Lexing

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CS3300 Compiler Design
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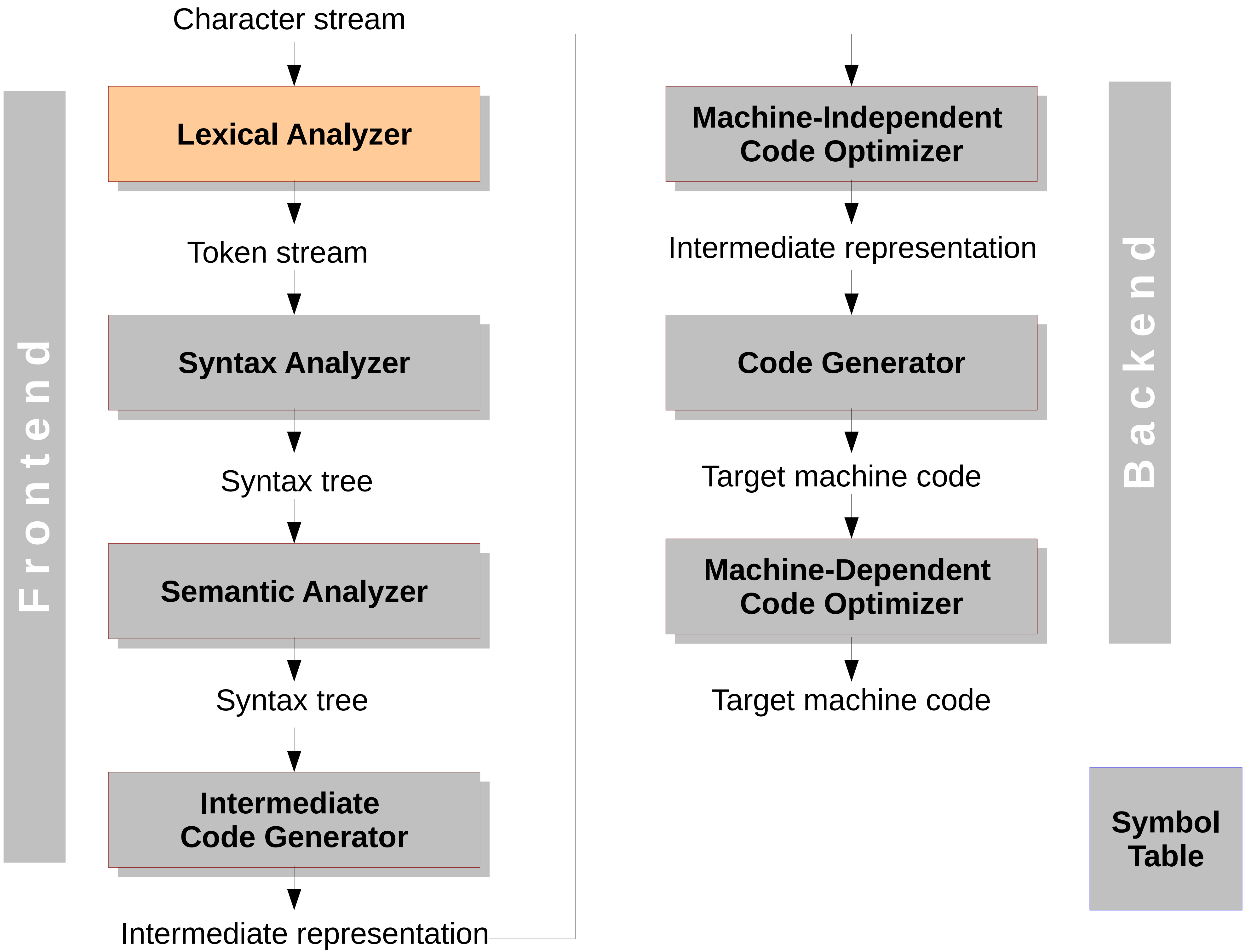
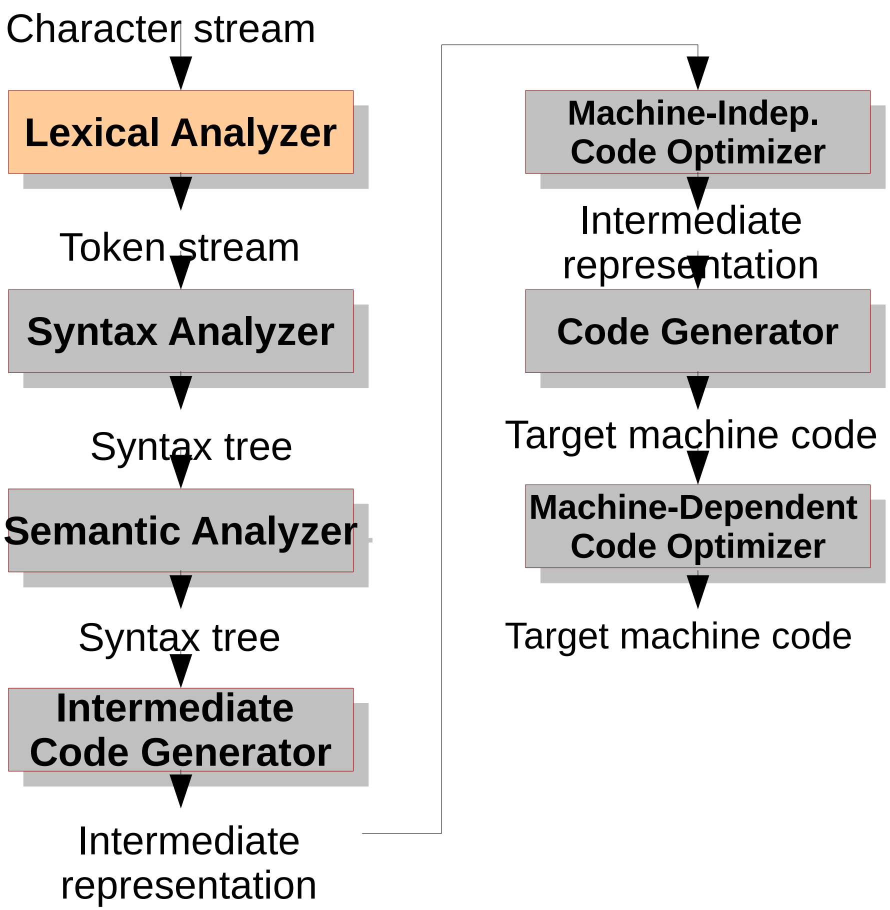

Character stream
Lexical Analyzer
Token stream
Syntax Analyzer
Syntax tree
Semantic Analyzer
Syntax tree
Intermediate Code Generator
Intermediate representation
Machine-Independent Code Optimizer
Intermediate representation
Code Generator
Target machine code
Machine-Dependent Code Optimizer
Target machine code
Frontend
Backend
Symbol Table

Lexing Summary

- Basic *lex*
- Input Buffering
- KMP String Matching
- Regex → NFA → DFA
- Regex → DFA



Role

- Read input characters
- Group into words (lexemes)
- Return sequence of tokens
- Sometimes
  - Eat-up whitespace
  - Remove comments
  - Maintain line number information

Token, Pattern, Lexeme

Token	Pattern	Sample lexeme
if	Characters i, f	if
comparison	<= or >= or < or > or == or !=	<=, !=
identifier	letter (letter + digit)*	pi, score, D2
number	Any numeric constant	3.14159, 0, 6.02e23
literal	Anything but “, surrounded by “”	“core dumped”

The following classes cover most or all of the tokens

- One token for each keyword
- Tokens for the operators, individually or in classes
- Token for identifiers
- One or more tokens for constants
- One token each for punctuation symbols

Representing Patterns

- Keywords can be directly represented (break, int).
- And so do punctuation symbols ({, +).
- Others are finite, but too many!
  - Numbers
  - Identifiers
  - They are better represented using a regular expression.
  - [a-z][a-z0-9]*, [0-9]+

Classwork: Regex Recap

- If L is a set of letters (A-Z, a-z) and D is a set of digits (0-9),
  - Find the size of the language LD.
  - Find the size of the language L U D.
  - Find the size of the language L^4.
- Write regex for real numbers
  - Without eE, without +- in mantissa (1.89)
  - Without eE, with +- in mantissa (-1.89)
  - With eE, with -+ in exponent (-1.89E-4)

Classwork

- Write regex for strings over alphabet {*a*, *b*} that start and end with *a*.
- Strings with third last letter as *a*.
- Strings with exactly three *b*s.
- Strings with even length.
- Homework
  - Exercises 3.3.6 from ALSU.

Example Lex

Patterns

Tokens

Lexemes

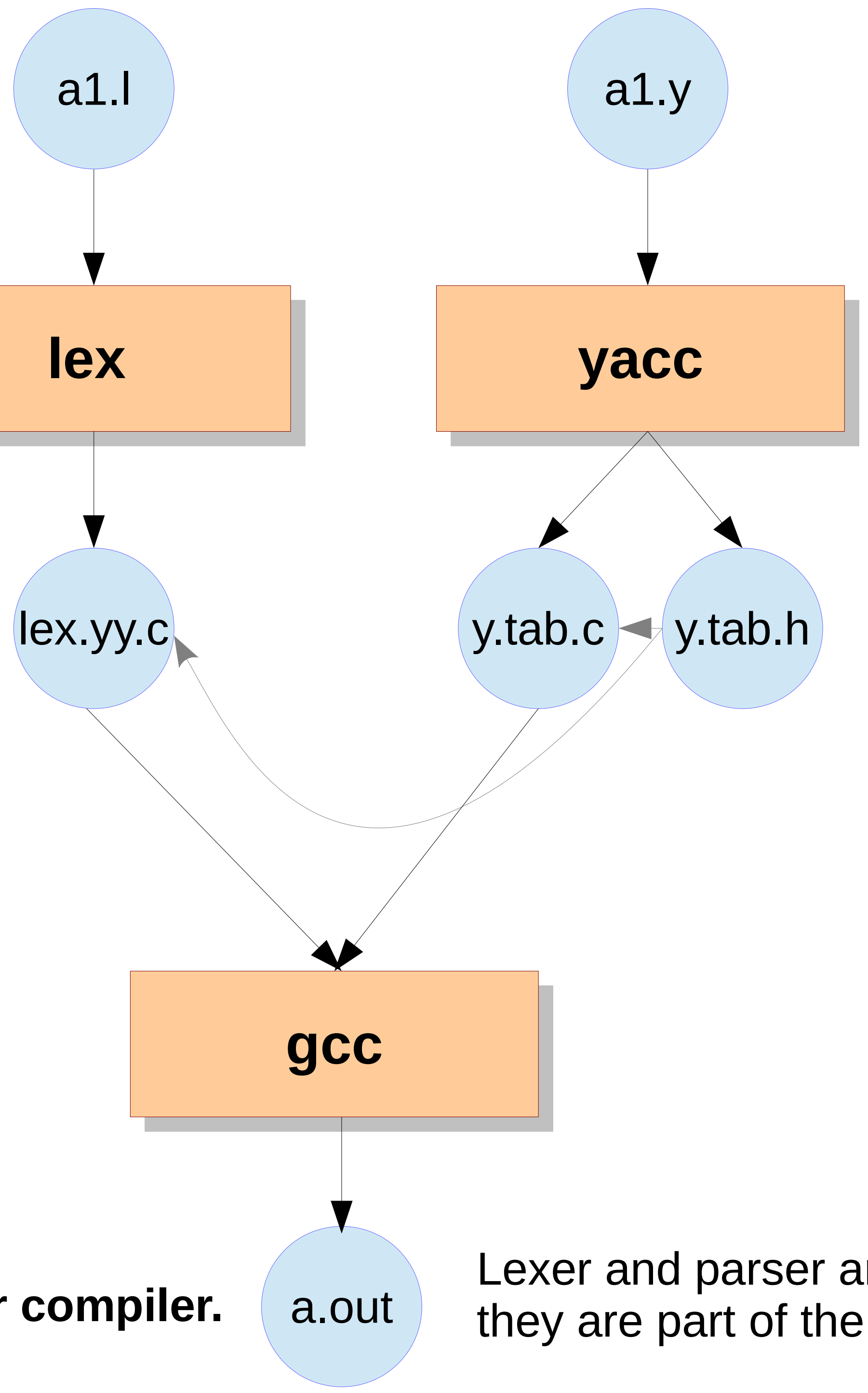
```
    /* variables */
[a-z]       {
                yylval = *yytext - 'a';
                return VARIABLE;
            }

    /* integers */
[0-9]+      {
                yylval = atoi(yytext);
                return INTEGER;
            }

    /* operators */
[-+()=/*\n] { return *yytext; }

    /* skip whitespace */
[ \t]       ;

    /* anything else is an error */
.               yyerror("invalid character");
```



This is your compiler.

Lexer and parser are not separate binaries; they are part of the same executable.

