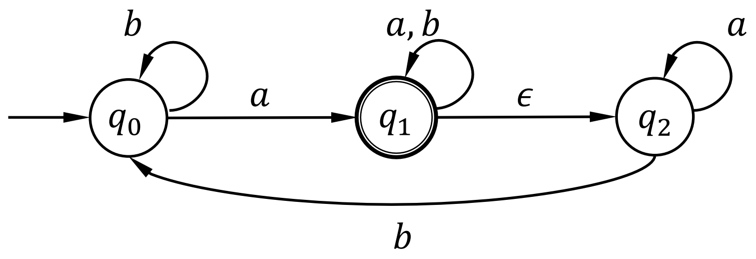

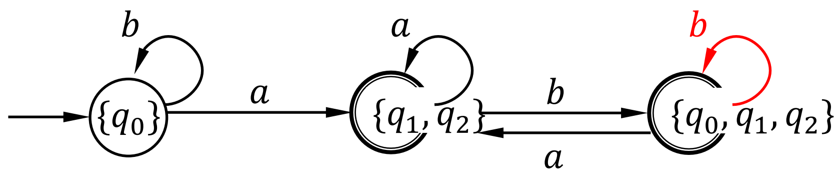

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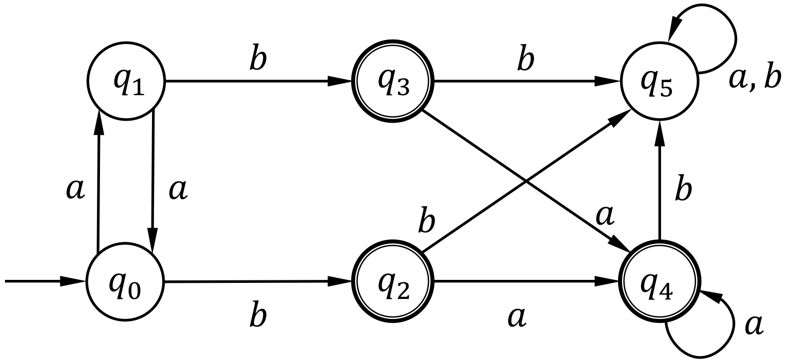

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q_0	q_1	q_2
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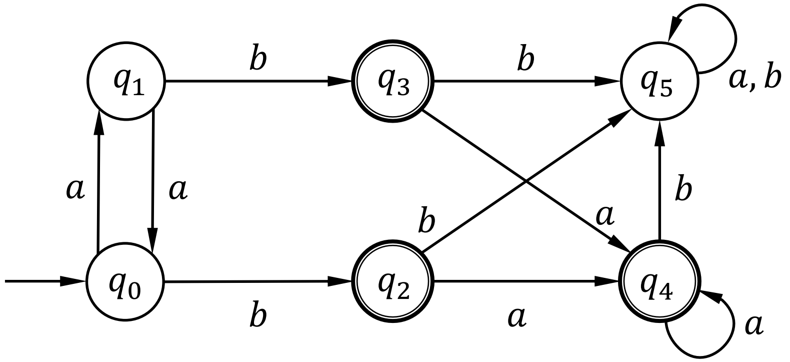

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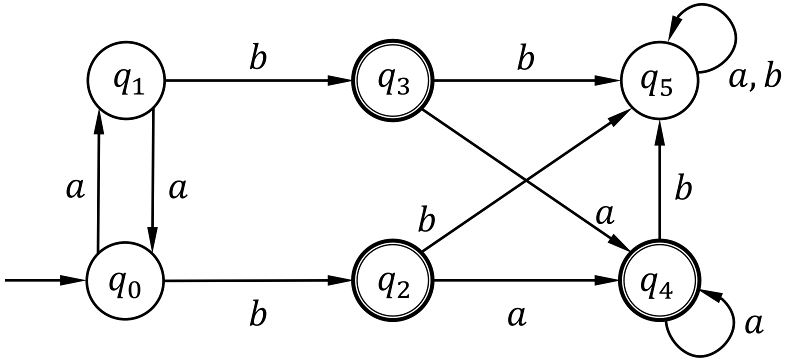

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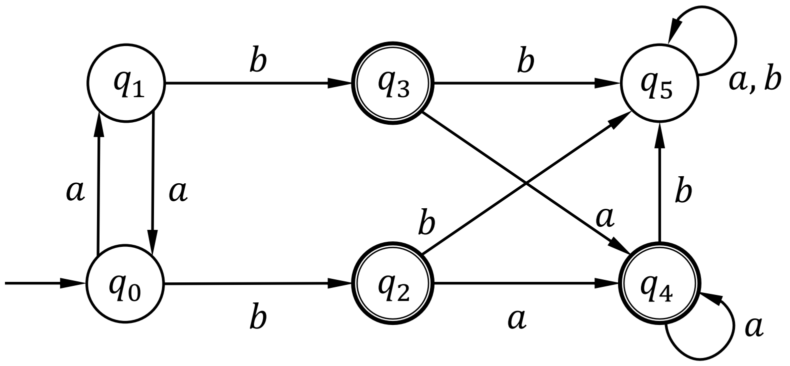

