Check-in

Review: Flex

Write a Flex rule for Fortran real literals:

- An optional sign (+ or -)
- One of the following:
  - An integer
  - One or more digits followed by a '.' followed by 0 or more digits
  - a '.' followed by one or more digits

Administrivia

Housekeeping

P1 Out

KU | EECS| Drew Davidson

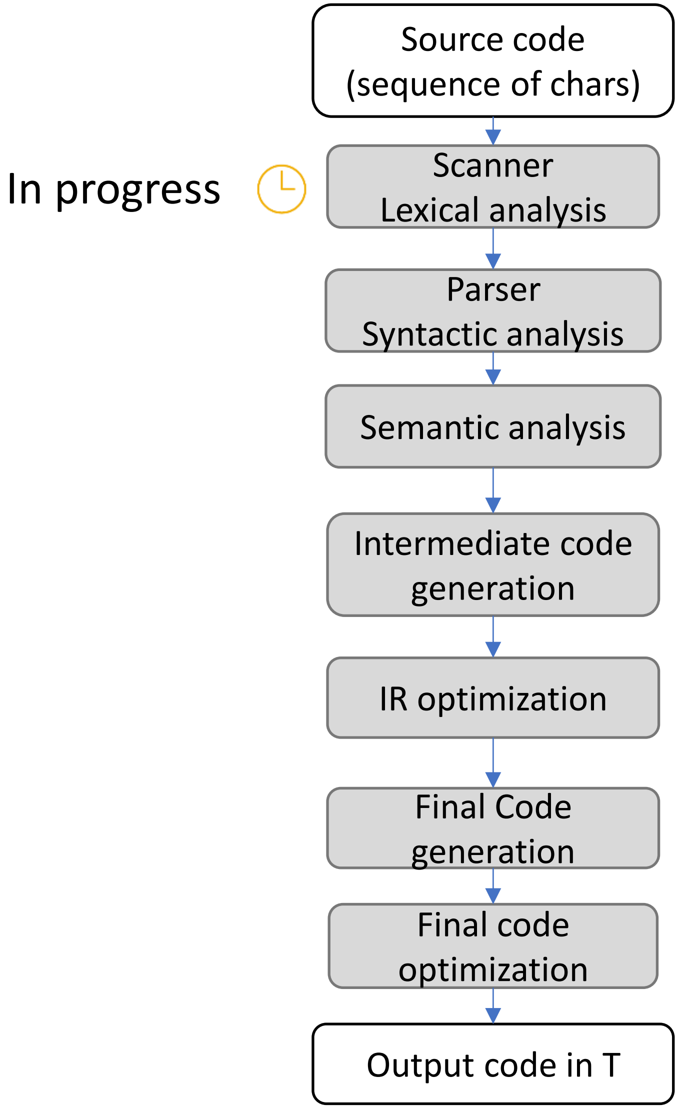
Lecture 3 Syntactic Definition

Compiler Construction

Progress Pics

Done:

- Shown RegEx as a good token formalism
- Lexical specification
- Lexical recognition



In progress

Source code (sequence of chars)

Scanner Lexical analysis

Parser Syntactic analysis

Semantic analysis

Intermediate code generation

IR optimization

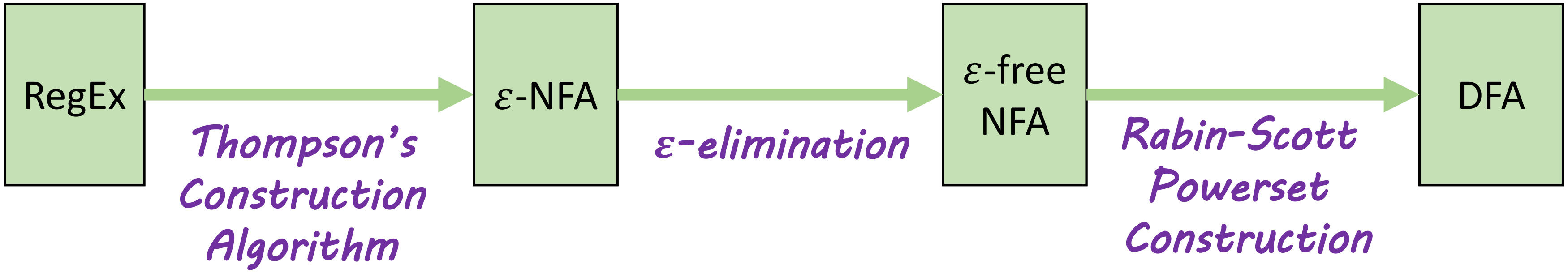
Final Code generation

Final code optimization

Output code in T

Last Time

Lecture Review


RegEx

Thompson's Construction Algorithm

ε-NFA

ε-elimination

ε-free NFA

Rabin-Scott Powerset Construction

DFA

Replace sub-RegExes with sub-FSMs "bottom-up" in the expression tree

Use the ε-closure to "bypass middleman" states and transitions

Create a DFA that tracks all possible states the NFA could be in

Good news

DFAs have a natural implementation (use a 2-D array)

Bad news

DFAs don't exactly do tokenization

Today's Lecture

Outline

Finish lexical analysis

- How to build a scanner

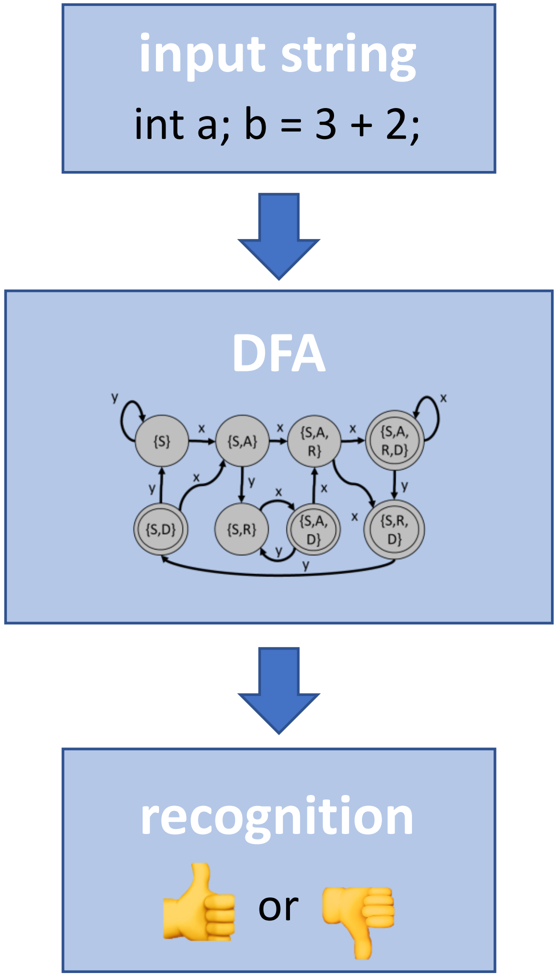
Begin discussing syntax

- How to specify the syntax of a programming language

DFA ≠ Tokenizer

Limitations

- Finite automata only check for language membership of a string (recognition)
- The Scanner needs to
  - Break the input into many different tokens
  - Know what characters comprise the token



input string

int a; b = 3 + 2;

DFA

recognition

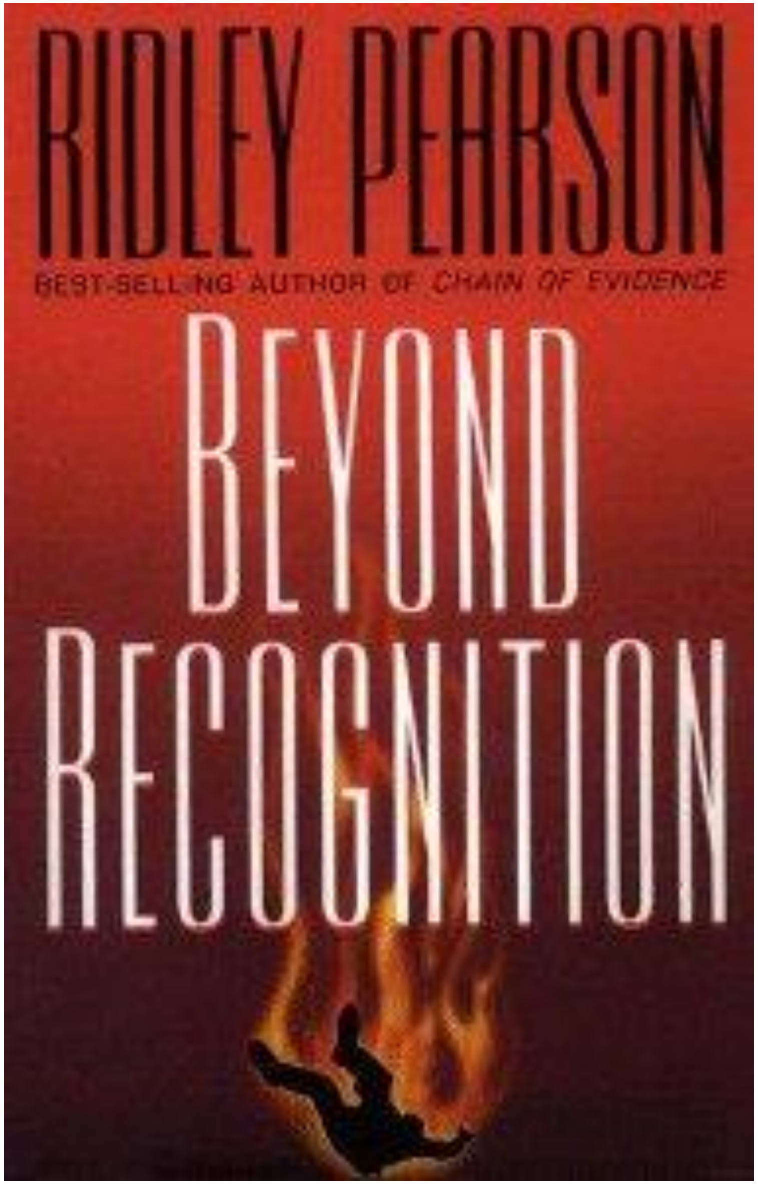
👍 or 👎

DFA ≠ Tokenizer

Limitations

- Finite automata only check for language membership of a string (recognition)
- The Scanner needs to
  - Break the input into many different tokens
  - Know what characters comprise the token