Lex Regex

<table>
<tr><th>Expression</th><th>Matches</th><th>Example</th></tr>
<tr><td>c</td><td>Character c</td><td>a</td></tr>
<tr><td>\c</td><td>Character c literally</td><td>*</td></tr>
<tr><td>“s”</td><td>String s literally</td><td>“**”</td></tr>
<tr><td>.</td><td>Any character but newline</td><td>a.*b</td></tr>
<tr><td>^</td><td>Beginning of a line</td><td>^abc</td></tr>
<tr><td>$</td><td>End of a line</td><td>abc$</td></tr>
<tr><td>[s]</td><td>Any of the characters in string s</td><td>[abc]</td></tr>
<tr><td>[^s]</td><td>Any one character not in string s</td><td>[^abc]</td></tr>
<tr><td>r*</td><td>Zero or more strings matching r</td><td>a*</td></tr>
<tr><td>r+</td><td>One or more strings matching r</td><td>a+</td></tr>
<tr><td>r?</td><td>Zero or one r</td><td>a?</td></tr>
<tr><td>r{m, n}</td><td>Between m and n occurrences of r</td><td>a{1,5}</td></tr>
<tr><td>r1r2</td><td>An r1 followed by an r2</td><td>ab</td></tr>
<tr><td>r1 | r2</td><td>An r1 or an r2</td><td>a | b</td></tr>
<tr><td>(r)</td><td>Same as r</td><td>(a | b)</td></tr>
<tr><td>r1/r2</td><td>r1 when followed by r2</td><td>abc/123</td></tr>
</table>

Homework

- Write a lexer to identify special words in a text.
  - Words like *stewardesses*: only one hand
  - Words like *typewriter*: only one keyboard row
  - Words like *skepticisms*: alternate hands
- Implement grep using lex with search pattern as alphabetical text (no operators *, ?, ., etc.).

Lexing and Context

- Language design should ensure that lexing can be done without context.
- Your assignments and most languages need context-insensitive lexing.

DO 5 I = 1.25

DO 5 I = 1,25

- “DO 5 I” is an identifier in Fortran, as spaces are allowed in identifiers.
- Thus, first is an assignment, while second is a loop.
- Lexer doesn't know whether to consider the input “DO 5 I” as an identifier or as a part of the loop, until parser informs it based on dot or comma.
- Alternatively, lexer may employ a lookahead.

Lookahead

Duniya usi ki hai jo aage dekhe

Lookahead

- Lexer needs to look into the future to know where it is presently.

DO 5 I = 1,25

DO / .* COMMA { return DO;}

- / signifies the lookahead symbol. The input is read and matched, but is left unconsumed in the current rule.

Corollary: DO loop index and increment must be on the same line – no arbitrary whitespace allowed.

Lexical Errors

- It is often difficult to report errors for a lexer.
  - fi (a == f(x)) …
  - A lexer doesn't know the context of fi. Hence it cannot “see” the structure of the sentence – structure is known only to the parser.
  - fi = 2; OR fi(a == f(x));
- But some errors a lexer can catch.
  - 23 = @a;
  - if $x friendof anil …

What should a lexer do on catching an error?

Error Handling

- Multiple options
  - exit(1);
  - Panic mode recovery: delete enough input to recognize a token
  - Delete one character from the input
  - Insert a missing character into the remaining input
  - Replace a character by another character
  - Transpose two adjacent characters
- In practice, most lexical errors involve a single character.
- Theoretical problem: Find the smallest number of transformations (add, replace, delete) needed to convert the source program into one that consists only of valid lexemes.
  - Too expensive in practice to be worth the effort.

Homework

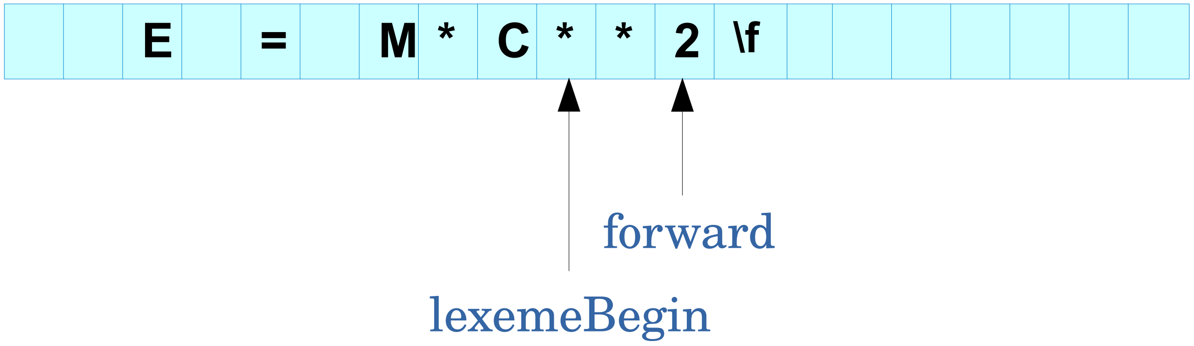
- Try exercise 3.1.2 from ALSU.

Input Buffering

- "*We cannot know we were executing a finite loop until we come out of the loop.*"
- In C, without reading the next character we cannot determine a binary minus symbol (a-b).
  - ->, -=, --, -e, ...
  - Sometimes we may have to look several characters in future, called *lookahead*.
  - In the fortran example (DO 5 I), the lookahead could be upto dot or comma.
- Reading character-by-character from disk is inefficient. Hence buffering is required.

Input Buffering

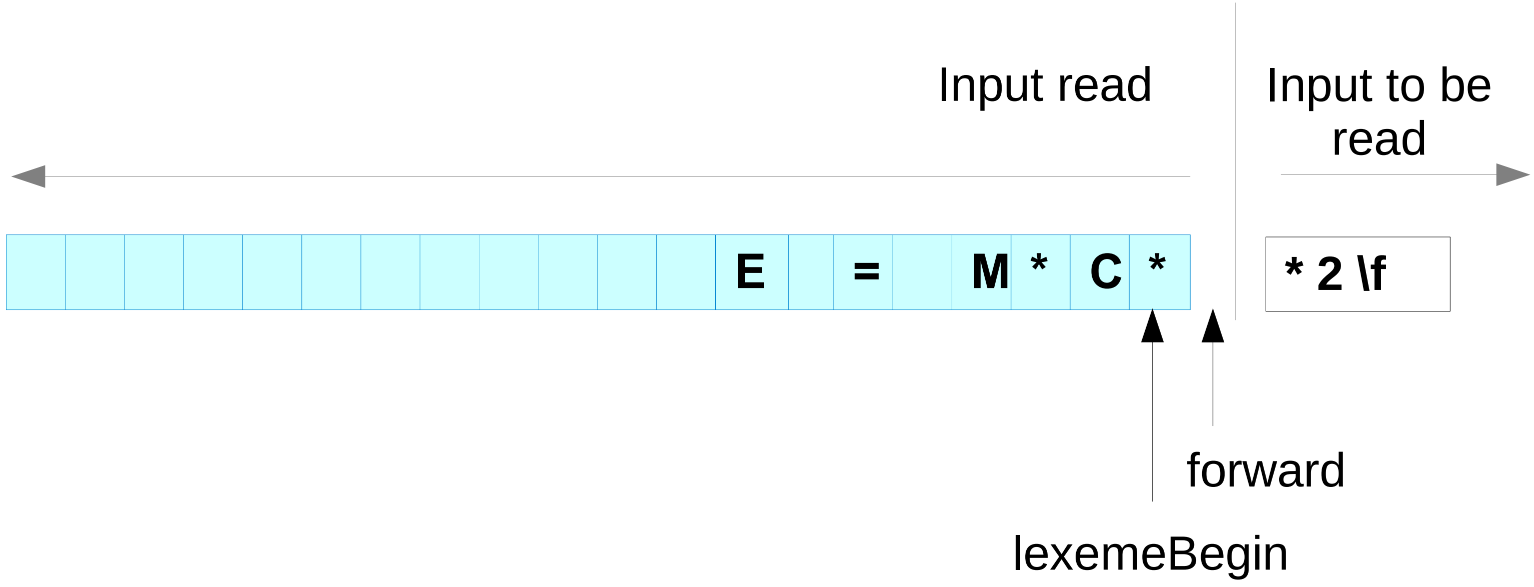
- A block of characters is read from disk into a buffer.
- Lexer maintains two pointers:
  - lexemeBegin
  - forward



What is the problem with such a scheme?

Input Buffering

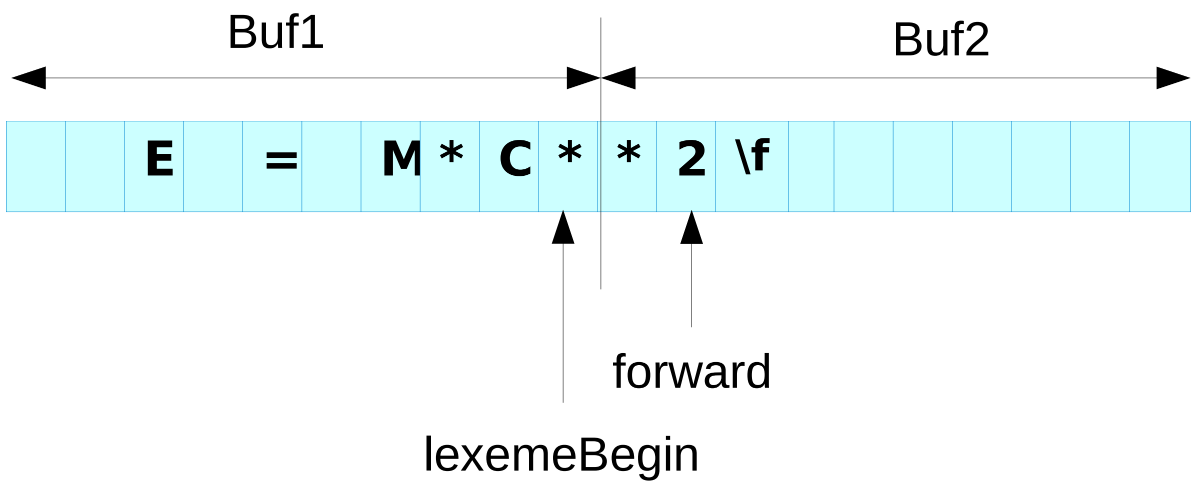
- The issue arises when the lookahead is beyond the buffer.
- When you load the buffer, the previous content is overwritten!



How do we solve this problem?

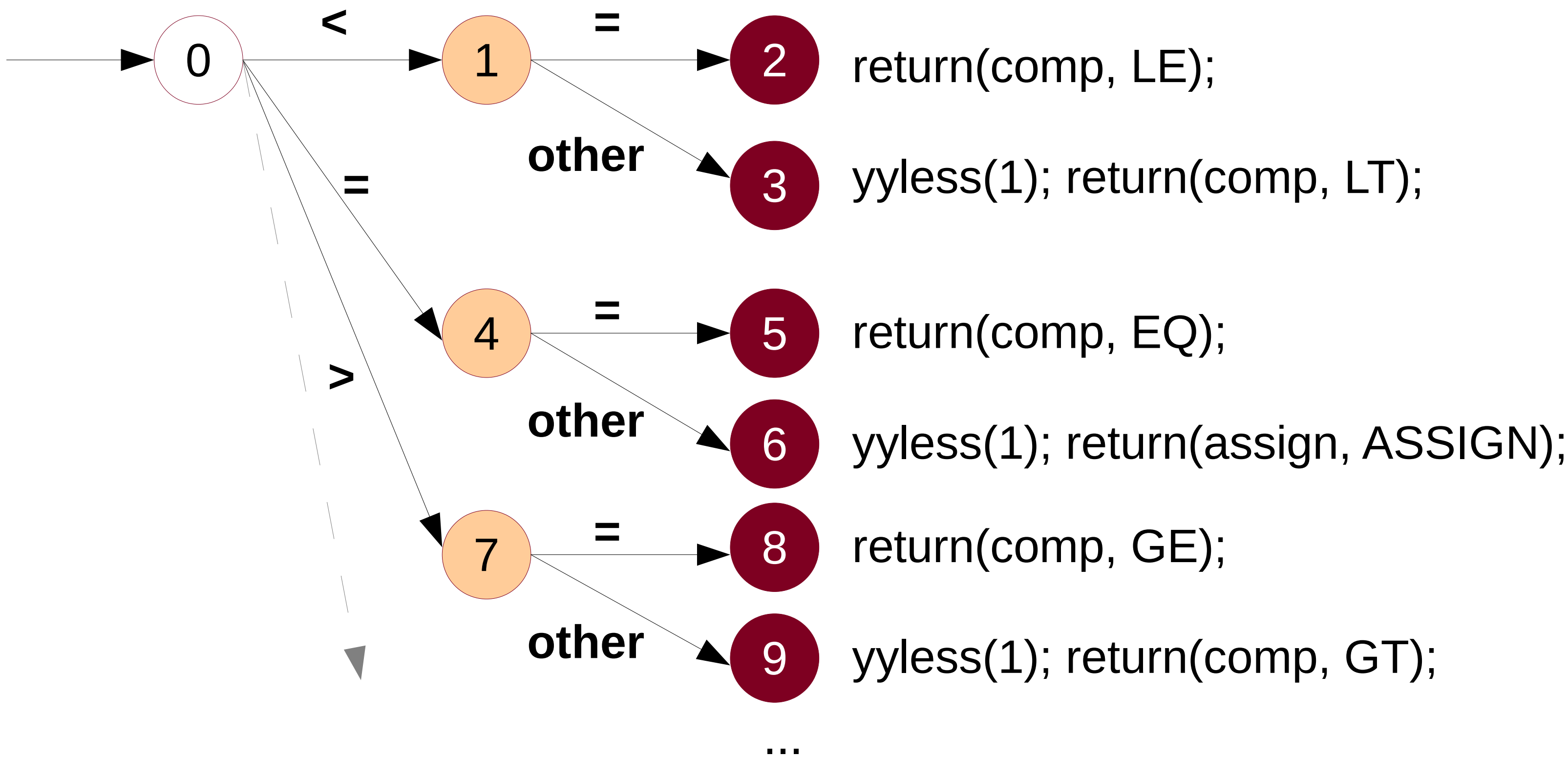
Double Buffering

- Uses two (half) buffers.
- Assumes that the lookahead would not be more than one buffer size.



