

Part II:
Regular
Languages

Marco T.
Morazán

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

Part II: Regular Languages

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Outline

1 Regular Expressions

2 Deterministic Finite Automata

3 Nondeterministic Finite Automata

4 Finite-State Automata and Regular Expressions

5 Regular Grammars

6 Pumping Theorem for Regular Languages

Regular Expressions

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- Defining English words as strings is a representation choice
- Consider three different representations of the word *cat*:

English: "cat"

FSM: '(c a t)

Binary: 011000110110000101110100

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- The representations of *cat* are different, but the same concept is being represented.
- A language may, for example, be represented as a set of strings, a set of lists, or a set of binary numbers
- Regardless of the representation, the same words in the English language are represented.

Regular Expressions

- Languages are represented using a finite representation
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- This means that the language of finite language representations is countably infinite
- 2^{Σ^*} , however, is uncountable
- There is a countable number of finite language representations and an uncountable number of languages to represent
- Therefore, a finite representation for each language does not exist
- The best that we can achieve is to develop a finite representation of some interesting languages
- As long as a representation is finite the majority of languages cannot be represented.

Regular Expressions

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- We start by considering languages formed by the union or the concatenation of words in two (not necessarily distinct) languages
- Such languages may be finitely represented using regular expressions
- A regular expression, over an alphabet Σ , is an FSM type instance:
 1. (empty-regexp)
 2. (singleton-regexp "a"), where $a \in \Sigma$
 3. (union-regexp $r_1\ r_2$), where r_1 and r_2 are regular expressions
 4. (concat-regexp $r_1\ r_2$), where r_1 and r_2 are regular expressions
 5. (kleenestar-regexp r), where r is a regular expression
- The language of a regular expression, r , is denoted by $L(r)$
- It contains all the words that can be generated with r
- A language that is described by a regular expression is called a *regular language*.

Regular Expressions

The Design Recipe for Regular Expressions

- ① Identify the input alphabet, pick a name for the regular expression, and describe the language
- ② Identify the sublanguages and outline how to compose them
- ③ Define a predicate to determine if a word is in the target language
- ④ Write unit tests
- ⑤ Define the regular expression
- ⑥ Run the tests and, if necessary, debug by revisiting the previous steps
- ⑦ Prove that the regular expression is correct

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- > (union-regexp 2 (singleton-regexp 'w))
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- > (concat-regexp 3 (empty-regexp))
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- > (kleenestar-regexp "A U B")
Step five of the design recipe for regular expressions has not been successfully completed. The argument to kleenestar-regexp must be a regular expression, but found: "A U B"
- > (singleton-regexp 1)
Step five of the design recipe for regular expressions has not been successfully completed. The argument to singleton-regexp must be a single lowercase Roman alphabet string, but found: 1

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Regular Expressions

- Selectors and Predicates

Regular Expressions

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- singleton-regexp-a: Extracts the embedded string
kleenestar-regexp-r1: Extracts the embedded regular expression
union-regexp-r1: Extracts the first embedded regular expression
union-regexp-r2: Extracts the second embedded regular expression
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- empty-regexp? singleton-regexp kleenestar-regexp?
union-regexp? concat-regexp?
- Function Template

```
;; regexp ... → ...
;; Purpose: ...
(define (f-on-regexp rexp ...)
  (cond [(empty-regexp? rexp) ...]
        [(singleton-regexp? rexp)
         ...(f-on-string (singleton-regexp-a rexp))...]
        [(kleenestar-regexp? rexp)
         ...(f-on-regexp (kleenestar-regexp-r1 rexp))...]
        [(union-regexp? rexp)
         ...(f-on-regexp (union-regexp-r1 rexp))...
          ...(f-on-regexp (union-regexp-r2 rexp))...]
        [else ...(f-on-regexp (concat-regexp-r1 rexp))...
          ...(f-on-regexp (concat-regexp-r2 rexp))...]]))
```

Regular Expressions

- Observers for regular expressions
(gen-regexp-word r): Nondeterministically generates a word in the language of the given regexp.
- Many more available for you to write your own gen-word-regexp (see documentation)

Regular Expressions

- FSM provides printable-regexp:
 - > (printable-regexp (empty-regexp))
"ε"
 - > (printable-regexp (singleton-regexp "z"))
"z"
 - > (printable-regexp
 - (union-regexp (singleton-regexp "z") (union-regexp
 - (singleton-regexp "1")
 - (singleton-regexp "q"))))
 - "(z U (1 U q))"
 - > (printable-regexp
 - (concat-regexp (singleton-regexp "i") (singleton-regexp "i")))
 - "ii"
 - > (printable-regexp
 - (kleenestar-regexp (concat-regexp (singleton-regexp "a") (singleton-regexp "b"))))
 - "(ab)*"

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- `#lang fsm`

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;; L(ENDS-WITH-A) = All words that end with an a   Alphabet = a b
(define ENDS-WITH-A
```

- `(concat-regexp`
- `#:sigma ` (a b)`

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- Design idea: Concatenate any word with a
- ;; word --> Boolean
 - ;; Purpose: Determine if given word is in $L(\text{ENDS-WITH-A})$
- (define (valid-ends-with-a? w)
 - (and (eq? (last w) 'a)
 - (andmap (λ (l) (or (eq? l 'a) (eq? l 'b))) w)))
- #lang fsm
 - ;; $L(\text{ENDS-WITH-A}) = \text{All words that end with an } a$ Alphabet = a b

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 - ;; $L(\text{ENDS-WITH-A}) = \text{All words that end with an } a$ Alphabet = a b

- (concat-regexp
- AUB* A
- #::sigma '(a b)
- #::gen-cases 20
- #::pred valid-ends-with-a?
- #::in-lang '((a) (b a) (b b a a b a a))
- #::not-in-lang '(((b) (a a a b))))

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`;; L(ENDS-WITH-A) = All words that end with an a Alphabet = a b`

`(define ENDS-WITH-A`

- `(local [;; L(A) = (a) Alphabet = a`
 `(define A (singleton-regexp "a"))`

`;; L(B) = b Alphabet = (b)`

`(define B (singleton-regexp "b"))`

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```
(define A (singleton-regexp "a"))

\text{;; } L(B) = b \quad \text{Alphabet} = (b)
(define B (singleton-regexp "b"))

\text{;; } L(A \cup B) = (a) (b) \quad \text{Alphabet} = a, b
(define AUB (union-regexp A B
                           #:in-lang '((a) (b))
                           #:not-in-lang '((() (a a) (b a b b)))))
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- ```
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- $\text{;; } L(A \cup B) = (a) \cup (b) \quad \text{Alphabet} = a, b$   

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(define AUB (union-regexp A B
 #:in-lang '((a) (b))
 #:not-in-lang '((() (a a) (b a b b))))
```
- $\text{;; } L(AUB^*) = \text{Words with an arbitrary number of as \& bs} \quad \text{Alphabet} = a, b$   

```
(define AUB* (kleenestar-regexp AUB
 #:in-lang '((() (a a a) (b b a b a a) (b a b))))
```
- $(\text{concat-regexp}$
- $AUB^* \text{ A}$
- $\#:sigma '(a b)$
- $\#:gen-cases 20$
- $\#:pred valid-ends-with-a?$
- $\#:in-lang '((a) (b a) (b b a a b a a))$
- $\#:not-in-lang '((() (b) (a a a b))))$

# Regular Expressions

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- Correctness of ENDS-WITH-A

A and B only generate, respectively, the word a and the word b. Thus, they are correct.

- $A \cup B$  nondeterministically generates either a or b, which is what  $\{a\} \cup \{B\}$  generates. Thus,  $A \cup B$  is correct.
- $A \cup B^*$  nondeterministically generates a word of arbitrary length containing only as and bs, which is what is generated by  $(\{a\} \cup \{B\})^*$ . Thus, it is correct.
- ENDS-WITH-A generates a word by concatenating a word generated by  $A \cup B^*$  and a word generated by A. That is,  $(\{a\} \cup \{B\})^*a$ . This means it generates any word ending with a. Thus, it is correct.

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- It does not provide any details about the structure of the binary numbers in the language nor any indication on how to build such numbers

# Regular Expressions

- Consider the following language:  
 $\text{BIN-NUMS} = \{w \mid w \text{ is a binary number without leading zeroes}\}$
- Although the above definition may sound clear it is lacking
- It does not provide any details about the structure of the binary numbers in the language nor any indication on how to build such numbers
- We shall attempt to formally define BIN-NUMS using a regular expressions

# Regular Expressions

- $\Sigma = \{0, 1\}$
- The minimum length of a binary number is 1
- A binary number with a length greater than 1 cannot start with 0
- ```
;; word --> Boolean Purpose: Test if the given word is a BIN-NUMS
(define (is-bin-nums? w)
  (and (list? w)  (<= 1 (length w))
       (or (= w '())
           (and (= (first w) 1))
               (andmap (λ (bit) (or (= bit 0) (= bit 1))) (rest w))))))
```

Regular Expressions

- ;; L(BIN-NUM) = all words representing binary numbers without leading 0s Alphabet={0 1}
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- `(union-regexp ZERO STARTS1
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Regular Expressions

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`(define BIN-NUMS`

- `(union-regexp ZERO STARTS1
#:sigma '(0 1) #:gen-cases 10 #:pred is-bin-nums?
#:in-lang '((1) (0) (1 0 0 1) (1 1 1))
#:not-in-lang '((0 0 0) (0 1 1 0 1))))`

Regular Expressions

- `;; L(BIN-NUM) = all words representing binary numbers without leading 0s Alphabet={0 1}`
`(define BIN-NUMS`
- `(local [;; L(ZERO) = (0) Alphabet={0}`
`(define ZERO (singleton-regexp "0"))`

- `(union-regexp ZERO STARTS1`
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`(define BIN-NUMS`
 `(local [;; L(ZERO) = (0) Alphabet={0}`
 `(define ZERO (singleton-regexp "0")))`
- `;; L(STARTS1) = all binary numbers starting with 1 Alphabet = {0 1}`
`(define STARTS1`
 `(concat-regexp ONE OU1*`
 `#:sigma '(0 1) #:gen-cases 6`
 `#:pred (λ (w) (and (= (first w) 1)`
 `(andmap (λ (s) (or (= s 0) (= s 1)))`
 `(rest w))))`
 `#:in-lang '((1) (1 0 0 0) (1 0 1))`
 `#:not-in-lang '((0) (0 1 1) (0 0))))]`
- `(union-regexp ZERO STARTS1`
 `#:sigma '(0 1) #:gen-cases 10 #:pred is-bin-nums?`
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 `(define ONE (singleton-regexp "1"))`

- `;; L(OU1*) = all words with an arbitrary number of 0s and 1s Alphabet={0 1}`
`(define OU1*`
 `(kleenestar-regexp OU1`
 `#:sigma '(0 1) #:gen-cases 20`
 `#:pred (λ (w) (or (eq? w EMP)`
 `(andmap (λ (s) (or (= s 0) (= s 1))) w)))`
 `#:in-lang '((0) (1) (1 0 0 0) (1 1 1)))`
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 `(rest w))))`
 `#:in-lang '((1) (1 0 0 0) (1 0 1))`
 `#:not-in-lang '((0) (0 1 1) (0 0))))])`
- `(union-regexp ZERO STARTS1`
 `#:sigma '(0 1) #:gen-cases 10 #:pred is-bin-nums?`
- `#:in-lang '((1) (0) (1 0 0 1) (1 1 1))`
 `#:not-in-lang '((0 0 0) (0 1 1 0 1))))])`

Regular Expressions

- `;; L(BIN-NUM) = all words representing binary numbers without leading 0s Alphabet={0 1}`
`(define BIN-NUMS`
 - `(local [; L(ZERO) = (0) Alphabet={0}`
`(define ZERO (singleton-regexp "0"))`
 - `;; L(ONE) = (1) Alphabet={1}`
`(define ONE (singleton-regexp "1"))`
 - `;; L(OU1) = (0) (1) Alphabet={0 1}`
`(define OU1`
`(union-regexp ZERO ONE`
 - #:sigma '(0 1) #:gen-cases 3
 - #:pred ($\lambda (w)$) (and (= (length w) 1)
(or (= (first w) 0) (= (first w) 1)))
 - #:in-lang '((0) (1))
 - #:not-in-lang '((1 1) (0 0 0) (0 1 1 0 1)))
- `;; L(OU1*) = all words with an arbitrary number of 0s and 1s Alphabet={0 1}`
`(define OU1*`
`(kleenestar-regexp OU1`
 - #:sigma '(0 1) #:gen-cases 20
 - #:pred ($\lambda (w)$) (or (eq? w EMP)
(andmap ($\lambda (s)$) (or (= s 0) (= s 1))) w)))
 - #:in-lang '((0) (1) (1 0 0 0) (1 1 1)))
- `;; L(STARTS1) = all binary numbers starting with 1 Alphabet = {0 1}`
`(define STARTS1`
`(concat-regexp ONE OU1*`
 - #:sigma '(0 1) #:gen-cases 6
 - #:pred ($\lambda (w)$) (and (= (first w) 1)
(andmap ($\lambda (s)$) (or (= s 0) (= s 1)))
(rest w))))
 - #:in-lang '((1) (1 0 0 0) (1 0 1))
 - #:not-in-lang '((0) (0 1 1) (0 0))))]
- `(union-regexp ZERO STARTS1`
`#:sigma '(0 1) #:gen-cases 10 #:pred is-bin-nums?`
- `#:in-lang '((1) (0) (1 0 0 1) (1 1 1))`
`#:not-in-lang '((0 0 0) (0 1 1 0 1))))`

Regular Expressions

- Correctness of BIN-NUMS
- ZERO and ONE only generate, respectively, the word 0 and the word 1. Thus, they are correct.

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- 0U1 nondeterministically generates the word 0 or the word 1, which is what is generated by 0 U 1. Thus, it is correct.

Regular Expressions

- Correctness of BIN-NUMS
- ZERO and ONE only generate, respectively, the word 0 and the word 1. Thus, they are correct.
- 0U1 nondeterministically generates the word 0 or the word 1, which is what is generated by $0 \cup 1$. Thus, it is correct.
- $0U1^*$ nondeterministically generates a word of arbitrary length containing 0s and 1s, which is what $0 \cup 1^*$ generates. Thus, it is correct.

Regular Expressions

- Correctness of BIN-NUMS
- ZERO and ONE only generate, respectively, the word 0 and the word 1. Thus, they are correct.
- 0U1 nondeterministically generates the word 0 or the word 1, which is what is generated by 0 U 1. Thus, it is correct.
- 0U1* nondeterministically generates a word of arbitrary length containing 0s and 1s, which is what 0 U 1* generates. Thus, it is correct.
- STARTS1 generates a word by concatenating the word 1 with a word generated by 0U1*. That is, it generates a word in 1(0 U 1)* (any word of 0s and 1s that starts with 1). Thus, it is correct.

Regular Expressions

- Correctness of BIN-NUMS
- ZERO and ONE only generate, respectively, the word 0 and the word 1. Thus, they are correct.
- OU1 nondeterministically generates the word 0 or the word 1, which is what is generated by $0 \cup 1$. Thus, it is correct.
- OU1* nondeterministically generates a word of arbitrary length containing 0s and 1s, which is what $0 \cup 1^*$ generates. Thus, it is correct.
- STARTS1 generates a word by concatenating the word 1 with a word generated by OU1*. That is, it generates a word in $1(0 \cup 1)^*$ (any word of 0s and 1s that starts with 1). Thus, it is correct.
- BIN-NUMS either generates 0 or a word generated by STARTS1. That is, it generates any binary number with no leading repeated 0s. Thus, it is correct.

