Check-In

Review: Compiler Overview

The “traditional” compiler workflow presented in class creates an intermediate format in the middle-end. Why not translate directly from the AST (abstract syntax tree) to final code?

Administriva

Housekeeping

Project 1

- Out tonight
- Add Flex rules for our language
- Might want to find a project partner!

Administriva

Housekeeping

What should we call our language?

Surveys (Mostly) Processed

Housekeeping

- We <u>will</u> do flipped Wednesdays
- I'll try to put out some 510 review

2 – Implementing Scanners

Compiler Construction

Progress Pics

Currently working on lexical analysis concepts

- Convert the character stream from the user into the token stream (the “words” of the programming language)

Scanner
Lexical analysis

Parser
Syntactic analysis

Semantic analysis

Intermediate code generation

IR optimization

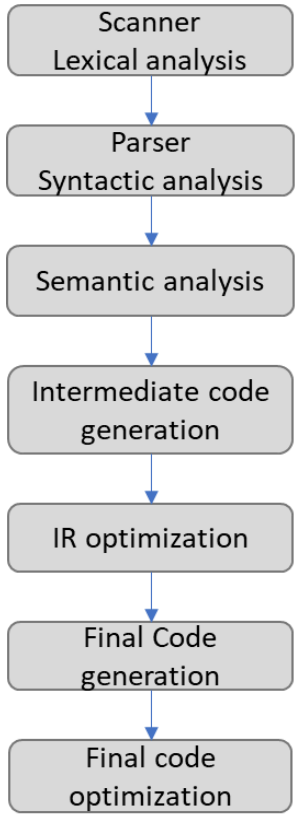
Final Code generation

Final code optimization

Last Time

Review: Overview

Introduced a definition of a compiler and its workflow



Used RegExs to *specify* languages of tokens

Token

Integer Literal

RegEx

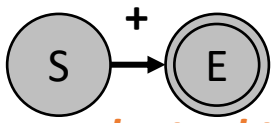
0|(1|2|…|9)(0|1|…|9)*

Claimed RegExs can be automatically translated to *recognize* languages

RegEx

"+"

DFA



In lab we showed a tool that automatically does this translation (Flex)

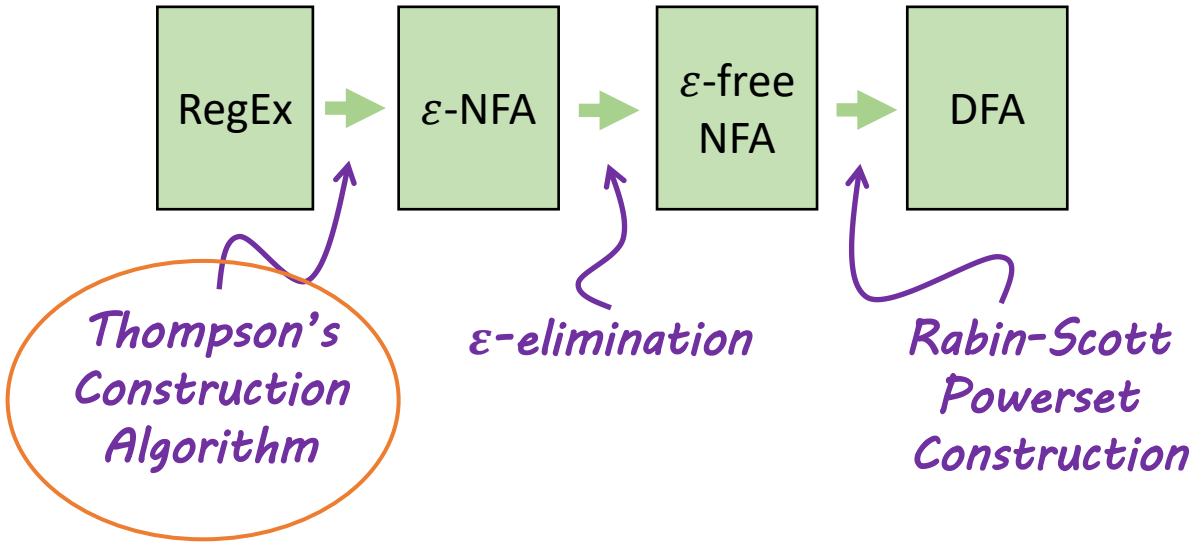
You Should Know

- The phases of the compiler and what each step does
- What errors the various phases catch
- How to specify a token's lexemes with a regex

Lecture Overview

Lecture 2 – Implementing Scanners

Walk through the translation process formally



Key Concept

Thompson's Construction Algorithm

Use an *expression tree*:

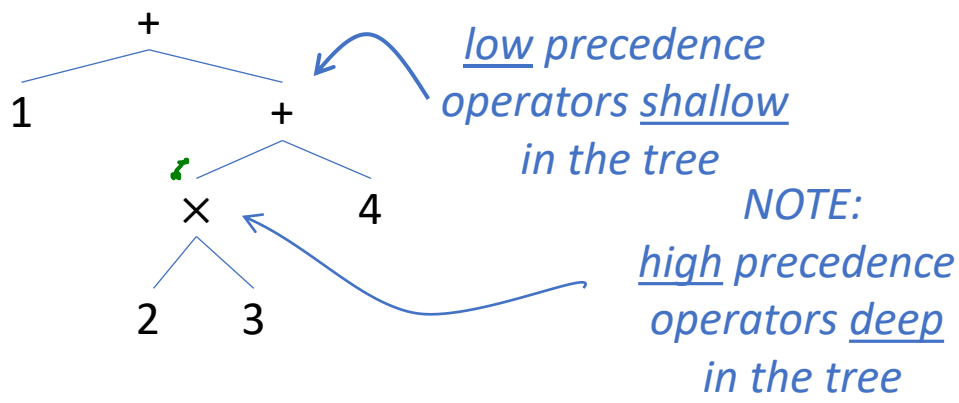
- Leaf: atomic operand
- Branch: operations joining subtrees

Expression Tree Examples

Arithmetic Expression

$1 + 2 \times 3 + 4$

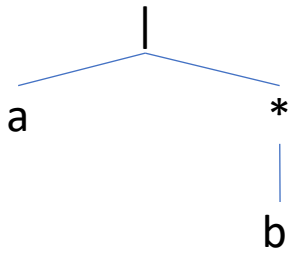
Arithmetic Expression Tree



RegEx

a|b*

Expression Tree



Thompson's Construction Intuition

Thompson's Construction Algorithm

Two-Step Process:

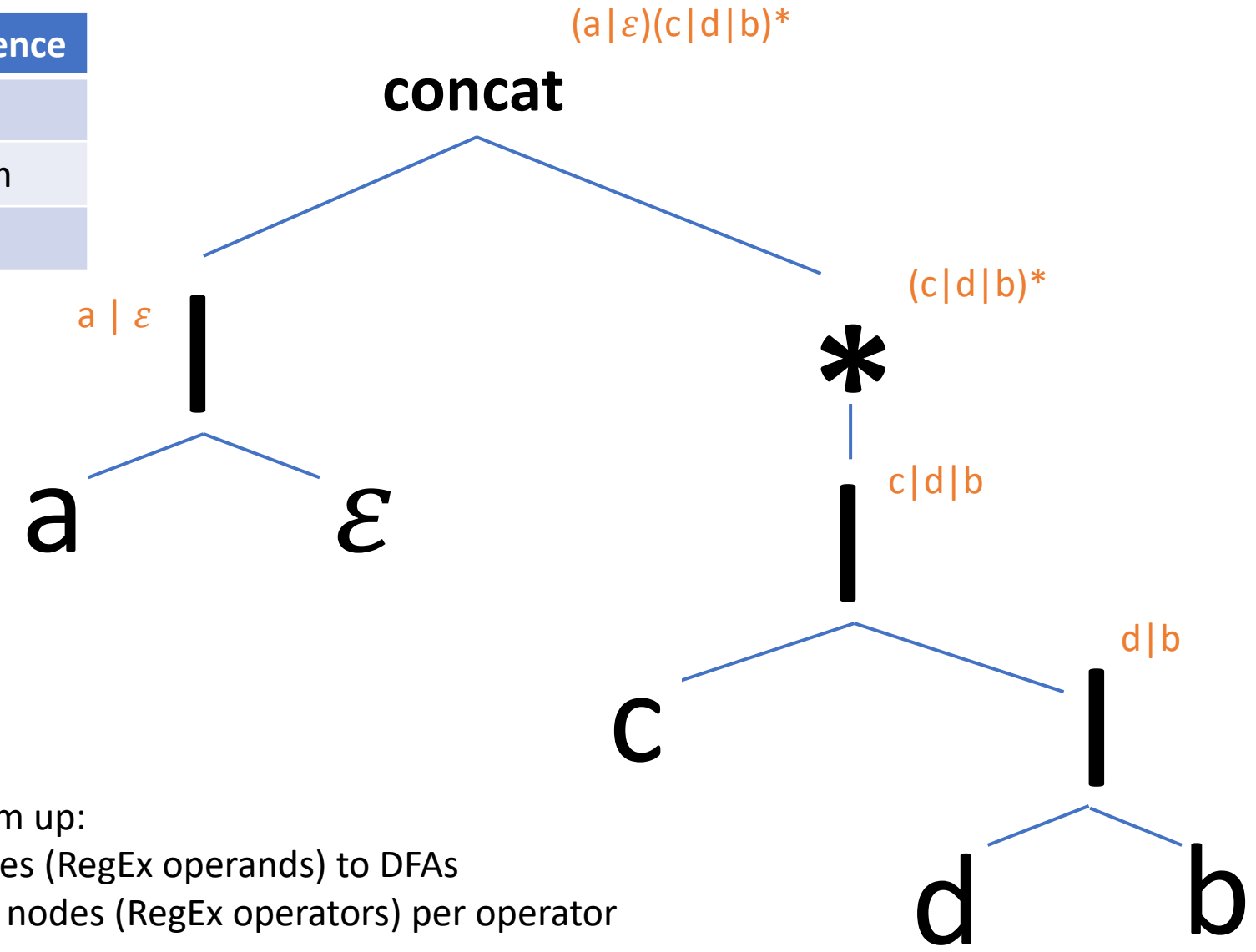
- Break the RegEx down to the simplest units with "obvious" FSMs (i.e. expression tree leaves)
- Combine the sub-FSMs according to operator rules (i.e. expression tree branch rules)

Recombobulate the Regex into an FSM piecewise

Thompson's Construction Alg.

Build the RegEx Tree | Replace nodes bottom-up

Op	Precedence
*	High
concat	Medium
|	Low



Apply rules bottom up:
- convert leaf nodes (RegEx operands) to DFAs
- combine branch nodes (RegEx operators) per operator

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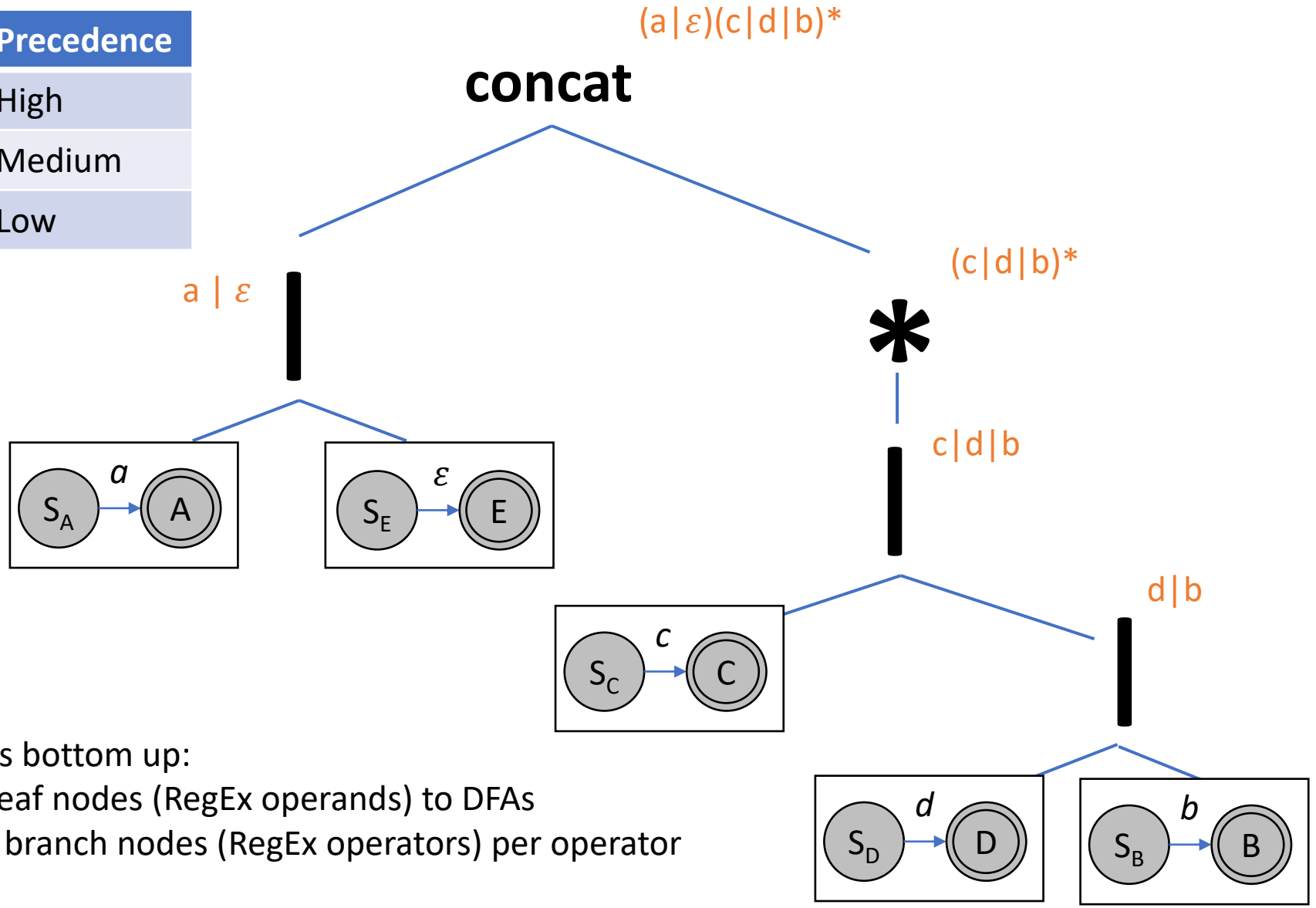