Transition Diagrams

- Step to be taken on each character can be specified as a state transition diagram.
  - Sometimes, action may be associated with a state.



Keywords vs. Identifiers

- Keywords may match identifier pattern
  - Keywords: int, const, break, ...
  - Identifiers: (alpha | _) (alpha | num | _)*
- If unaddressed, may lead to strange errors.
  - Install keywords a priori in the symbol table.
  - Prioritize keywords
- In lex, the rule for a keyword must precede that of the identifier.

```
[a-z_A-Z][a-zA-Z_0-9]*      { return IDENT; }

"break"                     { return BREAK; }
```

Incorrect (lex may give warning)

```
"break"                     { return BREAK; }

[a-z_A-Z][a-zA-Z_0-9]*      { return IDENT; }
```

Correct

Special vs. General

- In general, a specialized pattern must precede the general pattern (*associativity*).
- Lex also follows maximum substring matching rule (*precedence*).
  - Reordering the rules for < and <= would not affect the functionality.
- Compare with rule specialization in Prolog.
- **Classwork**: Count number of *he* and *she* in a text.
- **Classwork**: Write lex rules to recognize quoted strings in C.
  - Try to recognize \” inside it.

he and she

```
she    ++s;
he     ++h;
```

```
she    {++s; REJECT;}
he     {++h;}
```

Retries another rule

What if I want to count all possible substrings *he*?

In general, the action associated with a rule may not be easy / modular to duplicate.

Input: he ahe he she she fsfds fsf fs sfhe he she she she

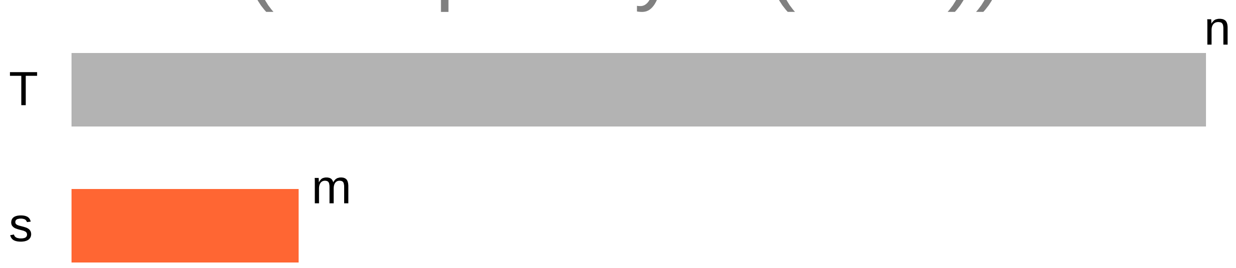
he=5, she=5 | he=10, she=5

By the way...

- Sometimes, you need not have a parser at all...
  - You could define *main* in your lex file.
  - Simply call *yylex()* from *main*.
  - Compile using *lex*, then compile *lex.yy.c* using *gcc* and execute *a.out*.

String Matching

- Lexical analyzer relies heavily on string matching.
- Given a program text T (length n) and a pattern string s (length m), we want to check if s occurs in T.
- A naive algorithm would try all positions of T to check for s (complexity O(m*n)).



Can we do better?

Where can we do better?

- T = abababaababbbabbababb
- s = ababaa

i = 0

abababaababbbabbababb

ababaa

Where can we do better?

- T = abababaababbbabbababb
- s = ababaa

i = 0

abababaababbbabbababb

ababaa

Where can we do better?

- T = ababaabaabbbabbababb
- s = ababaa

i = 1

ababaabaabbbabbababb

ababaa

Where can we do better?

- T = abababaababbbabbababb
- s = ababaa

i = 2

abababaababbbabbababb

ababaa

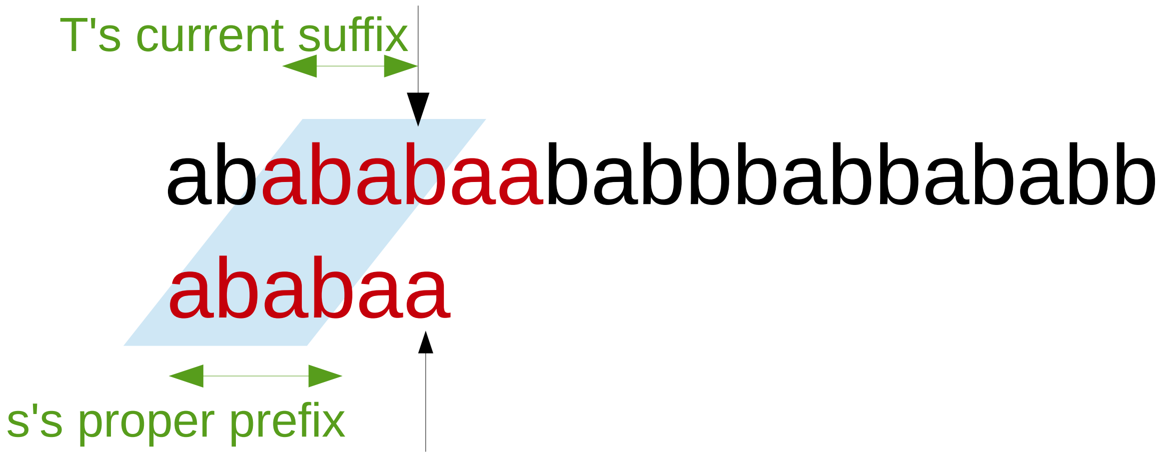
Match found

We need to handle the failure better.

Where can we do better?

- T = abababaababbbabbababb
- s = ababaa

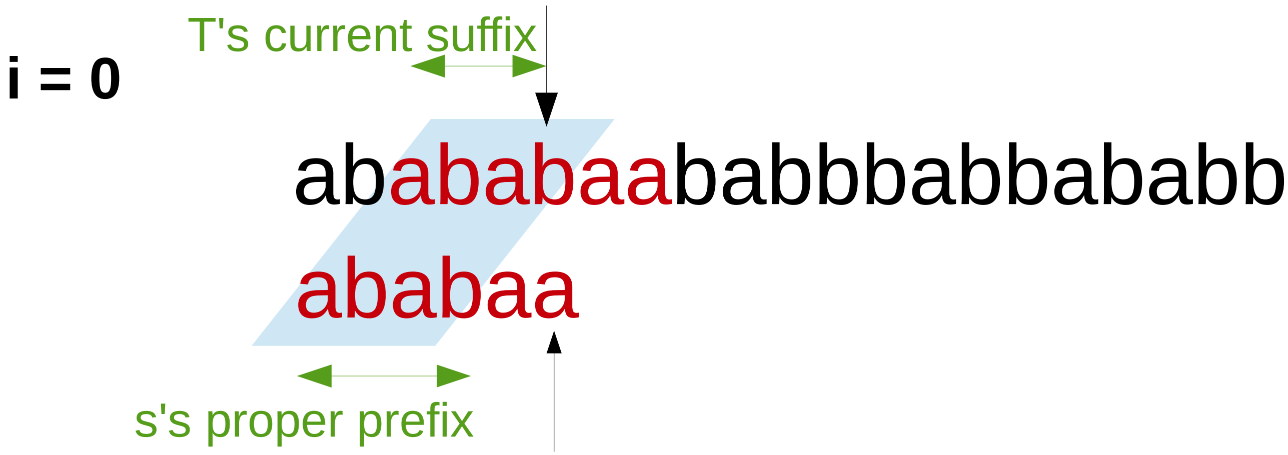
i = 0



Key observation: T's current suffix which is a <u>proper</u> prefix in s has the treasure for us.
Whenever there is a mismatch, we should utilize this overlap, rather than restarting.

Where can we do better?

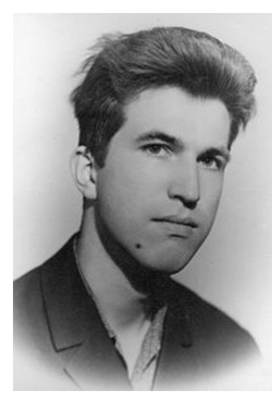
- T = ababaababbbabbababb
- s = ababaa



Key observation: T's current suffix which is a <u>proper</u> prefix in s has the treasure for us.
Whenever there is a mismatch, we should utilize this overlap, rather than restarting.

Knuth-Morris-Pratt Algorithm

- In 1970, Morris conceived the idea.
- After a few weeks, Knuth independently discovered the idea.
- In 1970, Morris and Pratt published a techreport.
- KMP published the algorithm jointly in 1977.
- In 1969, Matiyasevic discovered a similar algorithm.



Source: wikipedia

KMP String Matching

- First linear time algorithm for string matching.
- Whenver there is a mismatch, do not restart; rather *fail intelligently*.
- We define a failure function for each position, taking into account the suffix and the prefix.
- Note that the matched part of the large string T is essentially the pattern string s. Thus, failure function can be computed simply using pattern s.

Failure is not final.

Failure function for *ababaa*

i	1	2	3	4	5	6
f(i)	0	0	1	2	3	1

seen	a	ab	aba	abab	ababa	ababaa
prefix	ϵ	ϵ	a	ab	aba	a

Algorithm given as Figure 3.19 in ALSU.

String matching with failure function

Text = $a_1a_2...a_m$; pattern = $b_1b_2...b_n$ (both indexed from 1)

```
s = 0
for (i = 1; i <= m; ++i) {          ◄── Go over Text
    if (s > 0 && a_i != b_s+1) s = f(s)   ◄── Handle failure
    if (a_i == b_s+1) ++s           ◄── Character match
    if (s == n) return "yes"        ◄── Full match
}
return "no"
```

i	1	2	3	4	5	6
f(i)	0	0	1	2	3	1

seen	a	ab	aba	abab	ababa	ababaa
prefix	ϵ	ϵ	a	ab	aba	a

Find the flaw in the algorithm.

String matching with failure function

Text = $a_1a_2...a_m$; pattern = $b_1b_2...b_n$ (both indexed from 1)

```
s = 0
for (i = 1; i <= m; ++i) {                      ← Go over Text
    while (s > 0 && a_i != b_{s+1}) s = f(s)    ← Handle failure
    if (a_i == b_{s+1}) ++s                     ← Character match
    if (s == n) return "yes"                    ← Full match
}
return "no"
```

i	1	2	3	4	5	6
f(i)	0	0	1	2	3	1

seen	a	ab	aba	abab	ababa	ababaa
prefix	ϵ	ϵ	a	ab	aba	a

Find the flaw in the algorithm.

Classwork

- Find failure function for pattern *ababba*.
  - Test it on string *abababbaa*.
- Find failure function for *aaaaa* (and apply on aaaab)
  - Example needing multiple iterations of *while*.
  - Despite the nested loop, the complexity is O(m+n).
  - The backward traversal of the pattern is upper-bounded by the forward traversal.
  - Forward traversal increments text index.
  - For n-length pattern match, the backward traversal can be at most n. Thus, O(2n) for n-length match.
  - Examples at this link.