Regular Expressions

- HOMEWORK: 1–4

Regular Expressions

- Regular expressions may be used to describe data such as internet addresses, proteins, decimal numbers, and patterns to search for in text among others

Regular Expressions

- Regular expressions may be used to describe data such as internet addresses, proteins, decimal numbers, and patterns to search for in text among others
- To illustrate the use of regular expressions we explore the problem of generating passwords (**simpler version than what is in the textbook**)

Regular Expressions

- A password is a string that:
 - Has length ≥ 10
 - Includes at least one lowercase letter
 - Includes at least one special character: \$, &, !, and *

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```
(define lowers '(a b c d e f g h i j k l m n o p q  
                  r s t u v w x y z))  
  
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Regular Expressions

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```
(define lowers '(a b c d e f g h i j k l m n o p q
                 r s t u v w x y z))

(define spcls '($ & ! *))
```

- The needed singleton-regexps:

```
(define lc (map
            (lambda (lcl) (singleton-regexp (symbol->string lcl)))
            lowers))

(define spc (map
            (lambda (sc) (singleton-regexp (symbol->string sc)))
            spcls))
```

Regular Expressions

- Two different orderings the required elements may appear in:
 $S \ L \quad L \ S$
- Arbitrary number of elements before and after each
- What do LOWER, SPCHS, and ARBTRY need to be?

Regular Expressions

- Two different orderings the required elements may appear in:
 $S \ L \quad L \ S$
- Arbitrary number of elements before and after each
- What do LOWER, SPCHS, and ARBTRY need to be?
- ```
(define LOWER (create-union-regexp lc))
(define SPCHS (create-union-regexp spc))
(define ARBTRY (kleenestar-regexp (union-regexp LOWER SPCHS)))
```
- We need an auxiliary function (unless you want to type really long union-regexp)

# Regular Expressions

- We can define each sub-language:

```
(define LS (concat-regexp
 ARBTRY
 (concat-regexp
 LOWER
 (concat-regexp ARBTRY
 (concat-regexp SPCHS ARBTRY)))
 #:sigma (append lowers spcls)
 #:not-in-lang '((() (a b c) ($ $)))
 #:in-lang '((a $ w e *) ($ $ y w ! i &))))
(define SL (concat-regexp
 ARBTRY
 (concat-regexp
 SPCHS
 (concat-regexp ARBTRY
 (concat-regexp LOWER ARBTRY)))
 #:sigma (append lowers spcls)
 #:not-in-lang '((() (x x b w) (! ! & *)))
 #:in-lang '((a $ g q ! !) (! y w o *))))
```

# Regular Expressions

- The language of words is defined by having any ordering of required elements

# Regular Expressions

- The language of words is defined by having any ordering of required elements

- It is defined using a union regular expression:

```
(define WORDS ;; not passwords
 (union-regexp SL LS
 #:sigma (append lowers spcls)
 #:pred (λ (w)
 (and (>= (length w) 10)
 (list? (ormap (λ (c)
 (member c w))
 lowers)))
 (list? (ormap (λ (c)
 (member c w))
 spcls))))
 #:gen-cases 3
 #:in-lang '((a x ! ! z e y n $ u)
 (d r $ & h q ! * v z z))
 #:not-in-lang '((a b c d) ($ & ! *) (a z b))
))
```

# Regular Expressions

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- The constructor for a password takes no input and returns a string

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- A potential new password is locally defined
- A word is generated by applying FSM's gen-regexp-word to WORDS and then converting the generated word to a string
- If the length of the string is greater than or equal to 10 then it is returned as the generated password. Otherwise, a new word is generated.

# Regular Expressions

- DESIGN IDEA
- The constructor for a password takes no input and returns a string
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- A word is generated by applying FSM's gen-regexp-word to WORDS and then converting the generated word to a string
- If the length of the string is greater than or equal to 10 then it is returned as the generated password. Otherwise, a new word is generated.
- In order to prevent generated passwords from getting unwieldy long gen-regexp-word is given 5 as the maximum number of repetitions for a Kleene star regular expression

# Regular Expressions

- ```
;; --> string
;; Purpose: Generate a valid password
(define (generate-password))
```

Regular Expressions

- ```
;; --> string
;; Purpose: Generate a valid password
(define (generate-password)
```
- ```
;; string → Boolean
;; Purpose: Test if the given string is a valid password
(define (is-passwd? p)
  (let [(los (str->los p))]
    (and (>= (length los) 10)
         (ormap (λ (c) (member c los)) lowers)
         (ormap (λ (c) (member c los)) uppers)
         (ormap (λ (c) (member c los)) spcls))))
```

Regular Expressions

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```
- ```
(check-pred is-passwd? (generate-password))
```

# Regular Expressions

- ```
;;  --> string
;; Purpose: Generate a valid password
(define (generate-password)
```
- ```
(let [(new-passwd (passwd->string
 (gen-regexp-word WORDS 5)))]
 (if (>= (string-length new-passwd) 10)
 new-passwd
 (generate-password))))
```
- ```
;; string → Boolean
;; Purpose: Test if the given string is a valid password
(define (is-passwd? p)
  (let [(los (str->los p))]
    (and (>= (length los) 10)
         (ormap (λ (c) (member c los)) lowers)
         (ormap (λ (c) (member c los)) uppers)
         (ormap (λ (c) (member c los)) spcls))))
```
- ```
(check-pred is-passwd? (generate-password))
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```

# Regular Expressions

- ;; string → (listof symbol)  
;; Purpose: Convert the given string to a list of symbols  

```
(define (str->los str)
 (map (λ (c) (string->symbol (string c)))
 (string->list str)))
```

  
;; Tests  

```
(check-equal? (str->los "") '())
 (check-equal? (str->los "a!Cop") '(a ! C o p))
```

# Regular Expressions

- ```
;; string → (listof symbol)
;; Purpose: Convert the given string to a list of symbols
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        (string->list str)))

;; Tests
(check-equal? (str->los "") '())
(check-equal? (str->los "a!Cop") '(a ! C o p))
```
- ```
;; word → string
;; Purpose: Convert the given word to a string
(define (passwd->string passwd)
 (list->string
 (map (λ (s)
 (first (string->list (symbol->string s))))
 passwd)))

;;Tests
(check-equal? (passwd->string '(a j h B ! ! y y t c))
 "ajhb!!yytc")
(check-equal? (passwd->string '($ u t q x ! J i n * K C))
 "$utqx!Jin*KC")
```

# Regular Expressions

- ```
;; (listof regexp) → union-regexp
;; Purpose: Create a union-regexp using the given list of
;;           regular expressions
(define (create-union-regexp L)
  (cond [(< (length L) 2)
         (error "list too short")]
        [(empty? (rest (rest L)))
         (union-regexp (first L) (second L))]
        [else
         (union-regexp (first L)
                      (create-union-regexp (rest L))))])

;; Tests
(check-equal?
  (create-union-regexp (list (first lc) (first uc)))
  (union-regexp (singleton-regexp "a")
                (singleton-regexp "A")))

(check-equal?
  (create-union-regexp
    (list (first lc) (fourth uc) (third spc)))
  (union-regexp (singleton-regexp "a")
                (union-regexp (singleton-regexp "D")
                              (singleton-regexp "!"))))
```

Regular Expressions

- Run the program and make sure all the tests pass.

Regular Expressions

- Run the program and make sure all the tests pass.
- These are sample passwords generated:

```
> (generate-password)
"!&!!!!v*$&!#!*"
> (generate-password)
"q$e*n**!y&$!$!"
> (generate-password)
"!*$!gq$x!&*q**&&"
> (generate-password)
"$p!b!*v*ac**&"
> (generate-password)
"$or*z!!a!$"
```

- The passwords generated appear fairly robust

Regular Expressions

- HOMEWORK: 9, 11, 13
- QUIZ: 14 (due in 1 week)

Deterministic Finite Automata

- Regular expressions define how to generate words in a regular language
- How can we decide if it is a member of a language?

Deterministic Finite Automata

- Regular expressions define how to generate words in a regular language
- How can we decide if it is a member of a language?
- For this it is desirable to have some type of device or machine that takes as input a word and returns 'accept' if the given word is in the language and 'reject' if the given word is not in the language
- We need a model of a computer to determine if a word is part of a language
- How should such a machine operate?

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- How should such a machine operate?
- Analyzing how words in the language of a regular expression are generated can provide some insight
- Consider how a word is generated for the following regular expression:

```
(concat-regexp
  (union-regexp (singleton-regexp "a")
               (singleton-regexp "b"))
  (concat-regexp (kleenestar-regexp (singleton-regexp "a"))
                (singleton-regexp "b"))))
```

- Word generation traverses the structure of the regular expression
- An a or a b is generated
- An arbitrary number of as are generated
- A b is generated
- What does this tell you?

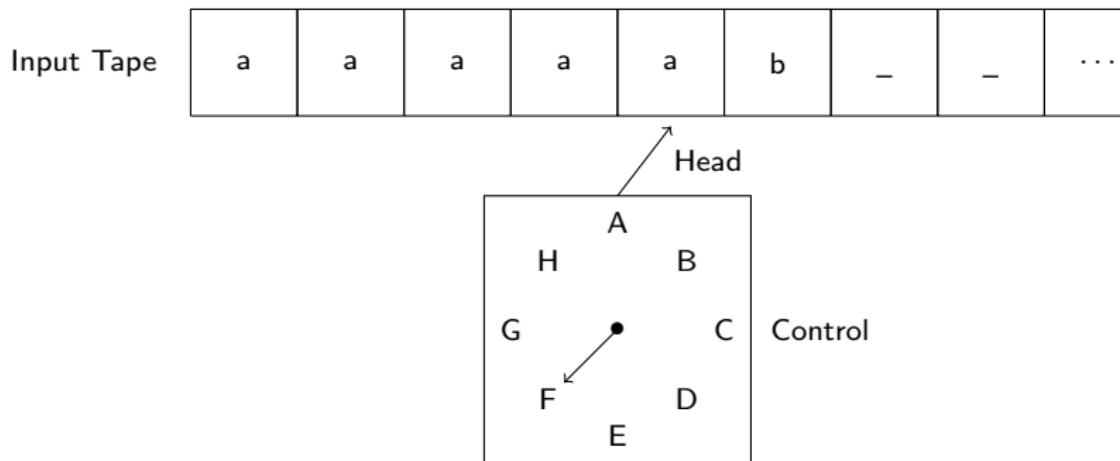
Deterministic Finite Automata

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```

- Word generation traverses the structure of the regular expression
- An a or a b is generated
- An arbitrary number of as are generated
- A b is generated
- What does this tell you?
- The elements of a word are generated from left to right
- Suggests that a word may be traversed from left to right to determine if it is in a language

Deterministic Finite Automata



- The machine outlined above is called a *finite-state automaton* (or *finite-state machine*)
- A (very) restricted model of a computer
- Only capable of accepting or rejecting words
- Has no memory other than what exists in the processing module: it can only remember the state that it is

Deterministic Finite Automata

Definition

A deterministic finite-state automaton, dfa , is a (`make-dfa S Σs F δ ['no-dead']`)

- δ is a transition function: must contain a transition, $(A \ a \ B)$, for every element in $S \times \Sigma$

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Definition

A deterministic finite-state automaton, dfa , is a (`make-dfa S Σs F δ ['no-dead']`)

- δ is a transition function: must contain a transition, $(A \ a \ B)$, for every element in $S \times \Sigma$
- The constructor automatically adds a *dead state*, ds (denoted by the FSM constant `DEAD`), and any missing transitions
- For any missing transition the added transition moves the machine to the dead state
- To inhibit the addition of the dead state the optional argument '`no-dead`' may be given to the constructor

Deterministic Finite Automata

- A computation for a dfa, M , is denoted by a list of configurations that M traverses to consume the input word
- A configuration is a two-list that has the unconsumed part of the input word and the state the machine

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- $C_i \vdash C_j$ is valid for M if and only if M can move from C_i to C_j using a single transition

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- Zero or more moves by M is denoted using \vdash^* .
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Deterministic Finite Automata

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- $C_i \vdash C_j$ is valid for M if and only if M can move from C_i to C_j using a single transition
- Zero or more moves by M is denoted using \vdash^* .
- $C_i \vdash^* C_j$ is valid for M if and only if M can move from C_i to C_j using zero or more transitions
- A word, w , is accepted by M if the following is a valid computation:
 $(w\ s) \vdash^* ('() q)$, where $q \in F$
- The language accepted by M , $L(M)$, is the set of all strings accepted by M

Deterministic Finite Automata

- **Selectors**

- (sm-states m): Returns the states of the given machine
- (sm-sigma m): Returns the alphabet of the given machine
- (sm-rules m): Returns the transition relation of the given machine
- (sm-start m): Returns the start state of the given machine
- (sm-finals m): Returns the final states of the given machine
- (sm-type m): Returns a symbol denoting the machine type

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- (sm-type m): Returns a symbol denoting the machine type

- Observers

- (sm-apply m w [n]): Applies the given machine to the given word. It returns either 'accept' or 'reject.'
- (sm-showtransitions m w [n]): Applies the given machine to the given word. It returns a list for the computation performed.

Deterministic Finite Automata

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- (sm-showtransitions m w [n]): Applies the given machine to the given word. It returns a list for the computation performed.

- Testers

- (sm-test m [n]): Applies m to 100 randomly generated words and returns a list of the results. The optional natural number specifies the number of tests to perform.
- (sm-sameresult? $m1$ $m2$ w): Applies the two given machines, $m1$ and $m2$, to, w , the given word and tests if the same result is obtained.
- (sm-testequiv? $m1$ $m2$ [n]): Applies the two given machines, $m1$ and $m2$, to the same 100 randomly generated words and tests if they produce the same results. If they do true is returned. Otherwise, a list of the words for which the results differ is returned. The optional natural number specifies the number of words to test.

Deterministic Finite Automata

- Machine Visualization

(sm-graph m): Returns a *transition diagram* rendered as a directed graph for the given machine.

(sm-visualize m) [(s p)*] : Starts the FSM visualization tool for the given machine. The optional two-lists contain a state of the given machine and a predicate invariant (we will soon discuss this in more detail).

(sm-cmpgraph m w): Returns a *computation graph* rendered as a directed graph for the given machine. The graph summarizes how a word is accepted or rejected. A computation graph only contains the nodes and edges in the transition diagram used by a computation. A state outlined in crimson denotes where a computation stops.

- Examples: abb-b.rkt

Deterministic Finite Automata

- Design Recipe for State Machines
 - ① Name the machine and specify alphabets
 - ② Write unit tests
 - ③ Identify conditions that must be tracked as input is consumed, associate a state with each condition, and determine the start and final states.
 - ④ Formulate the transition relation
 - ⑤ Implement the machine
 - ⑥ Test the machine using unit tests and random testing
 - ⑦ Design, implement, and test an invariant predicate for each state
 - ⑧ Prove $L = L(M)$

Deterministic Finite Automata

- $L = \{w \mid w \in \{a\ b\}^* \wedge w \text{ has an even number of } a \text{ and an odd number of } b\}$

Deterministic Finite Automata

- $L = \{w \mid w \in \{a\}^* \wedge w \text{ has an even number of } a \text{ and an odd number of } b\}$
- ; ; Name: EVEN-A-ODD-B
; ;
; ; $\Sigma: \{a, b\}$

Deterministic Finite Automata

- $L = \{w \mid w \in \{a\}^* \wedge w \text{ has an even number of } a \text{ and an odd number of } b\}$
- ;; Name: EVEN-A-ODD-B
;;
;; $\Sigma: \{a, b\}$
- ;; Tests for EVEN-A-ODD-B
#:accepts '((b) (a a b) (a a a b a b b))
#:rejects '(() (a b b a) (b a b b a a) (a b)
(a b b b b) (b a b b a a b))

Deterministic Finite Automata

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

- States
- As a word is processed the consumed input may contain:
 - ① an even number of a and an even number of b
 - ② an odd number of a and an odd number of b
 - ③ an even number of a and an odd number of b
 - ④ odd number of a and even number of b

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 - ④ odd number of a and even number of b
- When processing starts the consumed input has an even number of as and an even number of bs

Deterministic Finite Automata

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 - ② an odd number of a and an odd number of b
 - ③ an even number of a and an odd number of b
 - ④ odd number of a and even number of b
- When processing starts the consumed input has an even number of as and an even number of bs
- The state that represents that the consumed input has an even number of as and an odd number of bs must be the only final state.

Deterministic Finite Automata

- States
- As a word is processed the consumed input may contain:
 - ① an even number of a and an even number of b
 - ② an odd number of a and an odd number of b
 - ③ an even number of a and an odd number of b
 - ④ odd number of a and even number of b
- When processing starts the consumed input has an even number of as and an even number of bs
- The state that represents that the consumed input has an even number of as and an odd number of bs must be the only final state.
- The states may be documented as follows:

```
;; States
;; S: even number of a and even number of b, start state
;; M: odd number of a and odd number of b
;; N: even number of a and odd number of b, final state
;; P: odd number of a and even number of b
```

Deterministic Finite Automata

- Transition Function
 - $(S \ a \ P)$ from even-even to odd-even
 - $(S \ b \ N)$ from even-even to even-odd

Deterministic Finite Automata

- Transition Function
 - $(S \ a \ P)$ from even-even to odd-even
 - $(S \ b \ N)$ from even-even to even-odd
 - $(M \ a \ N)$ from odd-odd to even-odd
 - $(M \ b \ P)$ from odd-odd to odd-even

Deterministic Finite Automata

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

- Transition Function

- $(S \ a \ P)$ from even-even to odd-even
 $(S \ b \ N)$ from even-even to even-odd
- $(M \ a \ N)$ from odd-odd to even-odd
 $(M \ b \ P)$ from odd-odd to odd-even
- $(N \ a \ M)$ from even-odd to odd-even
 $(N \ b \ S)$ from even-odd to even-even

Deterministic Finite Automata

- Transition Function

- $(S \ a \ P)$ from even-even to odd-even
 $(S \ b \ N)$ from even-even to even-odd
- $(M \ a \ N)$ from odd-odd to even-odd
 $(M \ b \ P)$ from odd-odd to odd-even
- $(N \ a \ M)$ from even-odd to odd-even
 $(N \ b \ S)$ from even-odd to even-even
- $(P \ a \ S)$ from odd-even to even-even
 $(P \ b \ M)$ from odd-even to odd-even

Deterministic Finite Automata

- Implementation

```
(define EVEN-A-ODD-B
  (make-dfa '(S M N P)
             '(a b)
             'S
             '(N)
             '((S a P) (S b N)
                (M a N) (M b P)
                (N a M) (N b S)
                (P a S) (P b M)))
             'no-dead
             #:accepts '((b) (a a b) (a a a b a b b))
             #:rejects '((( ) (a b b a) (b a b b a a) (a b)
                           (a b b b b) (b a b b a a b))))
```

Deterministic Finite Automata

- Implementation

```
(define EVEN-A-ODD-B
  (make-dfa '(S M N P)
             '(a b)
             'S
             '(N)
             '((S a P) (S b N)
                (M a N) (M b P)
                (N a M) (N b S)
                (P a S) (P b M)))
             'no-dead
             #:accepts '((b) (a a b) (a a b a b b))
             #:rejects '(() (a b b a) (b a b b a a) (a b)
                          (a b b b b) (b a b b a a b))))
```

- > (sm-test EVEN-A-ODD-B 20)

```
'(((b a a a) reject)
   ((a a b a a b b) accept)
   ((b b a) reject)
   ((a b a) accept)
   () reject)
  ((a a a a) reject)
  ((b b b a a b b) accept)
  ((b b b a b a b) accept))
```

:

Deterministic Finite Automata

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

- You can always use `check-equal?`
- `#:accepts` list of words that ought to be accepted
- `#:rejects` list of words that ought to be rejected
- **Warning:** machine is not built if expected behavior for any word is not met (unlike using `check-equal?`)