We need to go… *beyond recognition*



Lecture Outline

Syntactic Definition

From DFAs to Tokenizer

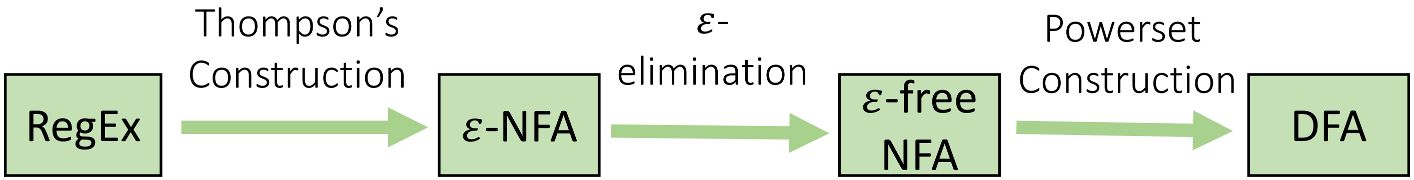
- Algorithms
- Implementation details

How Language Syntax is Formally Defined: CFGs

- Why we need context-free grammars
- How we use context-free grammars

From RegExes to Tokenizer

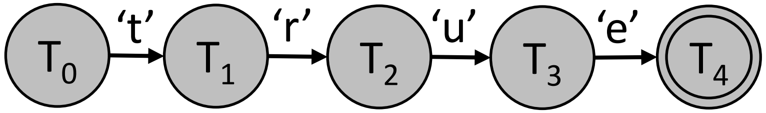
Algorithms



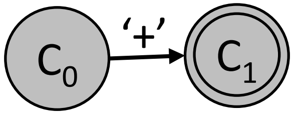
Language

true	{ Token(**true**) }
'+'	{ Token(**cross**) }
'-'	{ Token(**dash**) }

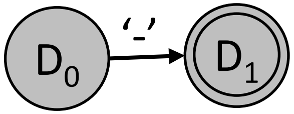
true



cross

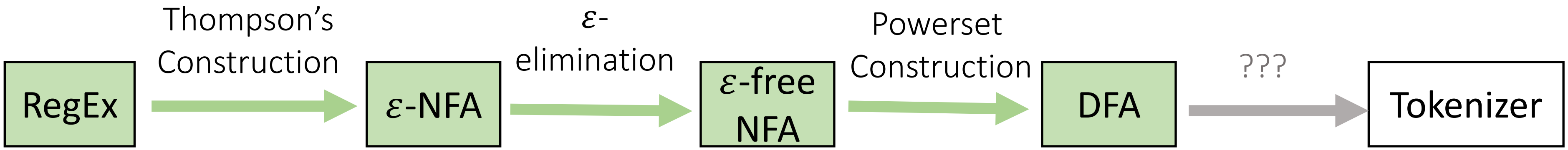


dash



From RegExes to Tokenizer

Algorithms



RegEx

Thompson's Construction

ε-NFA

ε-elimination

ε-free NFA

Powerset Construction

DFA

???

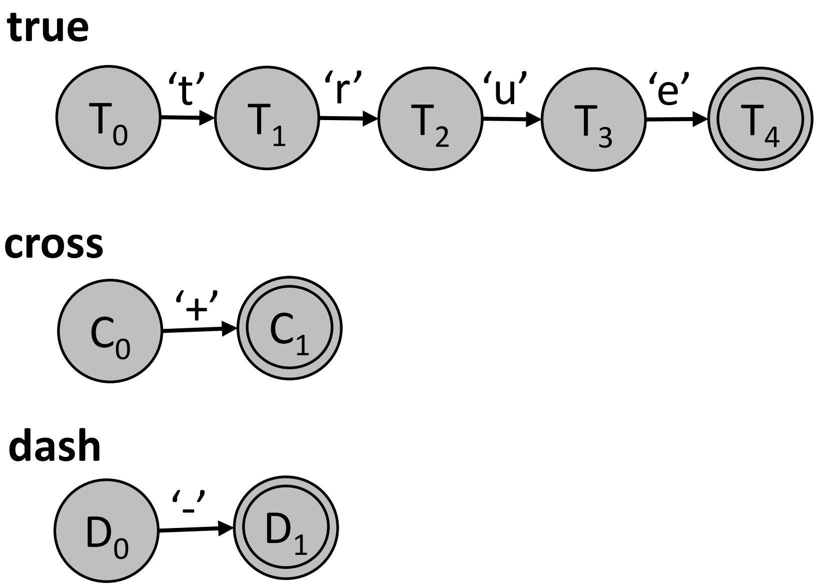
Tokenizer

1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

Language

true	{ Token(**true**) }
'+'	{ Token(**cross**) }
'-'	{ Token(**dash**) }



true

cross

dash

From RegExes to Tokenizer

Algorithms

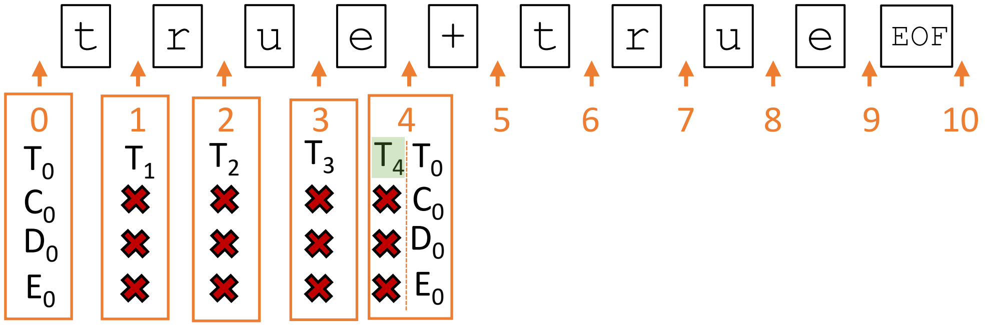
1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

Language

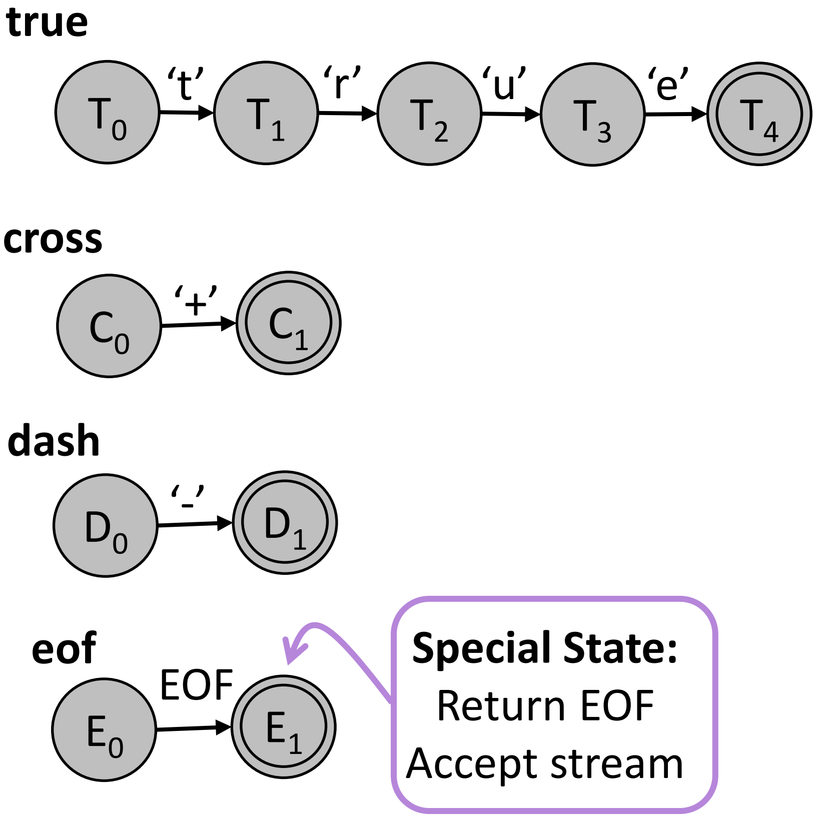
true	{ Token(**true**) }
‘+’	{ Token(**cross**) }
‘-’	{ Token(**dash**) }

Char Stream



Token Stream

true
[0,4]



Special State:
Return EOF
Accept stream

From RegExes to Tokenizer

Algorithms

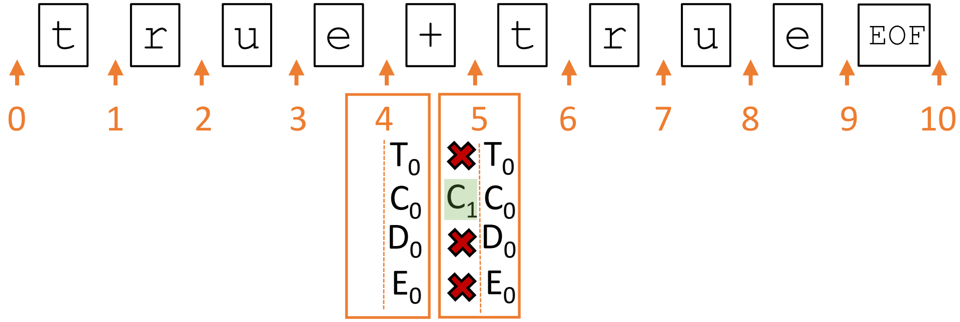
1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

Language

true	{ Token(**true**) }
‘+’	{ Token(**cross**) }
‘-’	{ Token(**dash**) }

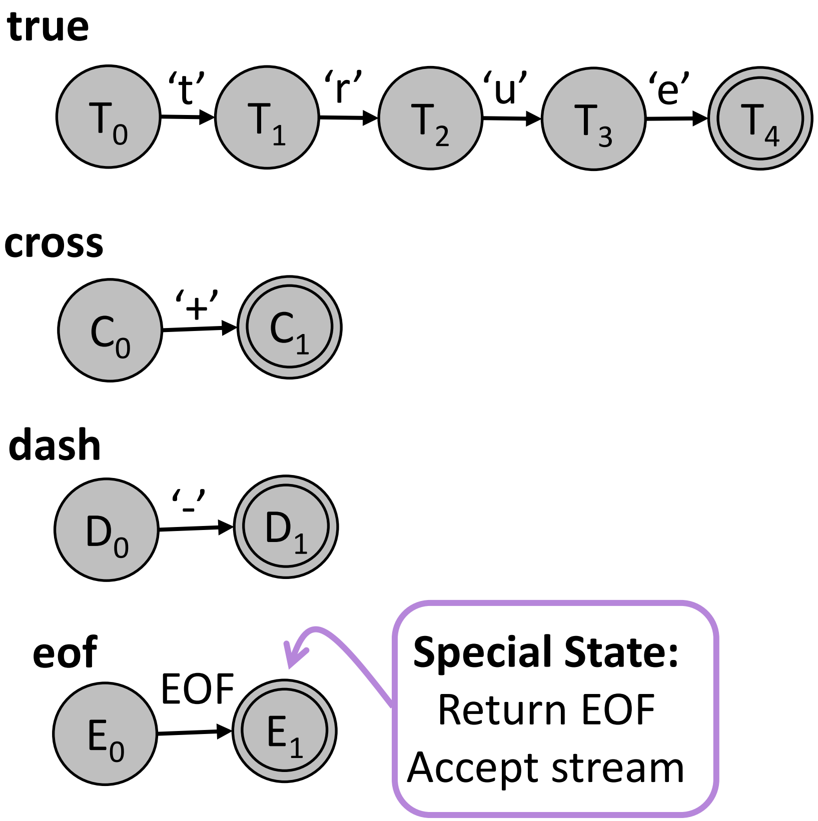
Char Stream



Token Stream

true
[0,4)

cross
[4,5)