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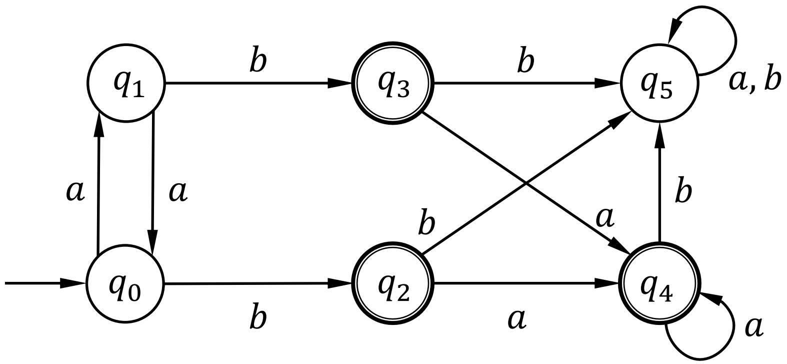

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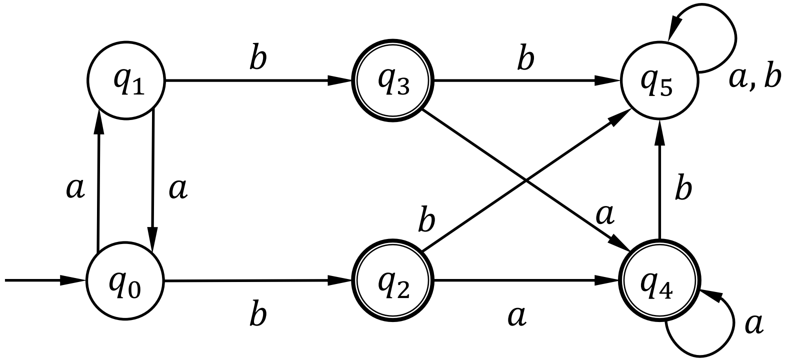

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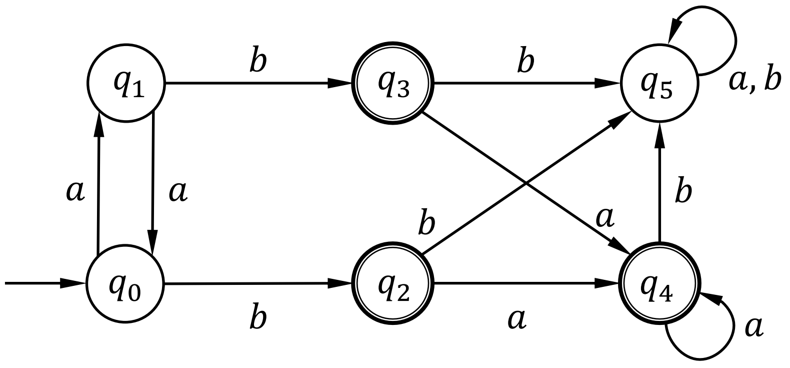

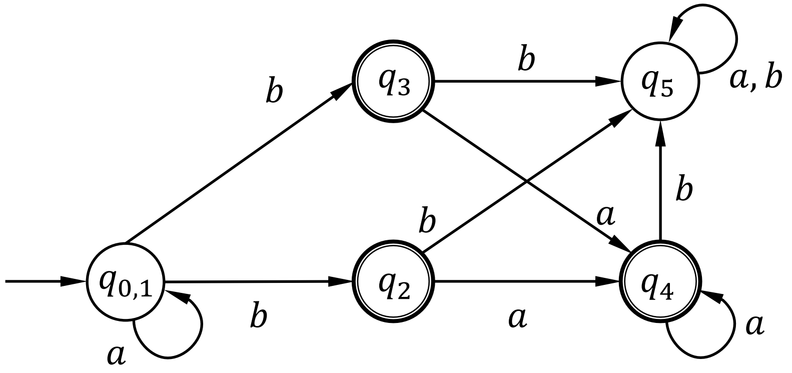

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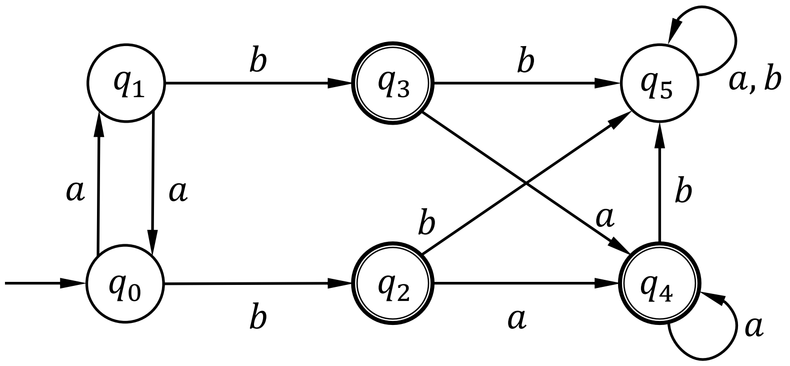

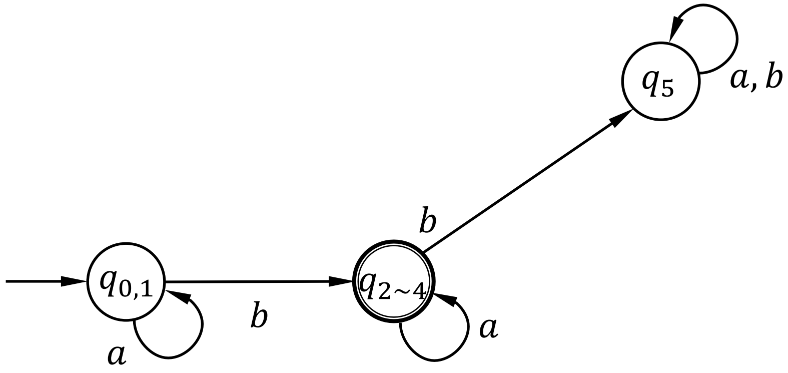

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PART II: CFG and Parsing

Context Free Grammar (CFG)