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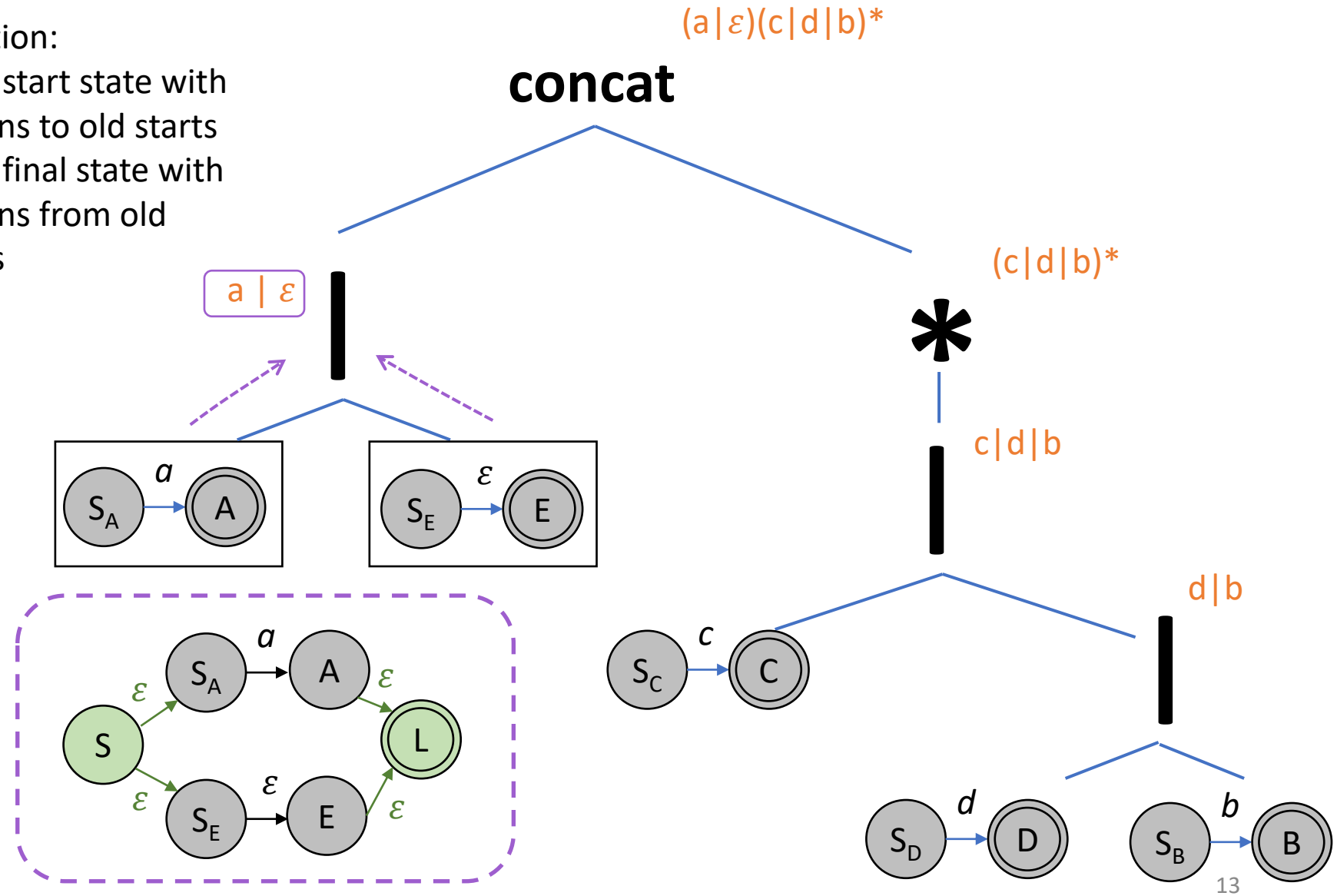
Build the RegEx Tree | Replace nodes bottom-up

Alternation:

- New start state with ε-trans to old starts
- New final state with ε-trans from old finals



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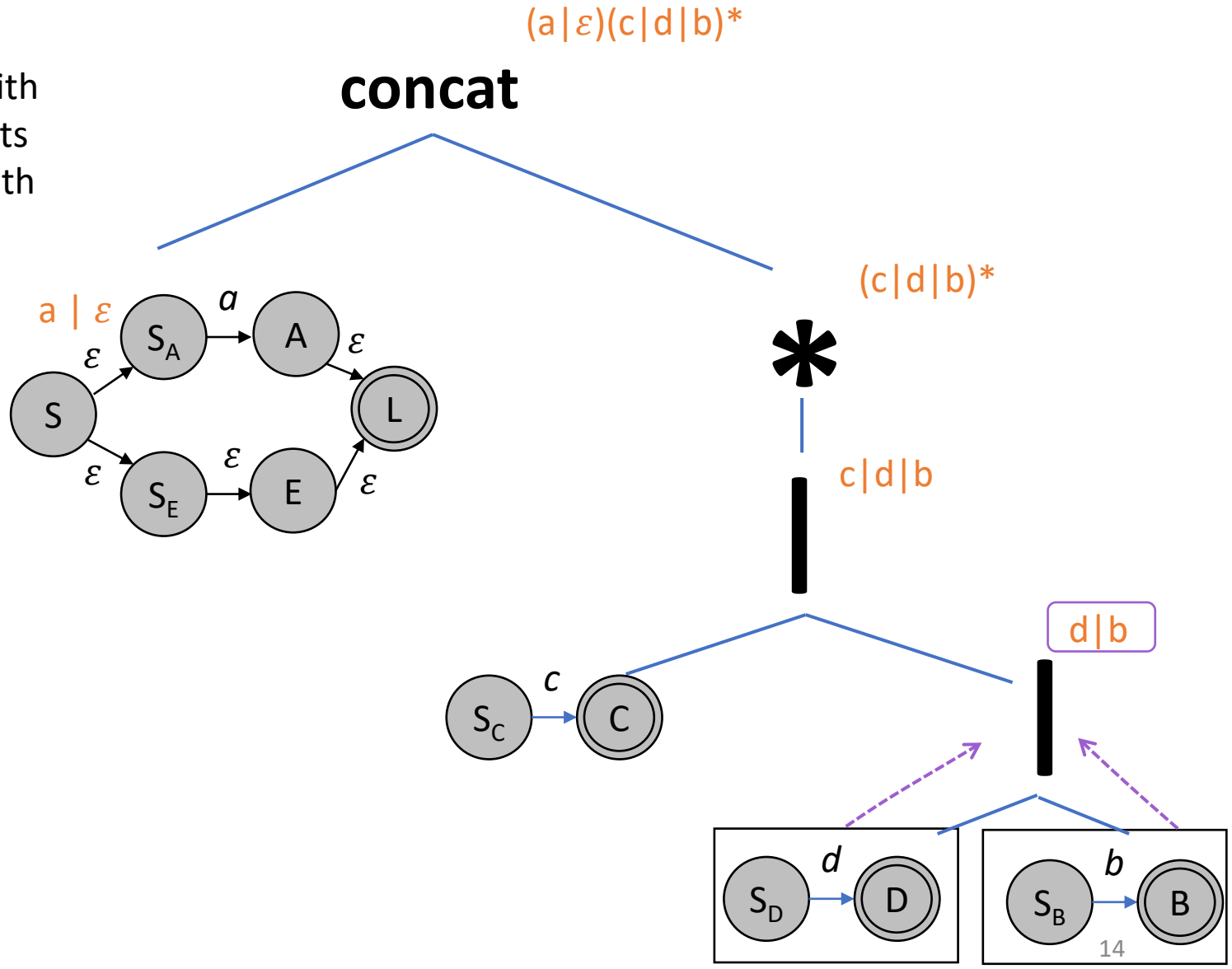

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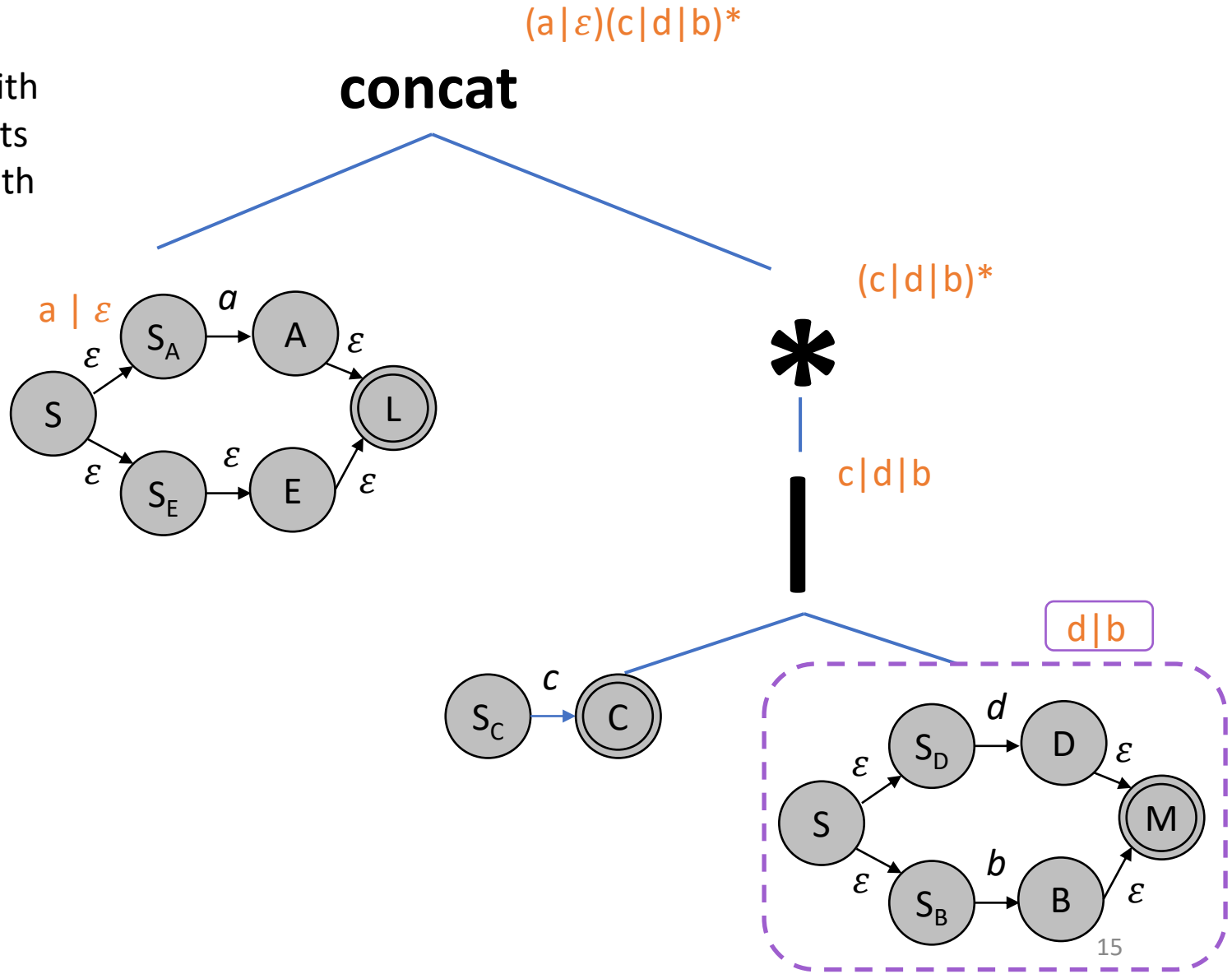

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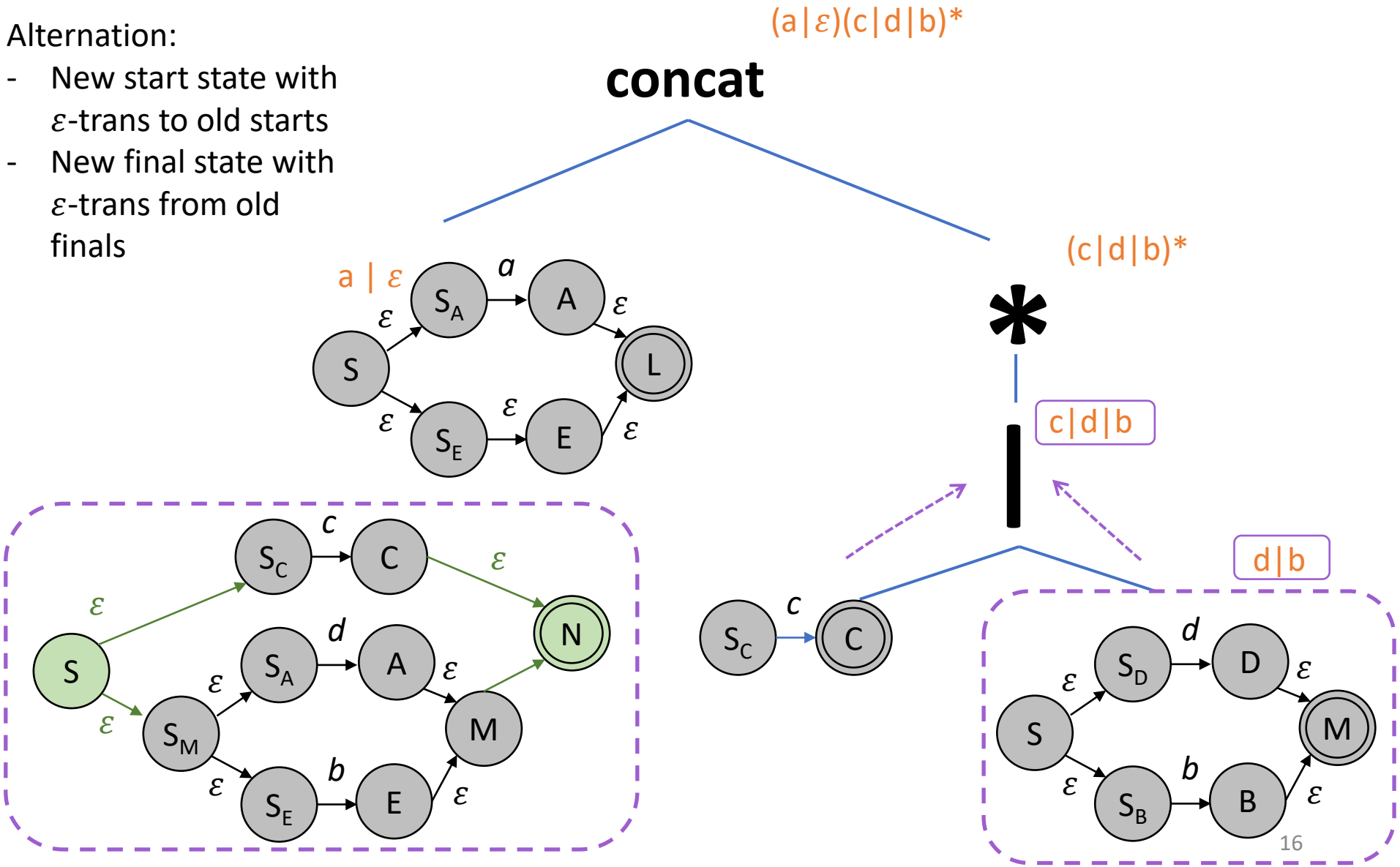

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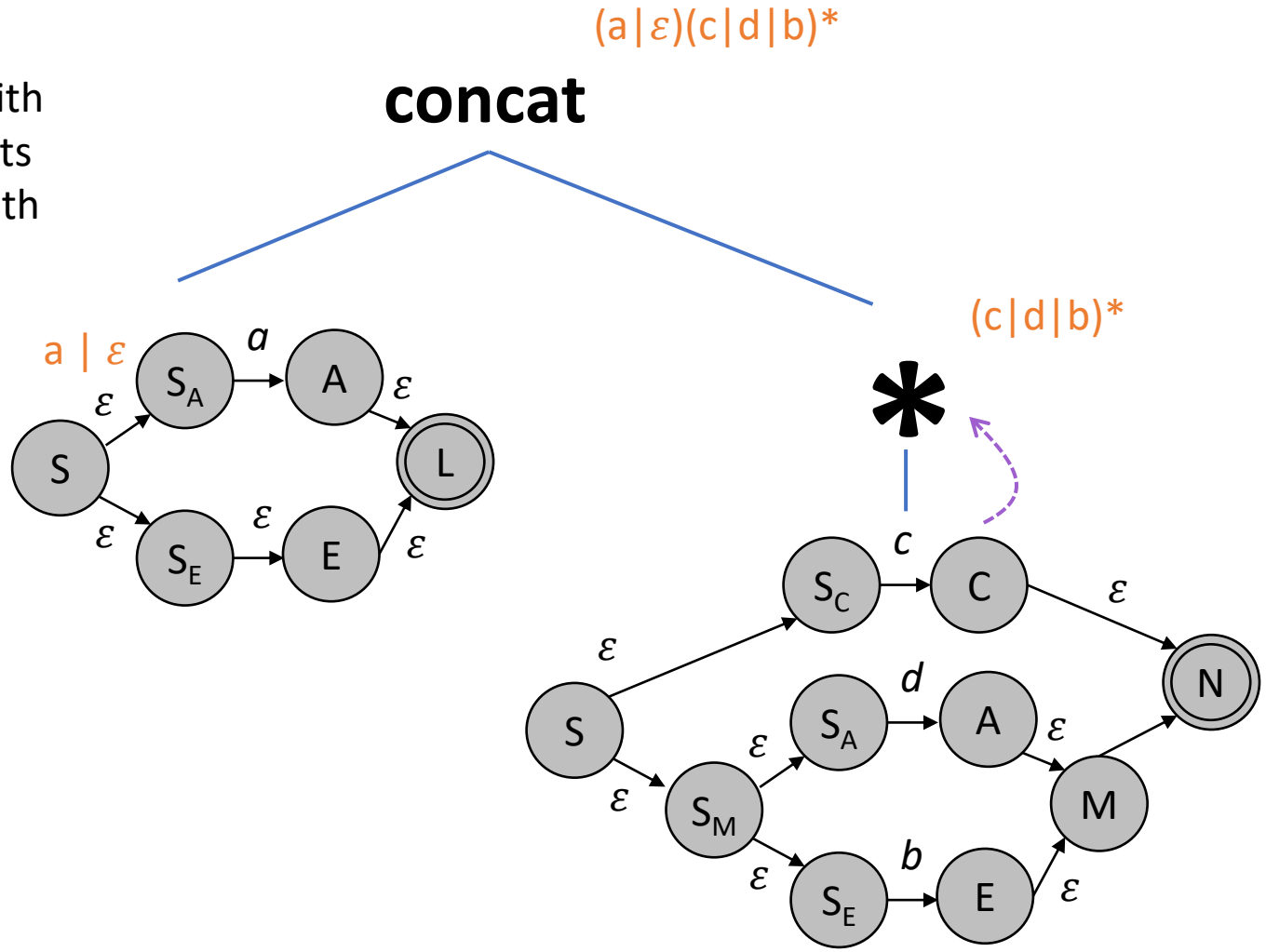