Special State:
Return EOF
Accept stream

From RegExes to Tokenizer

Algorithms

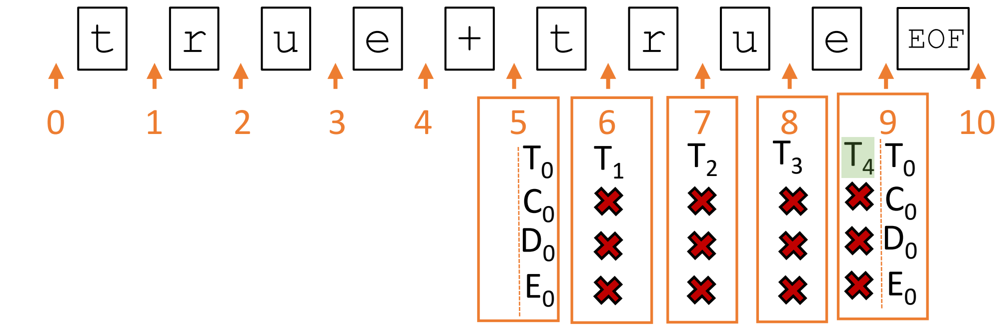
1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

Language

true	{ Token(**true**) }
‘+’	{ Token(**cross**) }
‘-’	{ Token(**dash**) }

Char Stream

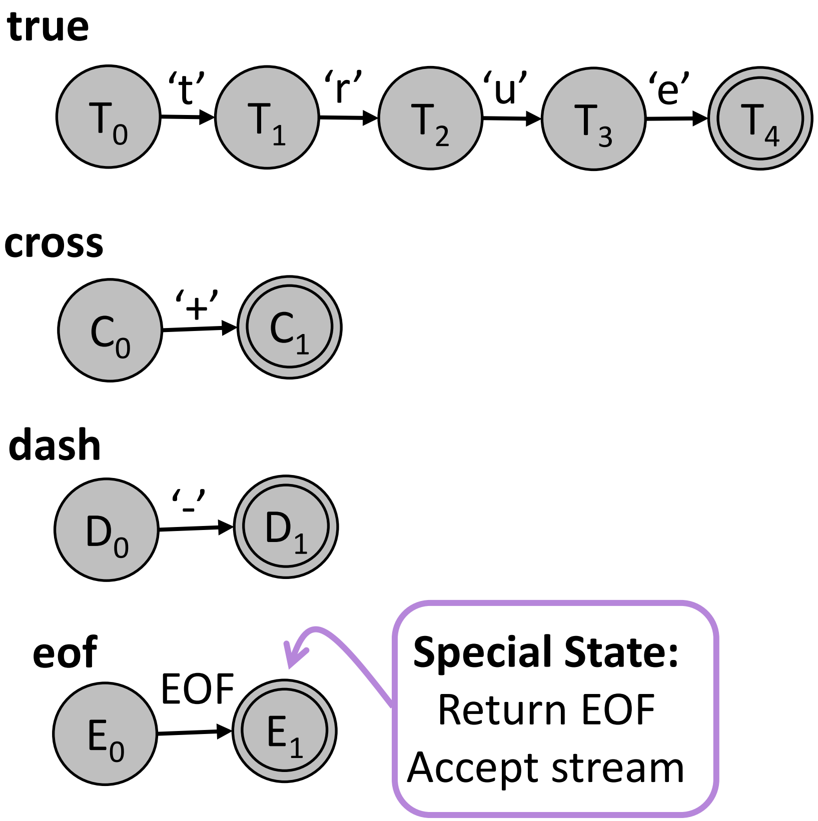


Token Stream

true [0,4]

cross [4,5]

true [5,9]



Special State:
Return EOF
Accept stream

From RegExes to Tokenizer

Algorithms

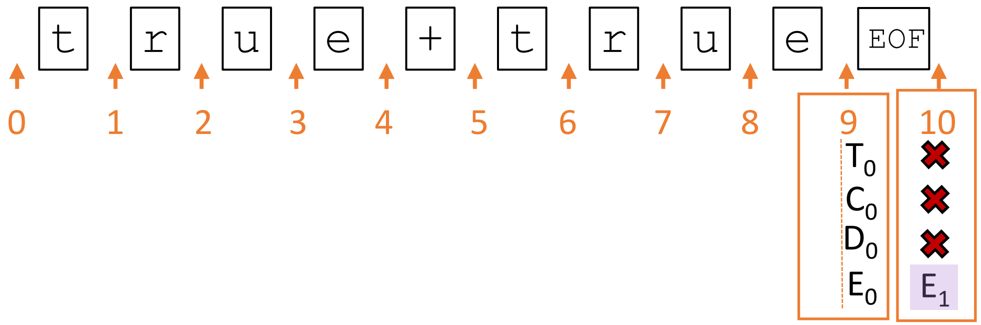
1st Idea (flawed)

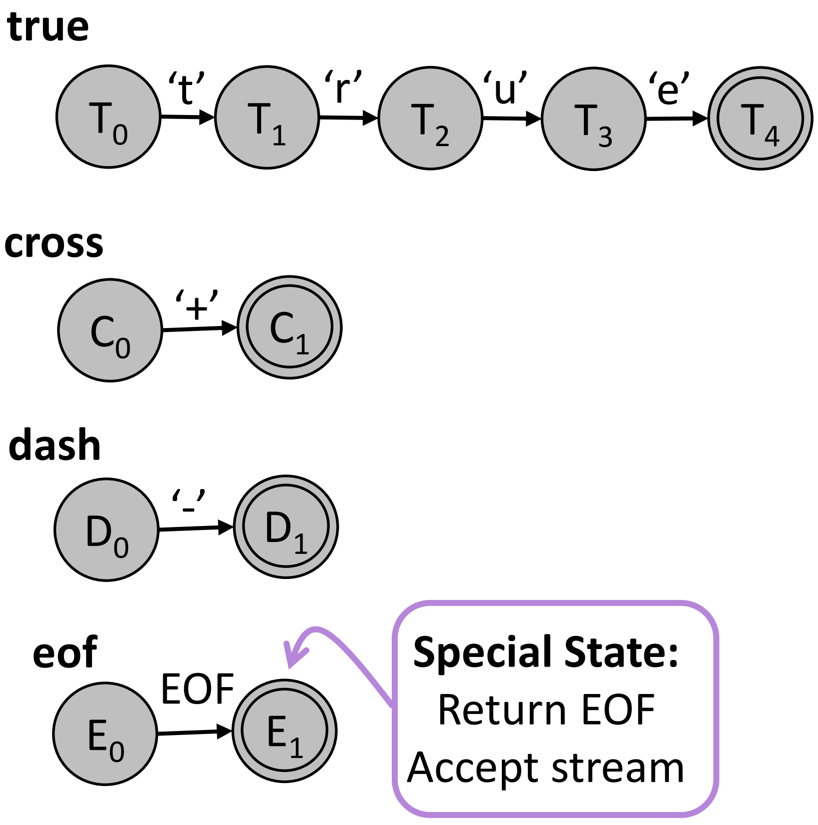
Consume char stream to **accept** state: return accepted token, restart DFAs with next char

Language

true	{ Token(**true**) }
'+'	{ Token(**cross**) }
'-'	{ Token(**dash**) }

Char Stream





Special State:
Return EOF
Accept stream

Token Stream

true [0,4)

cross [4,5)

true [5,9)

eof [9,10)

From RegExes to Tokenizer

Algorithms

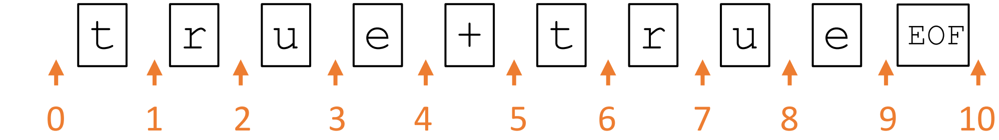
1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

Language

true { Token(**true**) }
'+' { Token(**cross**) }
'-' { Token(**dash**) }

Char Stream



Accept!

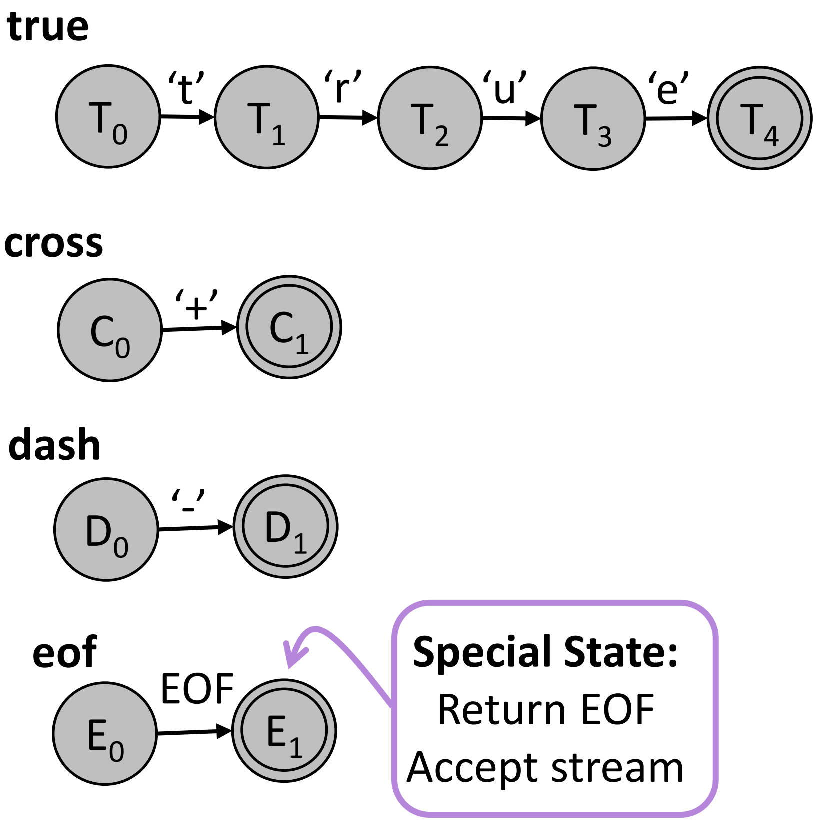
Token Stream

true [0,4)

cross [4,5)

true [5,9)

eof [9,10)



Special State:
Return EOF
Accept stream

Problem

What happens when token languages overlap / prefix each other?