- A context-free grammar is a tuple $G = (N, T, S, P)$
  - N: a finite set of non-terminals
  - T: a finite set of terminals, such that $N \cap T = \emptyset$
  - $S \in N$: start non-terminals
  - P: production rules in the form of $A \rightarrow a$, where $A \in N$ and $a \in (N \cup T)^*$

```
assignment → identifier = expression
 expression → term + term
        term → identifier
        term → identifier * number
```

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Building a Parser in Practice

- Each non-terminal has a procedure or function for parsing
- => Recursive-Descent Parser

- **Problem 1**: A **left-recursive** grammar can cause **infinite loops**
  - when expanding a non-terminal, we may find itself and expand it again
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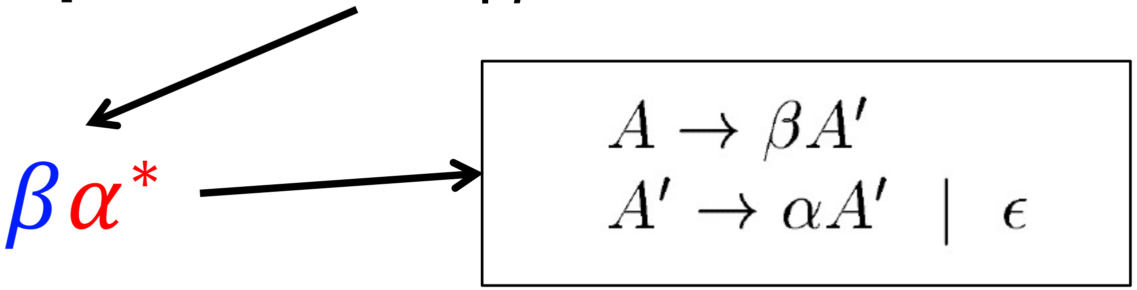

$\beta\alpha^{*}$

$$
\begin{aligned}
A &\to \beta A' \\
A' &\to \alpha A' \mid \epsilon
\end{aligned}
$$

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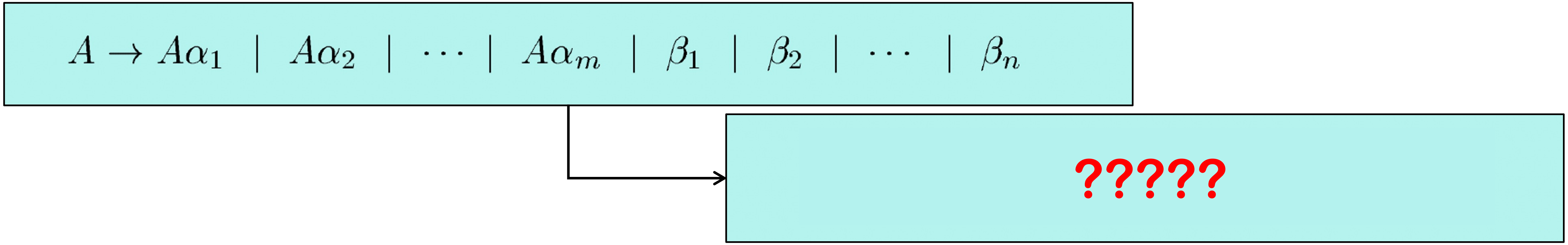

$$A \rightarrow A\alpha_1 \mid A\alpha_2 \mid \cdots \mid A\alpha_m \mid \beta_1 \mid \beta_2 \mid \cdots \mid \beta_n$$

?????

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$$\begin{aligned} A &\to \beta A' \\ A' &\to \alpha A' \mid \epsilon \end{aligned}$$

$$A \to A\alpha_1 \mid A\alpha_2 \mid \cdots \mid A\alpha_m \mid \beta_1 \mid \beta_2 \mid \cdots \mid \beta_n$$

$$\begin{aligned} A &\to \beta_1 A' \mid \beta_2 A' \mid \cdots \mid \beta_n A' \\ A' &\to \alpha_1 A' \mid \alpha_2 A' \mid \cdots \mid \alpha_m A' \mid \epsilon \end{aligned}$$