Deterministic Finite Automata

- State Invariants

- ```
;; word → Boolean
```

```
;; Purpose: Determine if given word has an even number
```

```
;; of a and an even number of b
```

```
(define (S-INV ci)
```

```
 (and (even? (length (filter (λ (s) (eq? s 'a)) ci)))
 (even? (length (filter (λ (s) (eq? s 'b)) ci))))))
```

```
;; Tests for S-INV
```

```
(check-equal? (S-INV '(a)) #f)
```

```
(check-equal? (S-INV '(a b b b a)) #f)
```

```
(check-equal? (S-INV '()) #t)
```

```
(check-equal? (S-INV '(a a b b)) #t)
```

# Deterministic Finite Automata

- State Invariants

- ```
;; word → Boolean
```

```
;; Purpose: Determine if given word has an even number
;;           of a and an even number of b
```

```
(define (S-INV ci)
  (and (even? (length (filter (λ (s) (eq? s 'a)) ci)))
        (even? (length (filter (λ (s) (eq? s 'b)) ci)))))
```

```
;; Tests for S-INV
```

```
(check-equal? (S-INV '(a)) #f)
(check-equal? (S-INV '(a b b b a)) #f)
(check-equal? (S-INV '()) #t)
(check-equal? (S-INV '(a a b b)) #t)
```

- ```
;; word → Boolean
```

```
;; Purpose: Determine if given word has an odd number
;; of a and an odd number of b
```

```
(define (M-INV ci)
 (and (odd? (length (filter (λ (s) (eq? s 'a)) ci)))
 (odd? (length (filter (λ (s) (eq? s 'b)) ci)))))
```

```
;; Tests for M-INV
```

```
(check-equal? (M-INV '(a)) #f)
(check-equal? (M-INV '(a b b b a)) #f)
(check-equal? (M-INV '(a b b b a a b)) #f)
(check-equal? (M-INV '(b a)) #t)
(check-equal? (M-INV '(b a a b a b)) #t)
```

# Deterministic Finite Automata

- ```
;; word → Boolean
;; Purpose: Determine if given word has an even number
;;           of a and an odd number of b
(define (N-INV ci)
  (and (even? (length (filter (λ (s) (eq? s 'a)) ci)))
        (odd? (length (filter (λ (s) (eq? s 'b)) ci))))
;; Tests for N-INV
(check-equal? (N-INV '()) #f)
(check-equal? (N-INV '(a b a b a)) #f)
(check-equal? (N-INV '(a b b a a b)) #f)
(check-equal? (N-INV '(b a a)) #t)
(check-equal? (N-INV '(a b a a b a b b b)) #t)
```

Deterministic Finite Automata

- ```
;; word → Boolean
;; Purpose: Determine if given word has an even number
;; of a and an odd number of b
(define (N-INV ci)
 (and (even? (length (filter (λ (s) (eq? s 'a)) ci)))
 (odd? (length (filter (λ (s) (eq? s 'b)) ci)))))
;; Tests for N-INV
(check-equal? (N-INV '()) #f)
(check-equal? (N-INV '(a b a b a)) #f)
(check-equal? (N-INV '(a b b a a b)) #f)
(check-equal? (N-INV '(b a a)) #t)
(check-equal? (N-INV '(a b a a b a b b b)) #t)
```
- ```
;; word → Boolean
;; Purpose: Determine if given word has an odd number
;;           of a and an even number of b
(define (P-INV ci)
  (and (odd? (length (filter (λ (s) (eq? s 'a)) ci)))
        (even? (length (filter (λ (s) (eq? s 'b)) ci)))))
;; Tests for P-INV
(check-equal? (P-INV '()) #f)
(check-equal? (P-INV '(a b)) #f)
(check-equal? (P-INV '(a b b a a b a)) #f)
(check-equal? (P-INV '(b a b)) #t)
(check-equal? (P-INV '(a b a a b b b)) #t)
```

Deterministic Finite Automata

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

- Validate invariants using `sm-visualize`

Deterministic Finite Automata

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

- Validate invariants using `sm-visualize`
- For the required proofs we use the following notation:

$M = \text{EVEN-A-ODD-B}$

$\Sigma = (\text{sm-sigma } M)$

$F = (\text{sm-finals } M)$

$w \in \Sigma^*$

$c_i = \text{the consumed input}$

Deterministic Finite Automata

Theorem

The state invariants hold when M is applied to w .

- Proof by induction on the number of transitions, n , M makes to consume w .

Deterministic Finite Automata

Theorem

The state invariants hold when M is applied to w.

- Proof by induction on the number of transitions, n , M makes to consume w .
- Base Case: $n = 0$
If n is 0 then the consumed input is '()' and M is in S . This means the consumed input has an even number of as and an even number of bs (0 of each). Therefore, S-INV holds.

Deterministic Finite Automata

Theorem

The state invariants hold when M is applied to w .

- Proof by induction on the number of transitions, n , M makes to consume w .
- Base Case: $n = 0$
If n is 0 then the consumed input is '()' and M is in S . This means the consumed input has an even number of as and an even number of bs (0 of each). Therefore, S-INV holds.
- Inductive Step:
Assume: State invariants hold for $n = k$.
Show: State invariants hold for $n = k+1$.

Deterministic Finite Automata

Theorem

The state invariants hold when M is applied to w.

- Proof by induction on the number of transitions, n, M makes to consume w.
- Base Case: n = 0
If n is 0 then the consumed input is '()' and M is in S. This means the consumed input has an even number of as and an even number of bs (0 of each). Therefore, S-INV holds.
- Inductive Step:
Assume: State invariants hold for n = k.
Show: State invariants hold for n = k+1.
- If n=k+1 then the consumed input cannot be '()' given that the machine must have consumed at least one symbol. Therefore, we can state that $c_i=x_a$ such that $|c_i|=k+1$, $x \in \Sigma^*$ and $a \in \Sigma$. M's computation to consume c_i has k+1 steps:

$$(x a s) \vdash^k (a r) \vdash ('() q), \text{ where } r, q \in S$$

- Given that $|x|=k$ the inductive hypothesis informs us that the state invariants hold when x is consumed by M

Deterministic Finite Automata

Theorem

The state invariants hold when M is applied to w.

- Proof by induction on the number of transitions, n, M makes to consume w.
- Base Case: n = 0
If n is 0 then the consumed input is '()' and M is in S. This means the consumed input has an even number of as and an even number of bs (0 of each). Therefore, S-INV holds.
- Inductive Step:
Assume: State invariants hold for n = k.
Show: State invariants hold for n = k+1.
- If n=k+1 then the consumed input cannot be '()' given that the machine must have consumed at least one symbol. Therefore, we can state that $c_i = x a$ such that $|c_i| = k+1$, $x \in \Sigma^*$ and $a \in \Sigma$. M's computation to consume c_i has k+1 steps:

$$(x a s) \vdash^k (a r) \vdash ('() q), \text{ where } r, q \in S$$

- Given that $|x|=k$ the inductive hypothesis informs us that the state invariants hold when x is consumed by M
- We must show that the state invariants hold for the k+1 transition into q

Deterministic Finite Automata

- (S a P): Assume S-INV holds. Consuming an a means c_i has an odd number of a s and an even number b s. Therefore, P-INV holds.

Deterministic Finite Automata

- (S a P): Assume S-INV holds. Consuming an a means c_i has an odd number of a s and an even number b s. Therefore, P-INV holds.
- (S b N): Assume S-INV holds. Consuming a b means c_i has an even number of a s and an odd number b s. Therefore, N-INV holds.

Deterministic Finite Automata

- (S a P): Assume S-INV holds. Consuming an a means c_i has an odd number of a s and an even number b s. Therefore, P-INV holds.
- (S b N): Assume S-INV holds. Consuming a b means c_i has an even number of a s and an odd number b s. Therefore, N-INV holds.
- (M a N): Assume M-INV holds. Consuming an a means c_i has an even number of a s and an odd number b s. Therefore, N-INV holds.

Deterministic Finite Automata

- (S a P): Assume S-INV holds. Consuming an a means c_i has an odd number of a s and an even number b s. Therefore, P-INV holds.
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Deterministic Finite Automata

- (S a P): Assume S-INV holds. Consuming an a means c_i has an odd number of a s and an even number b s. Therefore, P-INV holds.
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- (N a M): Assume N-INV holds. Consuming an a means c_i has an odd number of a s and an odd number b s. Therefore, M-INV holds.

Deterministic Finite Automata

- (S a P): Assume S-INV holds. Consuming an a means ci has an odd number of as and an even number bs. Therefore, P-INV holds.
- (S b N): Assume S-INV holds. Consuming a b means ci has an even number of as and an odd number bs. Therefore, N-INV holds.
- (M a N): Assume M-INV holds. Consuming an a means ci has an even number of as and an odd number bs. Therefore, N-INV holds.
- (M b P): Assume M-INV holds. Consuming an b means ci has an odd number of as and an even number bs. Therefore, P-INV holds.
- (N a M): Assume N-INV holds. Consuming an a means ci has an odd number of as and an odd number bs. Therefore, M-INV holds.
- (N b S): Assume N-INV holds. Consuming an b means ci has an even number of as and an even number bs. Therefore, S-INV holds.

Deterministic Finite Automata

- (S a P): Assume S-INV holds. Consuming an a means ci has an odd number of as and an even number bs. Therefore, P-INV holds.
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- (P b M): Assume P-INV holds. Consuming an b means ci has an odd number of as and an odd number bs. Therefore, M-INV holds

Deterministic Finite Automata

- The proof that $L(EVEN-A-ODD-B) = L$ is divided into two lemmas (i.e., two parts):
 - ① $w \in L \Leftrightarrow w \in L(M)$
 - ② $w \notin L \Leftrightarrow w \notin L(M)$

Deterministic Finite Automata

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

Lemma

$$w \in L \Leftrightarrow w \in L(M)$$

- (\Rightarrow) Assume $w \in L$.

$w \in L$ means that w has an even number of as and an odd number of bs. The proof that state invariants hold when w is consumed means that M can only halt in N , which is a final state. Therefore, $w \in L(M)$.

Deterministic Finite Automata

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

Lemma

$$w \in L \Leftrightarrow w \in L(M)$$

- (\Rightarrow) Assume $w \in L$.
 $w \in L$ means that w has an even number of as and an odd number of bs.
The proof that state invariants hold when w is consumed means that M can only halt in N , which is a final state. Therefore, $w \in L(M)$.
- (\Leftarrow) Assume $w \in L(M)$.
 $w \in L(M)$ means that M halts in N . N 's invariant guarantees that w has an even number of as and an odd number of bs. Therefore, $w \in L$.

Deterministic Finite Automata

Lemma

$$w \notin L \Leftrightarrow w \notin L(M)$$

- (\Rightarrow) Assume $w \notin L$.

$w \notin L$ means that w does not have an even number of as and an odd number of bs. This means M does not halt in N after consuming w . Given that the state invariants always hold, this means that $w \notin L(M)$.

Deterministic Finite Automata

Lemma

$$w \notin L \Leftrightarrow w \notin L(M)$$

- (\Rightarrow) Assume $w \notin L$.
 $w \notin L$ means that w does not have an even number of as and an odd number of bs. This means M does not halt in N after consuming w . Given that the state invariants always hold, this means that $w \notin L(M)$.
- (\Leftarrow) Assume $w \notin L(M)$.
 M does not halt in N (the only final state). Given that the state invariants always hold, this means that w does not have an even number of as and an odd number of bs. Therefore, $w \notin L$.

Deterministic Finite Automata

Theorem

$$L = L(\text{EVEN-A-ODD-B})$$

- The two previous lemmas establish the theorem.

Deterministic Finite Automata

- HOMEWORK: 1, 2, 4, 5, 7, 12
- QUIZ: 10 (due in 1 week)

Deterministic Finite Automata

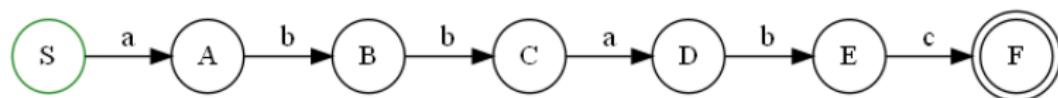
- Pattern Detection (i.e., Ctrl-F)

Deterministic Finite Automata

- Pattern Detection (i.e., Ctrl-F)
- Given a pattern, $patt$, and an alphabet, σ , the DFA built needs $|patt|+1$ states
- These states form the DFA's backbone and lead from the starting to the final state consuming the pattern

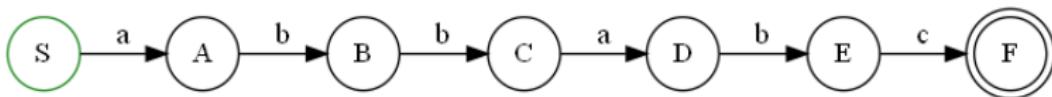
Deterministic Finite Automata

- Pattern Detection (i.e., Ctrl-F)
- Given a pattern, $patt$, and an alphabet, σ , the DFA built needs $|patt|+1$ states
- These states form the DFA's backbone and lead from the starting to the final state consuming the pattern
- The DFA backbone for the pattern '(a b b a b c)' has the following structure:



- Not the complete DFA because it is missing the transitions for when the next symbol in a given word does not match the next symbol in the pattern
- If the machine is in state E and the next symbol in the input word is not 'c', what state should the machine move to?

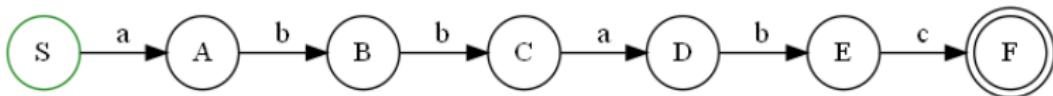
Deterministic Finite Automata



- Reason about what the states mean (i.e., their invariant properties). For the machine's backbone above we can state:

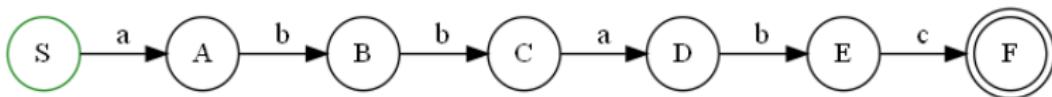
- S Nothing in the pattern has been matched
- A a has been matched
- B ab has been matched
- C abb has been matched
- D abba has been matched
- E abbab has been matched
- F abbabc has been matched

Deterministic Finite Automata



- Reason about what the states mean (i.e., their invariant properties). For the machine's backbone above we can state:
 - S Nothing in the pattern has been matched
 - A a has been matched
 - B ab has been matched
 - C abb has been matched
 - D abba has been matched
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 - F abbabc has been matched
- What state should the machine be in after reading '(a b b a b b)'?

Deterministic Finite Automata



- Reason about what the states mean (i.e., their invariant properties). For the machine's backbone above we can state:

- S Nothing in the pattern has been matched
- A a has been matched
- B ab has been matched
- C abb has been matched
- D abba has been matched
- E abbab has been matched
- F abbabc has been matched

- What state should the machine be in after reading '(a b b a b b)'?
- Observe that longest suffix of the read input that matches the beginning of the pattern is '(a b b)'
- The machine needs to move to state C.

Deterministic Finite Automata

Regular
Expressions

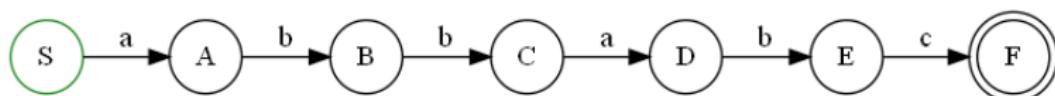
Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

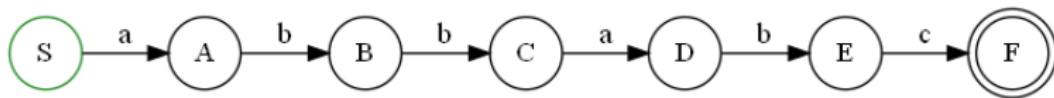
Regular
Grammars

Pumping
Theorem for
Regular
Languages



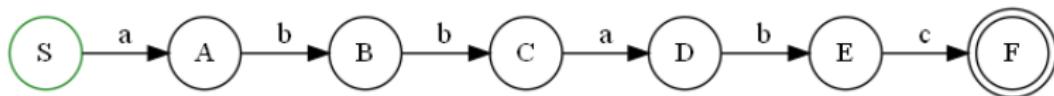
- How are the transition rules computed for when the next input symbol does not match the next symbol in the pattern?
- We say that the part of the pattern matched for each state represents the core prefix of the state
- For B the core prefix is '(a b)
- For E the core prefix is '(a b b a b)

Deterministic Finite Automata



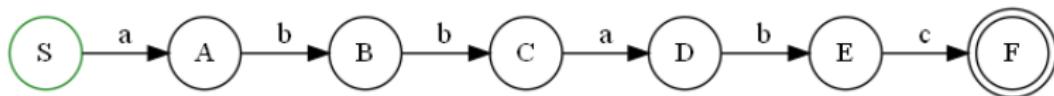
- We use core prefixes to compute the transitions needed for each state

Deterministic Finite Automata



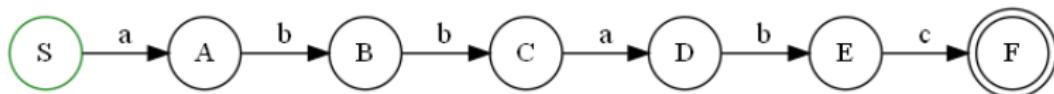
- We use core prefixes to compute the transitions needed for each state
- Assume the states are kept in a list such that the states appear in the direction of the arrows: `states = '(S A B C D E F)`

Deterministic Finite Automata



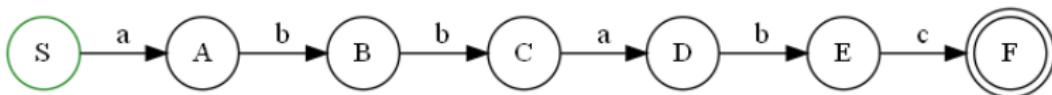
- We use core prefixes to compute the transitions needed for each state
- Assume the states are kept in a list such that the states appear in the direction of the arrows: states = '(S A B C D E F)
- What are the needed transitions out of E?