Fibonacci Strings

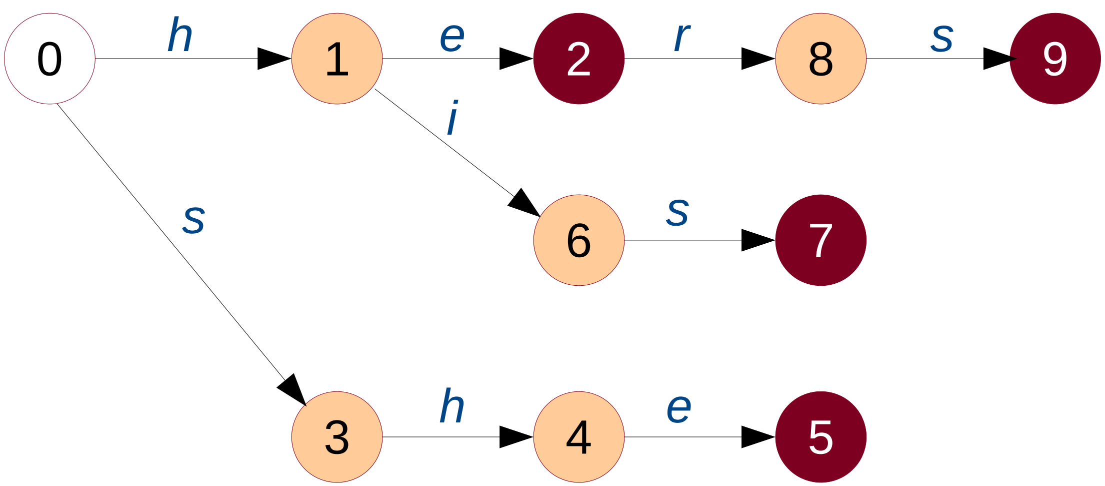
- $s_1 = b$, $s_2 = a$, $s_k = s_{k-1}s_{k-2}$ for $k > 2$
- e.g., $s_3 = ab$, $s_4 = aba$, $s_5 = abaab$

- Do not contain *bb* or *aaa*.
- The words end in *ba* and *ab* alternatively.
- Suppressing last two letters creates a palindrome.
- ...
- Find the failure function for Fibonacci String s_6.

Source: Wikipedia

KMP Generalization

- KMP can be used for keyword matching.
- Aho and Corasick generalized KMP to recognize any of a set of keywords in a text.

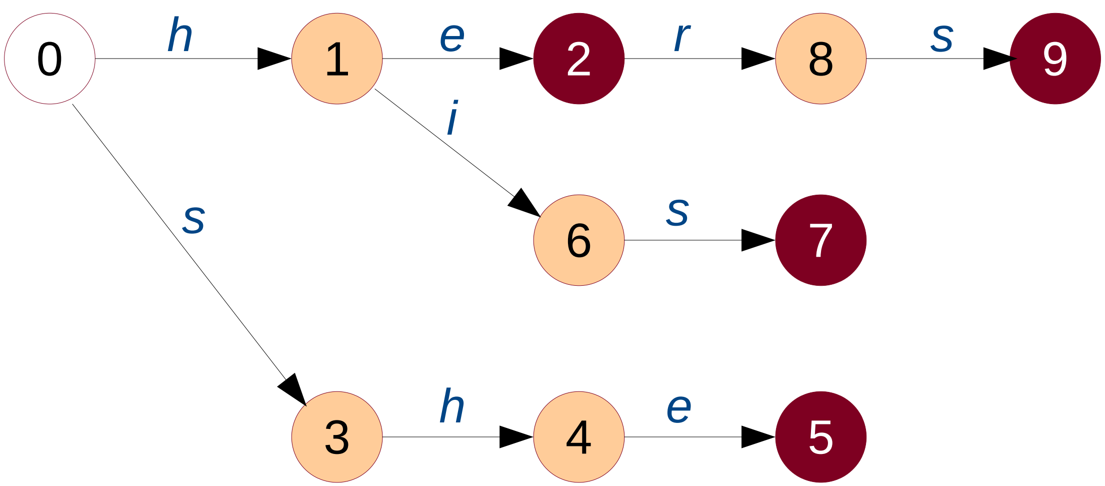


Transition diagram for keywords *he*, *she*, *his* and *hers*.

i	1	2	3	4	5	6	7	8	9
f(i)	0	0	0	1	2	0	3	0	3

KMP Generalization

- When in state *i*, the failure function *f(i)* notes the state corresponding to the longest proper suffix that is also a prefix of some keyword.



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i	1	2	3	4	5	6	7	8	9
f(i)	0	0	0	1	2	0	3	0	3

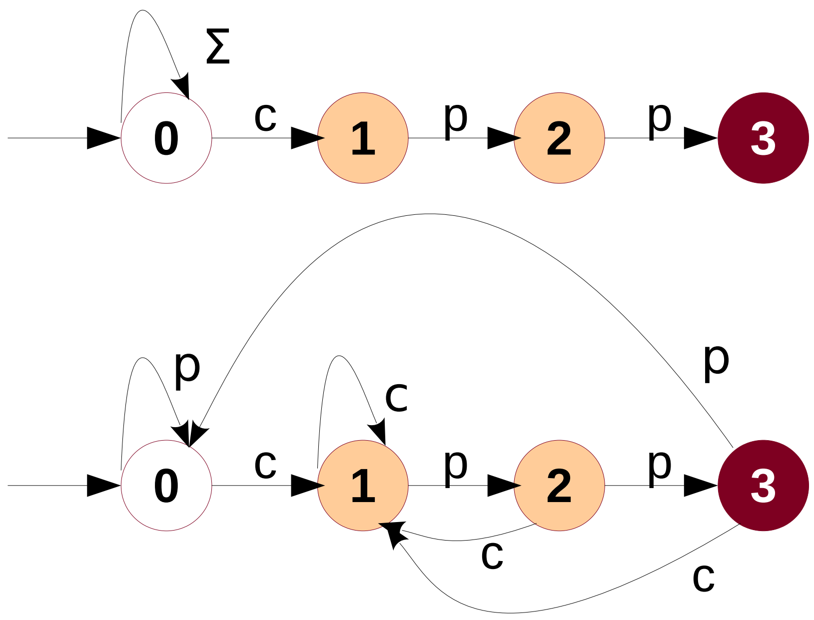
In state **7**, character s matches prefix of the keyword she to reach state **3**.

Regex to DFA

- Approach 1: Regex → NFA → DFA
- Approach 2: Regex → DFA
  - The ideas would be helpful in parsing too.

Regex → NFA → DFA

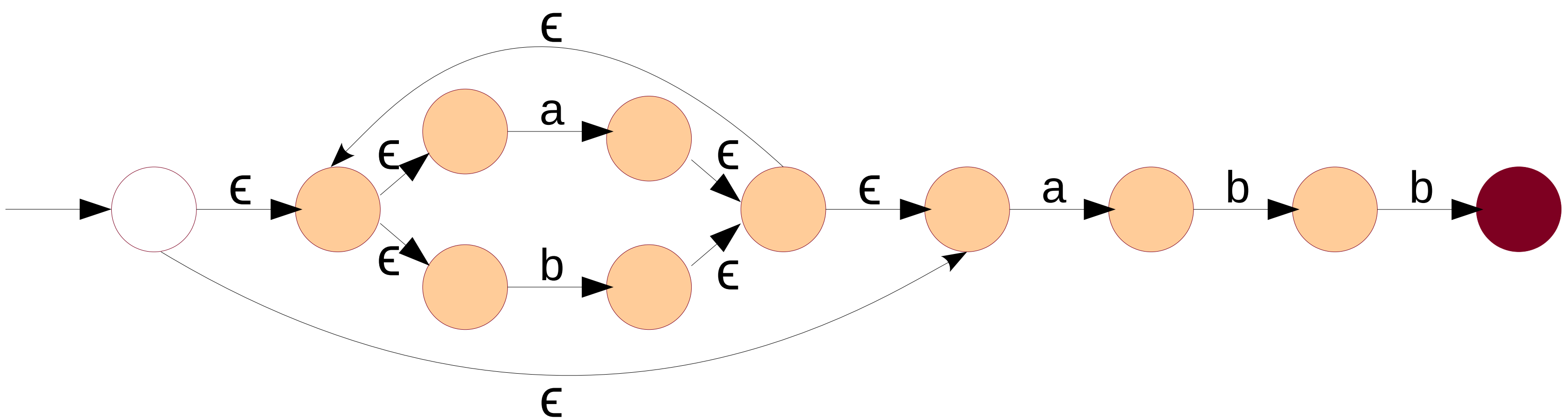
Draw an NFA for **cpp*



How does a machine draw an NFA for an arbitrary regular expression such as ((aa)*b(bb)*(aa)*)* ?

Regex → NFA → DFA

- For the sake of convenience, let's convert *cpp into *abb and restrict to alphabet {a, b}.
- Thus, the regex is (a|b)*abb.
- How do we create an NFA for (a|b)*abb?



Regex → NFA → DFA

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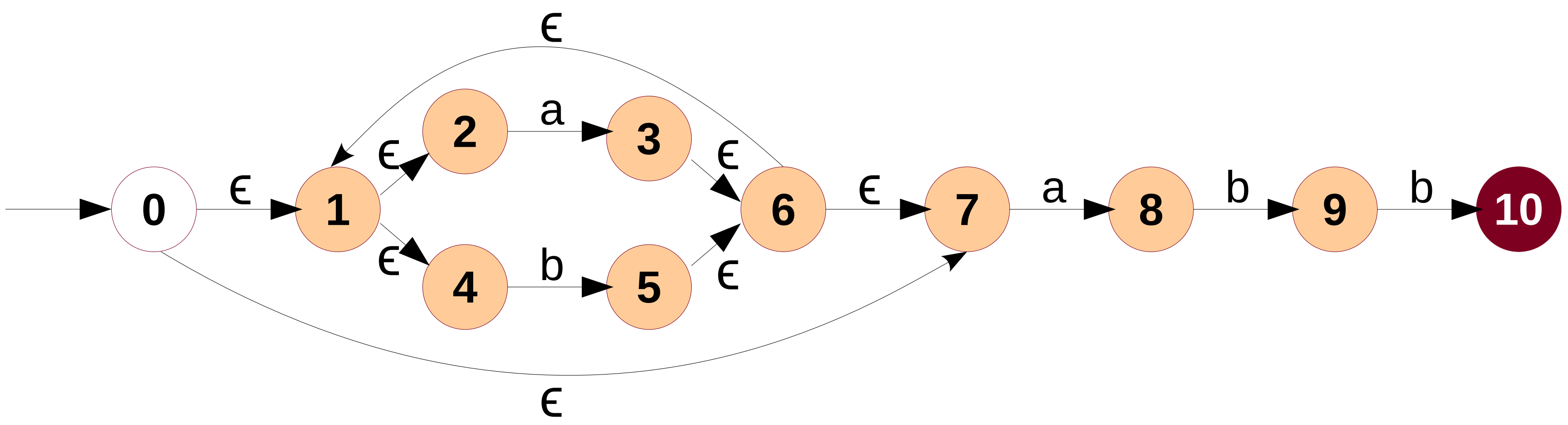
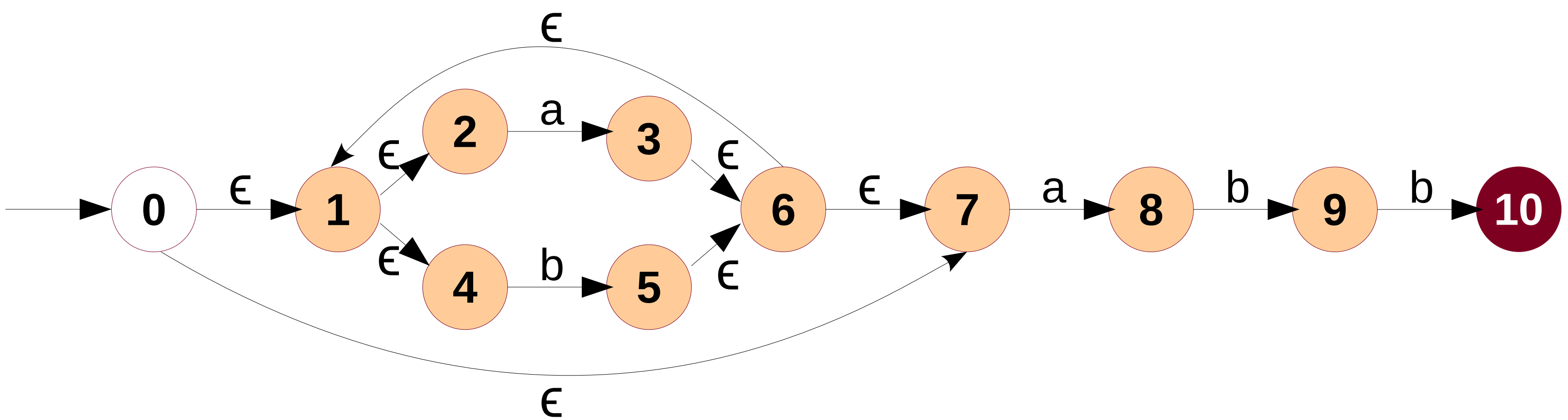