From RegExes to Tokenizer

Algorithms

1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

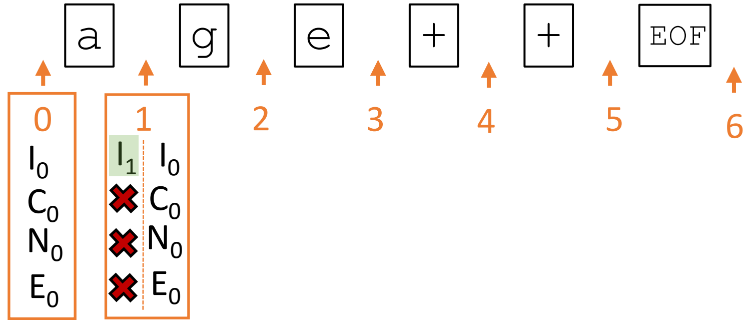
Problem

What happens when token languages overlap / prefix each other?

Language

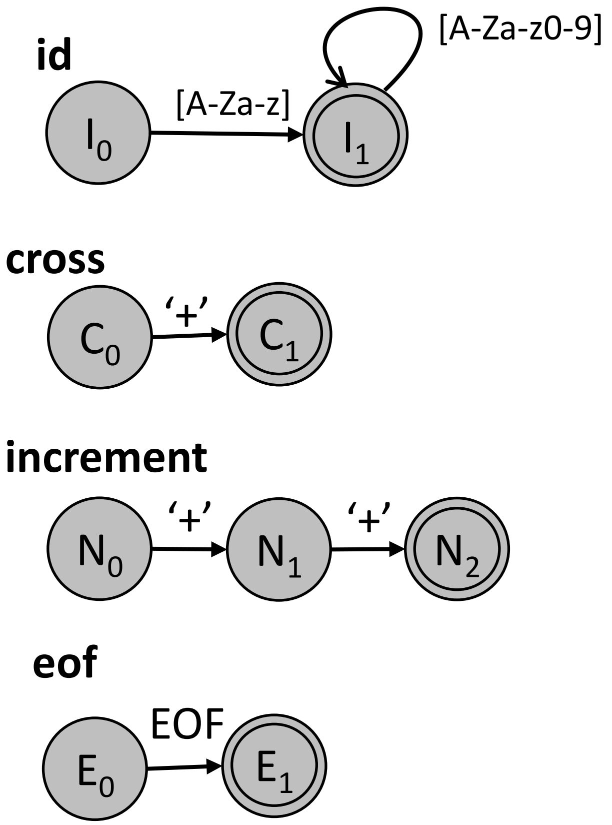
[A-Za-z][A-Za-z0-9]*	{ Token(**id**) }
+	{ Token(**cross**) }
++	{ Token(**increment**) }

Char Stream



Token Stream

id: a
[0,1)



From RegExes to Tokenizer

Algorithms

1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

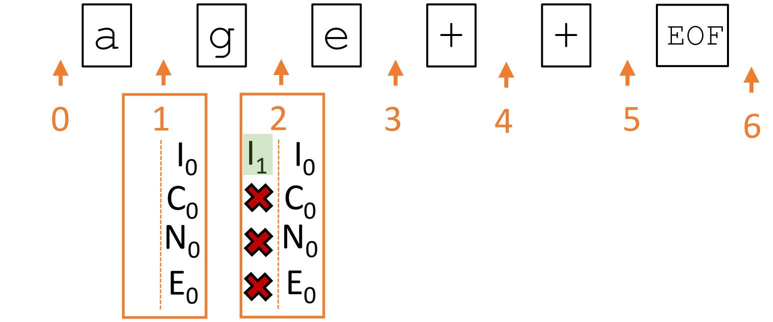
Problem

What happens when token languages overlap / prefix each other?

Language

[A-Za-z][A-Za-z0-9]*	{ Token(**id**) }
+	{ Token(**cross**) }
++	{ Token(**increment**) }

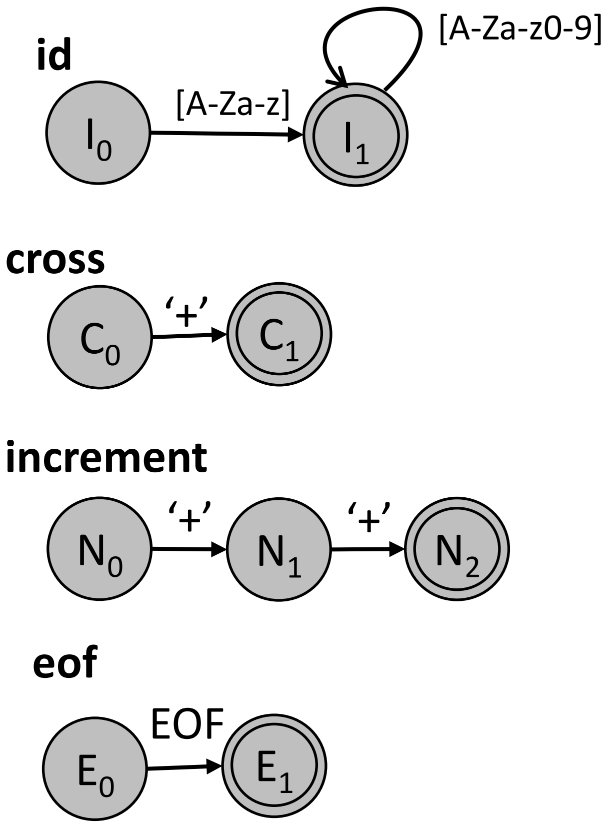
Char Stream



Token Stream

id: a [0,1)

id: g [1,2)



From RegExes to Tokenizer

Algorithms

1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

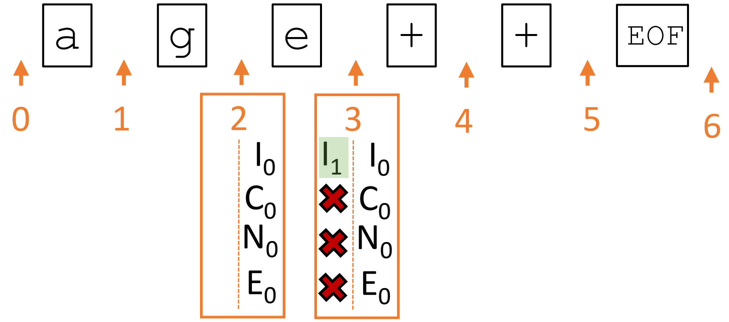
Problem

What happens when token languages overlap / prefix each other?

Language

[A-Za-z][A-Za-z0-9]*	{ Token(**id**) }
+	{ Token(**cross**) }
++	{ Token(**increment**) }

Char Stream

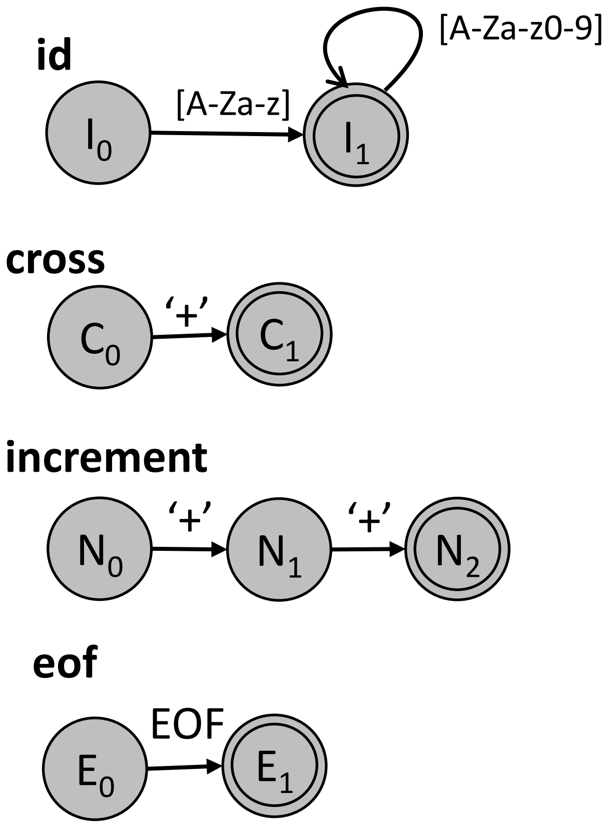


Token Stream

id: a [0,1)

id: g [1,2)

id: e [2,3)



From RegExes to Tokenizer

Algorithms

1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

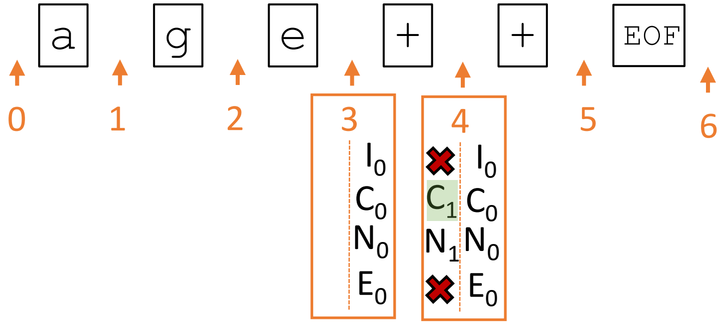
Problem

What happens when token languages overlap / prefix each other?

Language

[A-Za-z][A-Za-z0-9]*	{ Token(**id**) }
+	{ Token(**cross**) }
++	{ Token(**increment**) }

Char Stream



Token Stream

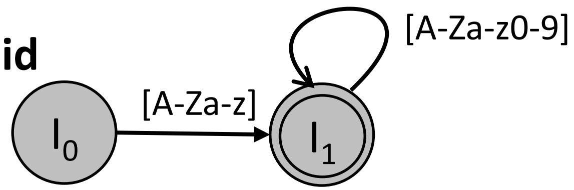
id: a [0,1)

id: g [1,2)

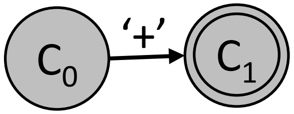
id: e [2,3)

cross [3,4)

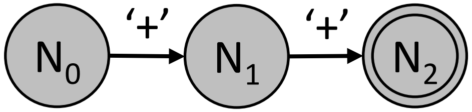
id



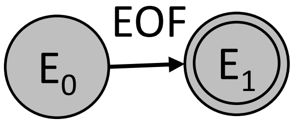
cross



increment



eof



From RegExes to Tokenizer

Algorithms

1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

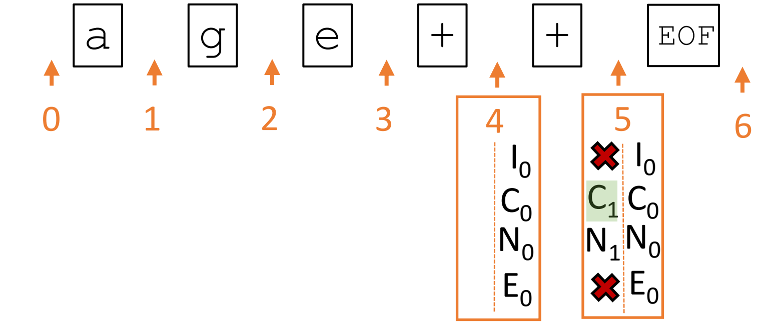
Problem

What happens when token languages overlap / prefix each other?