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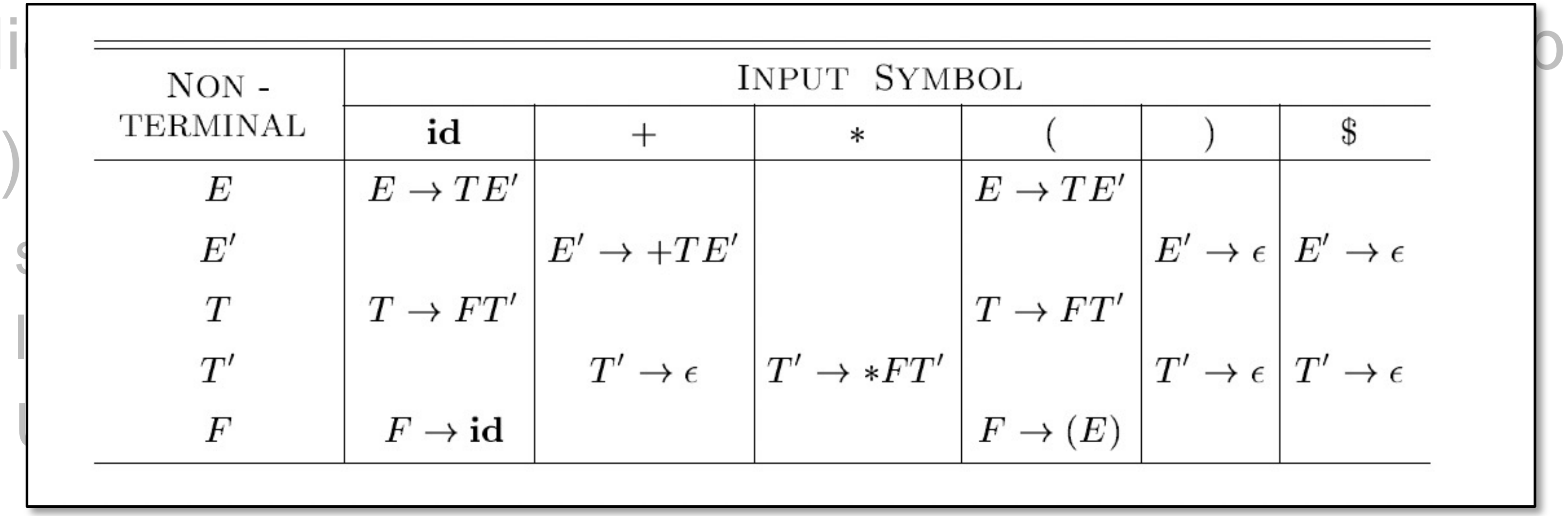
- LL(1) grammar (Not ambiguous! Not left-recursive!)
  - Rich enough to cover most programming constructs

Predictive Parsing

- Predi backtracking
- LL(1)
  - L: s
  - L: l
  - 1: U

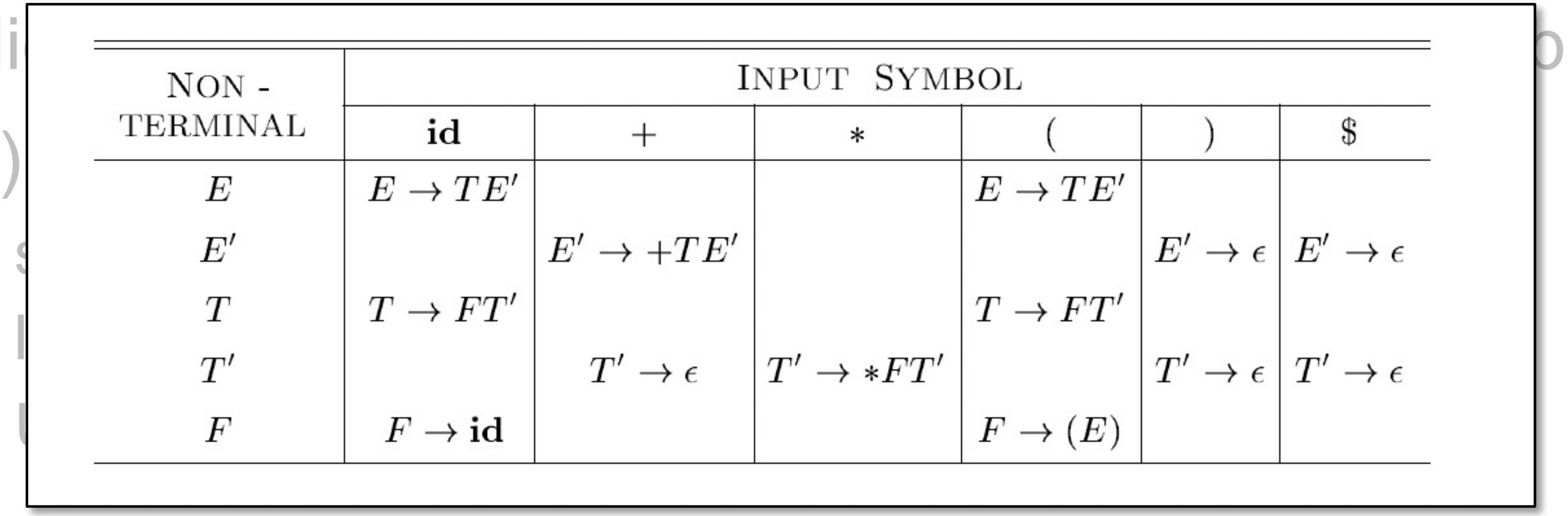


NON - TERMINAL	INPUT SYMBOL					
	id	$+$	$*$	(	)	\$
E	$E \to TE'$			$E \to TE'$		
E'		$E' \to +TE'$			$E' \to \epsilon$	$E' \to \epsilon$
T	$T \to FT'$			$T \to FT'$		
T'		$T' \to \epsilon$	$T' \to *FT'$		$T' \to \epsilon$	$T' \to \epsilon$
F	$F \to \textbf{id}$			$F \to (E)$		

- LL(1) grammar (Not ambiguous! Not left-recursive!)
  - Rich enough to cover most programming constructs

Predictive Parsing

- Predi backtracking
- LL(1)
  - L: s
  - L: l
  - 1: U



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- LL(1) grammar (Not ambiguous! Not left-recursive!)
  - Rich enough to cover most programming constructs
  - To build the predictive table, let's define $\mathrm{FIRST}(\alpha);\ \mathrm{FOLLOW}(\alpha)$

First() and Follow()

- $\mathrm{FIRST}(\alpha)$:
  - A set of terminals that α may start with

First() and Follow()