Deterministic Finite Automata



- We use core prefixes to compute the transitions needed for each state
- Assume the states are kept in a list such that the states appear in the direction of the arrows: states = '(S A B C D E F)
- What are the needed transitions out of E?
- E's core prefix is '(a b b a b)
- The next input symbol may be a, b, or c
- For each, identify longest suffix that matches the pattern's beginning

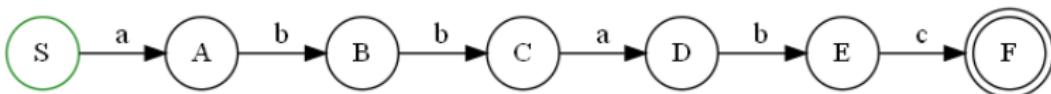
Deterministic Finite Automata



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Last 6 symbols of consumed input: '(a b b a b a)

Deterministic Finite Automata



- We use core prefixes to compute the transitions needed for each state
- Assume the states are kept in a list such that the states appear in the direction of the arrows: states = '(S A B C D E F)
- What are the needed transitions out of E?
- E's core prefix is '(a b b a b)
- The next input symbol may be a, b, or c
- For each, identify longest suffix that matches the pattern's beginning
- For a we have:

Last 6 symbols of consumed input: '(a b b a b a)
- Compare successively shorter suffixes with the pattern's beginning until a match is found or the suffix is empty:

Pattern: '(a b b a b c)

Suffix: '(a b b a b a) → does not match

'(b b a b a) → does not match

'(b a b a) → does not match

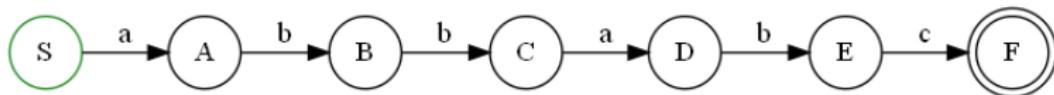
'(a b a) → does not match

'(b a) → does not match

'(a) → match

- The longest matching suffix with the pattern's beginning is A's core prefix
- This means that the machine must transition to A: (E a A)

Deterministic Finite Automata



- For b:

Pattern: '(a b b a b c)

Suffix: '(a b b a b b) → does not match

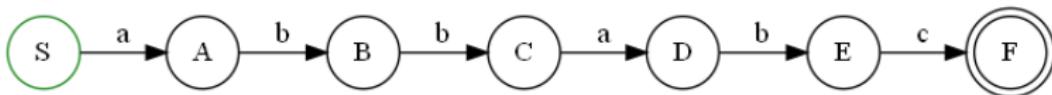
'(b b a b b) → does not match

'(b a b b) → does not match

'(a b b) → match

- The longest matching suffix with the pattern's beginning is C's core prefix
- The machine needs to transition to C: (E b C)

Deterministic Finite Automata



- For b:

Pattern: '(a b b a b c)

Suffix: '(a b b a b b) → does not match

'(b b a b b) → does not match

'(b a b b) → does not match

'(a b b) → match

- The longest matching suffix with the pattern's beginning is C's core prefix
- The machine needs to transition to C: (E b C)
- For c:

Pattern: '(a b b a b c)

Suffix: '(a b b a b c) → match

- The longest matching suffix with the pattern's beginning is F's core prefix
- The needed transition is (E c F)

Deterministic Finite Automata

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

- `states = '(S A B C D E F)`
- Have you noticed the pattern for the destination state in each of the computed transition rules?

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- `states = '(S A B C D E F)`
- Have you noticed the pattern for the destination state in each of the computed transition rules?
- It is always `(list-ref states (length lsuffix))`, where `lsuffix` is the longest matching suffix
- $$\begin{aligned} (\text{list-ref states } (\text{length } '(\text{a}))) &= \text{A} \\ (\text{list-ref states } (\text{length } '(\text{a b b}))) &= \text{C} \\ (\text{list-ref states } (\text{length } '(\text{a b b a b c}))) &= \text{F} \end{aligned}$$

Deterministic Finite Automata

- For a given pattern, $patt$, and a given input alphabet, σ , the goal is to build a dfa for the following language:

$$L = \{w \mid w \text{ contains } patt\}$$

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- The constructor needs to:
 - Generate the states for the new dfa
 - Compute the core prefix for each state
 - Compute the transitions for the new dfa

Deterministic Finite Automata

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$$L = \{w \mid w \text{ contains } patt\}$$

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 - Generate the states for the new dfa
 - Compute the core prefix for each state
 - Compute the transitions for the new dfa

- We choose to define the first state in the list of generated states as the starting state and the last state generated as the final state
- To generate a state the FSM function `gen-state` is used

`(gen-state l) → state`
`l : (listof state)`

Generates a state not in the given list of states.

Deterministic Finite Automata

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- To generate a state the FSM function `gen-state` is used

`(gen-state 1) → state`
`1 : (listof state)`

Generates a state not in the given list of states.

- The generation of the core prefixes may be done so as to correspond with the list of generated states.
- The core prefix for the i^{th} state is given by taking the first i elements of the pattern.

Deterministic Finite Automata

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 - Compute the core prefix for each state
 - Compute the transitions for the new dfa
- We choose to define the first state in the list of generated states as the starting state and the last state generated as the final state
- To generate a state the FSM function `gen-state` is used
 - (`gen-state 1`) → state
 - 1 : (`listof state`)
 - Generates a state not in the given list of states.
- The generation of the core prefixes may be done so as to correspond with the list of generated states.
- The core prefix for the i^{th} state is given by taking the first i elements of the pattern.
- To generate the transition function the needed transitions for each state, s , may be generated using the states, the input alphabet, the core prefix for s , and the pattern

Deterministic Finite Automata

- ```
;; word alphabet → dfa
;; Purpose: Build a dfa for L = all words that contain the
;; given pattern
(define (build-pattern-dfa patt sigma))
```

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- ```
;; Tests for build-pattern-dfa YUCK!
(define M (build-pattern-dfa '(a b b a) '(a b)))
(define N (build-pattern-dfa '(a d) '(a b c d))

(check-equal? (sm-apply M '()) 'reject)
(check-equal? (sm-apply M '(a a b b b a)) 'reject)
(check-equal? (sm-apply M '(b b b a a a b b)) 'reject)
(check-equal? (sm-apply M '(a b b a)) 'accept)
(check-equal? (sm-apply M '(b b a a a b b a b b a)) 'accept)
(check-equal? (sm-apply M '(a b b b a b b a)) 'accept)

(check-equal? (sm-apply N '()) 'reject)
(check-equal? (sm-apply N '(a b c d a b c c)) 'reject)
(check-equal? (sm-apply N '(c c b a b d)) 'reject)
(check-equal? (sm-apply N '(a d)) 'accept)
(check-equal? (sm-apply N '(b c a a d c c b)) 'accept)
(check-equal? (sm-apply N '(c d b c a d c a d)) 'accept)
```

# Deterministic Finite Automata

- ```
;; word alphabet → dfa
;; Purpose: Build a dfa for L = all words that contain the
;; given pattern
(define (build-pattern-dfa patt sigma)
  (let* [(sts (foldl (λ (s acc) (cons (gen-state acc) acc))
                     '()
                     (cons 1 patt))) ;; number of states = |patt|+1
```

- ```
;; Tests for build-pattern-dfa YUCK!
(define M (build-pattern-dfa '(a b b a) '(a b)))
(define N (build-pattern-dfa '(a d) '(a b c d))

(check-equal? (sm-apply M '()) 'reject)
(check-equal? (sm-apply M '(a a b b b a)) 'reject)
(check-equal? (sm-apply M '(b b b a a a b b)) 'reject)
(check-equal? (sm-apply M '(a b b a)) 'accept)
(check-equal? (sm-apply M '(b b a a a b b a b b a)) 'accept)
(check-equal? (sm-apply M '(a b b b a b b a)) 'accept)

(check-equal? (sm-apply N '()) 'reject)
(check-equal? (sm-apply N '(a b c d a b c c)) 'reject)
(check-equal? (sm-apply N '(c c b a b d)) 'reject)
(check-equal? (sm-apply N '(a d)) 'accept)
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(check-equal? (sm-apply N '(c d b c a d c a d)) 'accept)
```

# Deterministic Finite Automata

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;; Purpose: Build a dfa for L = all words that contain the
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(define (build-pattern-dfa patt sigma)
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                     '()
                     (cons 1 patt))) ;; number of states = |patt|+1
         (core-prefixes (build-list (add1 (length patt))
                                    (λ (i) (take patt i))))]
```

- ```
;; Tests for build-pattern-dfa YUCK!
(define M (build-pattern-dfa '(a b b a) '(a b)))
(define N (build-pattern-dfa '(a d) '(a b c d)))

(check-equal? (sm-apply M '()) 'reject)
(check-equal? (sm-apply M '(a a b b b a)) 'reject)
(check-equal? (sm-apply M '(b b b a a a b b)) 'reject)
(check-equal? (sm-apply M '(a b b a)) 'accept)
(check-equal? (sm-apply M '(b b a a a b b a b b a)) 'accept)
(check-equal? (sm-apply M '(a b b b a b b a)) 'accept)

(check-equal? (sm-apply N '()) 'reject)
(check-equal? (sm-apply N '(a b c d a b c c)) 'reject)
(check-equal? (sm-apply N '(c c b a b d)) 'reject)
(check-equal? (sm-apply N '(a d)) 'accept)
(check-equal? (sm-apply N '(b c a a d c c b)) 'accept)
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```

# Deterministic Finite Automata

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                      '()
                      (cons 1 patt))) ;; number of states = |patt|+1
         (core-prefixes (build-list (add1 (length patt))
                                    (λ (i) (take patt i))))
         (deltas (append-map
                  (λ (s cp)
                    (gen-state-trans s sts sigma cp patt))
                  sts
                  core-prefixes))]
    ;; Tests for build-pattern-dfa YUCK!
    (define M (build-pattern-dfa '(a b b a) '(a b)))
    (define N (build-pattern-dfa '(a d) '(a b c d))

      (check-equal? (sm-apply M '()) 'reject)
      (check-equal? (sm-apply M '(a a b b b a)) 'reject)
      (check-equal? (sm-apply M '(b b b a a a b b)) 'reject)
      (check-equal? (sm-apply M '(a b b a)) 'accept)
      (check-equal? (sm-apply M '(b b a a a b b a b b a)) 'accept)
      (check-equal? (sm-apply M '(a b b b a b b a)) 'accept)

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Deterministic Finite Automata

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 '()
 (cons 1 patt))) ;; number of states = |patt|+1
 (core-prefixes (build-list (add1 (length patt))
 (λ (i) (take patt i))))
 (deltas (append-map
 (λ (s cp)
 (gen-state-trans s sts sigma cp patt))
 sts
 core-prefixes))]
 (make-dfa sts sigma (first sts) (list (last sts)) deltas 'no-dead)))
 ;; Tests for build-pattern-dfa YUCK!
 (define M (build-pattern-dfa '(a b b a) '(a b)))
 (define N (build-pattern-dfa '(a d) '(a b c d))

 (check-equal? (sm-apply M '()) 'reject)
 (check-equal? (sm-apply M '(a a b b b a)) 'reject)
 (check-equal? (sm-apply M '(b b b a a a b b)) 'reject)
 (check-equal? (sm-apply M '(a b b a)) 'accept)
 (check-equal? (sm-apply M '(b b a a a b b a b b a)) 'accept)
 (check-equal? (sm-apply M '(a b b b a b b a)) 'accept)

 (check-equal? (sm-apply N '()) 'reject)
 (check-equal? (sm-apply N '(a b c d a b c c)) 'reject)
 (check-equal? (sm-apply N '(c c b a b d)) 'reject)
 (check-equal? (sm-apply N '(a d)) 'accept)
 (check-equal? (sm-apply N '(b c a a d c c b)) 'accept)
 (check-equal? (sm-apply N '(c d b c a d c a d)) 'accept))
```

# Deterministic Finite Automata

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;; Purpose: Build a dfa for L = all words that contain the
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(define (build-pattern-dfa patt sigma))
```
- ```
(let* [(sts (foldl (λ (s acc) (cons (gen-state acc) acc))
'()
(cons 1 patt))) ;; number of states = |patt|+1
 (core-prefixes (build-list (add1 (length patt))
 (λ (i) (take patt i))))]
 (deltas (append-map
 (λ (s cp)
 (gen-state-trans s sts sigma cp patt))
 sts
 core-prefixes)))]
```
- ```
(make-dfa sts sigma (first sts) (list (last sts)) deltas 'no-dead)))
```
- ```
;; Tests for build-pattern-dfa Poetry!
(define M (build-pattern-dfa '(a b b a) '(a b)))
(define N (build-pattern-dfa '(a d) '(a b c d)))

(check-reject? M '() '(a b b b a) '(b b b a a a b b))
(check-accept? M '(a b b a) '(b b a a a b b a b b a) '(a b b b a b b a))

(check-reject? N '() '(a b c d a b c c) '(c c b a b d))
(check-accept? N '(a d) '(b c a a d c c b) '(c d b c a d c a d))
```

# Deterministic Finite Automata

- `;; state (listof state) alphabet word word → (listof dfa-rule)`  
`;; Purpose: Generate failed match transitions for the`  
`;; given state`  
`(define (gen-state-trans s states sigma cp patt)`

# Deterministic Finite Automata

- ```
;; state (listof state) alphabet word word → (listof dfa-rule)
;; Purpose: Generate failed match transitions for the
;;           given state
(define (gen-state-trans s states sigma cp patt))
```
- ```
;; Tests for gen-state-trans
(check-equal?
 (gen-state-trans 'E
 '(S A B C D E F)
 '(a b c)
 '(a b b a b)
 '(a b b a b c))
 '((E a A) (E b C) (E c F)))

(check-equal?
 (gen-state-trans 'S
 '(S A B C D E F)
 '(a b c)
 '()
 '(a b b a b c))
 '((S a A) (S b S) (S c S))))
```

:

# Deterministic Finite Automata

- `;; state (listof state) alphabet word word → (listof dfa-rule)`  
`;; Purpose: Generate failed match transitions for the`  
`;; given state`  
`(define (gen-state-trans s states sigma cp patt))`
- `(map (λ (a)`  
`(gen-state-tran s (append cp (list a)) patt states a))`  
`sigma))`
- `;; Tests for gen-state-trans`  
`(check-equal?`  
`(gen-state-trans 'E`  
`'(S A B C D E F)`  
`'(a b c)`  
`'(a b b a b)`  
`'(a b b a b c))`  
`'((E a A) (E b C) (E c F)))`
- `(check-equal?`  
`(gen-state-trans 'S`  
`'(S A B C D E F)`  
`'(a b c)`  
`'()`  
`'(a b b a b c))`  
`'((S a A) (S b S) (S c S))))`

:

# Deterministic Finite Automata

- ```
;; state word word (listof state) symbol → dfa-rule
;; Purpose: Generate dfa rule for given state and given word
;;           to match in the given pattern
(define (gen-state-tran s to-match patt states last-read)
```

Deterministic Finite Automata

- ```
;; state word word (listof state) symbol → dfa-rule
;; Purpose: Generate dfa rule for given state and given word
;; to match in the given pattern
(define (gen-state-tran s to-match patt states last-read)
```

- ```
;; Tests for gen-state-tran
(check-equal?
  (gen-state-tran
    'C '(a b b b) '(a b b a b c) '(S A B C D E F) 'b)
    '(C b S))
  (check-equal?
    (gen-state-tran
      'S '(b) '(a b b a b c) '(S A B C D E F) 'b)
      '(S b S)) ...)
```

Deterministic Finite Automata

- ```
;; state word word (listof state) symbol → dfa-rule
;; Purpose: Generate dfa rule for given state and given word
;; to match in the given pattern
(define (gen-state-tran s to-match patt states last-read)
 (cond [(empty? to-match) (list s last-read (first states))]
```

- ```
;; Tests for gen-state-tran
(check-equal?
  (gen-state-tran
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      '(S b S)) ...)
```

Deterministic Finite Automata

- `;; state word word (listof state) symbol → dfa-rule`
`;; Purpose: Generate dfa rule for given state and given word`
`;; to match in the given pattern`
`(define (gen-state-tran s to-match patt states last-read)`
- `(cond [(empty? to-match) (list s last-read (first states))]`
- `[(> (length to-match) (length patt)) patt already-detected`
`(list s last-read s)]`

- `;; Tests for gen-state-tran`
`(check-equal?`
`(gen-state-tran`
`'C '(a b b b) '(a b b a b c) '(S A B C D E F) 'b)`
`'(C b S))`
`(check-equal?`
`(gen-state-tran`
`'S '(b) '(a b b a b c) '(S A B C D E F) 'b)`
`'(S b S)) ...`

Deterministic Finite Automata

- `;; state word word (listof state) symbol → dfa-rule`
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`(list s last-read s)]`
 - `[(equal? to-match (take patt (length to-match)))`
`(list s`
`(last to-match)`
`(list-ref states (length to-match)))]`
- `;; Tests for gen-state-tran`
`(check-equal?`
`(gen-state-tran`
`'C '(a b b b) '(a b b a b c) '(S A B C D E F) 'b)`
`'(C b S))`
`(check-equal?`
`(gen-state-tran`
`'S '(b) '(a b b a b c) '(S A B C D E F) 'b)`
`'(S b S)) ...`

Deterministic Finite Automata