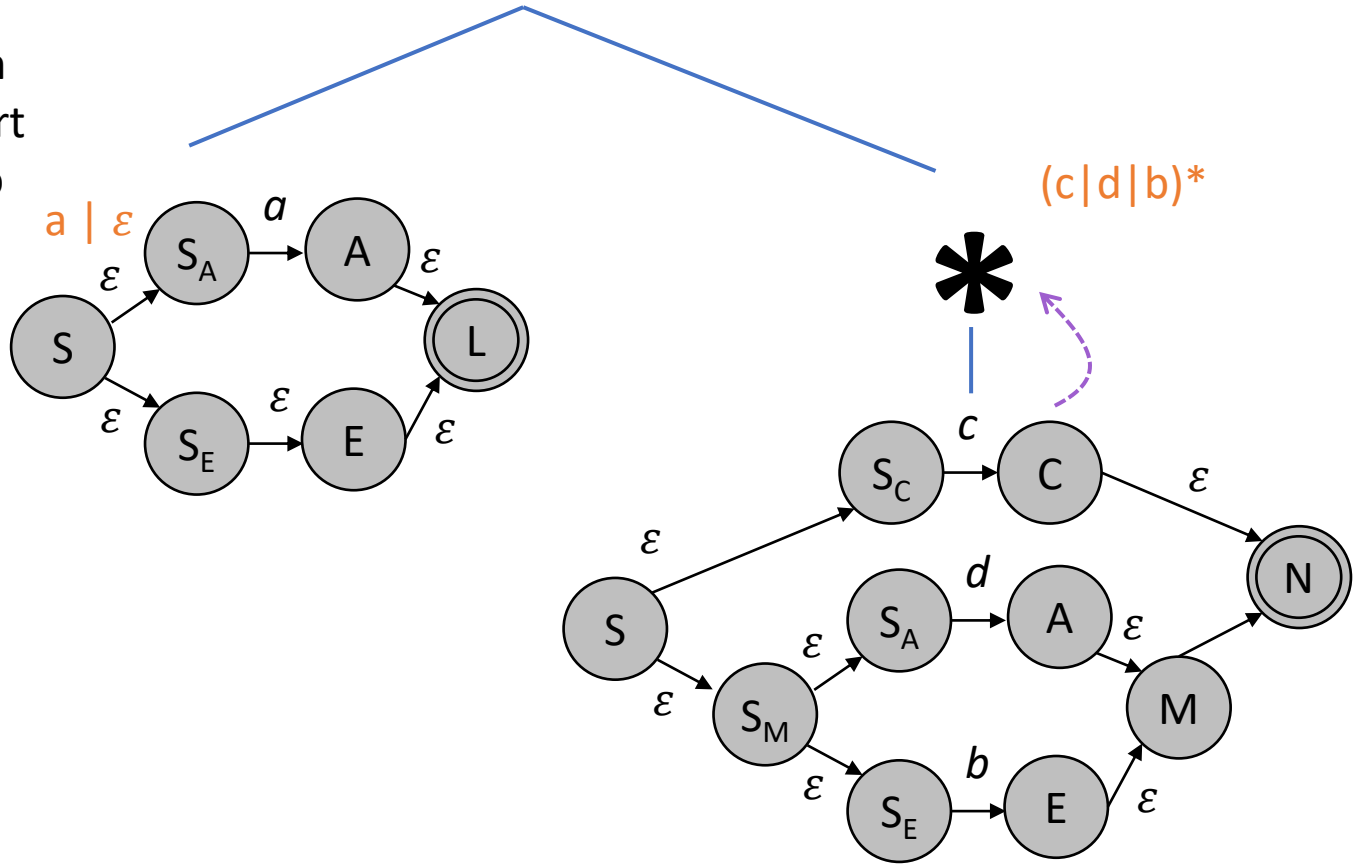
Thompson's Construction Alg.

Build the RegEx Tree | Replace nodes bottom-up

Repetition (* operator):
- New start state with ε-edge to old start
- New final state with ε-edge from new start
- ε-edge from final to start

(a|ε)(c|d|b)*

concat



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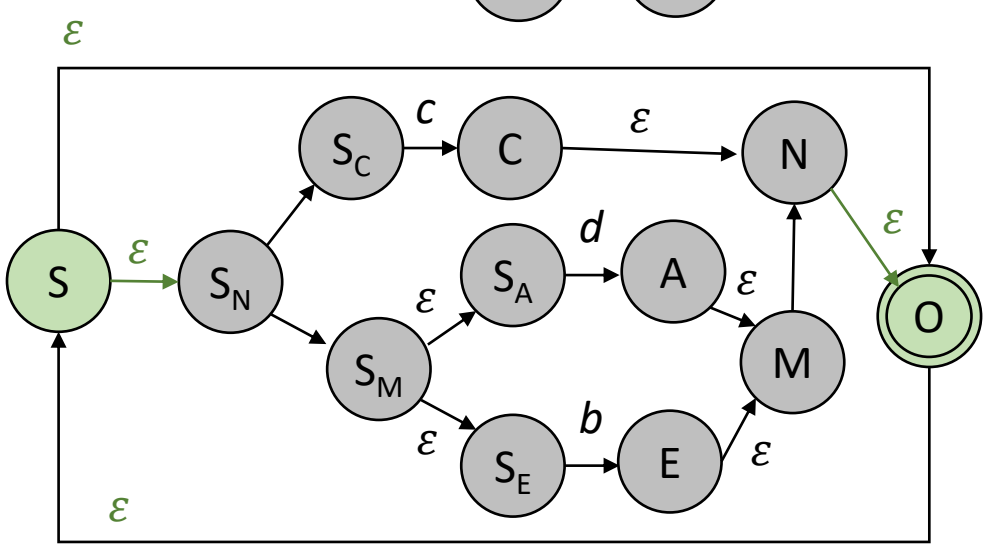
concat

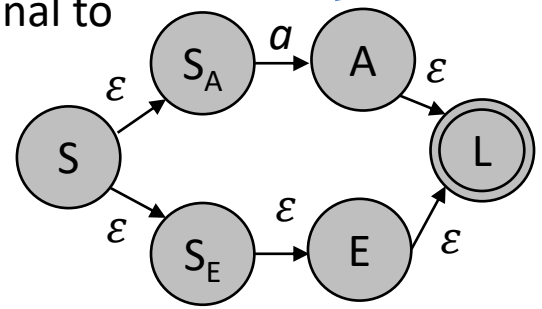
(c|d|b)*

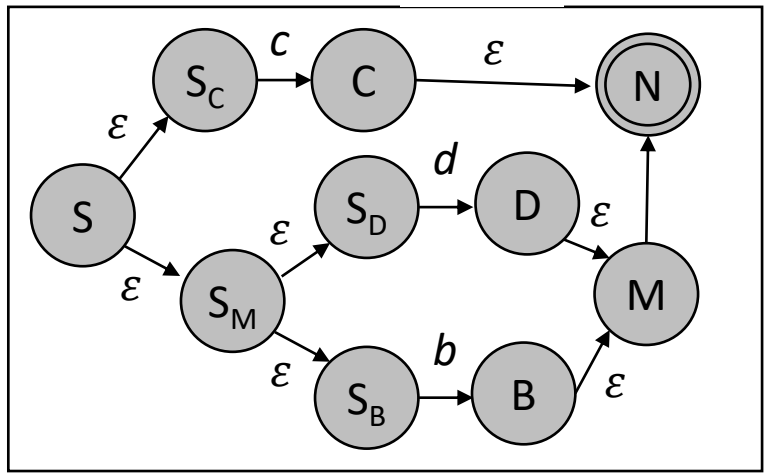
a | ε

*

c|d|b







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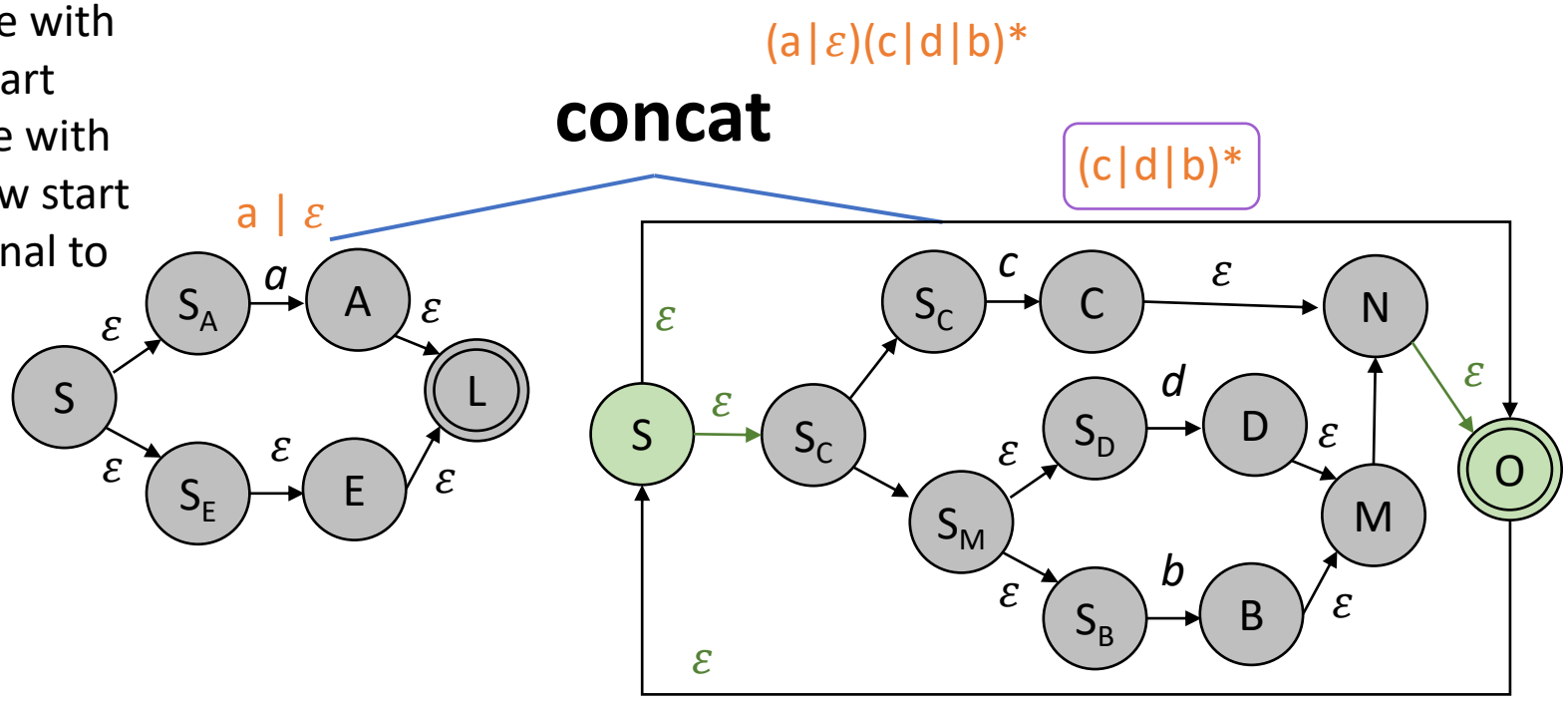


Thompson's Construction Alg.

Build the RegEx Tree | Replace nodes bottom-up

Concatenation:

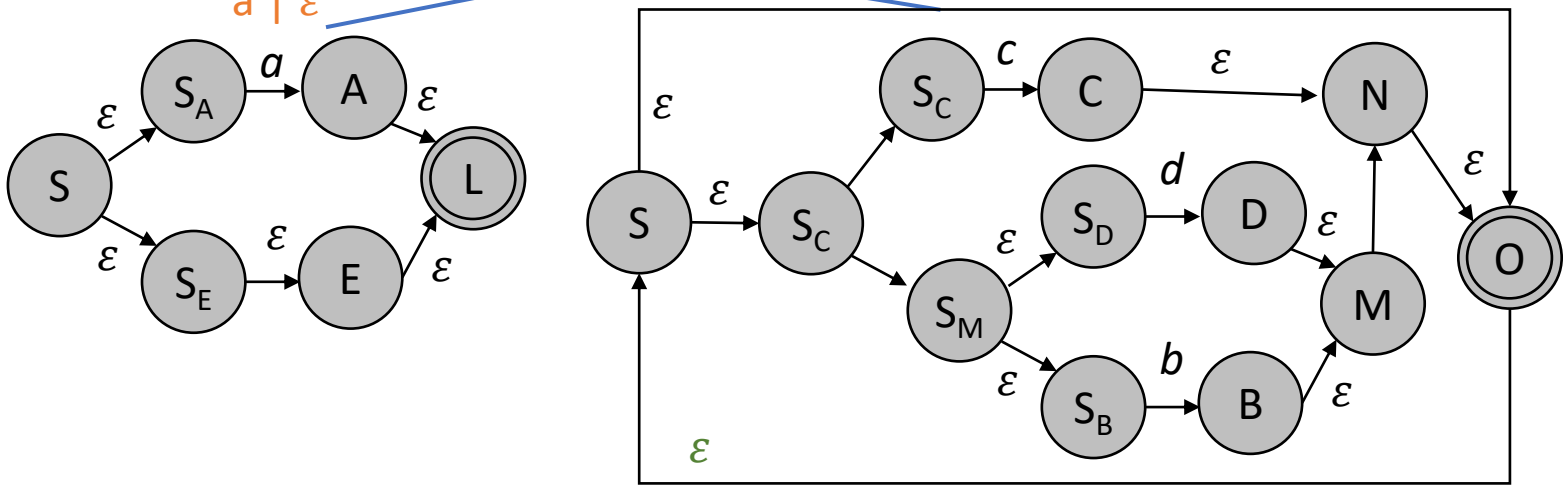
- Add ε-edge from first FSM's final state to second FSM's start state
- Remove final status from first FSM