- $\mathrm{FIRST}(\alpha)$:
  - A set of terminals that α may start with
- $\mathrm{FOLLOW}(\alpha)$:
  - A set of terminals that can appear immediately to the right of α

First()

- **Example**: $S \to c\ A\ b;\ \ A \to a\ b \mid a$
- $\mathrm{FIRST}(a) = \{a\}$
- $\mathrm{FIRST}(b) = \{b\}$
- $\mathrm{FIRST}(c) = \{c\}$

First()

- **Example**: $S \to c\ A\ b;\ \ A \to a\ b \mid a$
- $\mathrm{FIRST}(a) = \{a\}$
- $\mathrm{FIRST}(b) = \{b\}$
- $\mathrm{FIRST}(c) = \{c\}$
- $\mathrm{FIRST}(S) = \{c\}$
- $\mathrm{FIRST}(A) = \{a\}$

Follow()

- $\mathrm{FOLLOW}(\alpha)$:
  - A set of terminals that can appear immediately to the right of α
  - $\$ \in \mathrm{FOLLOW}(S)$, where $\$$ is string's end marker, S the start non-terminal

Follow()

- **Example**: $S \to c\ A\ b;\ \ A \to a\ b\ |\ a$
- $\mathrm{FOLLOW}(S) = \{\$\}$
- $\mathrm{FOLLOW}(A) = \{b\}$

Follow()

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- **Example**: $S \to c\ A\ A;\ \ A \to a\ b \mid a$
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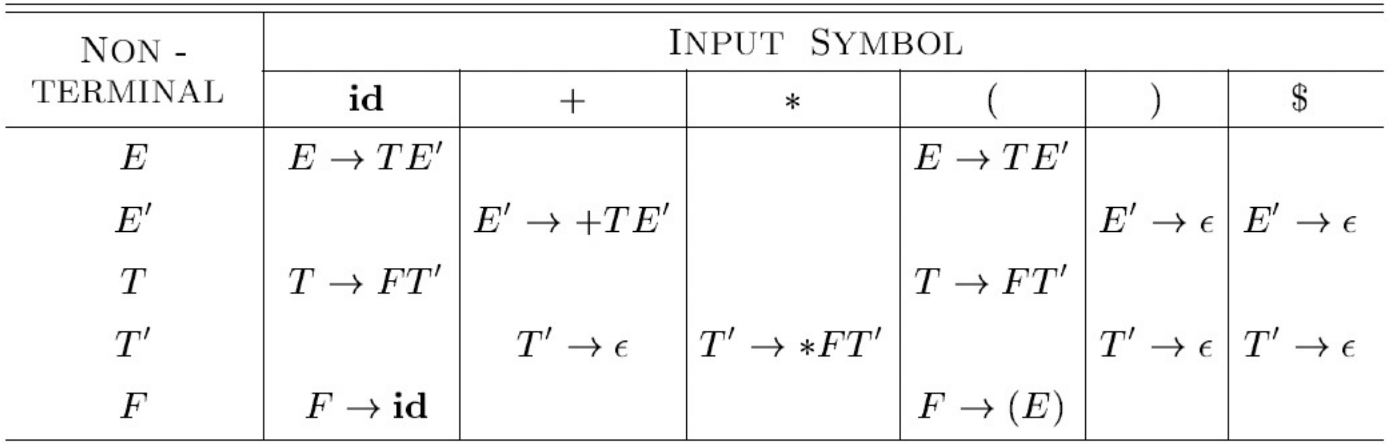
- $\text{FOLLOW}(A) \supseteq \text{FOLLOW}(S) = \{\$\}$

Predictive Parsing Table

- To build a parsing table $M[A, a]$, for each $A \rightarrow \alpha$
  - $\forall a \in \mathrm{FIRST}(\alpha){:}\ M[A, a] = A \rightarrow \alpha$
  - $\epsilon \in \mathrm{FIRST}(\alpha) \Rightarrow \ \forall b \in \mathrm{FOLLOW}(A){:}\ M[A, b] = A \rightarrow \alpha$

$$\begin{array}{lcl} E & \rightarrow & T\ E' \\ E' & \rightarrow & +\ T\ E' \mid \epsilon \\ T & \rightarrow & F\ T' \\ T' & \rightarrow & *\ F\ T' \mid \epsilon \\ F & \rightarrow & (\ E\ ) \mid \mathbf{id} \end{array}$$



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Predictive Parsing Table

- To build a parsing table $M[A, a]$, for each $A \rightarrow \alpha$
  - **$\forall a \in \mathbf{FIRST}(\alpha): M[A, a] = A \rightarrow \alpha$**
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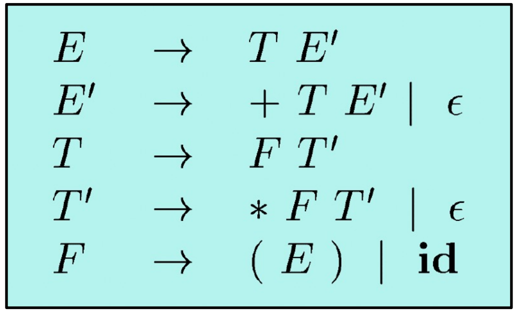