Language

[A-Za-z][A-Za-z0-9]*	{ Token(**id**) }
+	{ Token(**cross**) }
++	{ Token(**increment**) }

Char Stream



Token Stream

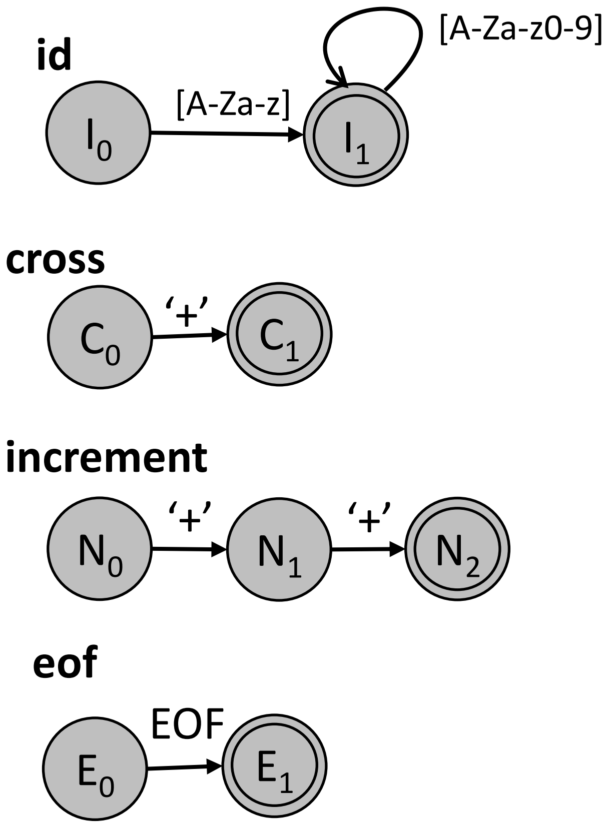
id: a [0,1)

id: g [1,2)

id: e [2,3)

cross [3,4)

cross [4,5)



From RegExes to Tokenizer

Algorithms

1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

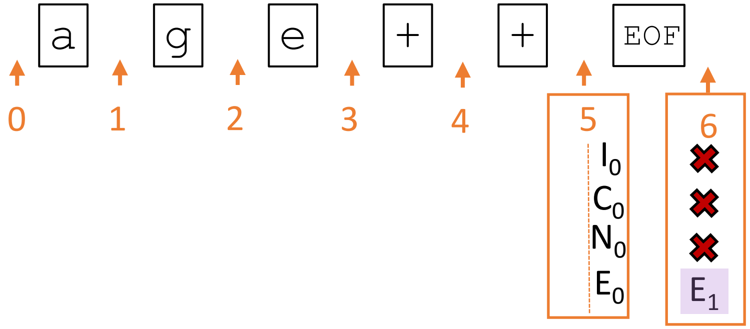
Problem

What happens when token languages overlap / prefix each other?

Language

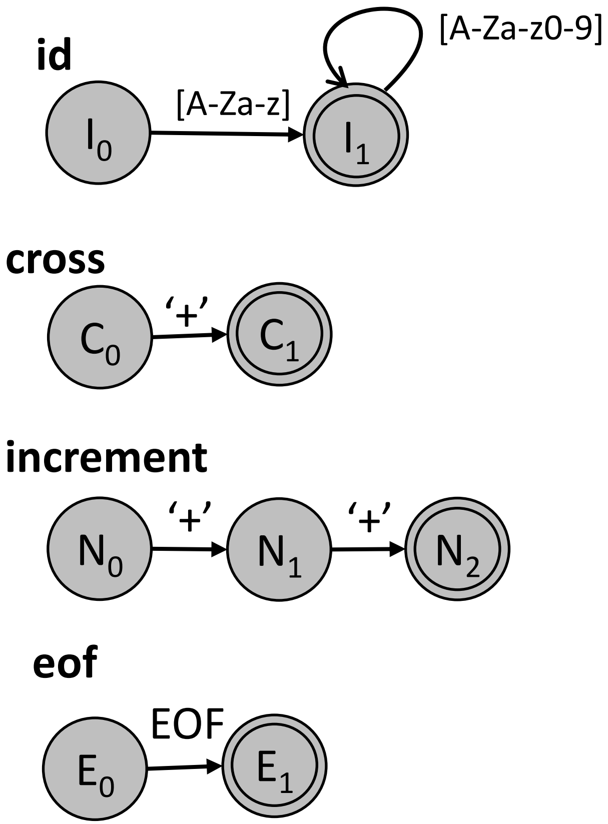
[A-Za-z][A-Za-z0-9]*	{ Token(**id**) }
+	{ Token(**cross**) }
++	{ Token(**increment**) }

Char Stream



Token Stream

id: a [0,1)	**id: g** [1,2)	**id: e** [2,3)	**cross** [3,4)	**cross** [4,5)	**eof** [5,6)



From RegExes to Tokenizer

Algorithms

1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

Problem

What happens when token languages overlap / prefix each other?

Language

[A-Za-z][A-Za-z0-9]*	{ Token(**id**) }
+	{ Token(**cross**) }
++	{ Token(**increment**) }

Char Stream

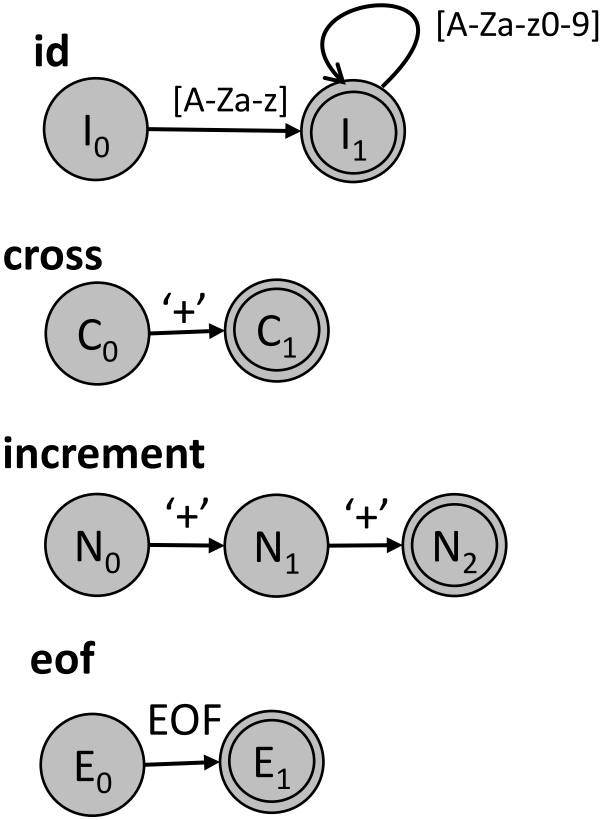
a	g	e	+	+	EOF

Accept, but…

shortest match!

Token Stream

id: a [0,1)	**id: g** [1,2)	**id: e** [2,3)	**cross** [3,4)	**cross** [4,5)	**eof** [5,6)



From RegExes to Tokenizer

Algorithms

1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

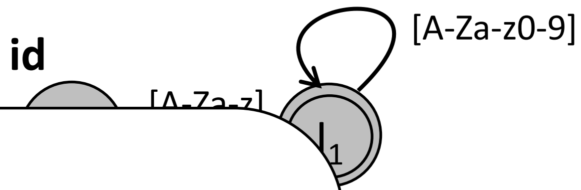
Problem

What happens when token languages overlap / prefix each other?

Language

[A-Za-z][A-Za-z0-9]* { Token(**id**) }

{ Token(**cross**) }



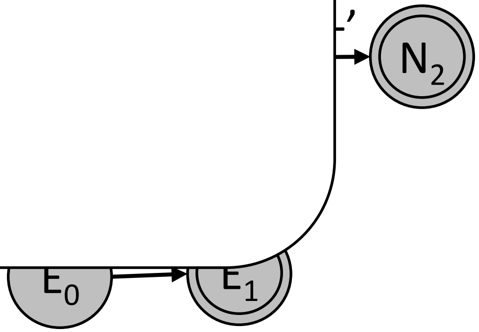
Char Stream

a g

Accept

but…

We want the *immediate longest* (AKA "greedy") match



Token Stream

id: a [0,1)	**id: g** [1,2)	[2,3)	[3,4)	[4,5)	[5,6)

From RegExes to Tokenizer

Algorithms

1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

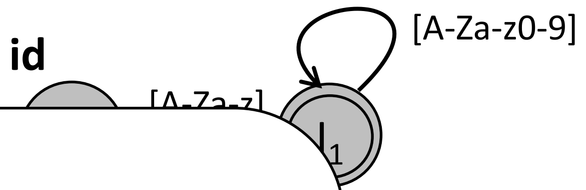
NEW Idea (good)

Consume char stream to **reject** states: return **last accepted** token, restart DFAs with that char

Language

[A-Za-z][A-Za-z0-9]* { Token(**id**) }

{ Token(**cross**) }



Char Stream

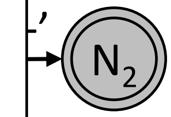
a g

We want the *immediate longest* (AKA “greedy”) match

Let’s modify the Implementation to support this!

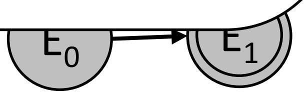
Accept

but…



Token Stream

id: a [0,1)	**id: g** [1,2)	[2,3)	[3,4)	[4,5)	[5,6)



From RegExes to Tokenizer

Algorithms

1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

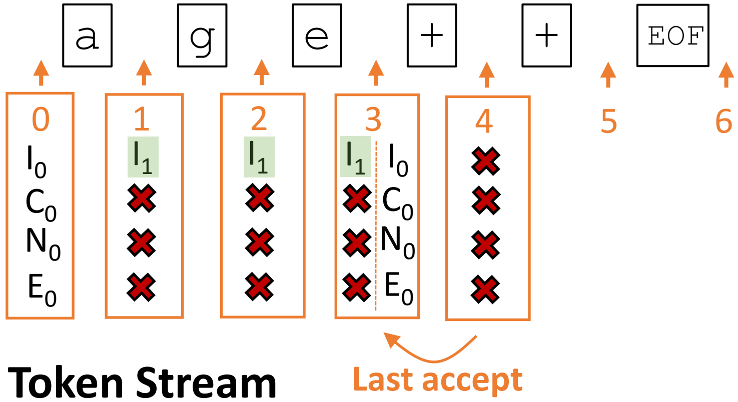
NEW Idea (good)

Consume char stream to **reject** states: return **last accepted** token, restart DFAs with that index