(a|ε)(c|d|b)*

concat

(c|d|b)*

a | ε



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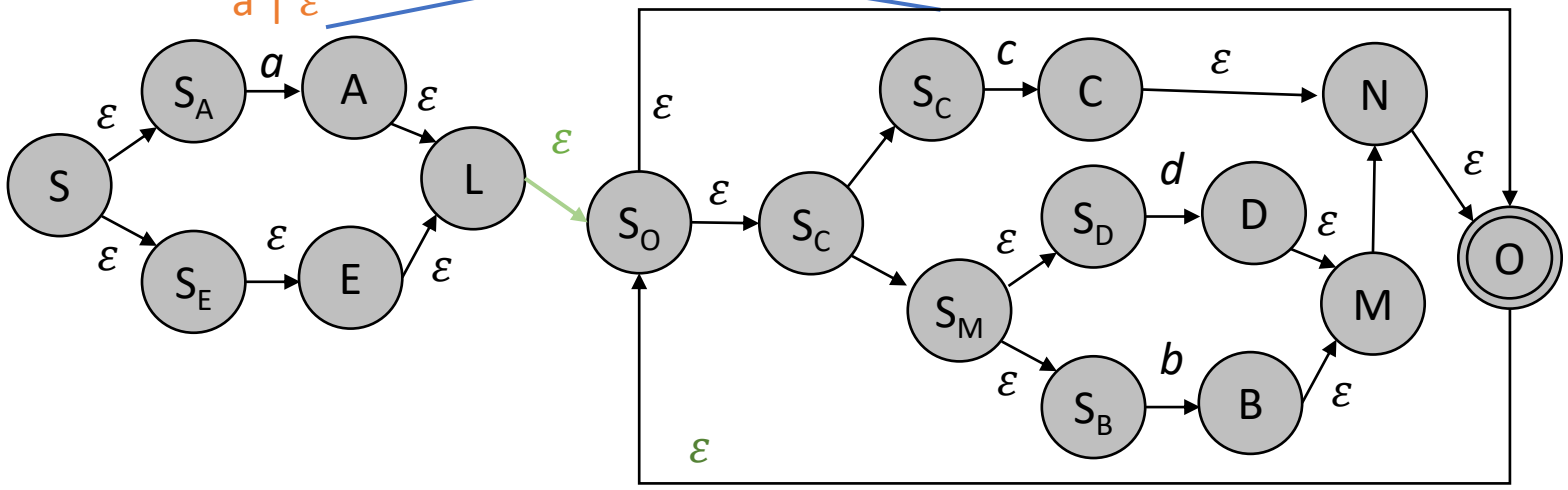

Thompson's Construction Alg.

Build the RegEx Tree | Replace nodes bottom-up

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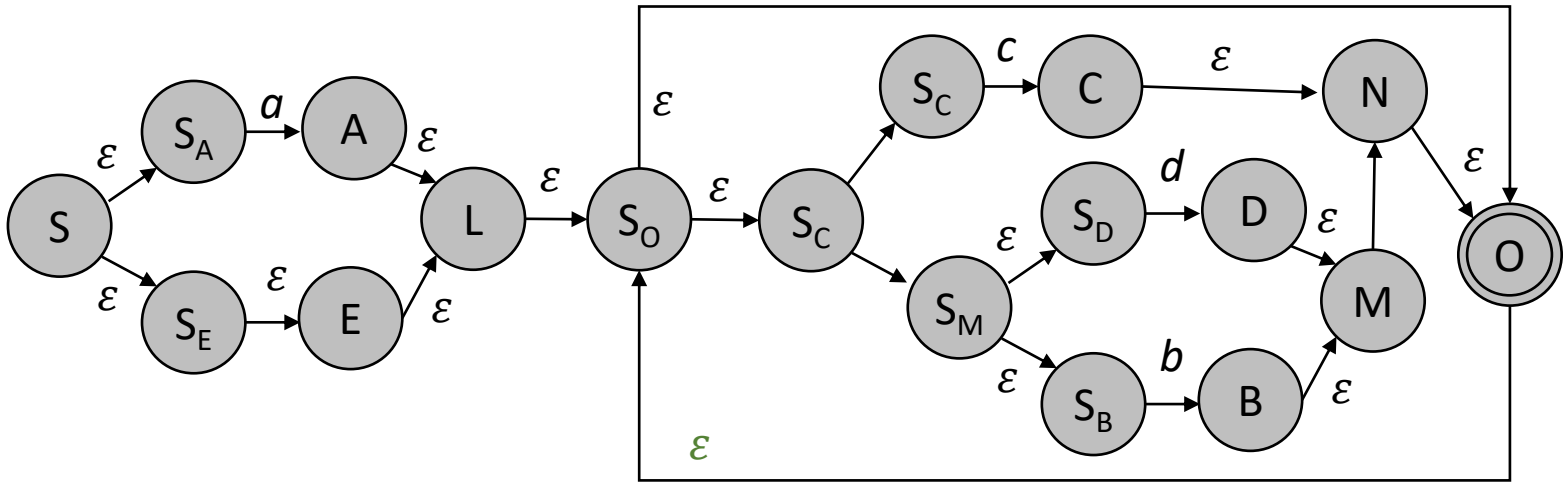
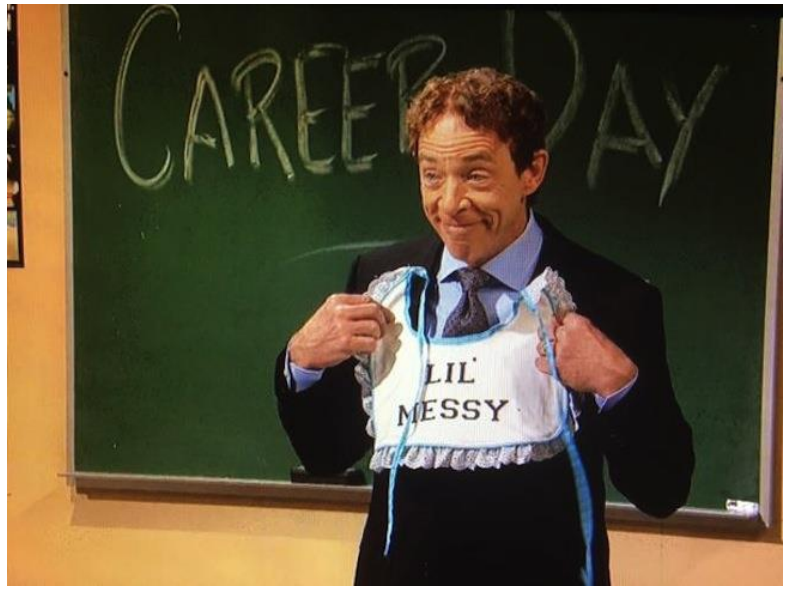


Thompson's Construction: Side-Note

Build the RegEx Tree | Replace nodes bottom-up

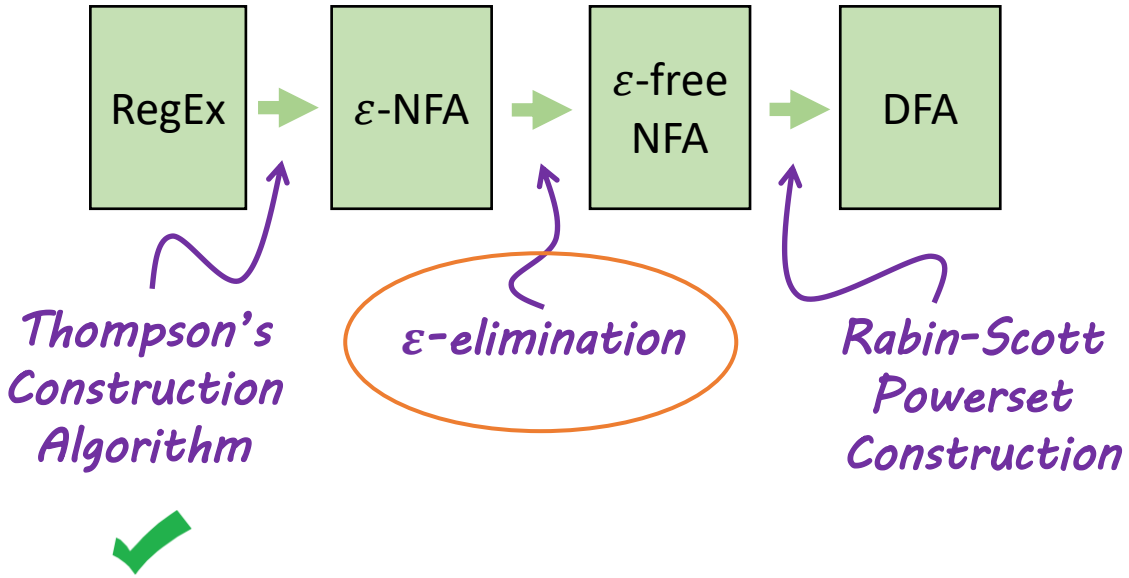
The FSMs produced by Thompsons Construction are a little bit messy!

- Clearly less efficient than what we would do by hand
- Designed for ease of proofs
- In practice, it's easy to minimize FSMs later



From RegEx to DFA

Lecture 2 – Implementing Scanners



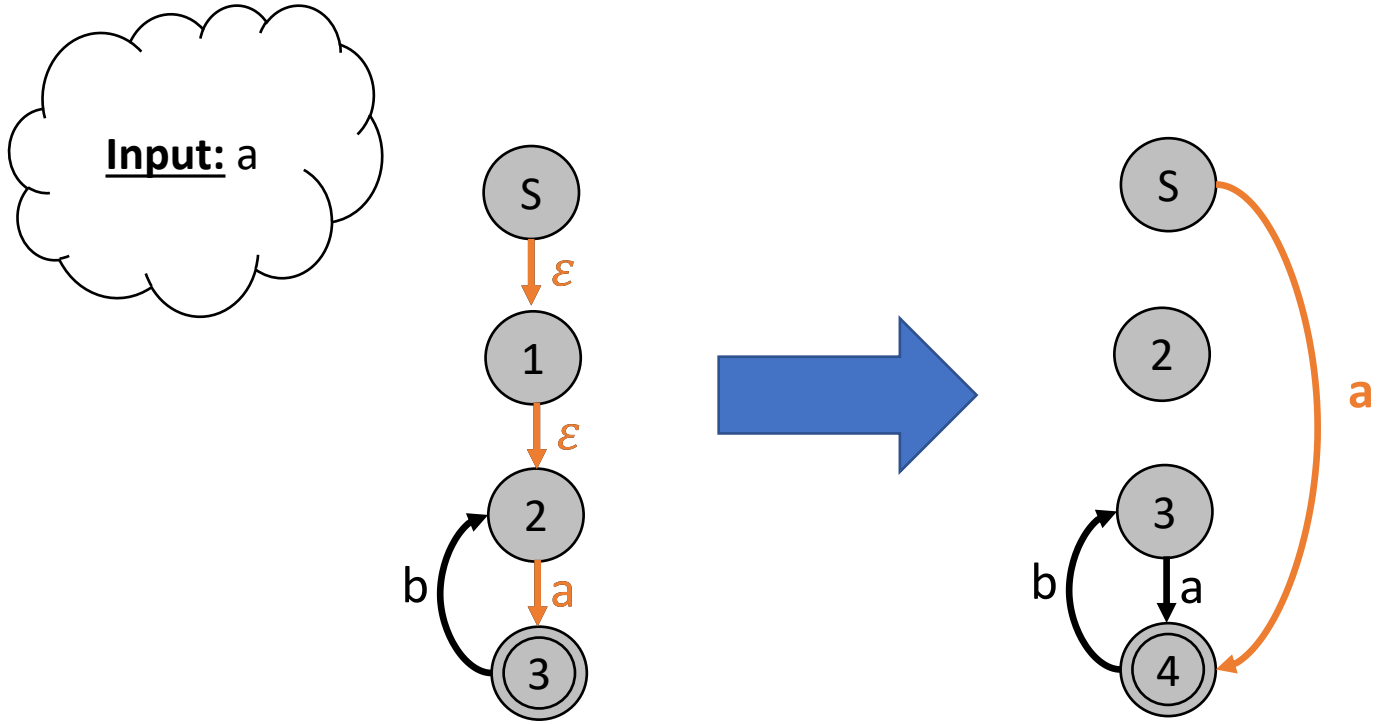
Eliminating ε-transitions

Observation: You never see an epsilon in the input

- Consuming a character means taking a "chain" of zero-or-more ε-edges then a real character edge

Algorithm Intuition: *cut out the middleman*

- Replace all "chains" with a direct real-character edge



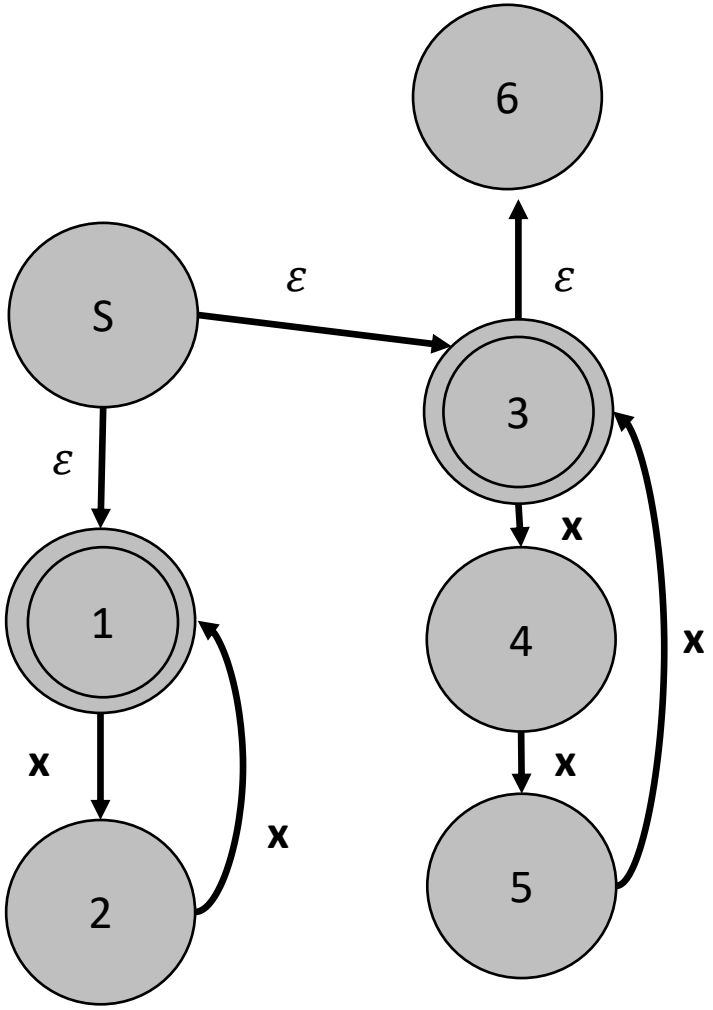
Eliminating ε-transitions

- Compute ε-close(s), the set of states reachable via 0 or more ε-edges from s
- Copy all states from N to an ε-free version, N'
- Put s in F' if ε-close(s) contains a state in F
- Put s,c $\rightarrow$ t in δ' if there is a c-edge to t in ε-close(s)