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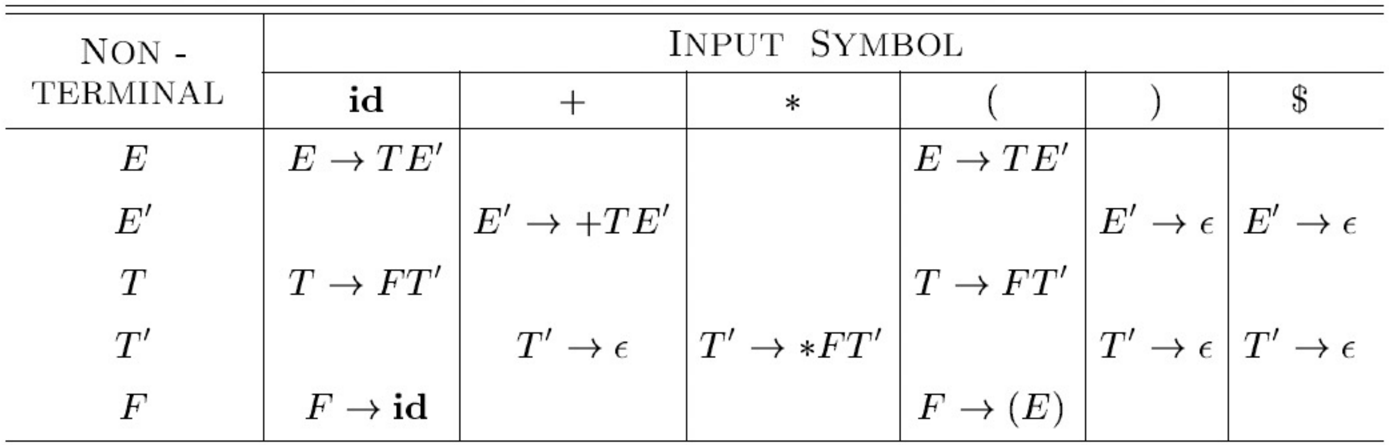

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Predictive Parsing Table

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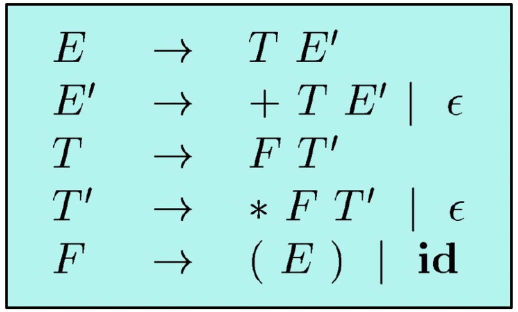
  - $\forall a \in \text{FIRST}(\alpha)$: $M[A, a] = A \to \alpha$
  - $\boldsymbol{\epsilon \in \textbf{FIRST}(\alpha) \Rightarrow \ \forall b \in \textbf{FOLLOW}(A)\text{: } M[A, b] = A \to \alpha}$



$$
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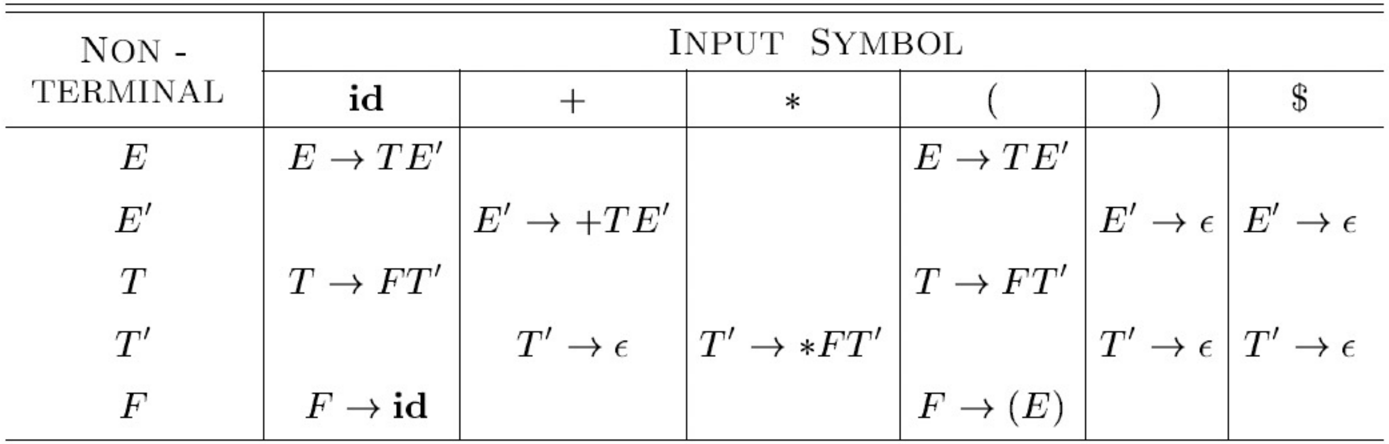
\end{array}
$$



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Predictive Parsing Table

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  - $\forall a \in \text{FIRST}(\alpha)\colon M[A, a] = A \rightarrow \alpha$
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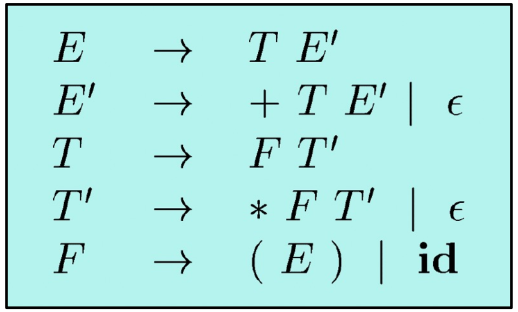