Regex → NFA → DFA

NFA state	DFA state	a	b
{0, 1, 2, 4, 7}	A	B	C
{1, 2, 3, 4, 6, 7, 8}	B	B	D
{1, 2, 4, 5, 6, 7}	C	B	C
{1, 2, 4, 5, 6, 7, 9}	D	B	E
{1, 2, 4, 5, 6, 7, 10}	E	B	C

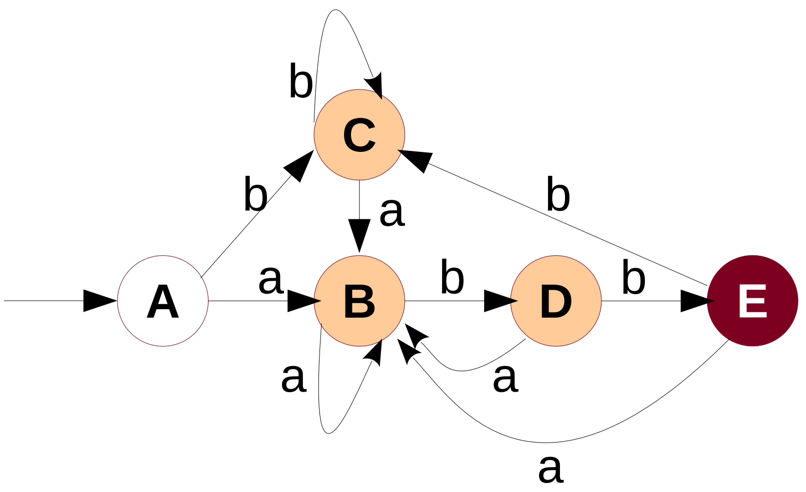
State Transition Table



Regex → NFA → DFA

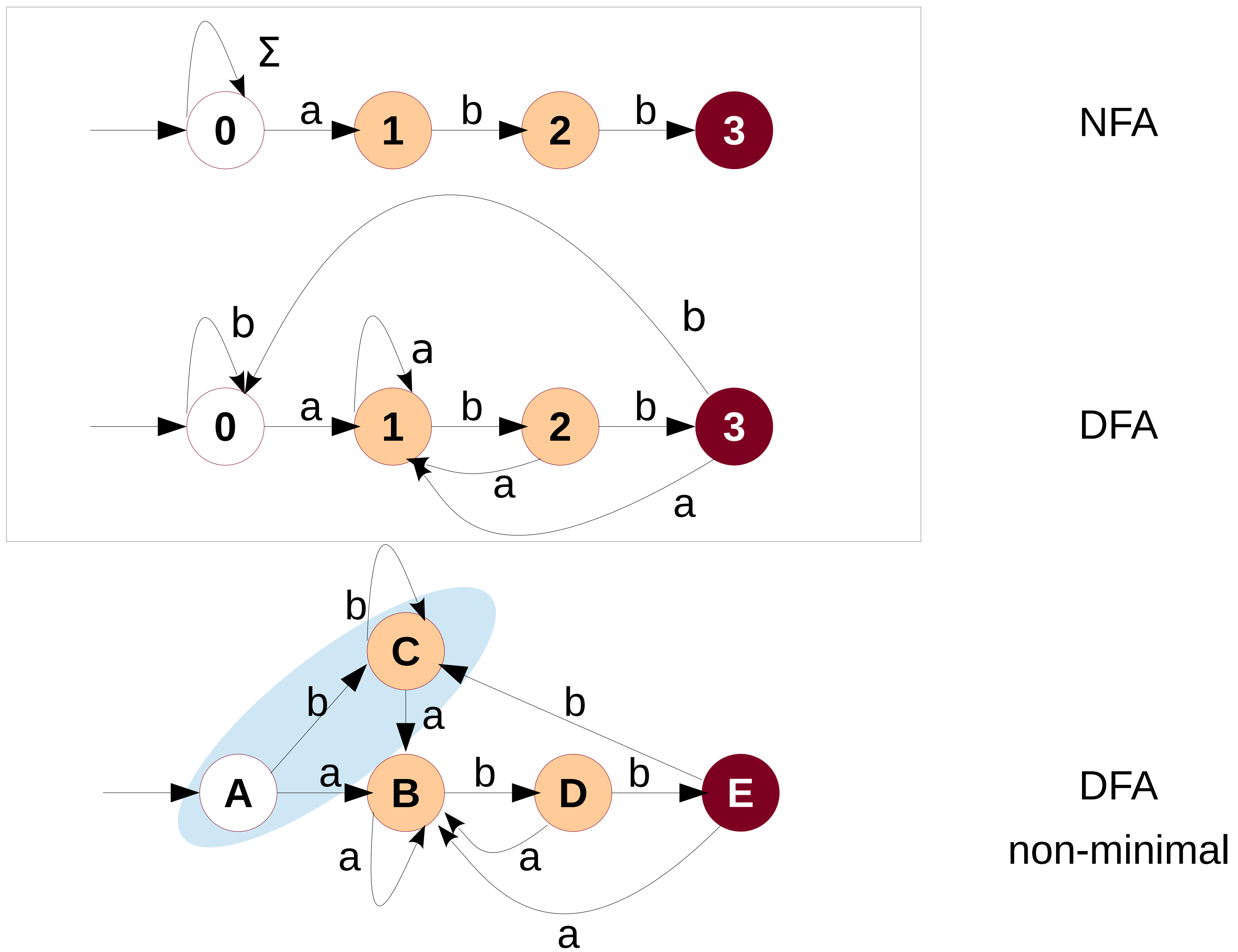
NFA state	DFA state	a	b
{0, 1, 2, 4, 7}	A	B	C
{1, 2, 3, 4, 6, 7, 8}	B	B	D
{1, 2, 4, 5, 6, 7}	C	B	C
{1, 2, 4, 5, 6, 7, 9}	D	B	E
{1, 2, 4, 5, 6, 7, 10}	E	B	C

State Transition Table



DFA

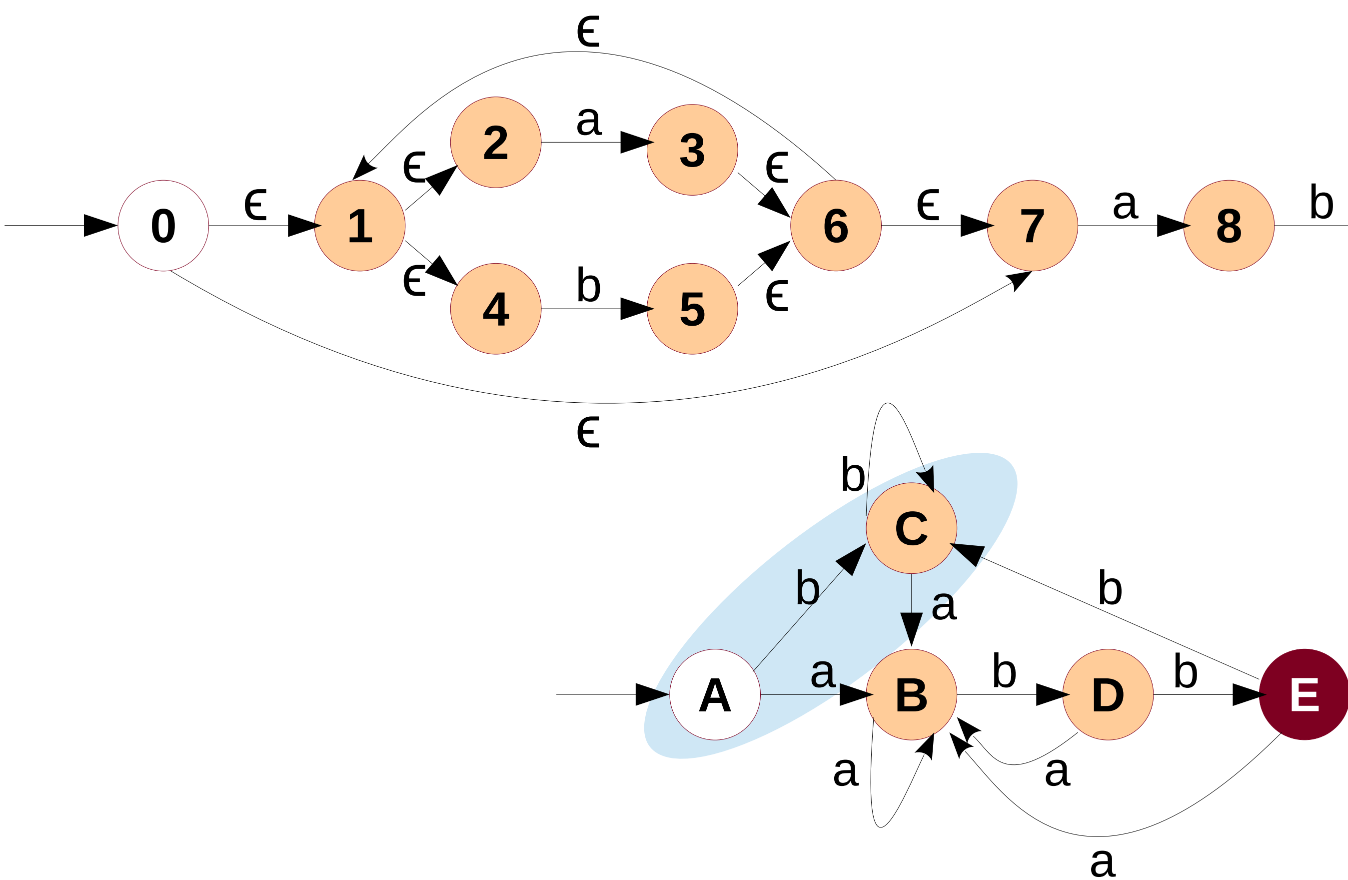
Regex → NFA → DFA



Regex → NFA → DFA

(a|b)*abb

Regex



NFA

DFA

non-minimal

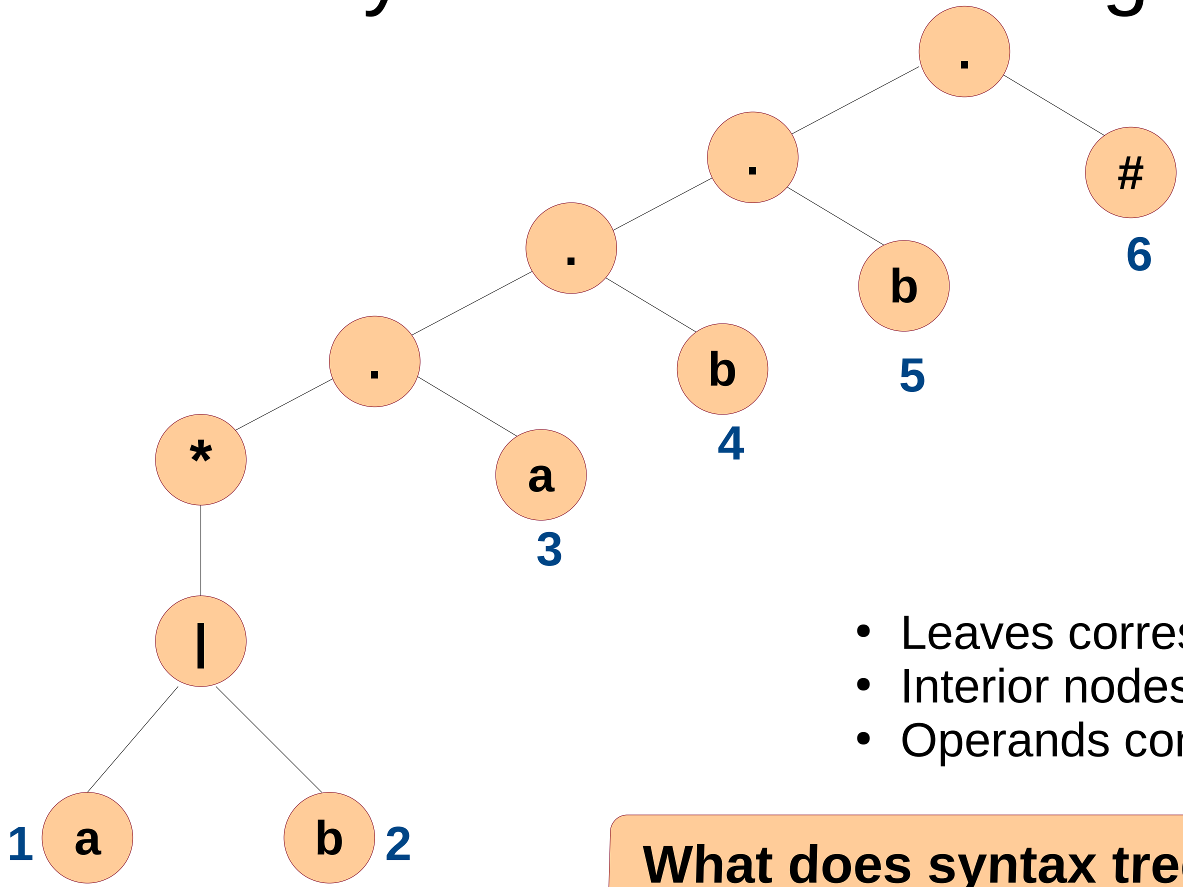
Lex directly converts Regex to DFA without an intermediate NFA. How?