Example, Step I

Eliminating ε-Transitions

Let ε-close(s) be the set of states reachable via 0 or more ε-edges



ε-close(S) = {S,1,3,6}

ε-close(3) = {3, 6}

ε-close(1) = {1}

ε-close(2) = {2}

ε-close(4) = {4}

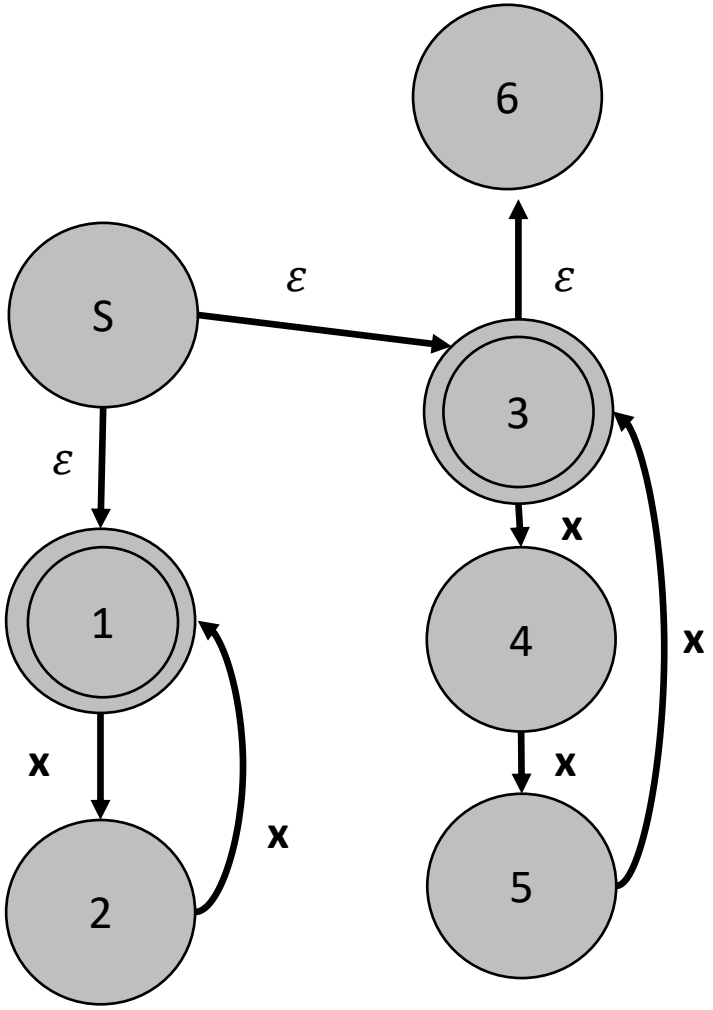
ε-close(5) = {5}

ε-close(6) = {6}

Example, Step II

Eliminating ε-Transitions

Copy all states from N to N’



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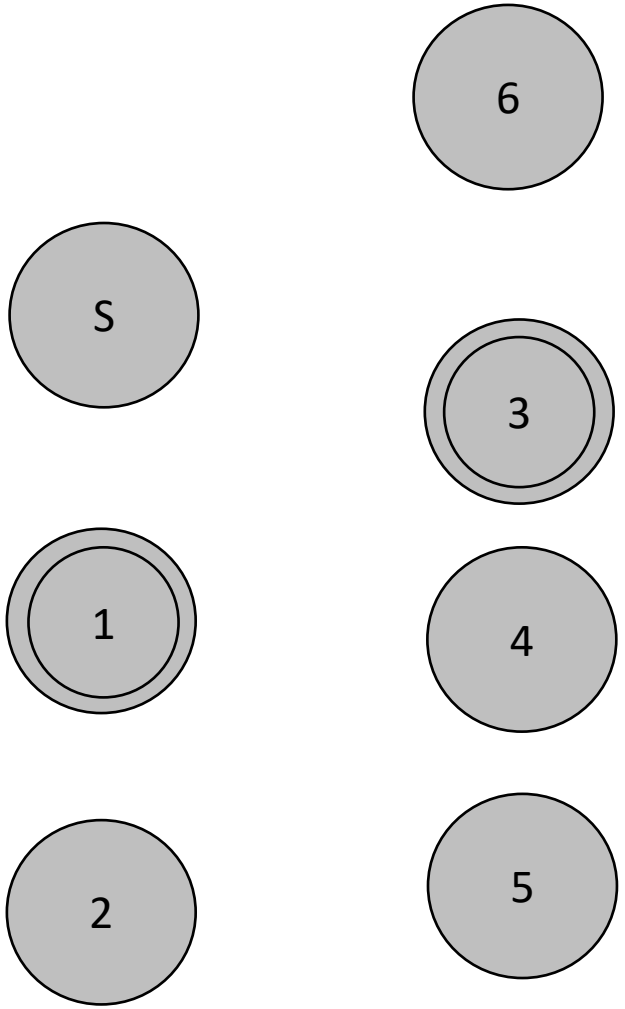
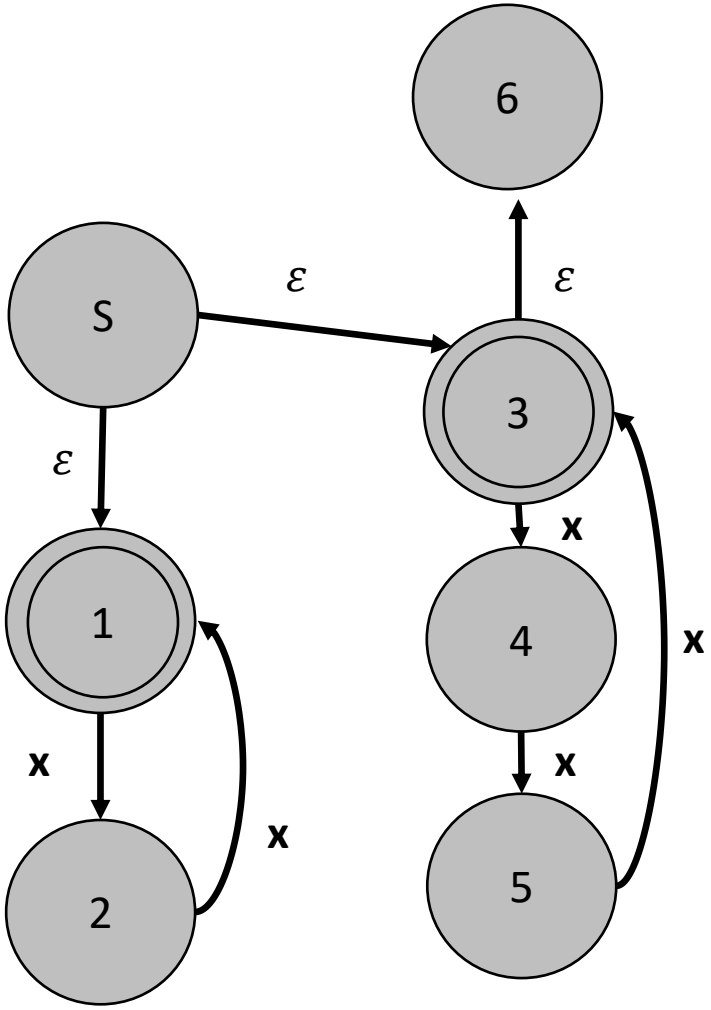


Example, Step III

Eliminating ε-Transitions

Put s in F' if ε-close(s) contains a state in F



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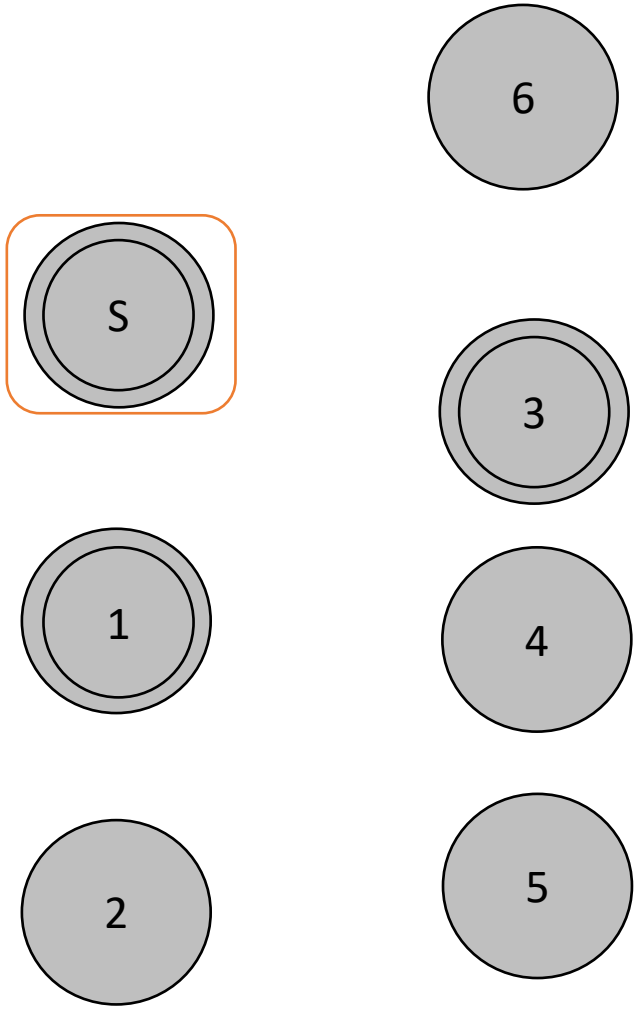
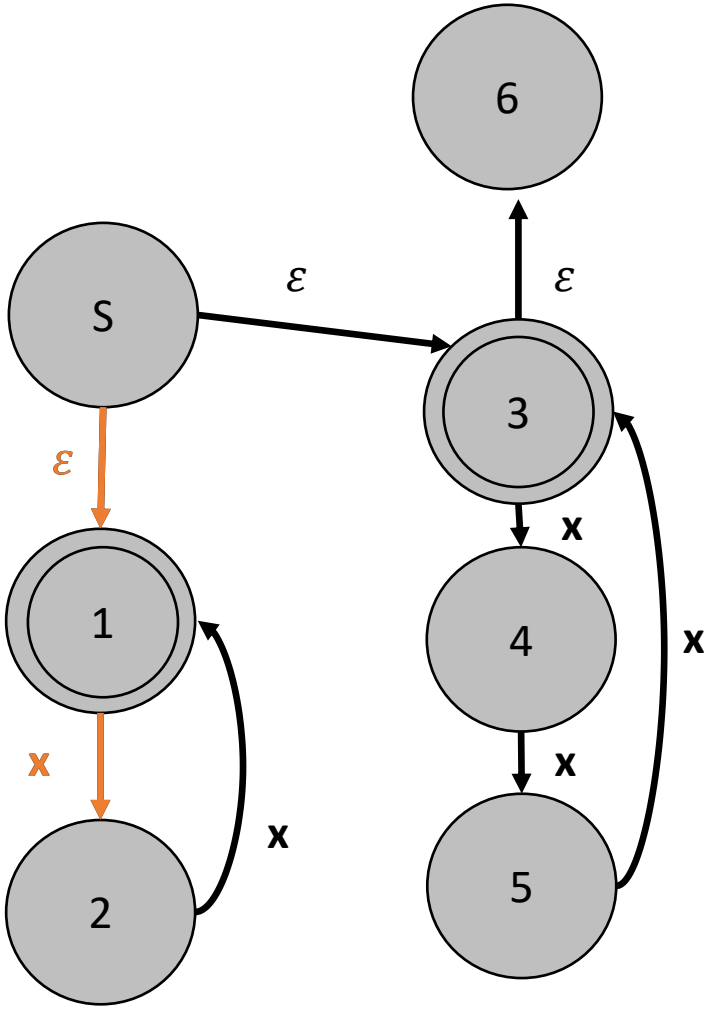


Example, Step IV

Eliminating ε-Transitions

Put s,c → t in δ' if there is a c-edge to t in ε-close(s)



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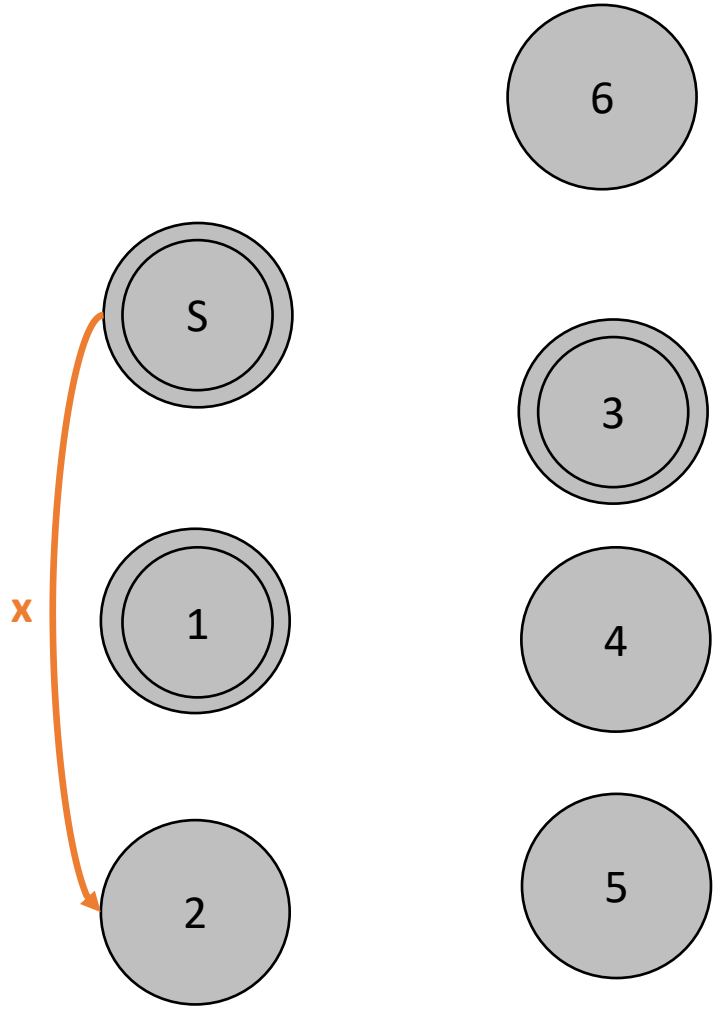

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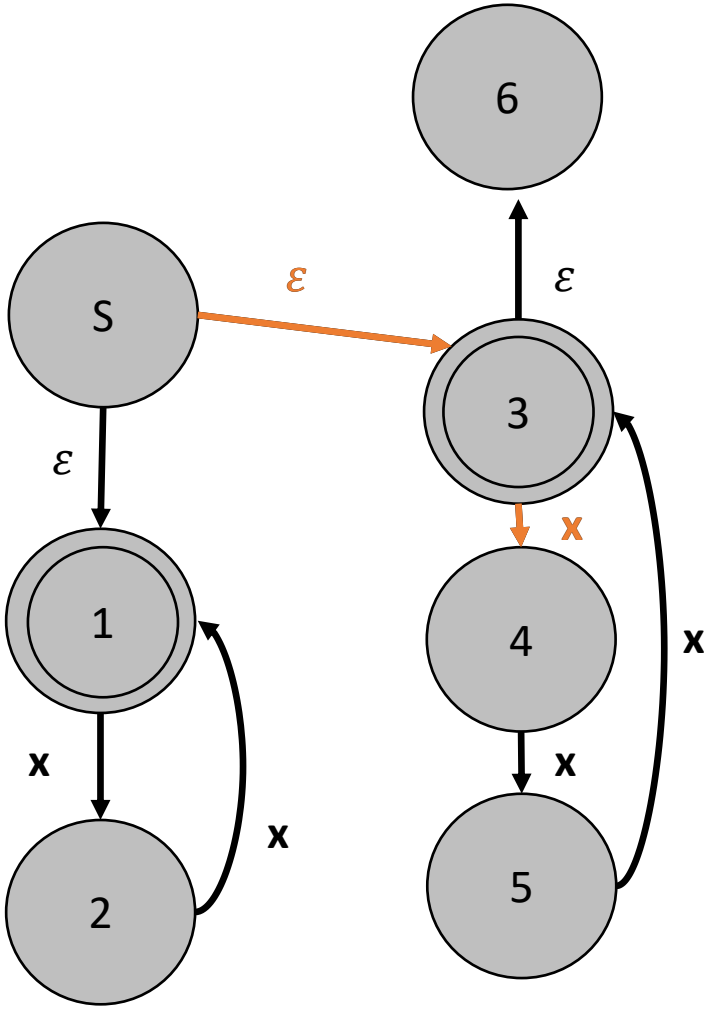