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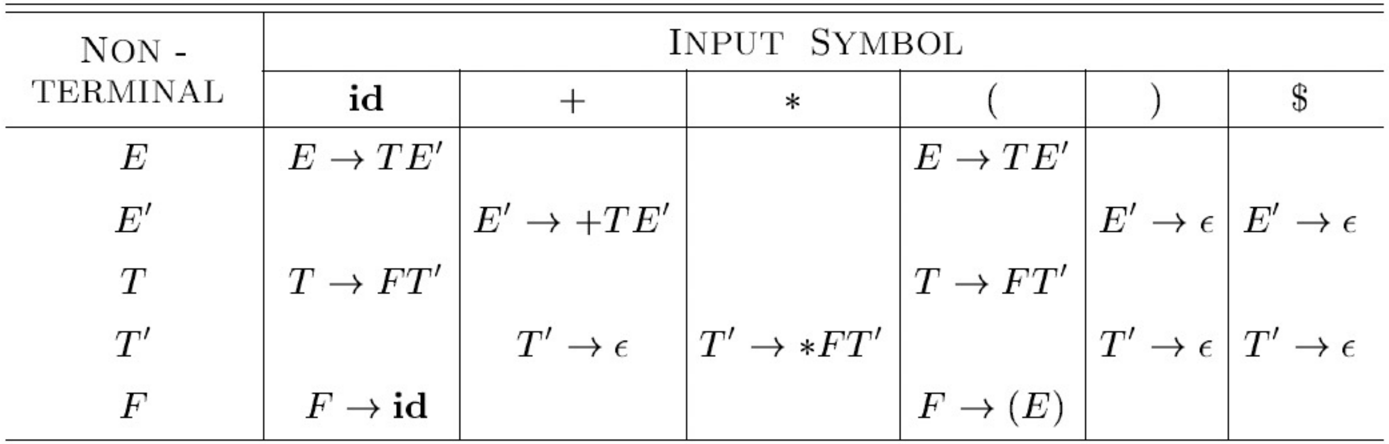

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- **Choose the production rule as per the table; empty means error**

Building a Parser in Practice

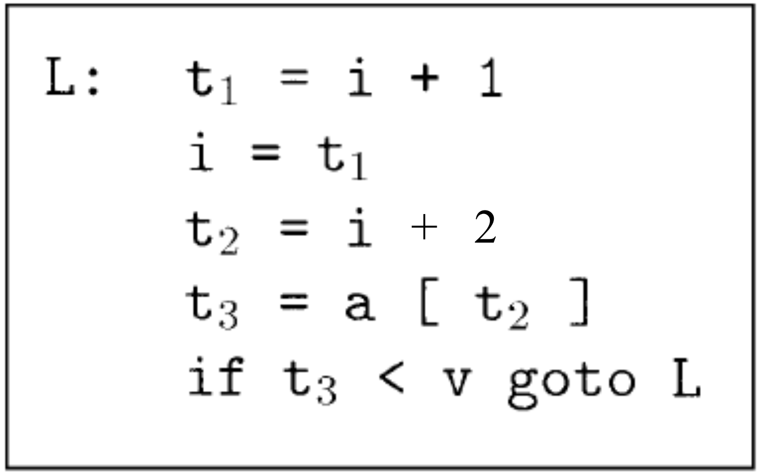
- Each non-terminal has a procedure or function for parsing
- => Recursive-Descent Parser

- **Problem** ✓ **1**: A **left-recursive** grammar can cause **infinite loops**
  - when expanding a non-terminal, we may find itself and expand it again
- **Problem** ✓ **2**: Backtracking may be necessary
  - when one derivation does not work, we may try others

PART III: IR Generation

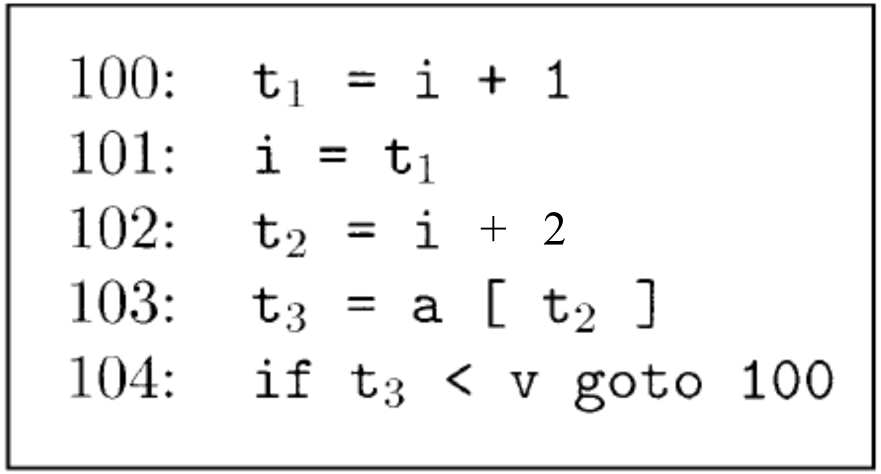
Three-Address Code

- do i = i + 1; while (a[i + 2] < v);



L: t_1 = i + 1
i = t_1
t_2 = i + 2
t_3 = a [t_2]
if t_3 < v goto L

Symbolic Labels



100: t_1 = i + 1
101: i = t_1
102: t_2 = i + 2
103: t_3 = a [t_2]
104: if t_3 < v goto 100

Numeric Labels

- Implementation methods: *quadruples*, *triples*, etc.