Regex → DFA

1. Construct a syntax tree for regex#.
2. Compute *nullable*, *firstpos*, *lastpos*, *followpos*.
3. Construct DFA using transition function.
4. Mark *firstpos(root)* as start state.
5. Mark states that contain position of # as accepting states.

Regex → DFA

- Regex is (a|b)*abb#.
- Construct a syntax tree for the regex.

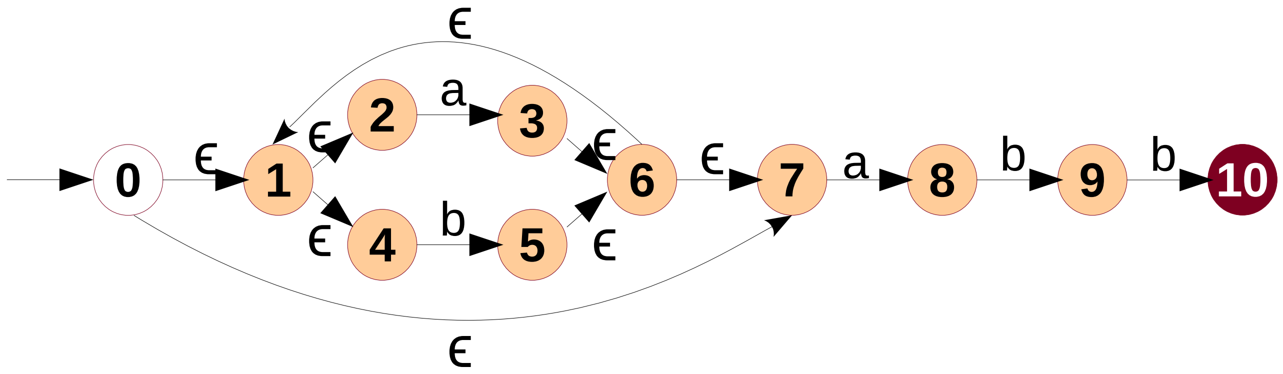


- Leaves correspond to operands.
- Interior nodes correspond to operators.
- Operands constitute strings.

What does syntax tree for regex indicate?

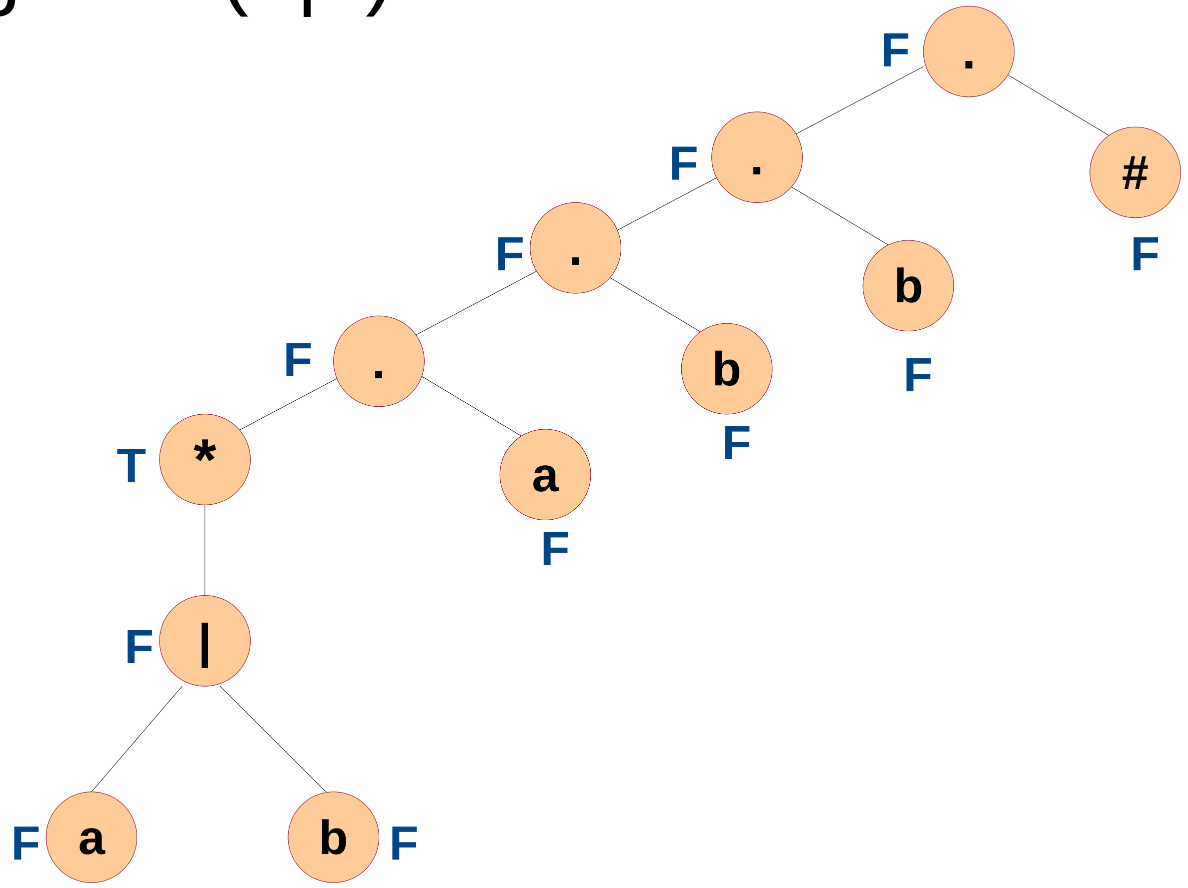
Functions from Syntax Tree

- For a syntax tree node n
  - *nullable*(n): true if n represents ϵ.
  - *firstpos*(n): set of positions that correspond to the first symbol of strings in n's subtree.
  - *lastpos*(n): set of positions that correspond to the last symbol of strings in n's subtree.
  - *followpos*(n): set of next possible positions from n for valid strings.



nullable

- *nullable*(n): true if n represents ϵ.
- Regex is (a|b)*abb#.



nullable

- *nullable*(n): true if n represents ϵ.

Node n	nullable(n)
leaf labeled ϵ	true
leaf with position i	false
or-node n = c1 | c2	nullable(c1) or nullable(c2)
cat-node n = c1c2	nullable(c1) and nullable(c2)
star-node n = c*	true

Classwork: Write down the rules for firstpos(n).

- *firstpos*(n): set of positions that correspond to the first symbol of strings in n's subtree.

firstpos

- *firstpos*(n): set of positions that correspond to the first symbol of strings in n's subtree.

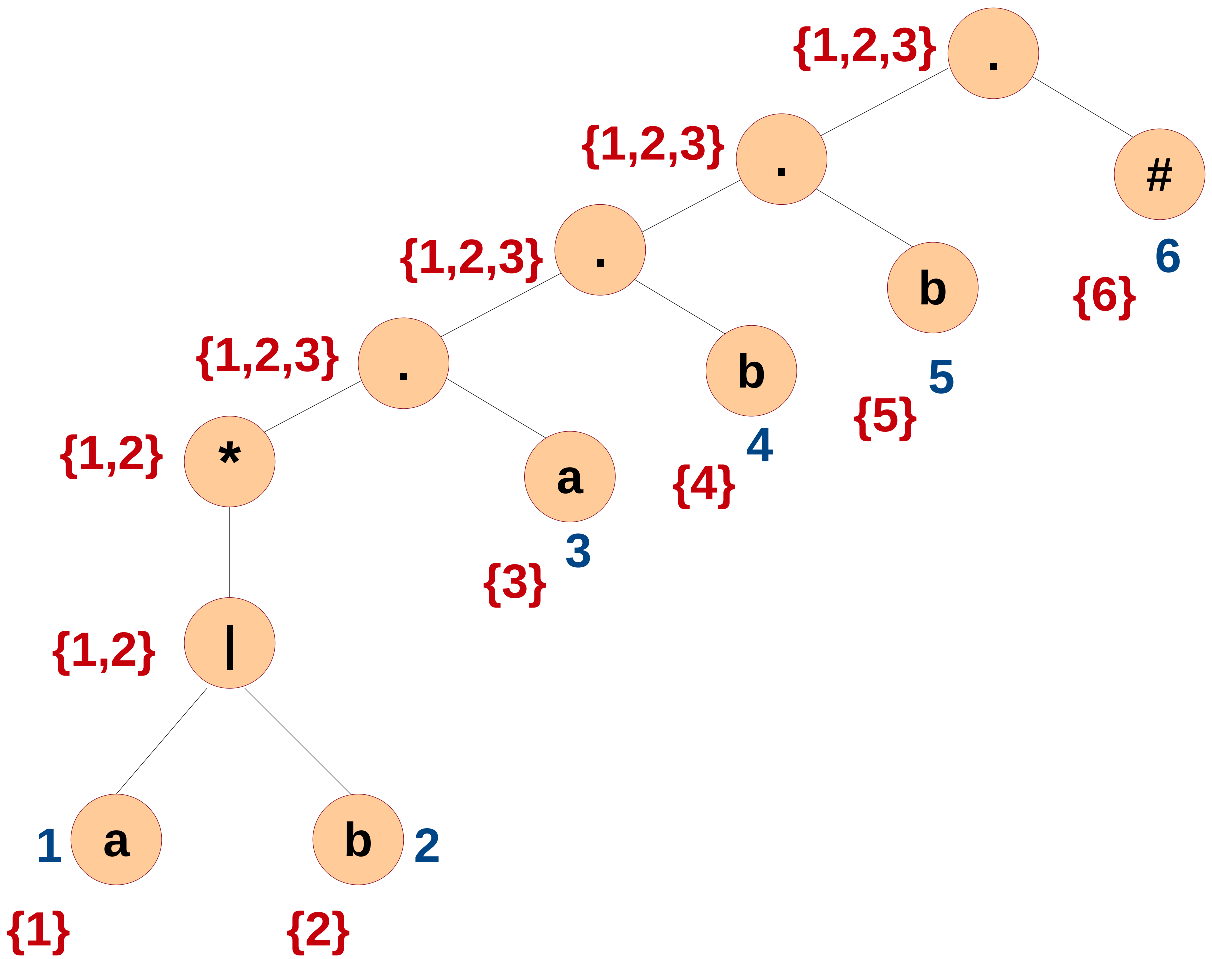
Node n	**firstpos(n)**
leaf labeled ϵ	{ }
leaf with position i	{i}
or-node n = c1 | c2	firstpos(c1) U firstpos(c2)
cat-node n = c1c2	
star-node n = c*	firstpos(c)

firstpos

- *firstpos*(n): set of positions that correspond to the first symbol of strings in n's subtree.

Node n	**firstpos(n)**
leaf labeled ϵ	{ }
leaf with position i	{i}
or-node n = c1 | c2	firstpos(c1) U firstpos(c2)
cat-node n = c1c2	if (nullable(c1)) firstpos(c1) U firstpos(c2) else firstpos(c1)
star-node n = c*	firstpos(c)

firstpos



firstpos

- *firstpos*(n): set of positions that correspond to the first symbol of strings in n's subtree.