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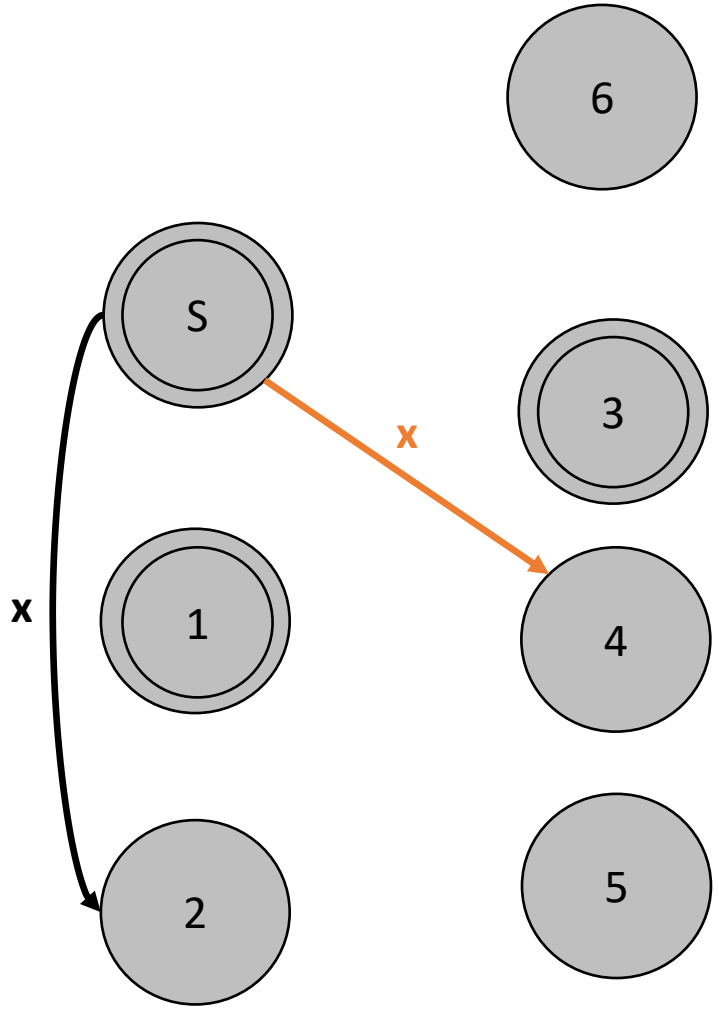

Example, Step IV

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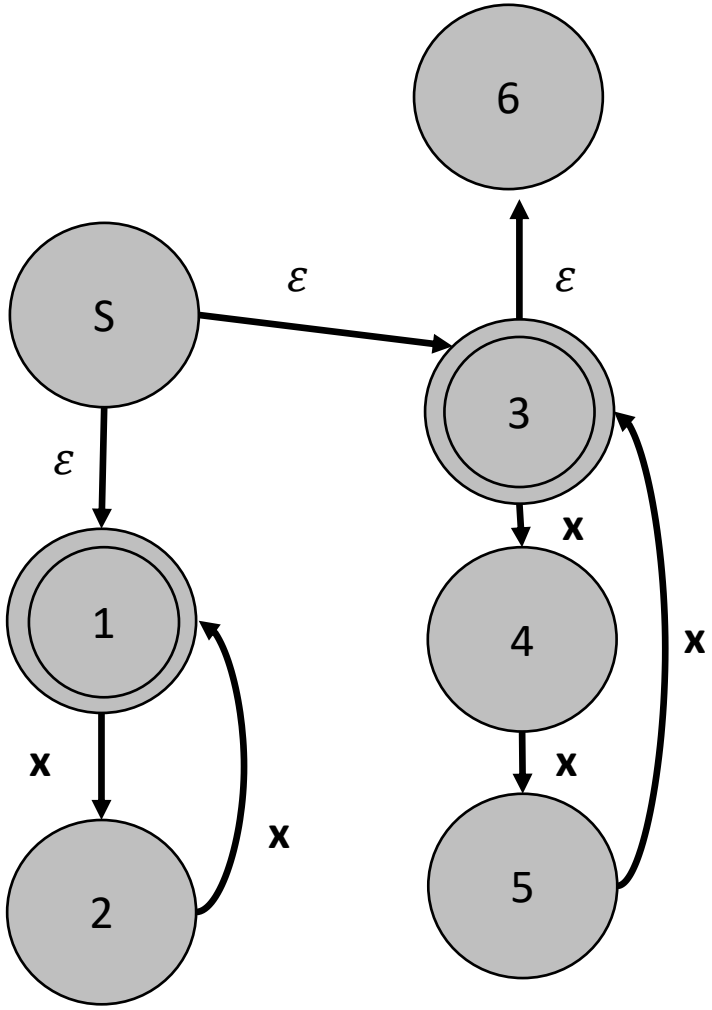

ε-close(S) = {S,1,3,6}

No edges out of 6!

ε-close(3) = {3, 6}

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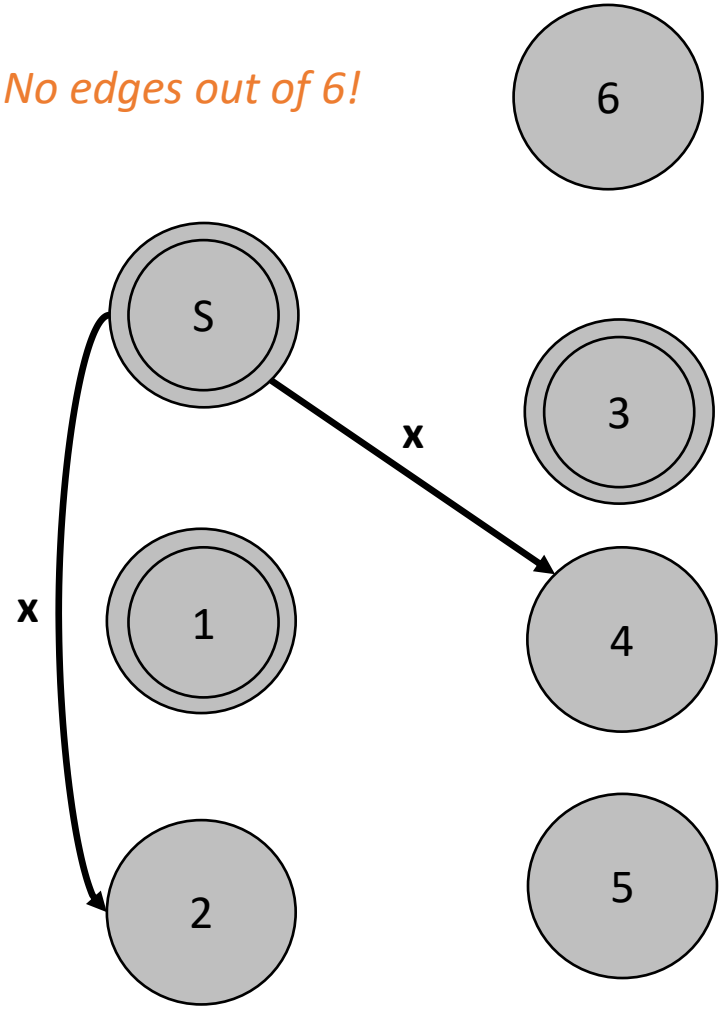
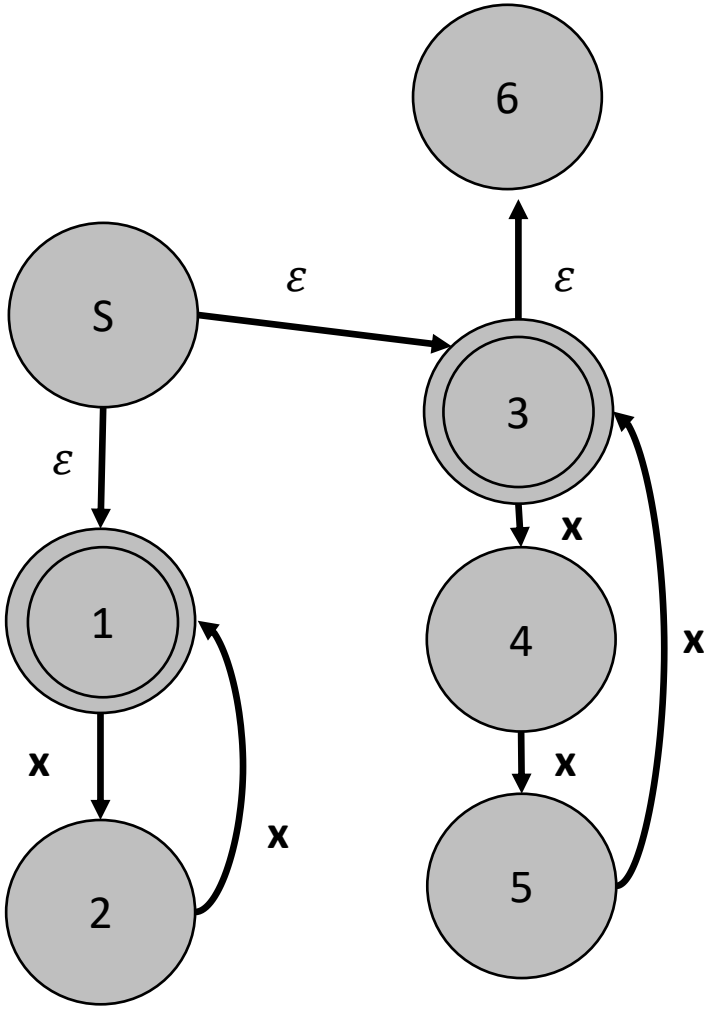


Example, Step IV

Eliminating ε-Transitions

Put s,c → t in δ' if there is a c-edge to t in ε-close(s)

Note: this definition necessarily preserves all original non-ε edges



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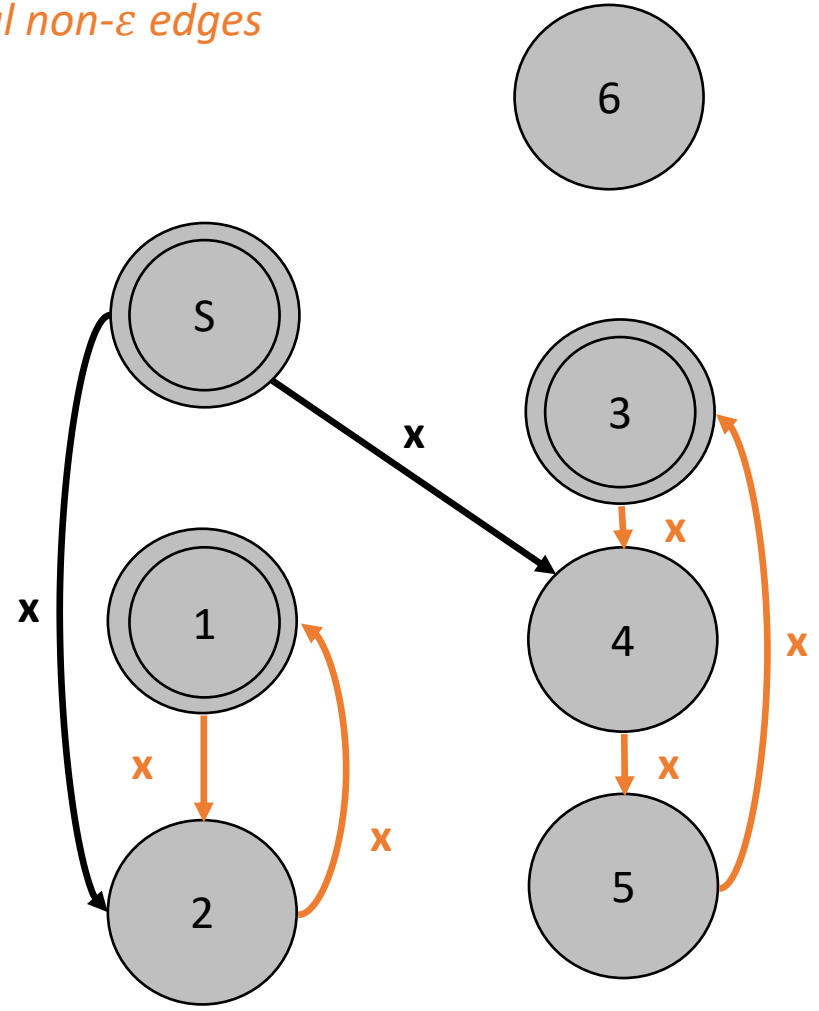
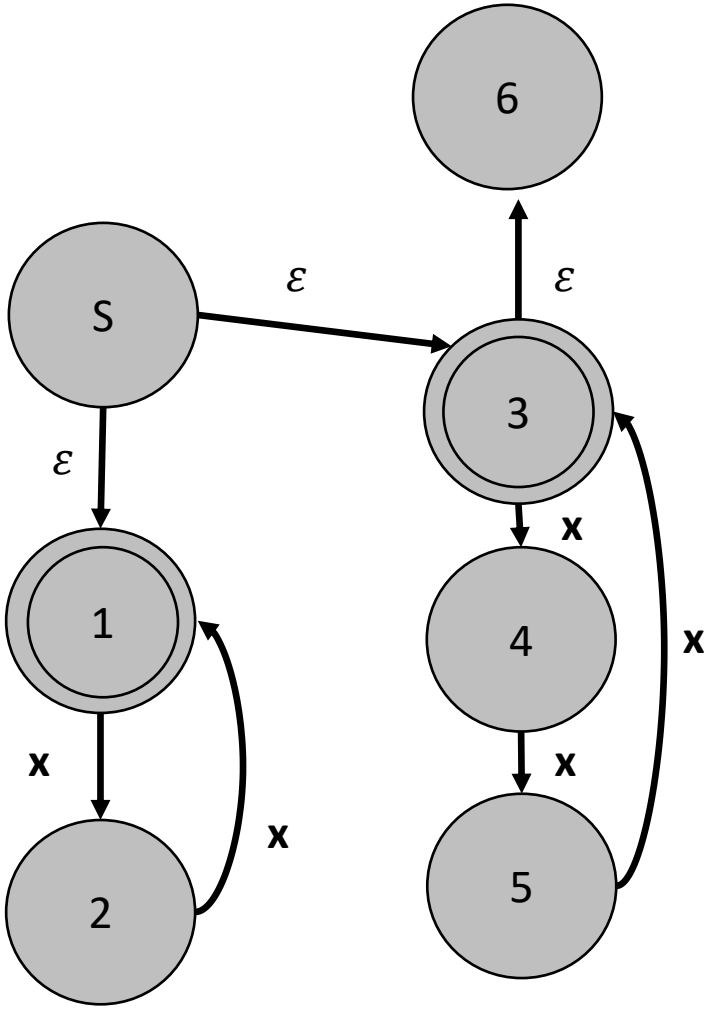


Example, Done!