Static Single-Assignment

- **Feature 1**: Every variable has only one definition
- **Feature 2**: Using φ to merge definitions from multi paths
- => Direct def-use chains

```
if ( flag ) x = -1; else x = 1;
y = x * a;
```

if (flag) x_1 = -1; else x_2 = 1;

$x_3 = \varphi\ (x_1, x_2);$

$y\ = x_3\ *\ a$

Dominance Relations

- A **dom** B
  - if all paths from Entry to B goes through A
- A **post-dom** B
  - if all paths from B to Exit goes through A

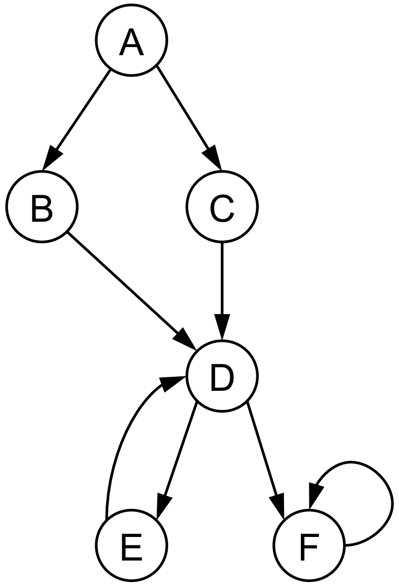
- Strict (post-)dominance – A (post-)**dom** B but A ≠ B

- Immediate dominance – A strict-dom B, but there’s no C, such that A strict-dom C, C strict-dom B

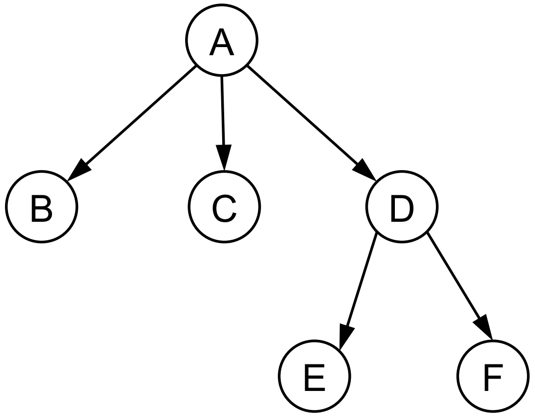
Dominator Tree

- Almost linear time to build a dominator tree.
  - Node: Block
  - Edge: Immediate dom relation

- Why is it a tree?



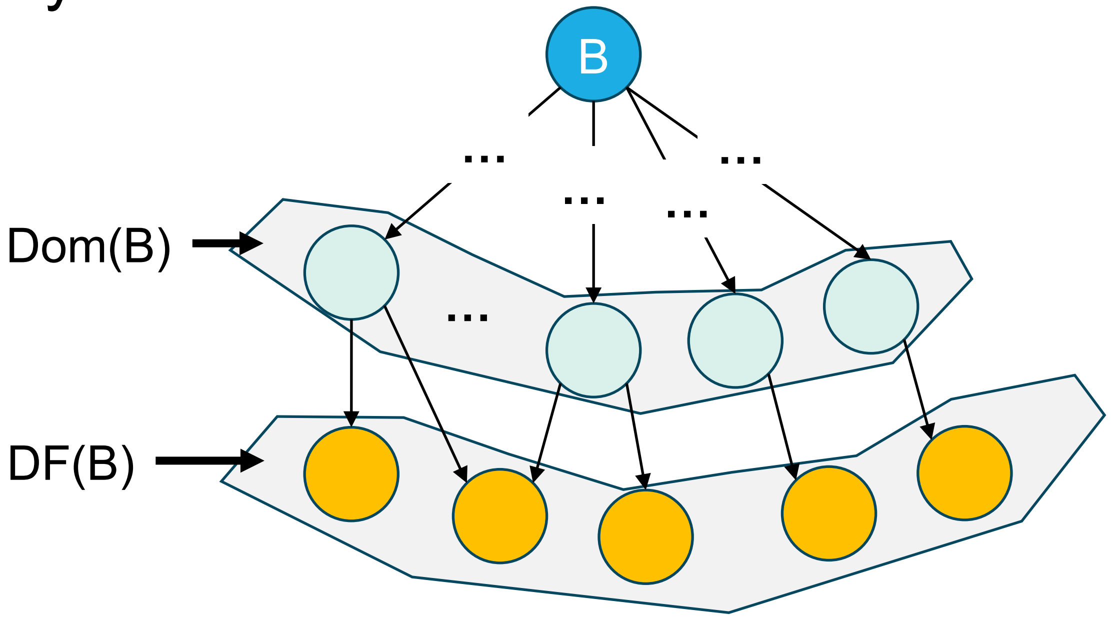
Flow Graph



Dominator Tree

Dominance Frontier

- DF(B) = { … } for the block B
  - The immediate successors of the blocks dominated by B
  - Not strictly dominated by B



Dominance Frontier

- DF(B) = { … } for the block B
  - The immediate successors of the blocks dominated by B
  - Not strictly dominated by B

- DF($\mathbb{B}$) = { … } for a set of blocks $\mathbb{B}$
  - DF($\mathbb{B}$) = $\cup_{B\in\mathbb{B}}$ DF(B)

Iterated Dominance Frontier

- Iterated DF of a block set $\mathbb{B}$
  - $DF_1 = DF(\mathbb{B}); \mathbb{B} = \mathbb{B} \cup DF_1$
  - $DF_2 = DF(\mathbb{B}); \mathbb{B} = \mathbb{B} \cup DF_2$
  - ……
  - until fixed point! (i.e., $DF_n = DF_{n-1}$)

THANKS!