- ```
;; state word word (listof state) symbol → dfa-rule
;; Purpose: Generate dfa rule for given state and given word
;; to match in the given pattern
(define (gen-state-tran s to-match patt states last-read)
 (cond [(empty? to-match) (list s last-read (first states))]
 [(> (length to-match) (length patt)) patt already detected]
 [(list s last-read s)]
 [(equal? to-match (take patt (length to-match)))
 (list s
 (last to-match)
 (list-ref states (length to-match)))]
 [else (gen-state-tran s
 (rest to-match)
 patt
 states
 last-read))]))
```
- ```
;; Tests for gen-state-tran
(check-equal?
  (gen-state-tran
    'C '(a b b b) '(a b b a b c) '(S A B C D E F) 'b)
  '(C b S))
(check-equal?
  (gen-state-tran
    'S '(b) '(a b b a b c) '(S A B C D E F) 'b)
  '(S b S)) ...)
```

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- This algorithm is the basis for the efficient and widely implemented Knuth-Morris-Pratt (KMP) algorithm
- The KMP algorithm is a string matching algorithm that looks for occurrences of a string in a block of text

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Pumping
Theorem for
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Languages

- This algorithm is the basis for the efficient and widely implemented Knuth-Morris-Pratt (KMP) algorithm
- The KMP algorithm is a string matching algorithm that looks for occurrences of a string in a block of text
- Given that most programming languages do not have a `dfa` type like FSM, the KMP algorithm represents the `dfa` differently
- It uses a vector of indices into the pattern to represent where matching ought to continue when the next element in the text does not match the next element in the pattern
- You are strongly encouraged to review the KMP algorithm.

Deterministic Finite Automata

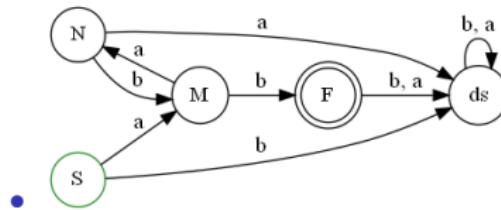
- HOMEWORK: 19
- Quiz: 20 (due in 1 week)

Nondeterministic Finite Automata

- dfa can decide a language whose words are built using concatenation and Kleene star

Nondeterministic Finite Automata

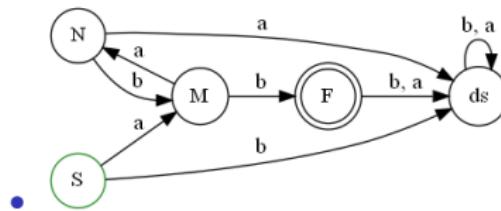
- dfa can decide a language whose words are built using concatenation and Kleene star



- A transition in a dfa represents concatenating an alphabet symbol
- A loop is concatenating a value generated by a Kleene star—the loop may be entered 0 or more times

Nondeterministic Finite Automata

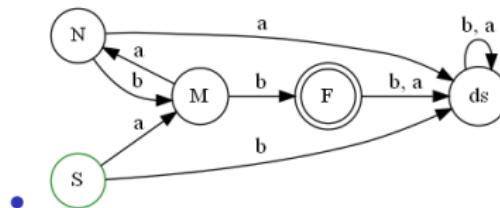
- dfa can decide a language whose words are built using concatenation and Kleene star



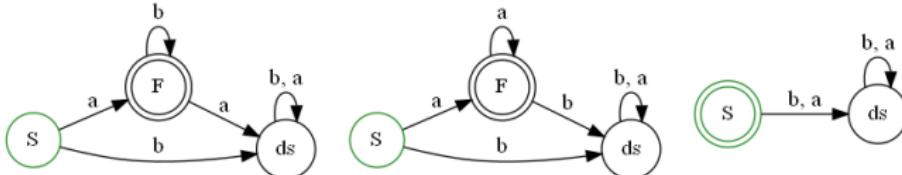
- A transition in a dfa represents concatenating an alphabet symbol
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- What about deciding a regular language that requires union?

Nondeterministic Finite Automata

- dfa can decide a language whose words are built using concatenation and Kleene star



- A transition in a dfa represents concatenating an alphabet symbol
- A loop is concatenating a value generated by a Kleene star—the loop may be entered 0 or more times
- What about deciding a regular language that requires union?
- $L = ab^* \cup aa^* \cup \epsilon$
- There are three types of words that may be generated.
- It is not difficult to build a dfa for the language represented by each regular expression choice in the union:



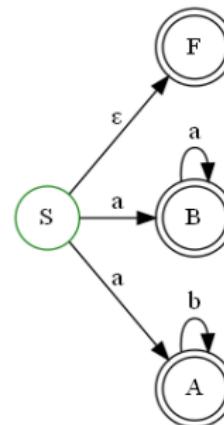
- It is difficult, however, to see how L can be decided by a dfa

Nondeterministic Finite Automata

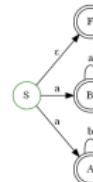
- A new model of a computer is needed
- One that allows a machine to change state in a manner that is not fully determined by the transition relation
- When the machine has a choice it nondeterministically chooses which transition (or transitions) to use

Nondeterministic Finite Automata

- A new model of a computer is needed
- One that allows a machine to change state in a manner that is not fully determined by the transition relation
- When the machine has a choice it nondeterministically chooses which transition (or transitions) to use
- For instance, consider a finite-state machine for L :

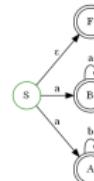


Nondeterministic Finite Automata



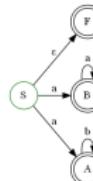
- Two new characteristics:
 - May change state without consuming anything
 - From a given state there may be more than one transition
- The transition relation is not a function
- Given the same input the machine may carry out different computations

Nondeterministic Finite Automata



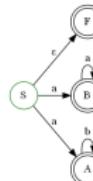
- Two new characteristics:
 - May change state without consuming anything
 - From a given state there may be more than one transition
- The transition relation is not a function
- Given the same input the machine may carry out different computations
- Processing ' $(a\ b\ b)$ ':
$$((a\ b\ b)\ S) \vdash ((a\ b\ b)\ F)$$
$$((a\ b\ b)\ S) \vdash ((b\ b)\ B)$$
$$((a\ b\ b)\ S) \vdash ((b\ b)\ A) \vdash ((b)\ A) \vdash (\emptyset\ A)$$
- The first two computations reject because input not consumed
- The third computation accepts ' $(a\ b\ b)$ '
- Based on this, is ' $(a\ b\ b)$ ' in L or not?

Nondeterministic Finite Automata



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- A word is in the language of a nondeterministic finite-state machine if there is at least one computation that leads to accept

Nondeterministic Finite Automata



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- The third computation accepts ' $(a\ b\ b)$ '
- Based on this, is ' $(a\ b\ b)$ ' in L or not?
- A word is in the language of a nondeterministic finite-state machine if there is at least one computation that leads to accept
- You may assume that if the input word is in the machine's language then every nondeterministic choice made during a computation is part of a computation that leads to the machine accepting the word
- Machines with such "intuition" sound very powerful

Nondeterministic Finite Automata

Definition

A nondeterministic finite-state automaton, ndfa, is a $(\text{make-ndfa } K \Sigma S F \delta)$

- δ is a transition relation, not a function, that may have ϵ -transitions and multiple transitions from a state on the same alphabet element

Nondeterministic Finite Automata

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A nondeterministic finite-state automaton, **ndfa**, is a $(\text{make-ndfa } K \Sigma S F \delta)$

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- An **ndfa** (transition) rule is defined as follows:

$(Q \xrightarrow{a} R)$, where $Q, R \in K \wedge a \in \{\Sigma \cup \{\epsilon\}\}$

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- An ndfa (transition) rule is defined as follows:
$$(Q \xrightarrow{a} R), \text{ where } Q, R \in K \wedge a \in \{\Sigma \cup \{\epsilon\}\}$$
- Given a configuration $(m \ r)$, where $m \in \Sigma^*$ and $r \in K$, the machine may have no transitions it may follow and halts or may move to one of several different configurations because of ϵ -transitions or multiple transitions from r on the same alphabet element

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- A word, w , is accepted by an ndfa , N , if there exists a computation such that:
$$(w \ s) \vdash^* ((\cdot) \ f), \text{ where } f \in F$$
- The language of N , $L(N)$, is all the words accepted by N .

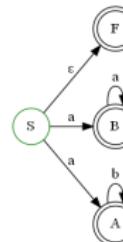
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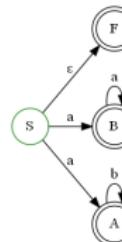
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- Every dfa is an ndfa

Nondeterministic Finite Automata



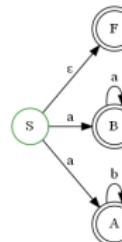
- ```
#lang fsm
;; L = {ε} ∪ aa* ∪ ab*
(define LNDFA
 (make-ndfa '(S A B F)
```

# Nondeterministic Finite Automata



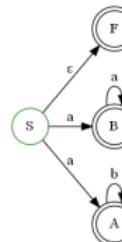
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#lang fsm
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```
- ```
#:rejects '((a b a) (b b b b b) (a b b b b a a a))
#:accepts '(() (a) (a a a a) (a b b)))
```

# Nondeterministic Finite Automata



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(define LNDFA
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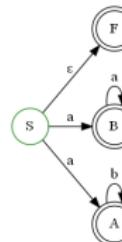
Nondeterministic Finite Automata



- `#lang fsm`
 `; ; L = {ε} ∪ aa* ∪ ab*`
 `(define LNDFA`
 `(make-ndfa '(S A B F)`
 • `'(a b)`
 • `'S`

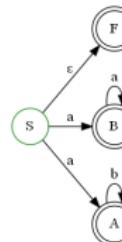
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Nondeterministic Finite Automata



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# Nondeterministic Finite Automata



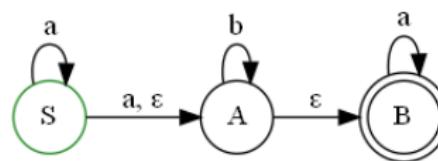
- ```
#lang fsm
;; L = {ε} ∪ aa* ∪ ab*
(define LNDFA
  (make-ndfa '(S A B F)
    ' (a b)
    ' S
    ' (A B F)
    ` ((S a A) (S a B) (S ,EMP F)
        (A b A) (B a B))
    #:rejects '((a b a) (b b b b b) (a b b b b a a a))
    #:accepts '(() (a) (a a a a) (a b b))))
```
- The only transitions listed are those that are on a path to an accepting state

Nondeterministic Finite Automata

- Designing an ndfa can prove easier than designing a dfa

Nondeterministic Finite Automata

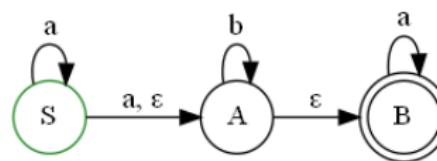
- Designing an ndfa can prove easier than designing a dfa
- Care must be taken when reasoning about the machine:



- What state does the machine move to if it is in S and consumes an a?

Nondeterministic Finite Automata

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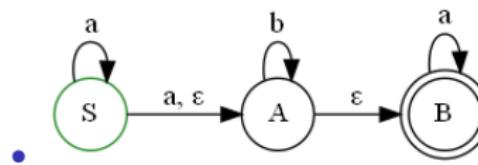
- What state does the machine move to if it is in S and consumes an a?
- The machine may end in S, A, or B
- State invariant must hold for any state in a computation that leads to accept

Nondeterministic Finite Automata

- To aid us in reasoning about ndfas we define the *empties* of a state R:
$$E(R) = \{\{R\} \cup \{P \mid ((\epsilon R) \vdash^* (\epsilon P))\}\}$$
- That is, $E(R)$ contains R and all states reachable from R by only following ϵ -transitions

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$$E(S) = \{S \ A \ B\}$$

$$E(A) = \{A \ B\}$$

$$E(B) = \{B\}$$

Nondeterministic Finite Automata

- $L = \{w \mid a \notin w \vee b \notin w \vee c \notin w\}$

Nondeterministic Finite Automata

- $L = \{w \mid a \notin w \vee b \notin w \vee c \notin w\}$
- Name: AT-LEAST-ONE-MISSING
- $\Sigma = \{a \ b \ c\}$

Nondeterministic Finite Automata

- $L = \{w \mid a \notin w \vee b \notin w \vee c \notin w\}$
- Name: AT-LEAST-ONE-MISSING
- $\Sigma = \{a \ b \ c\}$
- ;; Tests for AT-LEAST-ONE-MISSING
 - #rejects '((a b c) (b b a b c b a) (b a c))
 - #accepts '(() (a) (b) (c) (c c a a) (b b c b b b) (a a a b b b))

Nondeterministic Finite Automata

- Design Idea and conditions
- Nondeterministically decides to process the word as if a is missing, as if b is missing, or as if c is missing

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- The consumed input, c_i , must satisfy one of four conditions: nothing is consumed or for each $x \in (\text{sm}-\sigma)$ AT-LEAST-ONE-MISSING) $x \notin c_i$

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- Design Idea and conditions
- Nondeterministically decides to process the word as if a is missing, as if b is missing, or as if c is missing
- The consumed input, c_i , must satisfy one of four conditions: nothing is consumed or for each $x \in (\text{sm-sigma AT-LEAST-ONE-MISSING})$ $x \notin c_i$
- Four states are needed:

```
;; States
;; S: the consumed input is empty, starting state
;; A: the consumed input does not contain a, final state
;; B: the consumed input does not contain b, final state
;; C: the consumed input does not contain c, final state
```

Nondeterministic Finite Automata

- Transition Relation
- In S nondeterministically move to either A, B, or C
- The transition relation is:

$\sim((S, \text{EMP } A)$
 $(S, \text{EMP } B)$
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 - $(B \xrightarrow{a} B)$
 $(B \xrightarrow{c} B)$

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- In C process arbitrary number of as or bs.
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Nondeterministic Finite Automata

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```
- ```
;; word → Boolean
;; Purpose: Determine if the given word is empty
(define (S-INV ci) (empty? ci))

;; Test for S-INV
(check-equal? (S-INV '()) #t)
(check-equal? (S-INV '(a b)) #f)
```

Nondeterministic Finite Automata

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(check-equal? (S-INV '(a b)) #f)
```
- ```
;; word → Boolean
;; Purpose: Determine if the given word does not contain a
(define (A-INV ci) (empty? (filter (λ (a) (eq? a 'a)) ci)))

;; Test for A-INV
(check-equal? (A-INV '(a)) #f)
(check-equal? (A-INV '(a c b)) #f)
(check-equal? (A-INV '(c c b a b)) #f)
(check-equal? (A-INV '(b)) #t)
(check-equal? (A-INV '(c c b c b)) #t)
(check-equal? (A-INV '()) #t)
```

# Nondeterministic Finite Automata

- ```
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;; S: the consumed input is empty, starting state
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;; C: the consumed input does not contain c, final state
```
- ```
;; word → Boolean
;; Purpose: Determine if the given word does not contain b
(define (B-INV ci) (empty? (filter (λ (a) (eq? a 'b)) ci)))
```
- ```
;; Test for B-INV
(check-equal? (B-INV '(b)) #f)
(check-equal? (B-INV '(a c b)) #f)
(check-equal? (B-INV '(a a b a b)) #f)
(check-equal? (B-INV '(c)) #t)
(check-equal? (B-INV '(c c a c c a a a)) #t)
(check-equal? (B-INV '()) #t)
```

Nondeterministic Finite Automata

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```
- ```
;; word → Boolean
;; Purpose: Determine if the given word does not contain b
(define (B-INV ci) (empty? (filter (λ (a) (eq? a 'b)) ci)))
```
- ```
;; Test for B-INV
(check-equal? (B-INV '(b)) #f)
(check-equal? (B-INV '(a c b)) #f)
(check-equal? (B-INV '(a a b a b)) #f)
(check-equal? (B-INV '(c)) #t)
(check-equal? (B-INV '(c c a c c a a a)) #t)
(check-equal? (B-INV '()) #t)
```
- ```
;; word → Boolean
;; Purpose: Determine if the given word does not contain c
(define (C-INV ci) (empty? (filter (λ (a) (eq? a 'c)) ci)))
```

```
;; Test for C-INV
(check-equal? (C-INV '(c)) #f)
(check-equal? (C-INV '(a b c b)) #f)
(check-equal? (C-INV '(c c b a b)) #f)
(check-equal? (C-INV '(b)) #t)
```

Nondeterministic Finite Automata

- Validate AT-LEAST-ONE-MISSING's:

```
(sm-visualize AT-LEAST-ONE-MISSING
  (list 'S S-INV)
  (list 'A A-INV)
  (list 'B B-INV)
  (list 'C C-INV))
```

Nondeterministic Finite Automata

- We must show that R 's invariant implies the invariant for every state in $E(R)$ that can lead to accept

Nondeterministic Finite Automata

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- Nondeterministic choices not made do no concern us

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- Why are we only concerned with nondeterministic transitions that may lead to an accept?
- An ndfa never makes a nondeterministic transition unless it furthers a computation that leads to an accept
- Nondeterministic choices not made do no concern us
- We only need to reason about nondeterministic transitions that can lead to accept
- Nondeterministic transitions that cannot lead to an accept are never made and, thus, not part of any computation

Nondeterministic Finite Automata

- Assume:
 - $M = \text{AT-LEAST-ONE-MISSING}$
 - $w \in (\Sigma - \sigma)^*$
 - $F = (\Sigma - \text{finals } M)$
 - c_i is the consumed input

Nondeterministic Finite Automata

Theorem

The state invariants hold when M is applied to w.

- BASE CASE
- When M starts, S-INV holds because $c_i = '()$

Nondeterministic Finite Automata

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- If $w \in L(M)$ then M nondeterministically moves to A, B, or C using an ϵ -transition.

Nondeterministic Finite Automata

Theorem

The state invariants hold when M is applied to w.

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- When M starts, S-INV holds because $ci = '()$
- If $w \in L(M)$ then M nondeterministically moves to A, B, or C using an ϵ -transition.
- $(S \in A)$, $(S \in B)$, and $(S \in C)$ add nothing to the input and $ci = '()$ after using any of them

Nondeterministic Finite Automata

Theorem

The state invariants hold when M is applied to w.