Eliminating ε-Transitions

Can also remove unreachable "useless" state



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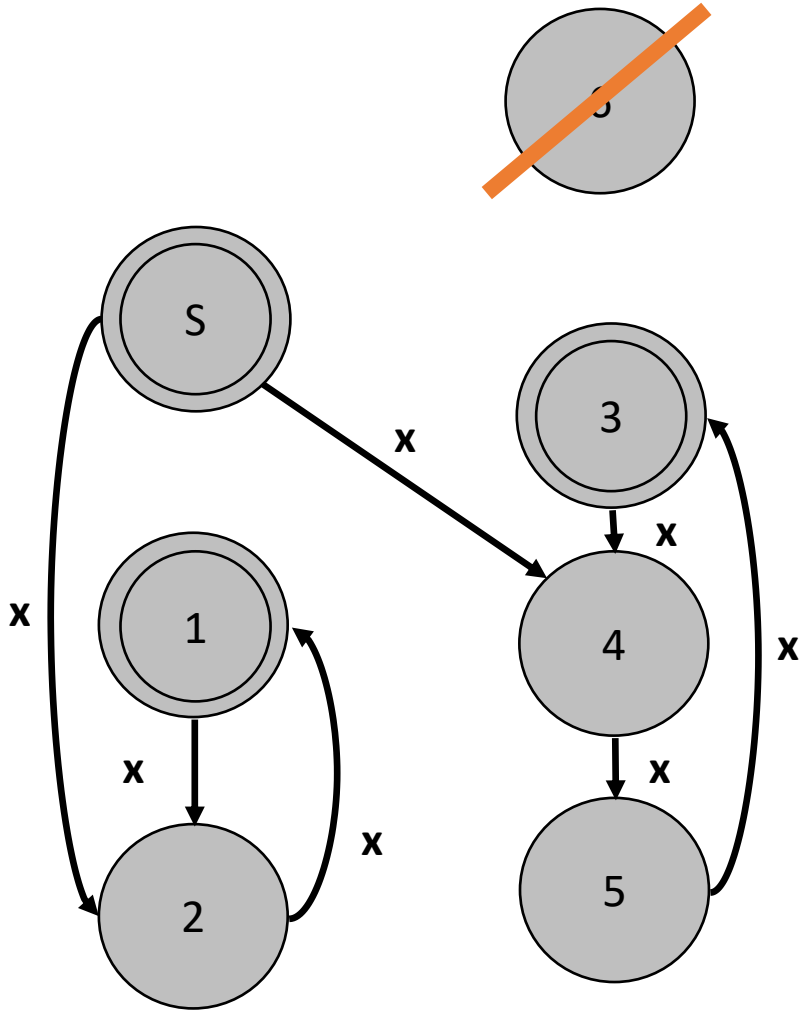
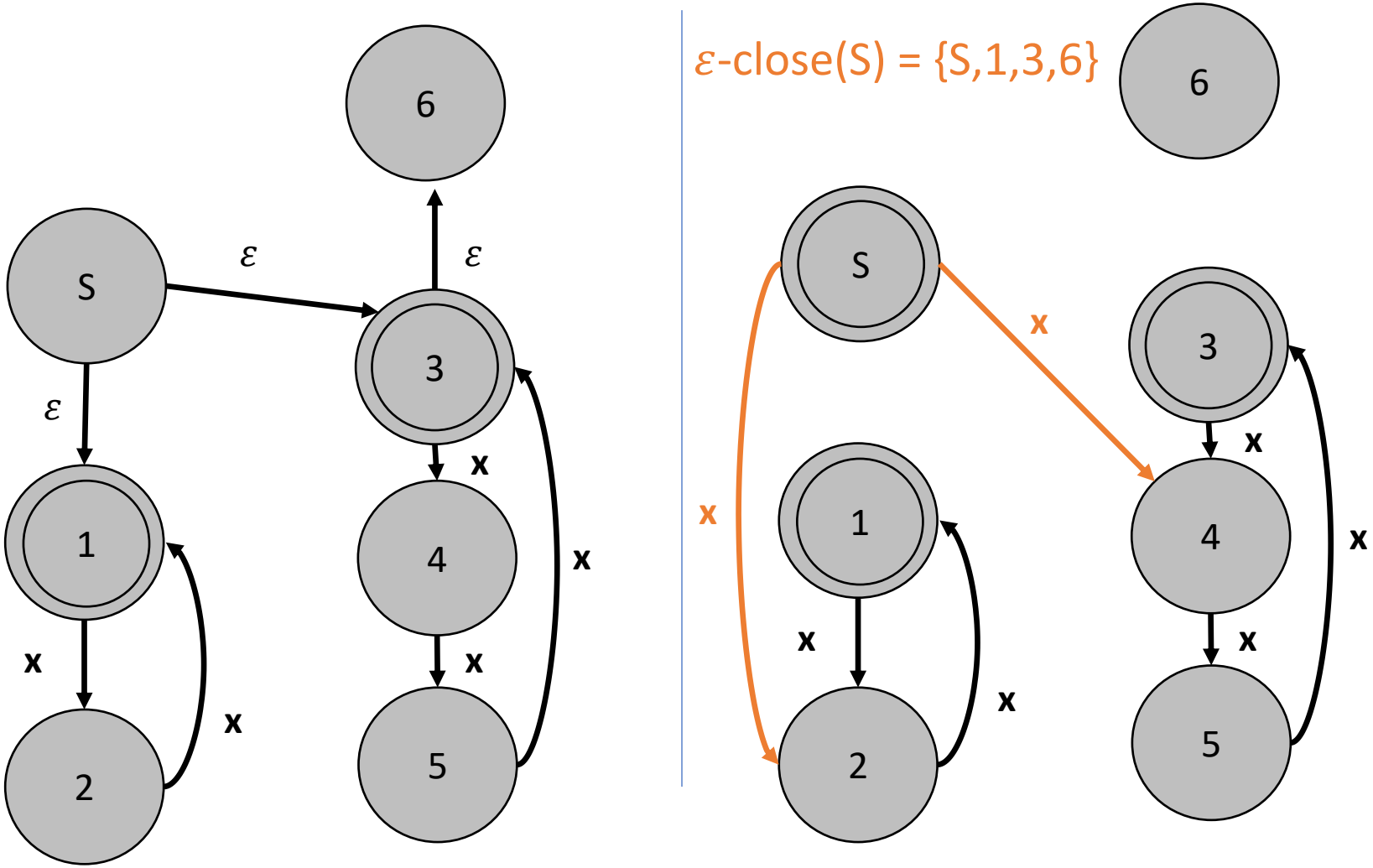


Example, Step IV

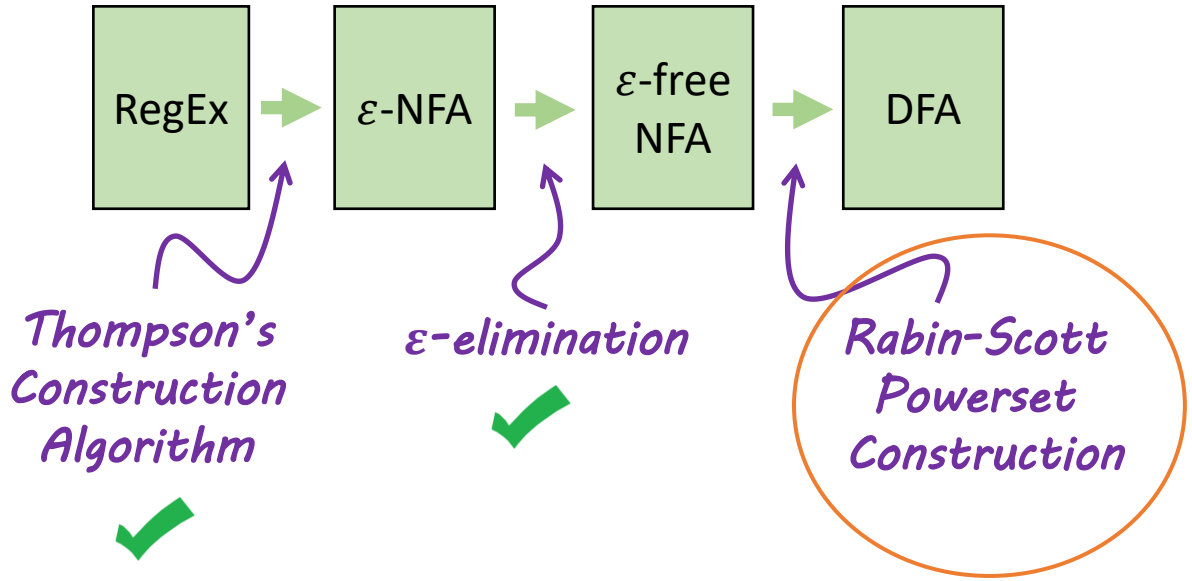
Eliminating ε-Transitions

Put s,c → t in δ' if there is a c-edge to t in ε-close(s)



From RegEx to DFA

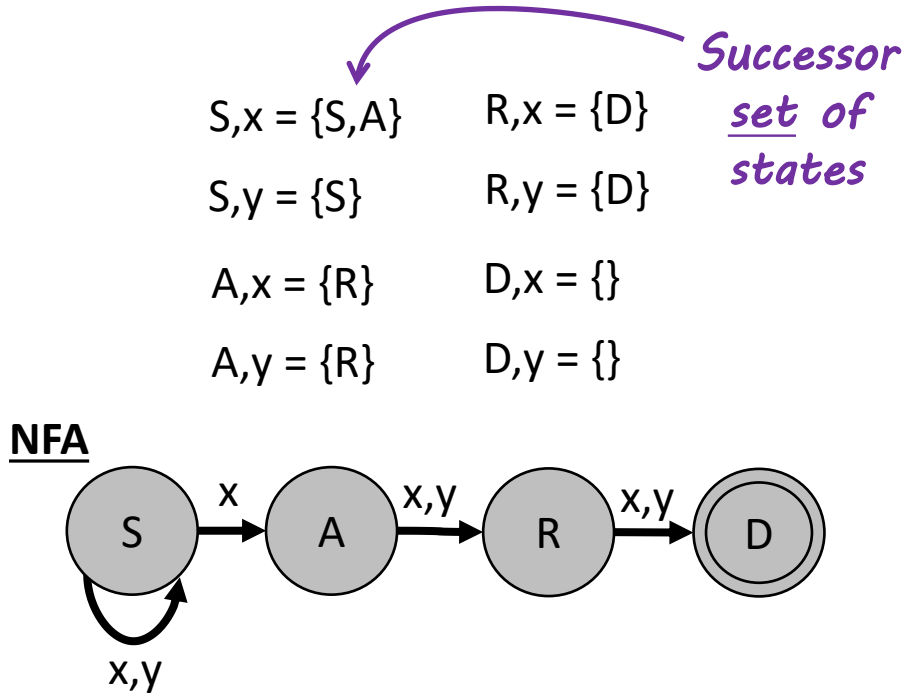
Lecture 2 – Implementing Scanners



Recall: NFA Matching Procedure

Rabin-Scott Powerset construction

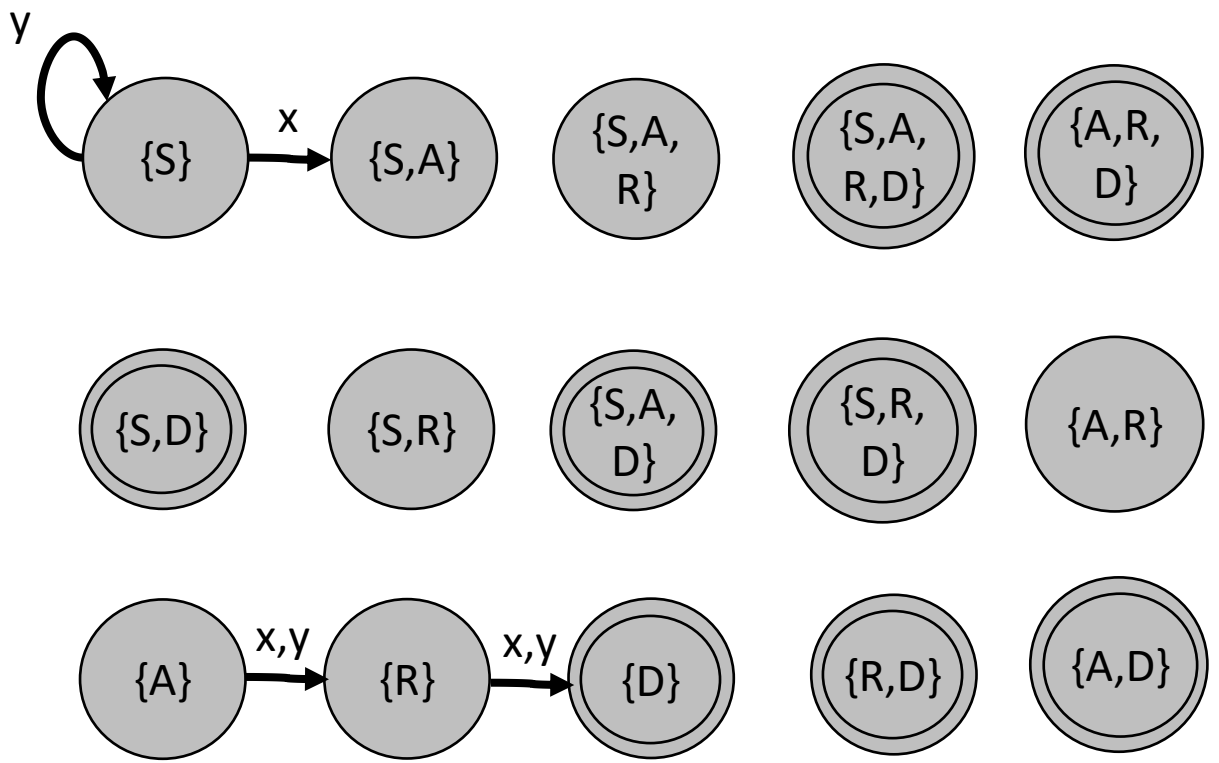
- NFA can "choose" which transition to take
  - Always moves to states that leads to acceptance (if possible)
- Simulate set of states the NFA *could* be in
  - If any state in the ending set is final, string accepted