Language

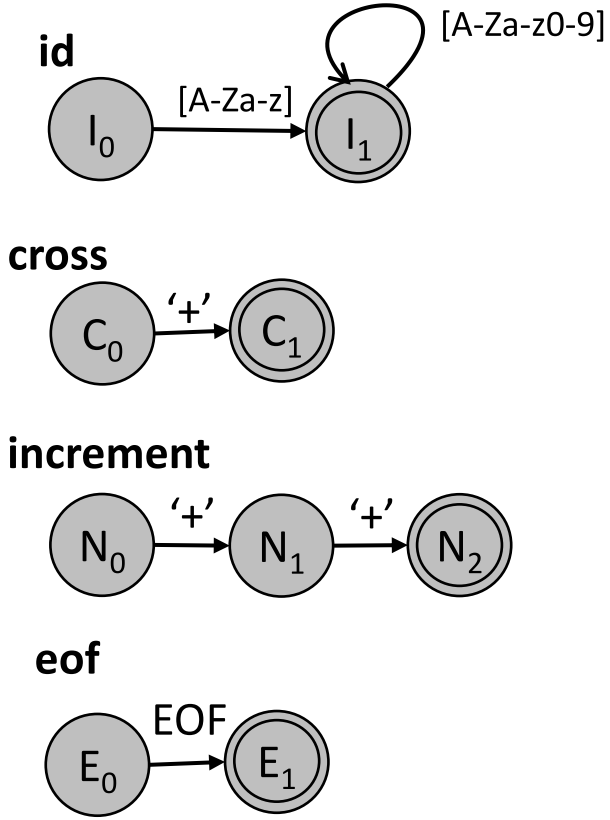
[A-Za-z][A-Za-z0-9]*	{ Token(**id**) }
+	{ Token(**cross**) }
++	{ Token(**increment**) }

Char Stream



Token Stream

id: age
[0,3)



From RegExes to Tokenizer

Algorithms

1st Idea (flawed)

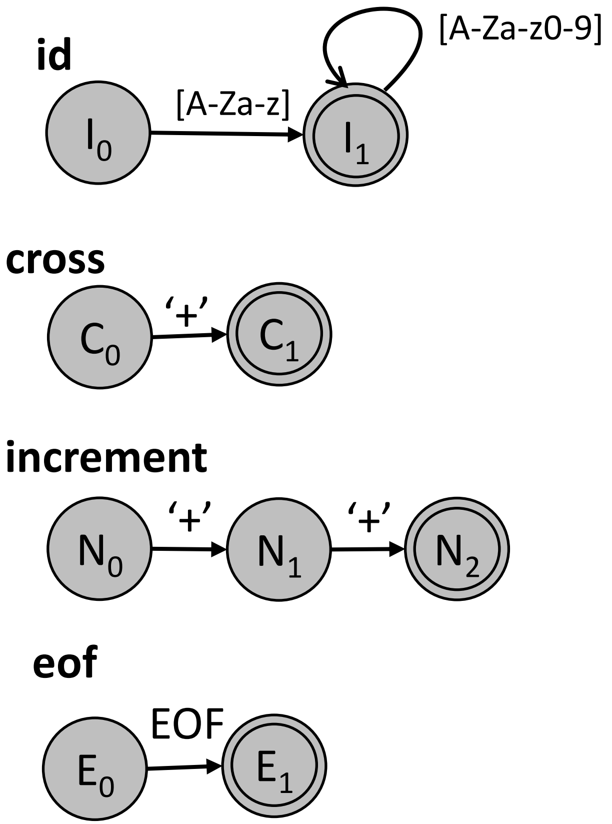
Consume char stream to **accept** state: return accepted token, restart DFAs with next char

NEW Idea (good)

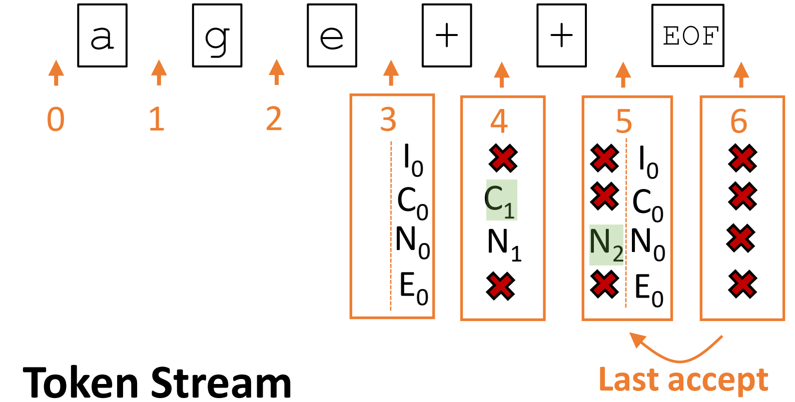
Consume char stream to **reject** states: return **last accepted** token, restart DFAs with that index

Language

[A-Za-z][A-Za-z0-9]*	{ Token(**id**) }
+	{ Token(**cross**) }
++	{ Token(**increment**) }



Char Stream



Token Stream

id: age [0,3)

increment [3,5)

From RegExes to Tokenizer

Algorithms

1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

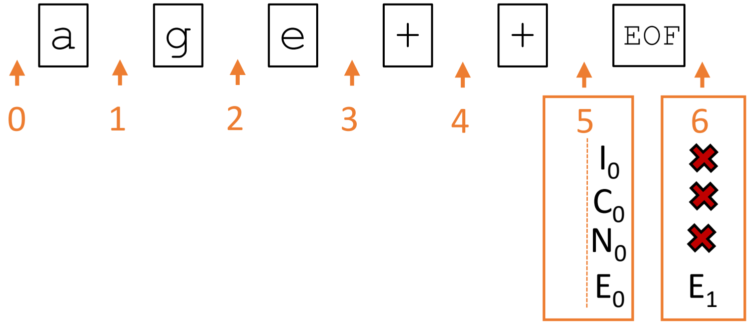
NEW Idea (good)

Consume char stream to **reject** states: return **last accepted** token, restart DFAs with that index

Language

[A-Za-z][A-Za-z0-9]*	{ Token(**id**) }
+	{ Token(**cross**) }
++	{ Token(**increment**) }

Char Stream

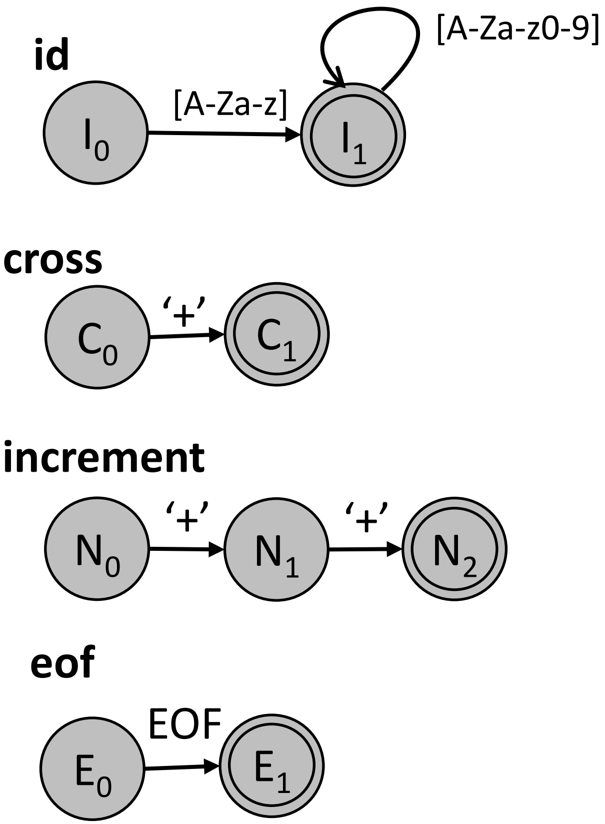


Token Stream

id: age [0,3)

increment [3,5)

eof [5,6)



From RegExes to Tokenizer

Algorithms

1st Idea (flawed)

Consume char stream to **accept** state: return accepted token, restart DFAs with next char

NEW Idea (good)

Consume char stream to **reject** states: return **last accepted** token, restart DFAs with that index

Language

[A-Za-z][A-Za-z0-9]*	{ Token(**id**) }
+	{ Token(**cross**) }
++	{ Token(**increment**) }

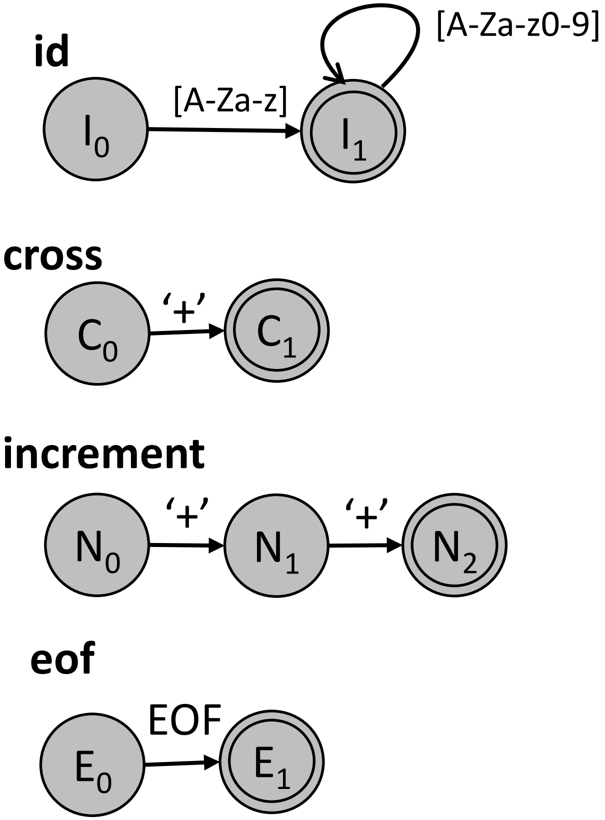
Char Stream

a	g	e	+	+	EOF

Accept longest match!