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- If $w \in L(M)$ then M nondeterministically moves to A, B, or C using an ϵ -transition.
- $(S \in A)$, $(S \in B)$, and $(S \in C)$ add nothing to the input and $c_i = '()$ after using any of them
- A-INV holds because c_i contains zero as

Nondeterministic Finite Automata

Theorem

The state invariants hold when M is applied to w.

- BASE CASE
- When M starts, S-INV holds because $c_i = '()$
- If $w \in L(M)$ then M nondeterministically moves to A, B, or C using an ϵ -transition.
- $(S \in A)$, $(S \in B)$, and $(S \in C)$ add nothing to the input and $c_i = '()$ after using any of them
- A-INV holds because c_i contains zero as
- B-INV holds because c_i contains zero bs

Nondeterministic Finite Automata

Theorem

The state invariants hold when M is applied to w.

- BASE CASE
- When M starts, S-INV holds because $c_i = '()$
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- B-INV holds because c_i contains zero bs
- C-INV holds because c_i contains zero cs.

Nondeterministic Finite Automata

Theorem

The state invariants hold when M is applied to w .

- INDUCTIVE STEP
- (A b A): By inductive hypothesis A-INV holds. A-INV guarantees that the consumed input does not contain an a. Consuming a b means that the consumed input remains without an a. Therefore, A-INV holds after the transition.

Nondeterministic Finite Automata

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- (A c A): By inductive hypothesis A-INV holds. A-INV guarantees that the consumed input does not contain an a. Consuming a c means that the consumed input remains without an a. Therefore, A-INV holds after the transition.

Nondeterministic Finite Automata

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- (B a B): By inductive hypothesis B-INV holds. B-INV guarantees that the consumed input does not contain an b. Consuming an a means that the consumed input remains without an b. Therefore, B-INV holds after the transition.

Nondeterministic Finite Automata

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- (B a B): By inductive hypothesis B-INV holds. B-INV guarantees that the consumed input does not contain an b. Consuming an a means that the consumed input remains without an b. Therefore, B-INV holds after the transition.
- (B c B): By inductive hypothesis B-INV holds. B-INV guarantees that the consumed input does not contain an b. Consuming a c means that the consumed input remains without a b. Therefore, B-INV holds after the transition.

Nondeterministic Finite Automata

Theorem

The state invariants hold when M is applied to w .

- INDUCTIVE STEP
- (C a C): By inductive hypothesis C-INV holds. C-INV guarantees that the consumed input does not contain a c. Consuming an a means that the consumed input remains without a c. Therefore, C-INV holds after the transition.

Nondeterministic Finite Automata

Theorem

The state invariants hold when M is applied to w .

- INDUCTIVE STEP
- (C a C): By inductive hypothesis C-INV holds. C-INV guarantees that the consumed input does not contain a c. Consuming an a means that the consumed input remains without a c. Therefore, C-INV holds after the transition.
- (C b C): By inductive hypothesis C-INV holds. C-INV guarantees that the consumed input does not contain a c. Consuming an b means that the consumed input remains without a c. Therefore, C-INV holds after the transition.

Nondeterministic Finite Automata

Lemma

$$w \in L \Leftrightarrow w \in L(M)$$

- (\Rightarrow) Assume $w \in L$.
- $w \in L$ means that w is missing a, b, or c. Given that the state invariants always hold, this means M consumes all its input in either A, B, or C. Given that $A, B, C \in F$, $w \in L(M)$.

Nondeterministic Finite Automata

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- $w \in L$ means that w is missing a, b, or c. Given that the state invariants always hold, this means M consumes all its input in either A, B, or C. Given that $A, B, C \in F$, $w \in L(M)$.
- (\Leftarrow) Assume $w \in L(M)$.
- $w \in L(M)$ means that M consumes all its input and halts in A, B, or C. Given that the state invariants always hold we may conclude that w is missing a, b, or c. Therefore, $w \in L$.

Nondeterministic Finite Automata

Lemma

$$w \notin L \Leftrightarrow w \notin L(M)$$

- (\Rightarrow) Assume $w \notin L$.
- $w \notin L$ means that w has at least one a , one b , and one c . This means M does not move out of S because there is no nondeterministic transition possible that leads to accept. Given that M halts without consuming all of its input, w is rejected and, therefore, $w \notin L(M)$.

Nondeterministic Finite Automata

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- (\Leftarrow) Assume $w \notin L(M)$.
- $w \notin L(M)$ means that M halts without consuming all of w . Given that the state invariants always hold, w must have at least one a , one b , and one c . Thus, $w \notin L$.

Nondeterministic Finite Automata

Theorem

$$L = L(AT-LEAST-ONE-MISSING)$$

- The previous two lemmas establish the theorem.

Nondeterministic Finite Automata

- HOMEWORK: 2–5
- BONUS QUIZ: 1 (due in 1 week)

Nondeterministic Finite Automata

- Does endowing a finite-state machine with nondeterminism give us more computational power?

Nondeterministic Finite Automata

- Does endowing a finite-state machine with nondeterminism give us more computational power?
- To simulate an `ndfa` a `dfa` needs to simulate all computations of the `ndfa` simultaneously
- At first glance this may sound like preposterous
- Do we need a `dfa` to be in multiple states at the same time?

Nondeterministic Finite Automata

- Does endowing a finite-state machine with nondeterminism give us more computational power?
- To simulate an ndfa a dfa needs to simulate all computations of the ndfa simultaneously
- At first glance this may sound like preposterous
- Do we need a dfa to be in multiple states at the same time?
- Consider an ndfa, $N = (\text{make-ndfa } S \ \Sigma s \ F \ \delta)$, making a transition:
 $(P \ a \ R_1)$
⋮
 $(P \ a \ R_n)$
- After consuming a, what states can N be in?

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 $E(R_1) \cup E(R_2) \cup \dots \cup E(R_n)$

Nondeterministic Finite Automata

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- $E(R_1) \cup E(R_2) \cup \dots \cup E(R_n)$
- Observe that the above is an element in 2^S
- Call it Z

Nondeterministic Finite Automata

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- After consuming a , what states can N be in?
 $E(R_1) \cup E(R_2) \cup \dots \cup E(R_n)$
- Observe that the above is an element in 2^S
- Call it Z
- Think of Z as a *super state* for a dfa that represents all the states N may be in
- To simulate all possible computations that may be performed by N a dfa transitions between super states
- After consuming all the input, it accepts if it is in a super state that contains a final state in N . Otherwise, it rejects.

Nondeterministic Finite Automata

- It is necessary to show how such a dfa, M, is constructed and to show that $L(M) = L(N)$
- Showing how to build something (like a dfa) and showing that the construction is correct (like $L(M) = L(N)$) is called a *constructive proof*
- A constructive proof has a construction algorithm and a proof of its correctness.

Nondeterministic Finite Automata

- Let $N = (\text{make-ndfa } S \Sigma s F \delta)$
- Building a dfa from N hinges on computing a transition function between super states for a dfa
- The dfa is constructed as follows:

```
(make-dfa <encoding of super states>
          Σ
          <encoding of E(s)>
          <encoding of super states that contain f ∈ F>
          <transition function between encoded super states>)
```

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- At the beginning, the only known super state is $E(s)$

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- The union of the super states obtained from processing a for each $p ∈ P$ is the super state the dfa moves to from P on an a

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- Let $P = \{p_1 p_2 p_3\}$
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Nondeterministic Finite Automata

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- On an a , from p_1 N may transition to any state in $E(r) ∪ E(s)$
- From p_2 N may transition nowhere
- From p_3 N may transition to any state in $E(t)$

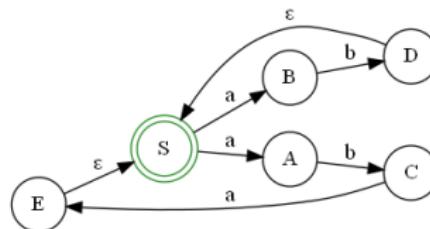
Nondeterministic Finite Automata

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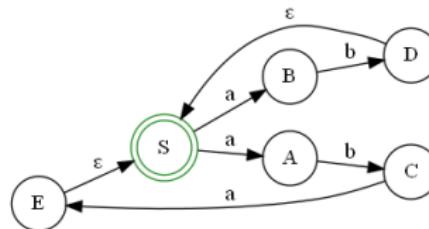
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- On an a , from p_1 N may transition to any state in $E(r) ∪ E(s)$
- From p_2 N may transition nowhere
- From p_3 N may transition to any state in $E(t)$
- We may describe a transition in the dfa as follows:
 $((p_1 p_2 p_3) a (E(r) ∪ E(s) ∪ E(t)))$
- That is, the dfa transitions from super state P on an a to a super state Q , where $Q = (E(r) ∪ E(s) ∪ E(t))$

Nondeterministic Finite Automata

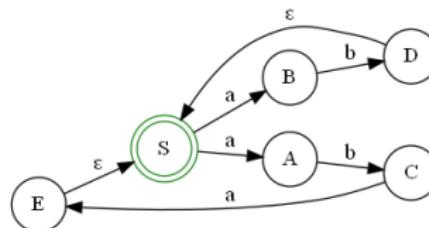


Nondeterministic Finite Automata



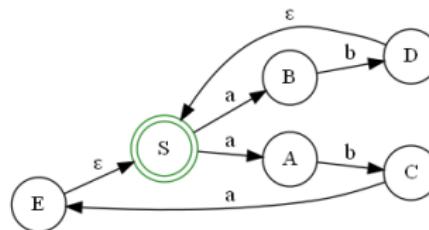
- | state | $E(state)$ |
|-------|------------|
| S | (S) |
| A | (A) |
| B | (B) |
| C | (C) |
| D | (D S) |
| E | (E S) |

Nondeterministic Finite Automata



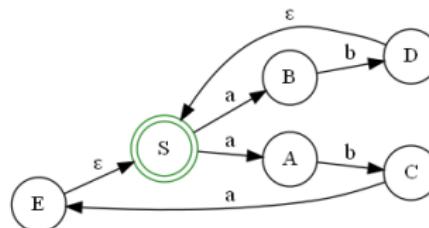
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|-------|------------|
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| A | (A) |
| B | (B) |
| C | (C) |
| D | (D S) |
| E | (E S) |
- $((S) \ a \ (A \ B))$
 $((S) \ b \ ())$

Nondeterministic Finite Automata



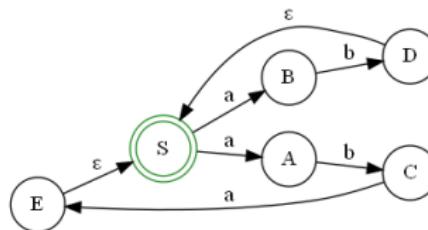
- | state | $E(state)$ |
|-------|------------|
| S | (S) |
| A | (A) |
| B | (B) |
| C | (C) |
| D | (D S) |
| E | (E S) |
- $((S) \ a \ (A \ B))$
 $((S) \ b \ ())$
- $((A \ B) \ a \ ())$
 $((A \ B) \ b \ (C \ D \ S))$

Nondeterministic Finite Automata



- | state | $E(state)$ |
|-------|------------|
| S | (S) |
| A | (A) |
| B | (B) |
| C | (C) |
| D | (D S) |
| E | (E S) |
- $((S) \ a \ (A \ B))$
 $((S) \ b \ ())$
- $((A \ B) \ a \ ())$
 $((A \ B) \ b \ (C \ D \ S))$
- $(() \ a \ ())$
 $(() \ b \ ())$

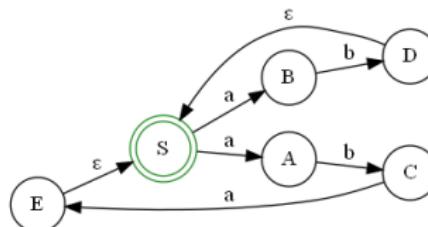
Nondeterministic Finite Automata



state	E(state)
S	(S)
A	(A)
B	(B)
C	(C)
D	(D S)
E	(E S)

- ((S) a (A B))
 ((S) b ())
- ((A B) a ())
 ((A B) b (C D S))
- (() a ())
 (() b ())
- ((C D S) a (E S A B))
 ((C D S) b ())

Nondeterministic Finite Automata



- | state | E(state) |
|-------|----------|
| S | (S) |
| A | (A) |
| B | (B) |
| C | (C) |
| D | (D S) |
| E | (E S) |
- $((S) \ a \ (A \ B))$
 $((S) \ b \ ())$
- $((A \ B) \ a \ ())$
 $((A \ B) \ b \ (C \ D \ S))$
- $(() \ a \ ())$
 $(() \ b \ ())$
- $((C \ D \ S) \ a \ (E \ S \ A \ B))$
 $((C \ D \ S) \ b \ ())$
- $((E \ S \ A \ B) \ a \ (A \ B))$
 $((E \ S \ A \ B) \ b \ (C \ D \ S))$

Nondeterministic Finite Automata

•

Super State	a	b
(S) = S	(A B) A	() DEAD
(A B) = A	() DEAD	(C D S) B
(C D S) = B	(E S A B) C	() DEAD
(E S A B) = C	(A B) A	(C D S) B
() = DEAD	() DEAD	() DEAD

Nondeterministic Finite Automata

Super State	a	b
(S) = S	(A B) A	() DEAD
(A B) = A	() DEAD	(C D S) B
(C D S) = B	(E S A B) C	() DEAD
(E S A B) = C	(A B) A	(C D S) B
() = DEAD	() DEAD	() DEAD

- (define D (make-dfa ` (S A B C ,DEAD)
 '(a b)
 'S
 '(S B C)
 ` ((S a A) (S b ,DEAD)
 (A a ,DEAD) (A b B)
 (B a C) (B b ,DEAD)
 (C a A) (C b B)
 (,DEAD a ,DEAD) (,DEAD b ,DEAD))))
;; Tests for D
(check-reject? D '(a) '(a b b) '(a a) '(b a a b) '(a b a b a b b))
(check-accept? D '() '(a b) '(a b a) '(a b a b) '(a b a a b a a b))
(check-equal? (sm-testequiv? D ND 500) #t)
(check-equal? (sm-testequiv? (ndfa->dfa ND) D 500) #t)
- Illustrate using (ndfa2dfa-viz AT-LEAST-ONE-MISSING)

Nondeterministic Finite Automata

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

- Implementation

Nondeterministic Finite Automata

- Implementation

- - ;; Data Definitions
 - ;;
 - ;; An ndfa transition rule, ndfa-rule, is a
;; (list state symbol state)
 - ;;
 - ;; A super state, ss, is a (listof state)
 - ;;
 - ;; A super state dfa rule, ss-dfa-rule, is a
;; (list ss symbol ss)
 - ;;
 - ;; An empties table, emps-tbl, is a
;; (listof (list state ss))
 - ;;
 - ;; A super state name table, ss-name-table, is a
;; (listof (list ss state))

Nondeterministic Finite Automata

- `;; ndfa → dfa`
`;; Purpose: Convert the given ndfa to an equivalent dfa`
`(define (ndfa2dfa M)`

Nondeterministic Finite Automata

- ```
;; ndfa → dfa
;; Purpose: Convert the given ndfa to an equivalent dfa
(define (ndfa2dfa M)
```
- ```
; Tests for ndfa2dfa
(define M (ndfa2dfa AT-LEAST-ONE-MISSING))
(check-reject? M '(a b c) '(b b a b c b a) '(b a c))
(check-accept? M '() '(a b) '(a b a) '(a b a b) '(a c a a c a a c) '(c c c b c c c))
(check-equal? (sm-testequiv? AT-LEAST-ONE-MISSING M 500) #t)
(check-equal? (sm-testequiv? M (ndfa->dfa AT-LEAST-ONE-MISSING) 500) #t)

(define D (ndfa2dfa ND))
(check-reject? D '(a) '(a b b) '(a a) '(b a a b) '(a b a b a b b))
(check-accept? D '() '(a b) '(a b a) '(a b a b) '(a b a a b a a b))
(check-equal? (sm-testequiv? ND D 500) #t)
(check-equal? (sm-testequiv? D (ndfa->dfa ND) 500) #t)
```

Nondeterministic Finite Automata

- ```
;; ndfa → dfa
;; Purpose: Convert the given ndfa to an equivalent dfa
(define (ndfa2dfa M)
 (if (eq? (sm-type M) 'dfa)
 M
```
- ```
; Tests for ndfa2dfa
(define M (ndfa2dfa AT-LEAST-ONE-MISSING))
(check-reject? M '(a b c) '(b b a b c b a) '(b a c))
(check-accept? M '() '(a b) '(a b a) '(a b a b) '(a c a a c a a c) '(c c c b c c c))
(check-equal? (sm-testequiv? AT-LEAST-ONE-MISSING M 500) #t)
(check-equal? (sm-testequiv? M (ndfa->dfa AT-LEAST-ONE-MISSING) 500) #t)

(define D (ndfa2dfa ND))
(check-reject? D '(a) '(a b b) '(a a) '(b a a b) '(a b a b a b b))
(check-accept? D '() '(a b) '(a b a) '(a b a b) '(a b a a b a a b))
(check-equal? (sm-testequiv? ND D 500) #t)
(check-equal? (sm-testequiv? D (ndfa->dfa ND) 500) #t)
```

Nondeterministic Finite Automata

- ```
;; ndfa → dfa
;; Purpose: Convert the given ndfa to an equivalent dfa
(define (ndfa2dfa M)
 (if (eq? (sm-type M) 'dfa)
 M
 (convert (sm-states M)
 (sm-sigma M)
 (sm-start M)
 (sm-finals M)
 (sm-rules M))))
```
- ```
;; Tests for ndfa2dfa
(define M (ndfa2dfa AT-LEAST-ONE-MISSING))
(check-reject? M '(a b c) '(b b a b c b a) '(b a c))
(check-accept? M '() '(a b) '(a b a) '(a b a b) '(a c a a c a a c) '(c c c b c c c))
(check-equal? (sm-testequiv? AT-LEAST-ONE-MISSING M 500) #t)
(check-equal? (sm-testequiv? M (ndfa->dfa AT-LEAST-ONE-MISSING) 500) #t)

(define D (ndfa2dfa ND))
(check-reject? D '(a) '(a b b) '(a a) '(b a a b) '(a b a b a b b))
(check-accept? D '() '(a b) '(a b a) '(a b a b) '(a b a a b a a b))
(check-equal? (sm-testequiv? ND D 500) #t)
(check-equal? (sm-testequiv? D (ndfa->dfa ND) 500) #t)
```