Node n	**firstpos(n)**
leaf labeled ϵ	{ }
leaf with position i	{i}
or-node n = c1 | c2	firstpos(c1) U firstpos(c2)
cat-node n = c1c2	if (nullable(c1)) firstpos(c1) U firstpos(c2) else firstpos(c1)
star-node n = c*	firstpos(c)

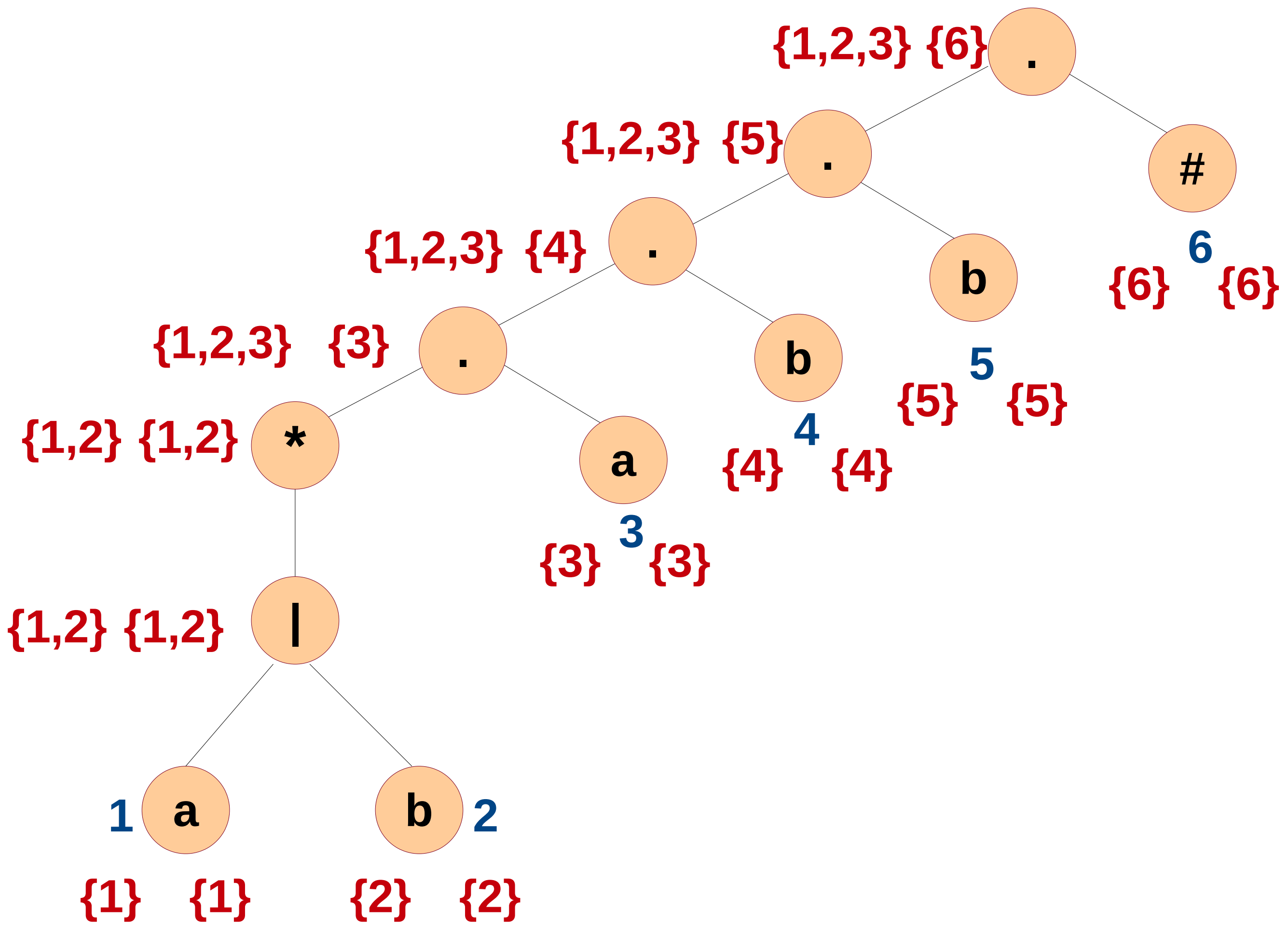
Classwork: Write down the rules for lastpos(n).

lastpos

- *lastpos*(n): set of positions that correspond to the last symbol of strings in n's subtree.

Node n	**lastpos(n)**
leaf labeled ϵ	{ }
leaf with position i	{i}
or-node n = c1 | c2	lastpos(c1) U lastpos(c2)
cat-node n = c1c2	if (nullable(c2)) lastpos(c1) U lastpos(c2) else lastpos(c2)
star-node n = c*	lastpos(c)

firstpos lastpos

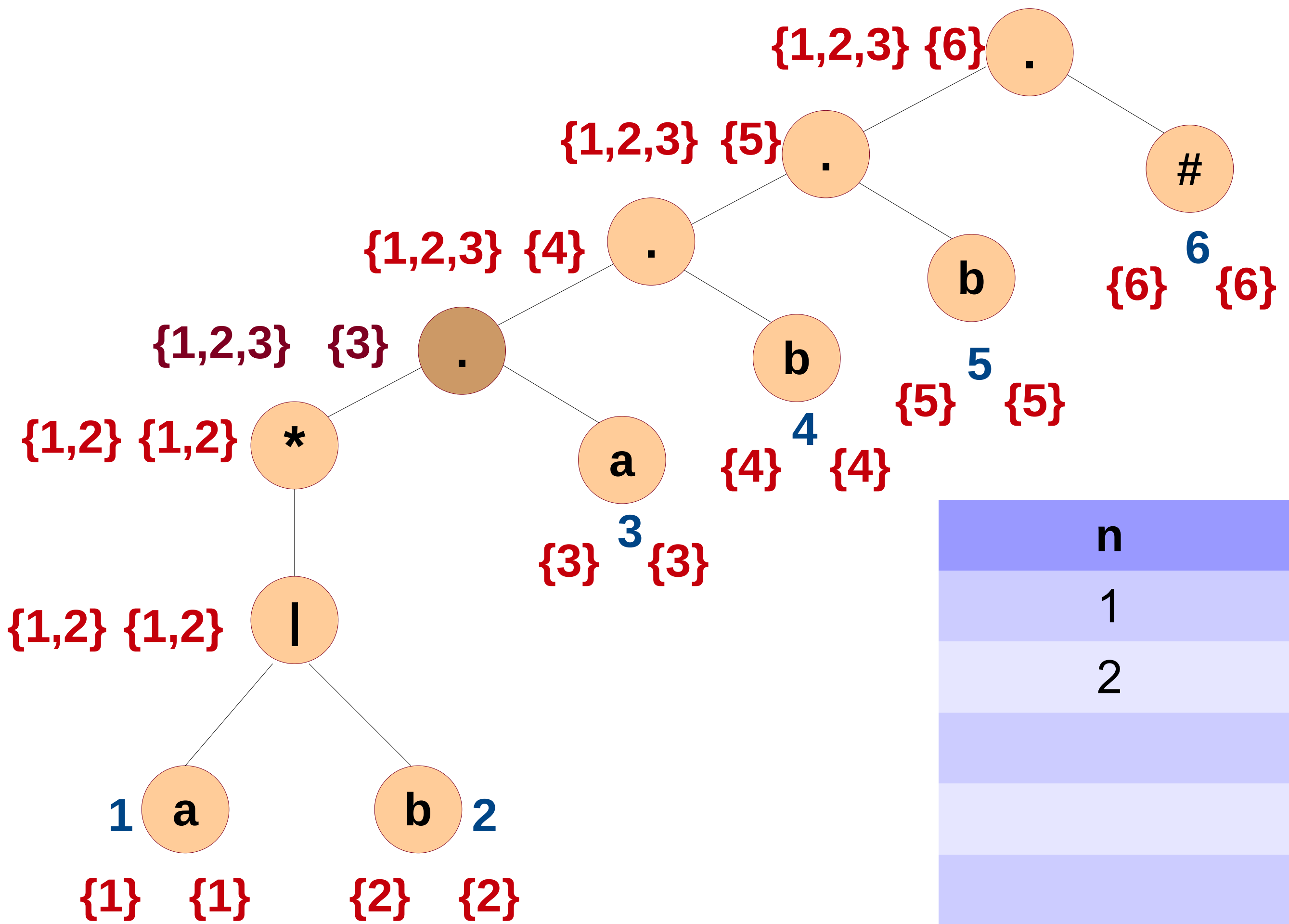


followpos

- *followpos*(n): set of next possible positions from n for valid strings.
  - If n is a **cat-node** with child nodes c1 and c2 (c1.c2), then for each position in *lastpos(c1)*, all positions in *firstpos(c2)* *follow*.
  - If n is a **star-node**, then for each position in *lastpos(n)*, all positions in *firstpos(n)* *follow*.
  - If n is an **or-node**, ...

followpos

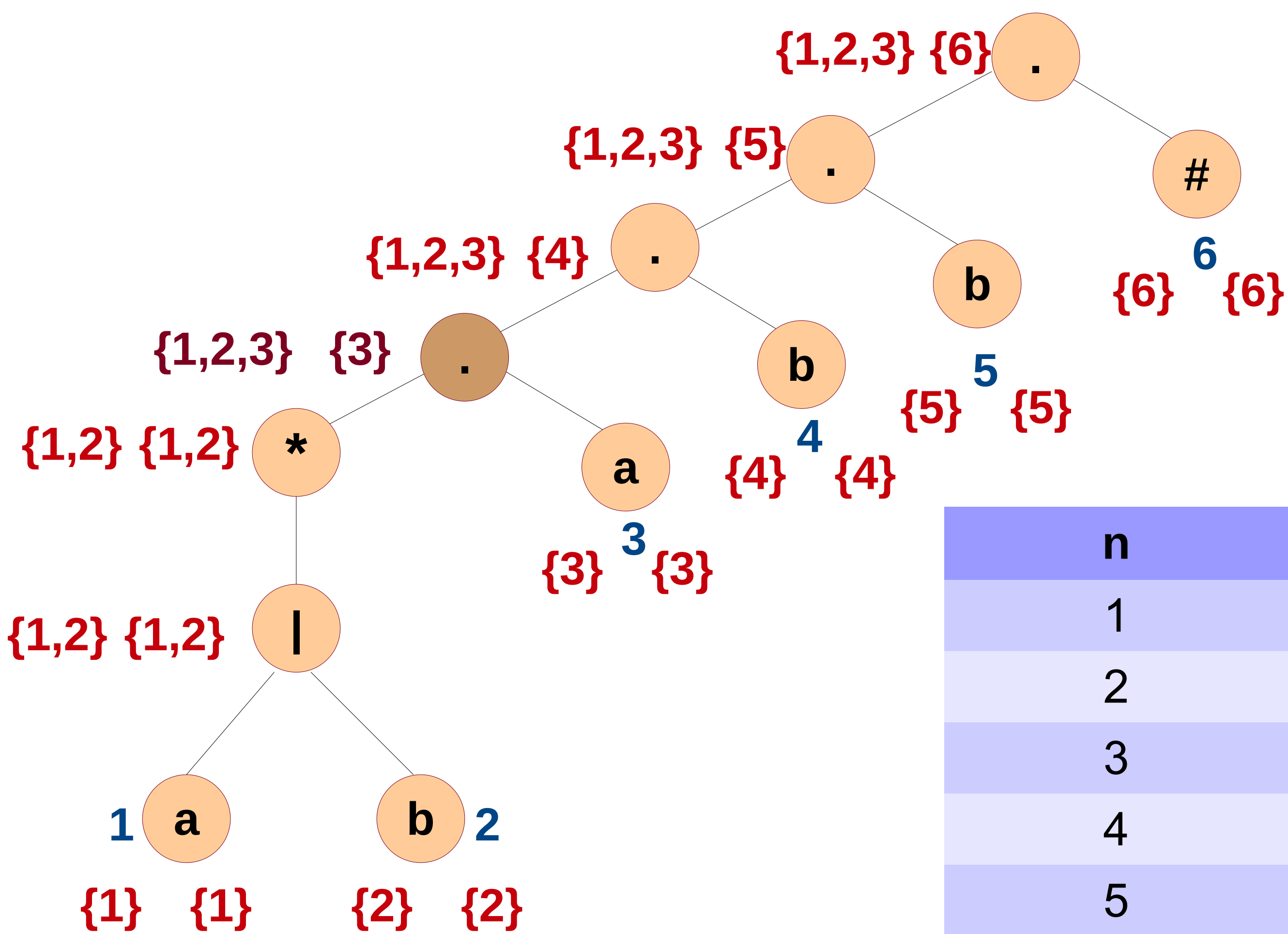
If n is a **cat-node** with child nodes c1 and c2, then for each position in *lastpos(c1)*, all positions in *firstpos(c2)* *follow*.