From Successors to Powerset DFA

Rabin-Scott Powerset Construction

S,x = {S,A}	A,x = {R}	R,x = {D}	D,x = {}
S,y = {S}	A,y = {R}	R,y = {D}	D,y = {}



From Successors to Powerset DFA

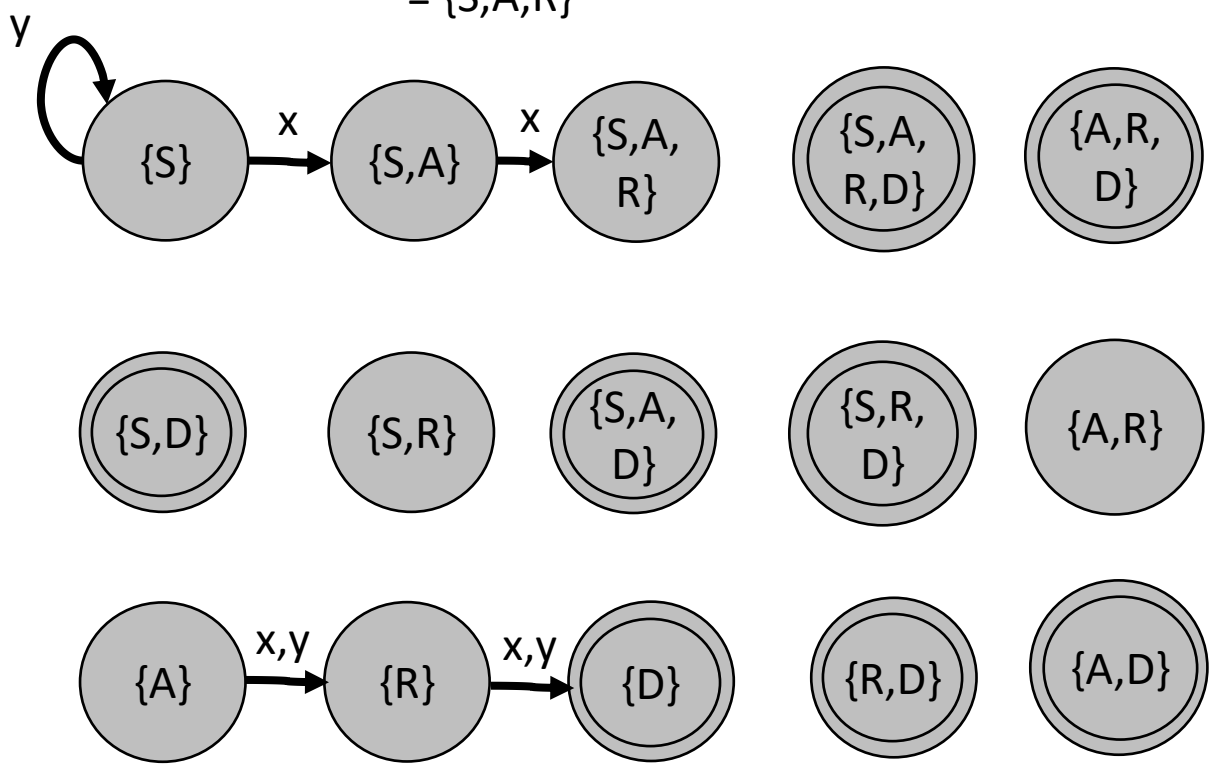
Rabin-Scott Powerset Construction

S,x = {S,A}	A,x = {R}	R,x = {D}	D,x = {}
S,y = {S}	A,y = {R}	R,y = {D}	D,y = {}

{S,A}, x = S,x U A,x

= {S,A} U {R}

= {S,A,R}



From Successors to Powerset DFA

Rabin-Scott Powerset Construction

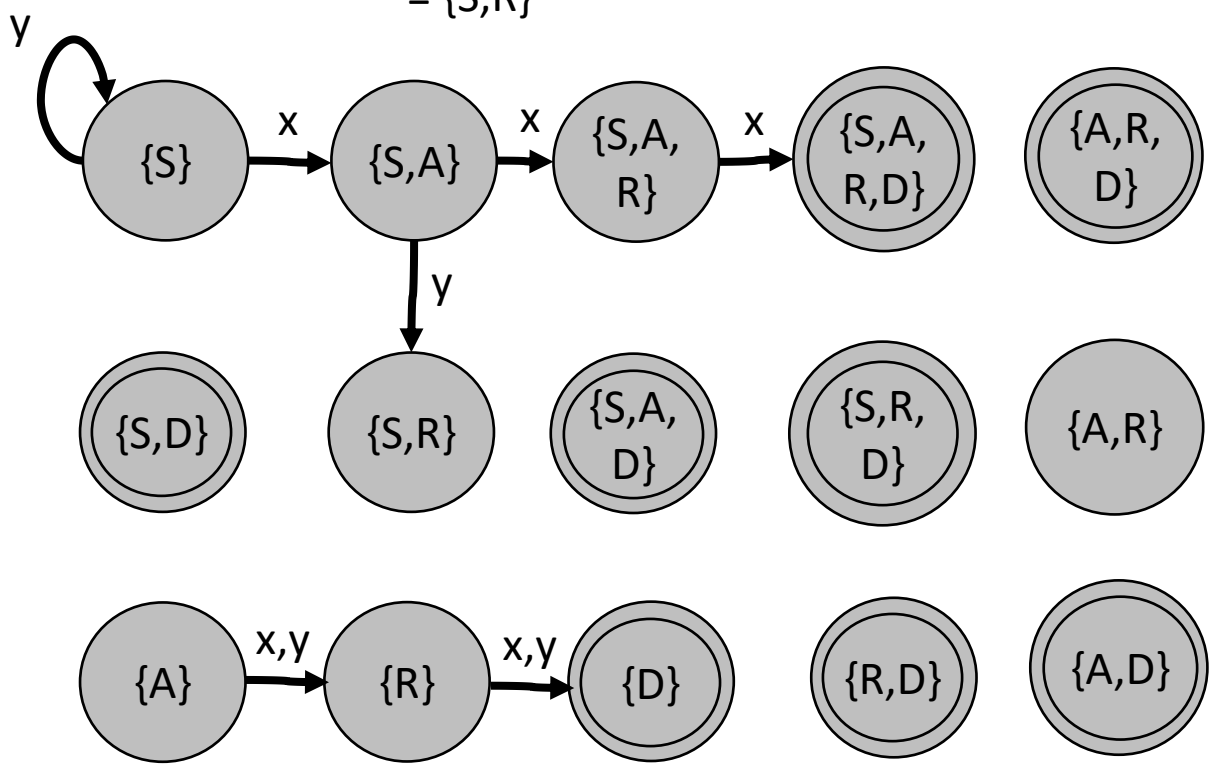
S,x = {S,A} A,x = {R} R,x = {D} D,x = {}

S,y = {S} A,y = {R} R,y = {D} D,y = {}

{S,A}, y = S,y U A,y

= {S} U {R}

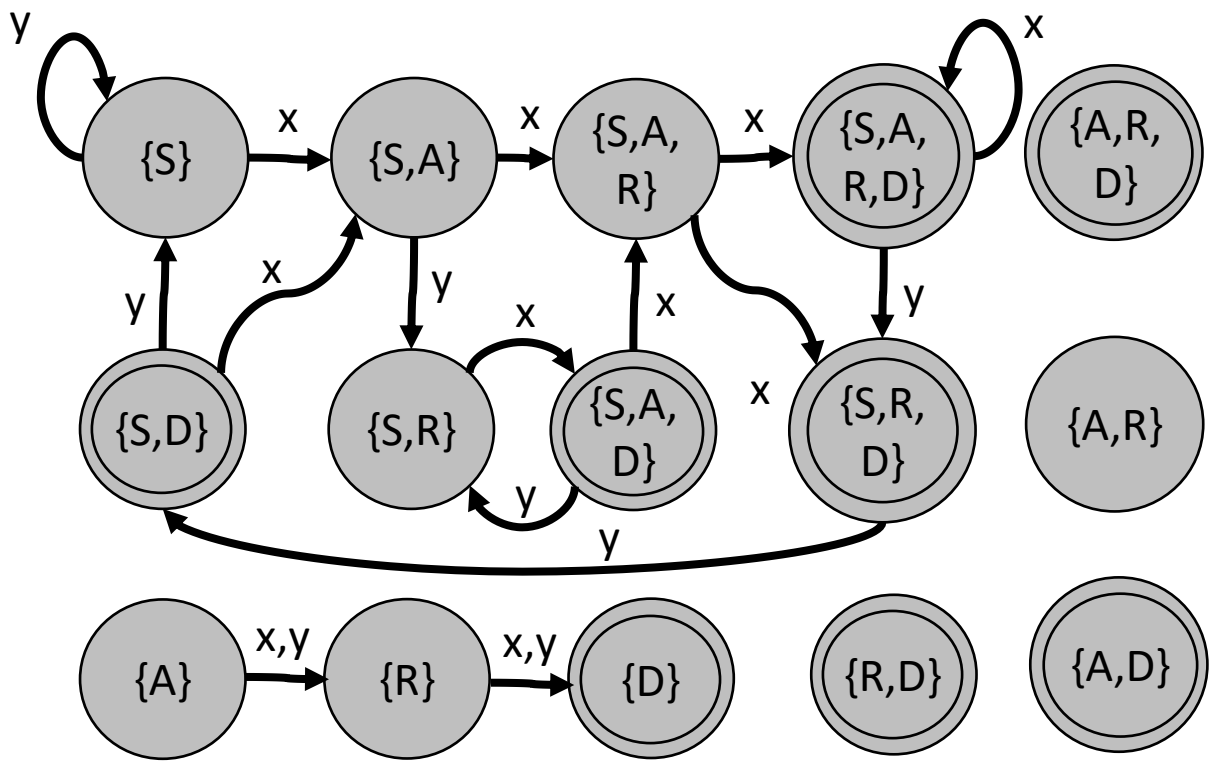
= {S,R}



From Successors to Powerset DFA

Rabin-Scott Powerset Construction

S,x = {S,A}	A,x = {R}	R,x = {D}	D,x = {}
S,y = {S}	A,y = {R}	R,y = {D}	D,y = {}

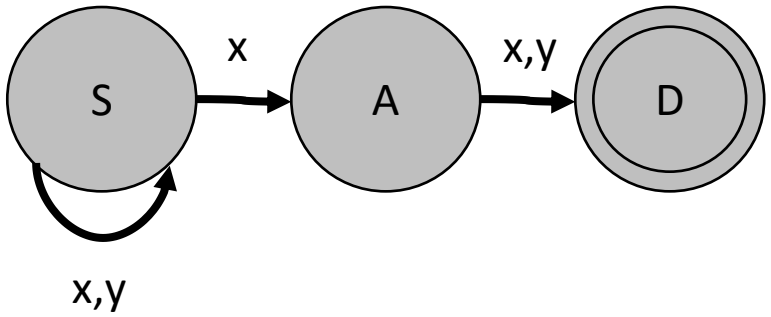


Exponential State Count

Rabin-Scott Powerset Construction

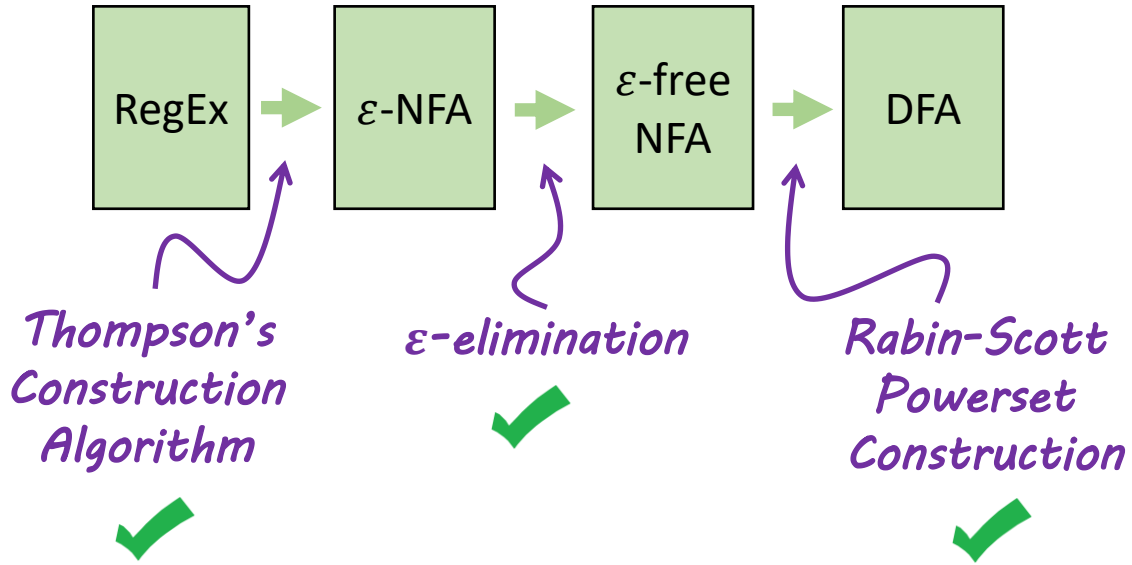
- How may states might the DFA have?
  - $2^{|Q|}$
- Why $2^{|Q|}$?

S	A	D	
0	0	0	{}
0	0	1	{D}
0	1	0	{A}
1	0	0	{S}
0	1	1	{A,D}
1	1	0	{S,A}
1	0	1	{S,D}
1	1	1	{S,A,D}



From RegEx to DFA

Lecture 2 – Implementing Scanners



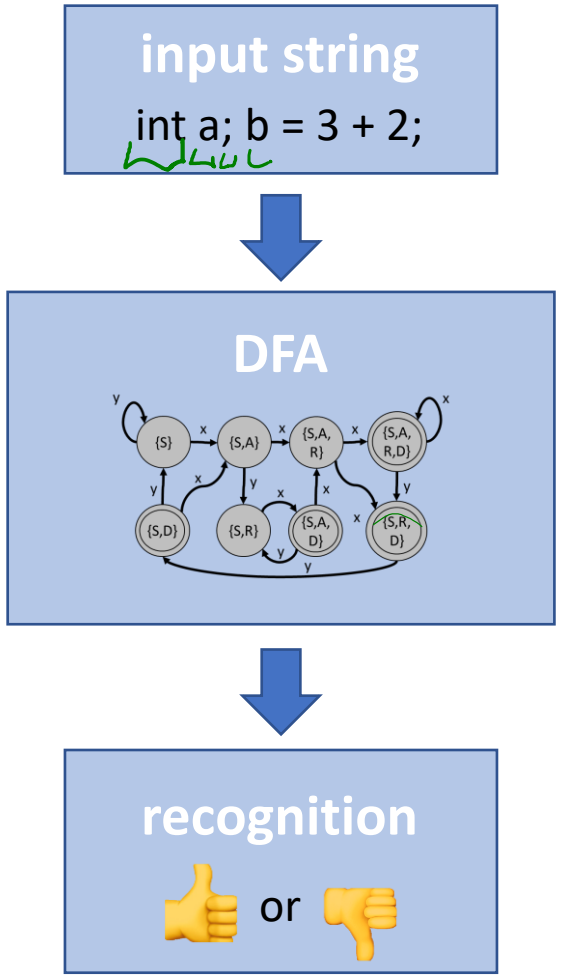
DONE!

… or are we?

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

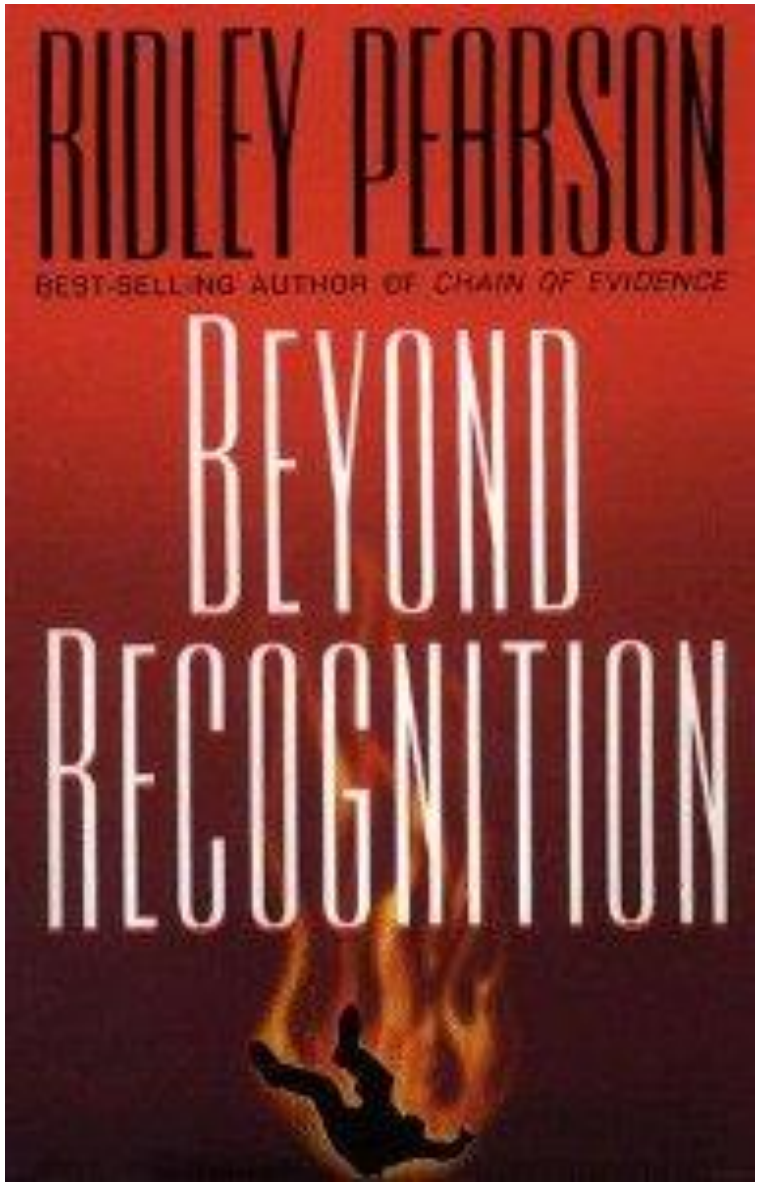


DFA ≠ Tokenizer

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*



Next Time

Lecture 3 Preview