Nondeterministic Finite Automata

- `;; (listof state) alphabet state (listof state) (list-of ndfa-rule)`
`;; → dfa`
`;; Purpose: Create a dfa from the given ndfa components`
`(define (convert states sigma start finals rules))`

Nondeterministic Finite Automata

- ;; Tests for convert

(check-equal?

```
(sm-testequiv? (convert '(S A B) '(a b) 'S '(A B) '((S a A)
(S a B)
(A a A)
(B b B)))
```

```
(make-ndfa '(S A B) '(a b) 'S '(A B) '((S a A)
(S a B)
(A a A)
(B b B)))
```

500)

#t)

(check-equal?

```
(sm-testequiv? (convert '(S A) '(a b) 'S '(S A) '((S a S)
(S a A)
(A b A)
(A a A)))
```

```
(make-ndfa '(S A) '(a b) 'S '(S A) '((S a S)
(S a A)
(A b A)
(A a A)))
```

500)

#t)

Nondeterministic Finite Automata

- (define (convert states sigma start finals rules)

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

Nondeterministic Finite Automata

- (define (convert states sigma start finals rules))
- (let* [(empties (compute-empties-tbl states rules))

Nondeterministic Finite Automata

- (define (convert states sigma start finals rules)
 - (let*
 - [(empties (compute-empties-tbl states rules))
 - (ss-dfa-rules
 - (compute-ss-dfa-rules (list (extract-empties start empties))
 - sigma empties rules '())

Nondeterministic Finite Automata

- (define (convert states sigma start finals rules)
 - (let*
 - [(empties (compute-empties-tbl states rules))]
 - (ss-dfa-rules
 - (compute-ss-dfa-rules (list (extract-empties start empties))
 - sigma empties rules '())
 - (super-states (remove-duplicates
 - (append-map (λ (r) (list (first r) (third r)))
 - ss-dfa-rules))

Nondeterministic Finite Automata

- (define (convert states sigma start finals rules)
 - (let*
 - [(empties (compute-empties-tbl states rules))]
 - (ss-dfa-rules
 - (compute-ss-dfa-rules (list (extract-empties start empties)
sigma empties rules '()))
 - (super-states (remove-duplicates
 - (append-map (λ (r) (list (first r) (third r)))
ss-dfa-rules)))
 - (ss-name-tbl (compute-ss-name-tbl super-states)))]

Nondeterministic Finite Automata

- (define (convert states sigma start finals rules)
 - (let*
 - [(empties (compute-empties-tbl states rules))]
 - (ss-dfa-rules
 - (compute-ss-dfa-rules (list (extract-empties start empties))
 - sigma empties rules '())
 - (super-states (remove-duplicates
 - (append-map (λ (r) (list (first r) (third r)))
 - ss-dfa-rules))
 - (ss-name-tbl (compute-ss-name-tbl super-states)))]
 - (make-dfa (map (λ (ss) (second (assoc ss ss-name-tbl)))
 - super-states)
 - sigma
 - (second (assoc (first super-states) ss-name-tbl))

Nondeterministic Finite Automata

- (define (convert states sigma start finals rules)
 - (let*
 - [(empties (compute-empties-tbl states rules))]
 - (ss-dfa-rules
 - (compute-ss-dfa-rules (list (extract-empties start empties))
 - sigma empties rules '())
 - (super-states (remove-duplicates
 - (append-map (λ (r) (list (first r) (third r)))
 - ss-dfa-rules))
 - (ss-name-tbl (compute-ss-name-tbl super-states)))]
 - (make-dfa (map (λ (ss) (second (assoc ss ss-name-tbl)))
 - super-states)
 - sigma
 - (second (assoc (first super-states) ss-name-tbl))
 - (map (λ (ss) (second (assoc ss ss-name-tbl)))
 - (filter (λ (ss) (ormap (λ (s) (member s finals))
 - super-states))

Nondeterministic Finite Automata

- (define (convert states sigma start finals rules)
 - (let*
 - [(empties (compute-empties-tbl states rules))]
 - (ss-dfa-rules
 - (compute-ss-dfa-rules (list (extract-empties start empties))
 - sigma empties rules '())
 - (super-states (remove-duplicates
 - (append-map (λ (r) (list (first r) (third r)))
 - ss-dfa-rules))
 - (ss-name-tbl (compute-ss-name-tbl super-states)))]
 - (make-dfa (map (λ (ss) (second (assoc ss ss-name-tbl)))
 - super-states)
 - sigma
 - (second (assoc (first super-states) ss-name-tbl))
 - (map (λ (ss) (second (assoc ss ss-name-tbl)))
 - (filter (λ (ss) (ormap (λ (s) (member s finals))
 - super-states))
 - (map (λ (r) (list (second (assoc (first r) ss-name-tbl))
 - (second r)
 - (second (assoc (third r) ss-name-tbl))
 - ss-dfa-rules)
 - 'no-dead))))

Nondeterministic Finite Automata

- `;; (listof state) rules → emps-tbl`
`;; Purpose: Compute empties table for all given states`
`(define (compute-empties-tbl states rules)`

Nondeterministic Finite Automata

- `;; (listof state) rules → emps-tbl`
`;; Purpose: Compute empties table for all given states`
`(define (compute-empties-tbl states rules)`
- `;; Tests for compute-empties-tbl`
`(check-equal? (compute-empties-tbl`
 `'(X Y Z)`
 ``((X ,EMP Y) (Y a Z) (Z ,EMP X)))`
 ``((X (Y X)) (Y (Y)) (Z (Y X Z))))`
- `(check-equal?`
 `(compute-empties-tbl`
 `'(W X Y Z)`
 ``((W ,EMP X) (X ,EMP Y) (Y a Z) Z ,EMP Y) (Z b Z)))`
 ``((W (Y X W)) (X (Y X)) (Y (Y)) (Z (Y Z))))`

Nondeterministic Finite Automata

- (define (compute-empties-tbl states rules)

Nondeterministic Finite Automata

- (define (compute-empties-tbl states rules)

- (map (λ (st) (list st (compute-empties (list st) rules '())))) states))

Nondeterministic Finite Automata

- (define (compute-empties-tbl states rules)
 - ```
;; (listof state) (listof ndfa-rules) (listof state) → (listof state)
;; Purpose: Compute the empties for the states left to explore in the first
;; given (listof state)
;; Accumulator Invariants:
;; to-search = unvisited states reachable by consuming no input
;; visited = visited states reachable by consuming no input
(define (compute-empties to-search rules visited)
 (if (empty? to-search)
 visited
 (let* [(curr (first to-search))
 (curr-e-rules
 (get-e-trans curr (append to-search visited) rules))]
 (compute-empties (append (rest to-search) (map third curr-e-rules))
 rules
 (cons curr visited))))))
```
  - (map (λ (st) (list st (compute-empties (list st) rules '()))) states))

# Nondeterministic Finite Automata

- (define (compute-empties-tbl states rules)
  - ;; state (listof state) (listof ndfa-rule) → (listof ndfa-rule)  
;; Purpose: Extract empty transitions to non-generated states for the  
;; given state  
(define (get-e-trans state gen-states rules)
    - (filter (λ (r) (and (eq? (first r) state)  
(eq? (second r) EMP)  
(not (member (third r) gen-states))))  
rules))
  - ;; (listof state) (listof ndfa-rules) (listof state) → (listof state)  
;; Purpose: Compute the empties for the states left to explore in the first  
;; given (listof state)  
;; Accumulator Invariants:  
;; to-search = unvisited states reachable by consuming no input  
;; visited = visited states reachable by consuming no input  
(define (compute-empties to-search rules visited)
    - (if (empty? to-search)  
visited  
(let\* [(curr (first to-search))  
(curr-e-rules  
          (get-e-trans curr (append to-search visited) rules))]  
(compute-empties (append (rest to-search) (map third curr-e-rules))  
rules  
(cons curr visited))))
  - (map (λ (st) (list st (compute-empties (list st) rules '())))) states))

# Nondeterministic Finite Automata

- 

```
;; state emps-tbl → ss
;; Purpose: Extract the empties of the given state
;; Assume: Given state is in the given list of states
(define (extract-empties st empties)
 (second (first (filter (λ (e) (eq? (first e) st))
 empties)))))

;; Tests for extract-empties
(check-equal? (extract-empties 'A '((S (S B))
 (F (F))
 (A (A C D))
 (C (C))
 (D (D)))))
 '(A C D))

(check-equal? (extract-empties 'Z '((Z (Z S))
 (S ()))))
 '(Z S))
```

# Nondeterministic Finite Automata

- ```
;; (listof ss) alphabet emps-tbl (listof ndfa-rule) (listof ss)
;;                                         → (listof ss-dfa-rule)
;; Purpose: Compute the supper state dfa rules
;; Accumulator Invariants:
;;           ssts = the super states explored
;;           to-search-ssts = the super states that must still be explored
(define (compute-ss-dfa-rules to-search-ssts sigma empties rules ssts)
  :
  :
```

Nondeterministic Finite Automata

- ```
;; (listof ss) alphabet emps-tbl (listof ndfa-rule) (listof ss)
;; → (listof ss-dfa-rule)
;; Purpose: Compute the supper state dfa rules
;; Accumulator Invariants:
;; ssts = the super states explored
;; to-search-ssts = the super states that must still be explored
(define (compute-ss-dfa-rules to-search-ssts sigma empties rules ssts)
 :
 :
 • (if (empty? to-search-ssts)
 '()
```

# Nondeterministic Finite Automata

- ```
;; (listof ss) alphabet emps-tbl (listof ndfa-rule) (listof ss)
;;                                         → (listof ss-dfa-rule)
;; Purpose: Compute the supper state dfa rules
;; Accumulator Invariants:
;;           ssts = the super states explored
;;           to-search-ssts = the super states that must still be explored
(define (compute-ss-dfa-rules to-search-ssts sigma empties rules ssts)
  :
  :
  • (if (empty? to-search-ssts)
      '()
    • (let* [(curr-ss (first to-search-ssts))
            (reachables (find-reachables curr-ss sigma rules empties))]
```

Nondeterministic Finite Automata

- ```
;; (listof ss) alphabet emps-tbl (listof ndfa-rule) (listof ss)
;; → (listof ss-dfa-rule)
;; Purpose: Compute the supper state dfa rules
;; Accumulator Invariants:
;; ssts = the super states explored
;; to-search-ssts = the super states that must still be explored
(define (compute-ss-dfa-rules to-search-ssts sigma empties rules ssts)
 :
 :
 • (if (empty? to-search-ssts)
 '()
 • (let* [(curr-ss (first to-search-ssts))
 (reachables (find-reachables curr-ss sigma rules empties))]
 • (to-super-states
 (build-list (length sigma) (λ (i) (get-reachable i reachables))))
```

# Nondeterministic Finite Automata

- ```
;; (listof ss) alphabet emps-tbl (listof ndfa-rule) (listof ss)
;;                                         → (listof ss-dfa-rule)
;; Purpose: Compute the supper state dfa rules
;; Accumulator Invariants:
;;           ssts = the super states explored
;;           to-search-ssts = the super states that must still be explored
(define (compute-ss-dfa-rules to-search-ssts sigma empties rules ssts)
  :
  :
  • (if (empty? to-search-ssts)
      '()
      • (let* [(curr-ss (first to-search-ssts))
              (reachables (find-reachables curr-ss sigma rules empties))]
          • (to-super-states
              (build-list (length sigma) (λ (i) (get-reachable i reachables))))
          • (new-rules (map (λ (sst a) (list curr-ss a sst))
                            to-super-states
                            sigma))]
```

Nondeterministic Finite Automata

- ```
;; (listof ss) alphabet emps-tbl (listof ndfa-rule) (listof ss)
;; → (listof ss-dfa-rule)
;; Purpose: Compute the supper state dfa rules
;; Accumulator Invariants:
;; ssts = the super states explored
;; to-search-ssts = the super states that must still be explored
(define (compute-ss-dfa-rules to-search-ssts sigma empties rules ssts)
 :
 :
 • (if (empty? to-search-ssts)
 '()
 • (let* [(curr-ss (first to-search-ssts))
 (reachables (find-reachables curr-ss sigma rules empties))]
 • (to-super-states
 (build-list (length sigma) (λ (i) (get-reachable i reachables))))
 • (new-rules (map (λ (sst a) (list curr-ss a sst))
 to-super-states
 sigma))]
 • (append
 new-rules
 (compute-ss-dfa-rules
 (append (rest to-search-ssts)
 (filter (λ (ss)
 (not (member ss (append to-search-ssts ssts))))
 to-super-states)
 sigma
 empties
 rules
 (cons curr-ss ssts))))))
```

# Nondeterministic Finite Automata

- ```
;; ss alphabet (listof ndfa-rule) emps-tbl
;;
;; Purpose: Compute reachable super states from given
;;           super state
(define (find-reachables ss sigma rules empties)
  (map (λ (st)
          (find-reachables-from-st st sigma rules empties))
        ss))
```

Nondeterministic Finite Automata

- ```
;; state alphabet (listof ndfa-rule) emps-tbl → (listof ss)
;; Purpose: Find the reachable super state from the given state
;; for each element of the given alphabet
(define (find-reachables-from-st st sigma rules empties)
 (map (λ (a)
 (find-reachables-from-st-on-a st a rules empties))
 sigma))
```
- ```
;; ss alphabet (listof ndfa-rule) emps-tbl → (listof (listof ss))
;; Purpose: Compute reachable super states from given
;;           super state
(define (find-reachables ss sigma rules empties)
  (map (λ (st)
           (find-reachables-from-st st sigma rules empties))
        ss))
```

Nondeterministic Finite Automata

- ```
;; state symbol (listof ndfa-rule) emps-tbl → ss
;; Purpose: Find the reachable super state from the given state
;; and the given alphabet element
(define (find-reachables-from-st-on-a st a rules empties)
 (let* [(rls (filter
 (λ (r)
 (and (eq? (first r) st) (eq? (second r) a)))
 rules))
 (to-states (map third rls))]
 (remove-duplicates
 (append-map (λ (st) (extract-empties st empties))
 to-states))))
```
- ```
;; state alphabet (listof ndfa-rule) emps-tbl → (listof ss)
;; Purpose: Find the reachable super state from the given state
;;           for each element of the given alphabet
(define (find-reachables-from-st st sigma rules empties)
  (map (λ (a)
         (find-reachables-from-st-on-a st a rules empties)))
       sigma))
```
- ```
;; ss alphabet (listof ndfa-rule) emps-tbl → (listof (listof ss))
;; Purpose: Compute reachable super states from given
;; super state
(define (find-reachables ss sigma rules empties)
 (map (λ (st)
 (find-reachables-from-st st sigma rules empties))
 ss))
```

# Nondeterministic Finite Automata

- ```
;; natnum (listof (listof ss)) → (listof ss)
;; Purpose: Return ss of ith (listof state) in each given
;;           list element
(define (get-reachable i reachables)
  (remove-duplicates (append-map
                      (λ (reached) (list-ref reached i))
                      reachables)))
```

Nondeterministic Finite Automata

- ```
;; (listof ss) → ss-name-tbl
;; Purpose: Create a table for ss names
(define (compute-ss-name-tbl super-states)
```

# Nondeterministic Finite Automata

- ```
;; (listof ss) → ss-name-tbl
;; Purpose: Create a table for ss names
(define (compute-ss-name-tbl super-states)
```
- ```
;; Tests for compute-ss-name-tbl
(check-pred (lambda (tbl)
 (and (list? tbl)
 (andmap (λ (e) (= (length e) 2)) (tbl))
 (andmap (λ (e) (andmap symbol? (first e)))
 (tbl))
 (andmap (λ (e) (symbol? (second e))) (tbl))))
 (compute-ss-name-tbl '())))
(check-pred (lambda (tbl)
 (and (list? tbl)
 (andmap (λ (e) (= (length e) 2)) (tbl))
 (andmap (λ (e) (andmap symbol? (first e)))
 (tbl))
 (andmap (λ (e) (symbol? (second e))) (tbl))))
 (compute-ss-name-tbl '((A B) (A B C) () (C))))
```

# Nondeterministic Finite Automata

- `;; (listof ss) → ss-name-tbl`  
`;; Purpose: Create a table for ss names`  
`(define (compute-ss-name-tbl super-states)`
- `(foldl (λ (ss acc)`  
    `(cons (list ss (gen-state (map second acc))) acc))`  
    `'()`  
    `super-states))`
- `;; Tests for compute-ss-name-tbl`  
`(check-pred (lambda (tbl)`  
    `(and (list? tbl)`  
        `(andmap (λ (e) (= (length e) 2)) tbl)`  
        `(andmap (λ (e) (andmap symbol? (first e)))`  
            `tbl)`  
        `(andmap (λ (e) (symbol? (second e))) (tbl)))`  
        `(compute-ss-name-tbl '()))`
- `(check-pred (lambda (tbl)`  
    `(and (list? tbl)`  
        `(andmap (λ (e) (= (length e) 2)) (tbl))`  
        `(andmap (λ (e) (andmap symbol? (first e)))`  
            `tbl)`  
        `(andmap (λ (e) (symbol? (second e))) (tbl)))`  
        `(compute-ss-name-tbl '((A B) (A B C) () (C))))`

# Nondeterministic Finite Automata

- Correctness Proof

# Nondeterministic Finite Automata

- Correctness Proof
- $ND = (\text{make-ndfa } S \Sigma A F \delta)$   
 $D = (\text{make-dfa } S' \Sigma A' F' \delta')$ , where
  - $S'$  = the states computed in convert
  - $A'$  = the starting state computed in convert
  - $F'$  = the final states computed in convert
  - $\delta'$  = the transition function computed in convert
- We need to prove  $L(ND) = L(D)$

# Nondeterministic Finite Automata

## Theorem

$(w Q) \vdash^*_{ND} ((P)) \Leftrightarrow (w Q') \vdash^*_D ((P'))$ , where  $Q' = E(Q) \wedge P \in P'$

- Base Case
- $\Rightarrow$  Assume  $(w Q) \vdash^*_{ND} ((P))$

Base Case:  $|w| = 0$   $|w| = 0 \Rightarrow w = ()$

By assumption,  $((Q)) \vdash^*_{ND} ((P))$ . This means that  $P \in E(Q)$

By construction of D,  $P \in Q'$ . This means that ND's computation is carried out as follows by D:

$((Q')) \vdash ((Q'))$

This establishes the base case.