n	followpos(n)
1	{3}
2	{3}

followpos

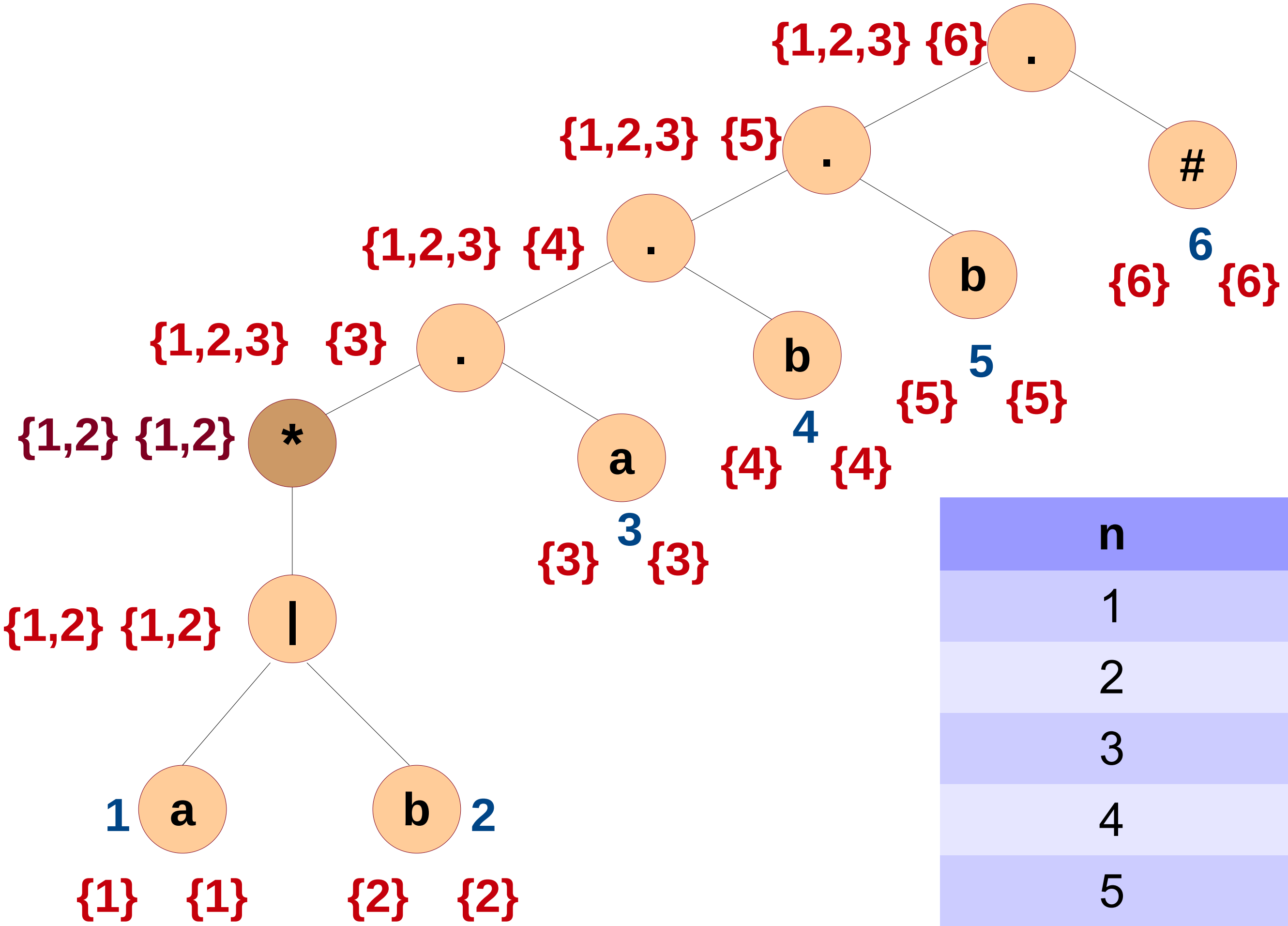
If n is a **cat-node** with child nodes c1 and c2, then for each position in *lastpos(c1)*, all positions in *firstpos(c2)* *follow*.



n	followpos(n)
1	{3}
2	{3}
3	{4}
4	{5}
5	{6}
6	{ }

followpos

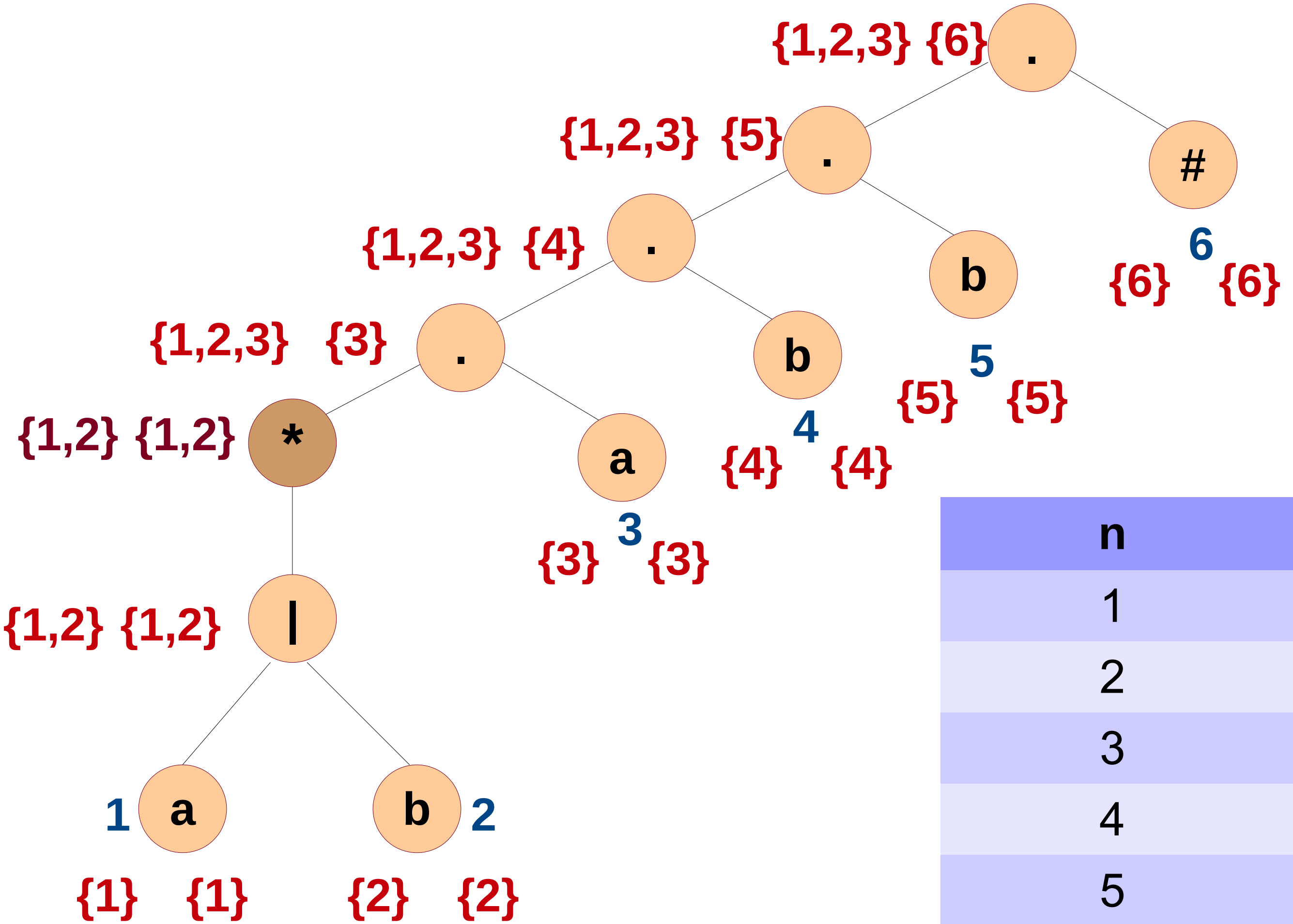
If n is a **star-node**, then for each position in *lastpos(n)*, all positions in *firstpos(n)* *follow*.



n	followpos(n)
1	{3}
2	{3}
3	{4}
4	{5}
5	{6}
6	{ }

followpos

If n is a **star-node**, then for each position in *lastpos(n)*, all positions in *firstpos(n)* *follow*.



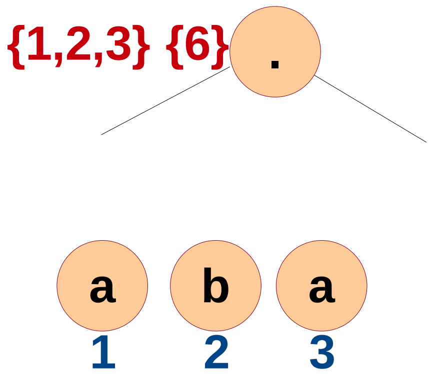
n	followpos(n)
1	{3, 1, 2}
2	{3, 1, 2}
3	{4}
4	{5}
5	{6}
6	{ }

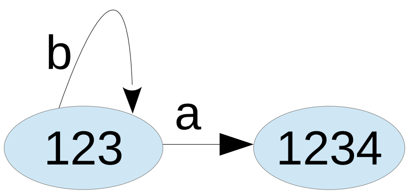
Regex → DFA

1. Construct a syntax tree for regex#.
2. Compute *nullable*, *firstpos*, *lastpos*, *followpos*.
3. Construct DFA using transition function *(next slide)*.
4. Mark *firstpos(root)* as start state.
5. Mark states that contain position of # as accepting states.

DFA Transitions

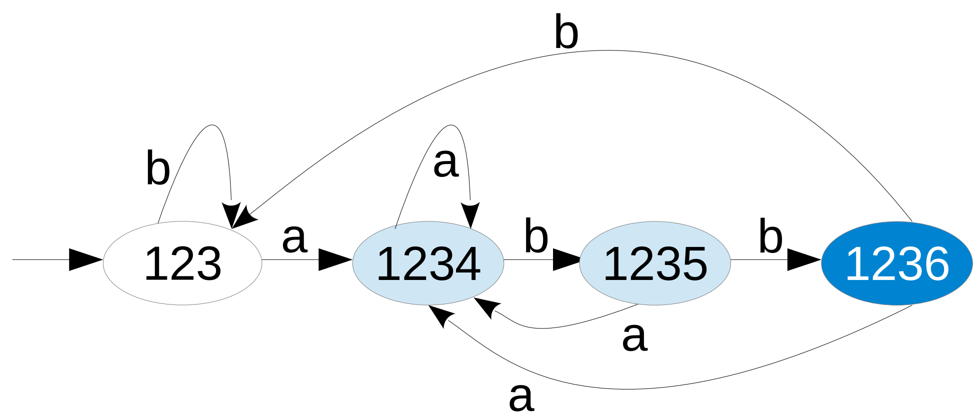
create unmarked state *firstpos(root)*.
while there exists unmarked state s {
    mark s
    for each input symbol *x* {
        uf = U followpos(p) where p is in s labeled *x*
        transition[s, *x*] = uf
        if uf is newly created
            unmark uf
    }
}



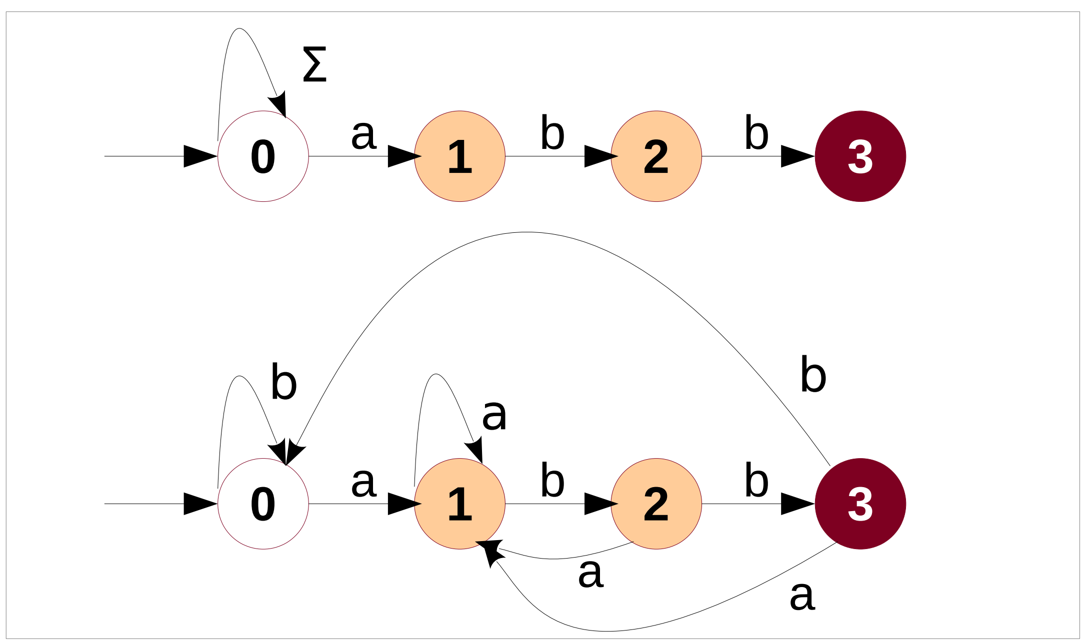


n	followpos(n)
1	{3, 1, 2}
2	{3, 1, 2}
3	{4}
4	{5}
5	{6}
6	{ }

Final DFA



DFA



NFA

DFA

Regex → DFA

1. Construct a syntax tree for regex#.
2. Compute *nullable*, *firstpos*, *lastpos*, *followpos*.
3. Construct DFA using transition function.
4. Mark *firstpos(root)* as start state.
5. Mark states that contain position of # as accepting states.

Do this for (b|ab)*(aa|b)*.

In case you are wondering...

- What to do with this DFA?
  - Recognize strings during lexical analysis.
  - Could be used in utilities such as *grep*.
  - Could be used in regex libraries as supported in php, python, perl, ...

Lexing Summary

- Basic *lex*
- Input Buffering
- KMP String Matching
- Regex → NFA → DFA
- Regex → DFA