Token Stream

id: age [0,3]	**increment** [3,5]	**eof** [5,6]



Tokenizer Action Tables

Implementation

NEW Idea (good)

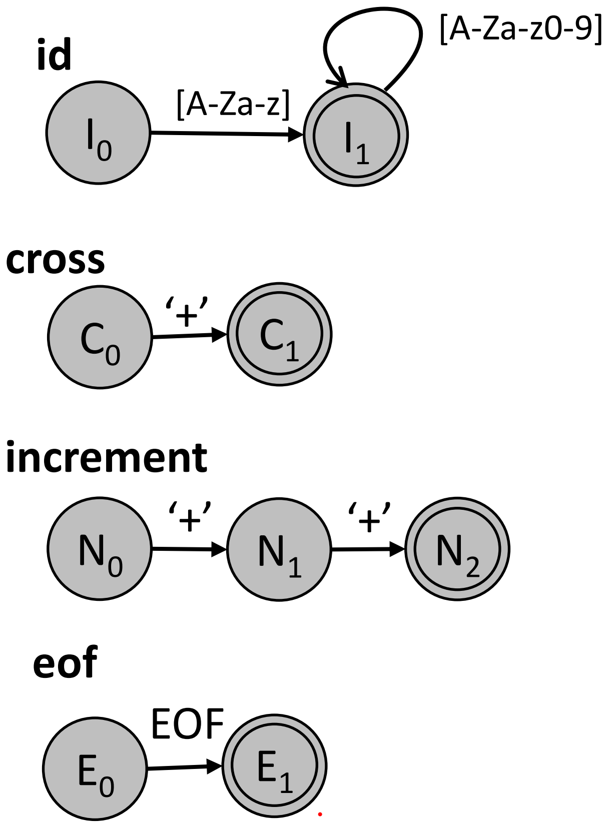
Consume char stream to **reject** states: return **last accepted** token, restart DFAs with that index

Language

[A-Za-z][A-Za-z0-9]*	{ Token(**id**) }
+	{ Token(**cross**) }
++	{ Token(**increment**) }

	+	**letter**	**digit**	**EOF**
I_0		I_1		
I_1		I_1	I_1	
C_0	C_1			
C_1				
N_0	N_1			
N_1	N_2			
N_2				
E_0				E_1
E_1				

	Token
I_0	
I_1	**id**
C_0	
C_1	**cross**
N_0	
N_1	
N_2	**increment**
E_0	
E_1	**eof** + accept



Tokenizer Action Tables

Implementation

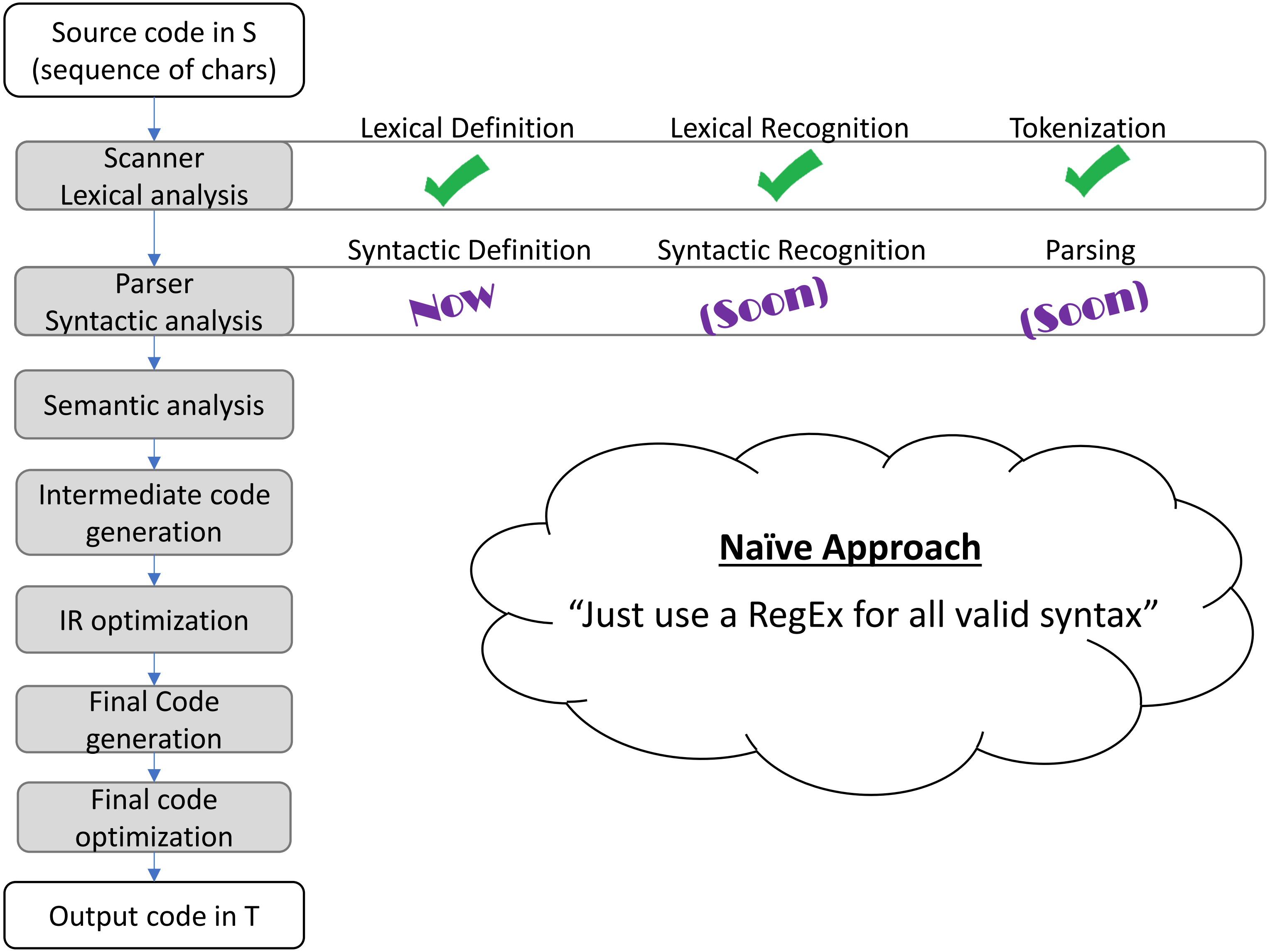
	+	**letter**	**digit**	**EOF**
I_0		I_1		
I_1		I_1	I_1	
C_0	C_1			
C_1				
N_0	N_1			
N_1	N_2			
N_2				
E_0				E_1
E_1				

	Token
I_0	
I_1	**id**
C_0	
C_1	**cross**
N_0	
N_1	
N_2	**increment**
E_0	
E_1	**eof** + accept

This basic machinery lets us implement a scanner from a RegEx spec!

Lexical Analysis Done

Lecture 3 Preview



Source code in S (sequence of chars)

Scanner Lexical analysis

Parser Syntactic analysis

Semantic analysis

Intermediate code generation

IR optimization

Final Code generation

Final code optimization

Output code in T

	Lexical Definition	Lexical Recognition	Tokenization
Scanner Lexical analysis	✓	✓	✓

	Syntactic Definition	Syntactic Recognition	Parsing
Parser Syntactic analysis	Now	(Soon)	(Soon)

Naïve Approach

"Just use a RegEx for all valid syntax"

Regular Languages Lack Strength

How Languages are Defined: CFGs

- Our RegEx-based scanner can emit a stream of tokens:

<u>Char Stream</u>

`X` `\t` `Y` `=` `Z` `+` `EOF`

<u>Token Stream</u>

ID: X | ID: Y | ASSIGN | ID: Z | PLUS | EOF

Cute, but weak

Observation: scanner ignores token order

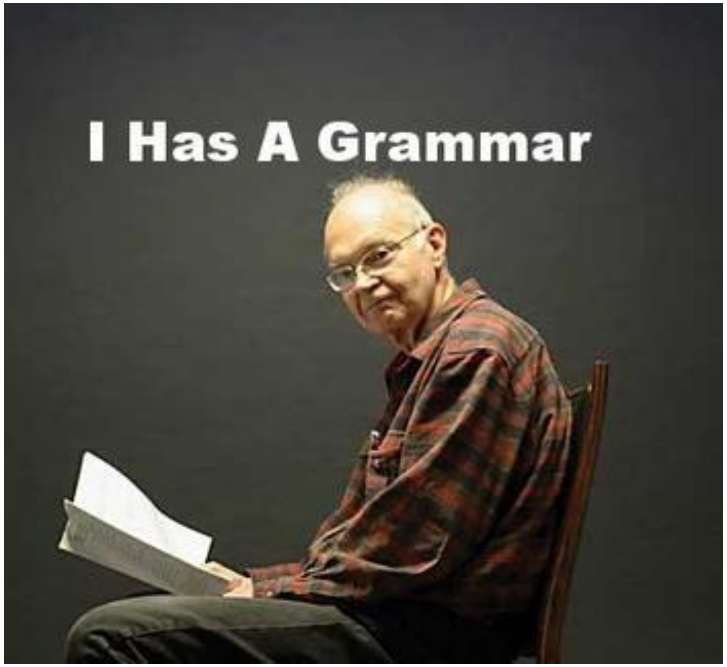
Audience Q: Could you enforce construct order another RegEx?

Answer: Nope! RegEx simply can’t capture all PL structures (e.g. parentheses nesting)

Defining Languages with Grammars

Syntactic Definition: How we use CFGs

- A set of (recursive) rewriting rules to rewrite sequence of symbols
- Any “completed” sequence represents a string in the language



Defining Languages with Grammars

Syntactic Definition: How we use CFGs

- A set of (recursive) rewriting rules to rewrite sequence of symbols
- Any "completed" sequence represents a string in the language

CFG = $(\mathrm{N},\Sigma,\mathrm{P},\mathrm{S})$ where:

- N: set of nonterminal symbols
- Σ: set of terminal symbols
- P: set of productions
- S: start nonterminal in N

Rules where
LHS: a single nonterminal symbol
RHS: a sequence of any symbols

Defining Languages with Grammars

Syntactic Definition: How we use CFGs

Example:

N = { A }

Σ = { **(**, **)** }

S = A

$$\mathrm{P} = \begin{Bmatrix} \mathrm{P1:}\ A \ \rightarrow (\ A\ ) \\ \mathrm{P2:}\ A \ \rightarrow \ \boldsymbol{\varepsilon} \end{Bmatrix}$$

CFG = (N,Σ,P,S) where:

- N: set of nonterminal symbols
- Σ: set of terminal symbols
- P: set of productions
- S: start nonterminal in N

Defining Languages with Grammars

Syntactic Definition: How we use CFGs

Example:

$N = \{ A \}$

$\Sigma = \{ \mathbf{(}, \mathbf{)} \}$

$S = A$

$$P = \left\{ \begin{array}{l} \text{P1: } A \rightarrow (A) \\ \text{P2: } A \rightarrow \boldsymbol{\varepsilon} \end{array} \right\}$$

Producing a string

A Begin with start symbol

$A \rightarrow (A)$ Apply production P1 (a *derivation step, denoted* ⇒)

(A) Get a new symbol string

$A \rightarrow (A)$ Apply production P1 again

$((A))$ Get a new symbol string

$A \rightarrow \boldsymbol{\varepsilon}$ Apply another production in P

$(( ))$ Get a new symbol string

All terminals, this string is in language (a *sentence*)

Simplifying Notation: Shorthand

Syntactic Definition: How we use CFGs

Example:

$\mathrm{N} = \{ A \}$

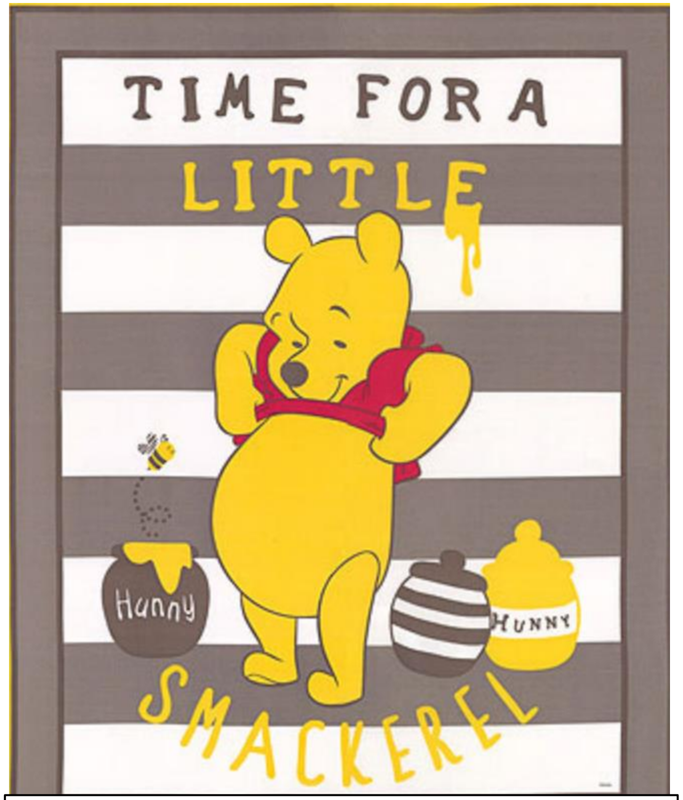
$\Sigma = \{ \textbf{(}, \textbf{)} \}$

Say N and Σ Implicit: Whatever symbols appears in productions

$\mathrm{S} = A$ ← Say S Implicit: LHS of top production

$$\mathrm{P} = \left\{ \begin{array}{l} \mathrm{P1}: A \rightarrow (\ A\ ) \\ \mathrm{P2}: A \rightarrow \boldsymbol{\varepsilon} \end{array} \right\}$$

Collapse rules with the same LHS using bar



of context-free grammar notation

Simplifying Notation: Shorthand

Syntactic Definition: How we use CFGs

Example:

$\mathrm{N} = \{\ A\ \}$

$\Sigma = \{\ \mathbf{(}, \mathbf{)}\ \}$

Say N and Σ Implicit: Whatever symbols appears in productions

$\mathrm{S} = A$ ← Say S Implicit: LHS of top production

$$\mathrm{P} = \begin{Bmatrix} \mathrm{P1:}\ A & \rightarrow & (\ A\ ) \\ \mathrm{P2:}\ A & \rightarrow & \boldsymbol{\varepsilon} \end{Bmatrix}$$

Collapse rules with the same LHS using bar

Denote grammar as

$$A \ ::= \mathbf{(}\ A\ \mathbf{)}$$
$$A \ ::= \ \boldsymbol{\varepsilon}$$

or equivalently as

$$\begin{aligned} A &::= (\ A\ ) \\ &\quad\ |\quad \boldsymbol{\varepsilon} \end{aligned}$$

or even

$$A ::= (\ A\ )\ |\ \boldsymbol{\varepsilon}$$

Simplifying Notation: Shorthand

Syntactic Definition: How we use CFGs

“BNF”

Denote grammar as

$$A \ ::= \mathbf{(}\ A\ \mathbf{)}$$
$$A \ ::= \ \boldsymbol{\varepsilon}$$

or equivalently as

$$\begin{aligned} A ::=&(\ A\ ) \\ |& \quad \boldsymbol{\varepsilon} \end{aligned}$$

or even

$$A ::= (\ A\ ) \mid \boldsymbol{\varepsilon}$$

Some languages denoted in BNF

Syntactic Definition: How we use CFGs

$A ::= (\ A\ )$

$\quad |\ \ \varepsilon$

$F ::= \mathbf{b}\ G\ \mathbf{y\ e}$ $\qquad$ $F \Rightarrow \mathbf{b}\ G\ \mathbf{y\ e} \Rightarrow \mathbf{b\ y\ e}$

$\quad |\ \mathbf{see\ ya}$ $\qquad$ $F \Rightarrow \mathbf{b}\ G\ \mathbf{y\ e} \Rightarrow \mathbf{b}\ G\ \mathbf{y\ y\ e} \Rightarrow \mathbf{b\ y\ y\ e}$

$G ::= G\mathbf{y}$ $\qquad$ $F \Rightarrow \mathbf{see\ ya}$

$\quad |\ \ \varepsilon$

$Y ::= \mathbf{a}\ Y$

$Z ::= \mathbf{w\ t\ f}$

$Y \Rightarrow \text{a}\ \text{Y} \Rightarrow \text{a a Y} \Rightarrow \text{a a a Y} \Rightarrow \ldots$

Accepts no strings

(not even the empty string)

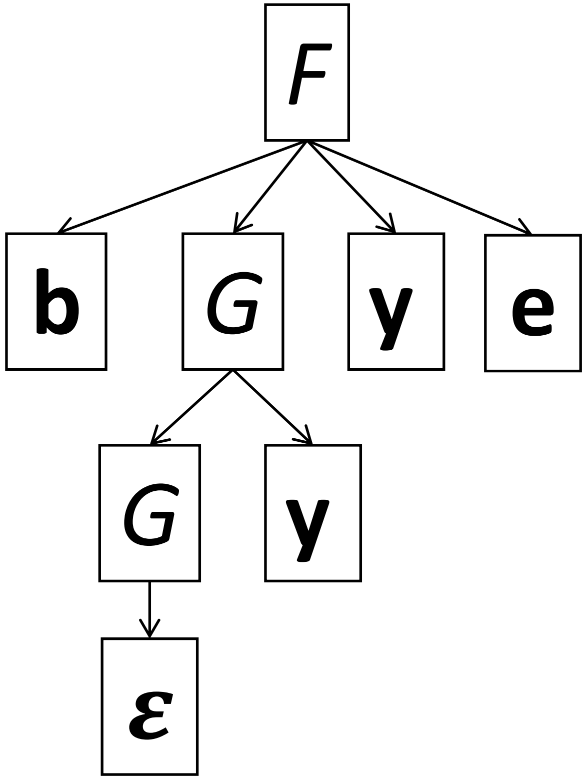
Parse Trees

Syntactic Definition: How we use CFGs

$$\underline{F} \Rightarrow \mathbf{b}\ \underline{G}\ \mathbf{y}\ \mathbf{e} \Rightarrow \mathbf{b}\ \underline{G}\ \mathbf{y}\ \mathbf{y}\ \mathbf{e} \Rightarrow \mathbf{b}\ \mathbf{y}\ \mathbf{y}\ \mathbf{e}$$

Represent Derivations

- Nodes are symbols in a tree
- Rooted at start symbol
- Children are derivation step
- Leaves are final string (if all nonterminals)



CFG use in the Compiler

Syntactic Definition: How we use CFGs

Compile

Push Symbols

CFG use in the Compiler

Syntactic Definition: How we use CFGs

CFG for PL Syntactic Structure

Productions specify valid programs

- Let the terminals be the tokens in the language
- Let the nonterminals be the groupings that form language constructs
  - (loops, statements, functions, calls, etc)
- The grammar will recognize (or reject) the stream of tokens from the Lexer

Let's see an example with this grammar

Productions

1. *Prog* ::= **begin** *Stmts* **end**
2. Stmts ::= *Stmts* **semi** *Stmt*
3. | *Stmt*
4. *Stmt* ::= **id assign** *Expr*
5. *Expr* ::= **id**
6. | *Expr* **cross id**

Derivation Sequence

Prog

Prod. 1

⇒ **begin** Stmts **end**

Prod. 2

⇒ **begin** Stmts **semi** Stmt **end**

Prod. 3

⇒ **begin** Stmt **semi** Stmt **end**

Prod. 4

⇒ **begin id assign** *Expr* **semi** *Stmt* **end**

Prod. 4

⇒ **begin id assign** *Expr* **semi id assign** *Expr* **end**

Prod. 5

⇒ **begin id assign id semi id assign** *Expr* **end**

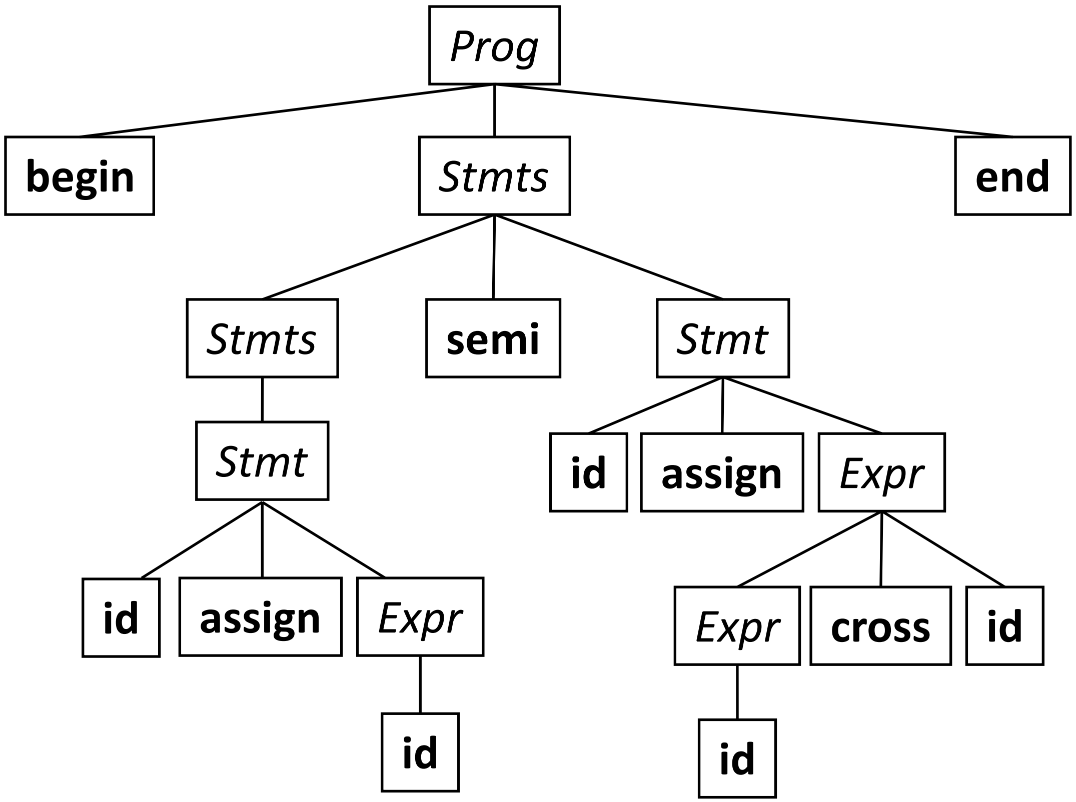
Prod. 6

⇒ **begin id assign id semi id assign** *Expr* **cross id end**

Prod. 5

⇒ **begin id assign id semi id assign id cross id end**

Parse Tree



Productions

1. *Prog* ::= **begin** *Stmts* **end**

2. *Stmts* ::= *Stmts* **semi** *Stmt*

3. | *Stmt*

4. *Stmt* ::= **id assign** *Expr*

5. *Expr* ::= **id**

6. | *Expr* **cross id**

End of Lecture

Syntactic Definition

Next Time

Parsing - Beyond specification for CFGs

- Extracting the *correct* tree from a token stream

Time Permitting

- Proof sketch: why RegExs can’t match PL constructs