# Nondeterministic Finite Automata

## Theorem

$(w Q) \vdash^*_{ND} ((P)) \Leftrightarrow (w Q') \vdash^*_D ((P'))$ , where  $Q' = E(Q) \wedge P \in P'$

- Base Case

- ( $\Rightarrow$ ) Assume  $(w Q) \vdash^*_{ND} ((P))$

Base Case:  $|w| = 0 \Rightarrow w = ()$

By assumption,  $((Q)) \vdash^*_{ND} ((P))$ . This means that  $P \in E(Q)$

By construction of D,  $P \in Q'$ . This means that ND's computation is carried out as follows by D:  
 $((Q')) \vdash ((Q'))$

This establishes the base case.

- Inductive Step:

Assume:  $(w Q) \vdash^*_{ND} ((P)) \Rightarrow (w Q') \vdash^*_D ((P'))$ , where  $Q' = E(Q) \wedge P \in P'$ , for  $|w|=k$   
Show:  $(w Q) \vdash^*_{ND} ((P)) \Rightarrow (w Q') \vdash^*_D ((P'))$ , where  $Q' = E(Q) \wedge P \in P'$ , for  $|w|=k+1$

$|w|=k+1 \Rightarrow w=(xa)$ , where  $x \in \Sigma^*$  and  $a \in \Sigma$ .

To prove the implication assume  $((xa) Q) \vdash^*_{ND} ((P))$ .

This means that ND's computation is:

$((xa) Q) \vdash^*_{ND} ((a) R) \vdash_{ND} ((T)) \vdash^*_{ND} ((P))$

That is, consuming x takes ND from Q to some intermediate state R. From R on an a ND goes to T. Then by  $\epsilon$ -transitions ND gets to P.

By inductive hypothesis:

$((xa) Q') \vdash^*_D ((a) R')$ , where  $R \in R'$

Observe that  $(R \ a \ T) \in \delta$  and  $P \in E(T)$ . Let  $P' \in E(T)$ . By construction of D, this means that the following is D's computation:

$((xa) Q') \vdash^*_D ((a) R') \vdash_D ((P'))$ , where  $P \in P'$ .

Clearly, we have that  $(w Q') \vdash^*_D ((P'))$ , where  $P \in P'$ . This completes the proof of the implication.

# Nondeterministic Finite Automata

## Theorem

$(w Q) \vdash^*_{ND} (\lambda P) \Leftrightarrow (w Q') \vdash^*_D (\lambda P')$ , where  $Q' = E(Q) \wedge P \in P'$

- ( $\Leftarrow$ ) Assume:  $(w Q') \vdash^*_D (\lambda P')$ , where  $Q' = E(Q) \wedge P \in P'$ , for  $|w|=k+1$ .  
Base Case:  $|w| = 0$   $|w| = 0 \Rightarrow w = \lambda$   
By assumption,  $Q' = P'$  because D is deterministic. This means that  $P \in E(Q)$ .  
By construction of D:  
 $(\lambda Q) \vdash^*_{ND} (\lambda P)$   
This establishes the base case.

# Nondeterministic Finite Automata

## Theorem

$(w Q) \vdash^*_{ND} ((P)) \Leftrightarrow (w Q') \vdash^*_D ((P'))$ , where  $Q' = E(Q) \wedge P \in P'$

- ( $\Leftarrow$ ) Assume:  $(w Q') \vdash^*_D ((P'))$ , where  $Q' = E(Q) \wedge P \in P'$ , for  $|w|=k+1$ .  
Base Case:  $|w|=0 \Rightarrow w=()$   
By assumption,  $Q' = P'$  because D is deterministic. This means that  $P \in E(Q)$ .  
By construction of D:  
 $((Q) \vdash^*_{ND} ((P))$   
This establishes the base case.
- Inductive Step:  
Assume:  $(w Q') \vdash^*_D ((P')) \Rightarrow (w Q) \vdash^*_{ND} ((P))$ , where  $Q' = E(Q) \wedge P \in P'$ , for  $|w|=k$   
Show:  $(w Q') \vdash^*_D ((P')) \Rightarrow (w Q) \vdash^*_{ND} ((P))$ , where  $Q' = E(Q) \wedge P \in P'$ , for  $|w|=k+1$   
 $|w|=k+1 \Rightarrow w=(xa)$ , where  $x \in \Sigma^*$  and  $a \in \Sigma$ .  
To prove the implication assume  $(w Q') \vdash^*_D ((P'))$ , where  $Q' = E(Q) \wedge P \in P'$ , for  $|w|=k+1$   
This means that D's computation is:  
 $((xa) Q') \vdash^*_D ((a) R') \vdash_D ((P'))$   
By construction of D, the above means:  
 $((xa) Q) \vdash^*_{ND} ((a) R) \vdash_{ND} ((T)) \vdash^*_{ND} ((P))$ , where  $R \in R'$  and  $P \in E(T)=P'$ .  
This completes the proof of the theorem.

# Nondeterministic Finite Automata

## Lemma

$$w \in L(ND) \Leftrightarrow w \in L(D)$$

# Nondeterministic Finite Automata

## Lemma

$$w \in L(ND) \Leftrightarrow w \in L(D)$$

- ( $\Rightarrow$ ) Assume  $w \in L(ND)$

This means that:

$(w S) \vdash^*_{ND} (( P), \text{ where } P \in F)$ .

By Theorem, we have that:

$(w S') \vdash^*_{D'} (( P'), \text{ where } P' \in F')$ .

By construction of D,  $P' \in F'$ . Thus,  $w \in L(D)$

# Nondeterministic Finite Automata

## Lemma

$$w \in L(ND) \Leftrightarrow w \in L(D)$$

- ( $\Rightarrow$ ) Assume  $w \in L(ND)$

This means that:

$(w S) \vdash^*_{ND} (( P), \text{ where } P \in F)$ .

By Theorem, we have that:

$(w S') \vdash^*_D (( P'), \text{ where } P' \in P')$ .

By construction of D,  $P' \in F'$ . Thus,  $w \in L(D)$

- ( $\Leftarrow$ ) Assume  $w \in L(D)$

This means that:

$(w S') \vdash^*_D (( P'), \text{ where } P' \in F')$ .

By Theorem and construction of D, we have that:

$(w S) \vdash^*_{ND} (( P), \text{ where } P \in F \text{ and } P \in P')$ .

Thus,  $w \in L(ND)$

# Nondeterministic Finite Automata

## Lemma

$$w \notin L(ND) \Leftrightarrow w \notin L(D)$$

# Nondeterministic Finite Automata

## Lemma

$$w \notin L(ND) \Leftrightarrow w \notin L(D)$$

- ( $\Rightarrow$ ) Assume  $w \notin L(ND)$   
This means that for all ND computations:  
 $(w S) \vdash^*_{ND} (( P), \text{ where } P \notin F)$ .  
By Theorem, we have that:  
 $(w S') \vdash^*_{D'} (( P'), \text{ where } P' \in P')$ .  
By construction of D,  $P' \notin F'$ . Thus,  $w \notin L(D)$

# Nondeterministic Finite Automata

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By construction of D,  $P' \notin F'$ . Thus,  $w \notin L(D)$

- ( $\Leftarrow$ ) Assume  $w \notin L(D)$

This means that:

$(w S') \vdash^*_{D} (( P'), \text{ where } P' \notin F')$ .

By Theorem and construction of D, we have that:

$(w S) \vdash^*_{ND} (( P), \text{ where } P \notin F \text{ and } P \in P')$ .

Thus,  $w \notin L(ND)$ .

# Nondeterministic Finite Automata

## Theorem

$$L(ND) = L(D)$$

- Follows from the two previous lemmas.

# Nondeterministic Finite Automata

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- For a computer scientist the answer is clearly no
- Why?

# Nondeterministic Finite Automata

- It is a remarkable result that endowing dfas with nondeterminism yields no extra computational power
- Does this mean that ndfas are worthless?
- For a computer scientist the answer is clearly no
- Why?
- Make the design process easier
- A useful abstraction programmers may use to design solutions using a dfa

# Nondeterministic Finite Automata

- QUIZ: 6 (due in 1 week)

# FSA and Regular Expressions

- Finite-state automata decide regular languages?

# FSA and Regular Expressions

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- We have seen DFA examples that read concatenated symbols or that loop to read a collection of concatenated symbols an arbitrary number of times
- This suggests that the languages they decide may be closed under concatenation and Kleene star

# FSA and Regular Expressions

Regular  
Expressions

Deterministic  
Finite  
Automata

Nondeterministic  
Finite  
Automata

Finite-State  
Automata and  
Regular  
Expressions

Regular  
Grammars

Pumping  
Theorem for  
Regular  
Languages

- Finite-state automata decide regular languages?
- We have seen dfa examples that read concatenated symbols or that loop to read a collection of concatenated symbols an arbitrary number of times
- This suggests that the languages they decide may be closed under concatenation and Kleene star
- We have seen ndfa examples that suggest the languages they decide are closed under union
- These are operations used by regular expressions!

# FSA and Regular Expressions

- We ought to be able to combine the languages decided by finite-state automatas using concatenation, union, and Kleene star to create machines for bigger languages
- Such an ability would provide programmers with a new set of constructors to create finite-state automatas
- Simplifying the amount of work a programmer must do to create “complex” finite-state automatas

# FSA and Regular Expressions

## Theorem

*The languages decided by finite-state automata are closed under:*

1. union
2. concatenation
3. Kleene star
4. complement
5. intersection

# FSA and Regular Expressions

## Theorem

*The languages decided by finite-state automata are closed under:*

1. union
2. concatenation
3. Kleene star
4. complement
5. intersection

- The proof is divided into 5 theorems
- They are all proven using a constructive proof

# FSA and Regular Expressions

- To test the constructors the following machines are defined:

```
;; L = ab*
(define ab* (make-ndfa '(S A) '(a b) 'S '(A)
 '((S a A) (A b A))))

;; L = a(a U ab)b*
(define a-aUb-b* (make-ndfa '(Z H B C D F)
 '(a b)
 'Z
 '(F)
 `((Z a H)
 (Z a B) (H a D) (D ,EMP F)
 (B a C) (C b F) (F b F))))

;; L = aab*
(define aab* (make-ndfa '(W X Y) '(a b) 'W '(Y)
 '((W a X) (X a Y) (Y b Y))))

;; L = a*
(define a* (make-dfa '(S D)
 '(a b)
 'S
 '(S)
 `((S a S) (S b D) (D a D) (D b D))
 'no-dead))
```

# FSA and Regular Expressions

## Theorem

*The languages accepted by finite-state machines are closed under union.*

- Let the following be the two machines that decide the languages to union:  
 $M = (\text{make-ndfa } S_M \Sigma_M A F_M \delta_M)$   
 $N = (\text{make-ndfa } S_N \Sigma_N R F_N \delta_N)$
- We need to construct an ndfa that decides  $L = L(M) \cup L(N)$

# FSA and Regular Expressions

## Theorem

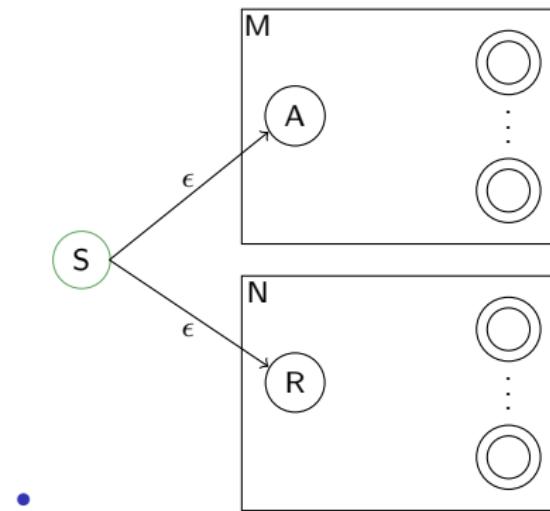
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- Illustrate union-viz using closure-algorithms.rkt

# FSA and Regular Expressions

- ```
;; ndfa ndfa → ndfa
;; Purpose: Construct ndfa for the union of given ndfas
;; Assume: The intersection of states is empty
(define (union-fsa M N)
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FSA and Regular Expressions

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- ```
;; Tests for union-fsa
(define ab*Ua-aUb-b* (union-fsa ab* a-aUb-b*))
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• (check-reject? ab*Ua-aUb-b* '() '(a a a a))
  (check-accept? ab*Ua-aUb-b* '(a b) '(a a b b))
  (check-equal? (sm-testequiv? ab*Ua-aUb-b* (sm-union ab* ab*Ua-aUb-b*)) #t)

  (check-reject? ab*Uaab* '(a a a) '(b a b a))
  (check-accept? ab*Uaab* '(a b b) '(a a b) '(a b b b b))
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(define (union-fsa M N))
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- ```
(let* [(new-start (gen-state (append (sm-states M) (sm-states N))))
```

- ```
; Tests for union-fsa
(define ab*Ua-aUb-b* (union-fsa ab* a-aUb-b*))
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```

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(new-states (cons new-start
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 (append (sm-sigma M) (sm-sigma N))))]
```
- ```
(new-states (cons new-start
                     (append (sm-states M) (sm-states N))))
```
- ```
(new-finals (append (sm-finals M) (sm-finals N)))
```

- ```
; Tests for union-fsa
(define ab*Ua-aUb-b* (union-fsa ab* a-aUb-b*))
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 (new-rules (append (list (list new-start EMP (sm-start M))
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- ```
(make-ndfa new-states new-sigma new-start new-finals new-rules)))
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```

FSA and Regular Expressions

Lemma

$$w \in L \Leftrightarrow w \in L(U)$$

- Define three machines as follows:

$$M = (\text{make-ndfa } S \ \Sigma \ Z \ F \ \delta)$$

$$N = (\text{make-ndfa } S' \ \Sigma' \ Z' \ F' \ \delta')$$

$$U = (\text{union-fsa } M \ N) = (\text{make-ndfa } S'' \ \Sigma'' \ Z'' \ F'' \ \delta'')$$

- Let $L = L(M) \cup L(N)$

FSA and Regular Expressions

Lemma

$$w \in L \Leftrightarrow w \in L(U)$$

- (\Rightarrow) We need to show that $w \in L \Rightarrow w \in L(U)$

FSA and Regular Expressions

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- (\Rightarrow) We need to show that $w \in L \Rightarrow w \in L(U)$
- Assume $w \in L$
- This means that $w \in L(M)$ or $w \in L(N)$
- By construction, U nondeterministically correctly chooses to simulate M or to simulate N
- Thus, $w \in L(U)$.

FSA and Regular Expressions

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- (\Leftarrow) We need to show that $w \in L(U) \Rightarrow w \in L$
- Assume $w \in L(U)$
- This means that there is a computation that consumes w such that:

$$(w \text{ } z'') \vdash^*_{\mathcal{U}} ((\cdot) \text{ } K), \text{ where } K \in F''$$

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- Assume $w \in L(U)$
- This means that there is a computation that consumes w such that:
$$(w \text{ } z'') \vdash^*_U ((\text{ }) \text{ } K), \text{ where } K \in F^{**}$$
- By U 's construction, either M or N is simulated
- U 's final states are the final states of M and N
- This means $w \in L(M)$ or $w \in L(N)$
- Thus, $w \in L$

FSA and Regular Expressions

Lemma

$$w \notin L \Leftrightarrow w \notin L(U)$$

- (\Rightarrow) We need to show that $w \notin L \Rightarrow w \notin L(U)$

FSA and Regular Expressions

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$$w \notin L \Leftrightarrow w \notin L(U)$$

- (\Rightarrow) We need to show that $w \notin L \Rightarrow w \notin L(U)$
- Assume $w \notin L$
- This means that $w \notin L(M)$ and $w \notin L(N)$
- By U's construction, $F'' = F \cup F'$
- And all possible computations of U on w never reach a state in F''
- Thus, $w \notin L(U)$

FSA and Regular Expressions

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FSA and Regular Expressions

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- And all possible computations of U on w never reach a state in F''
- Thus, $w \notin L(U)$
- (\Leftarrow) We need to show that $w \notin L(U) \Rightarrow w \notin L$.
- Assume $w \notin L(U)$
- This means that all possible computations on w are described as follows:
 $(w \mid Z'') \vdash^*_U ((\cdot) \mid K), \text{ where } K \notin F''$
- By U's construction, either M or N is simulated
- $F'' = F \cup F'$
- This means $w \notin L(M)$ and $w \notin L(N)$
- Thus, $w \notin L$

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Pumping
Theorem for
Regular
Languages

Theorem

The languages accepted by finite-state machines are closed under union.

- The theorem is established by the previous two lemmas

FSA and Regular Expressions

- HOMEWORK: 1, 3, 4

FSA and Regular Expressions

Theorem

The languages accepted by finite-state machines are closed concatenation.

- Let the following be the two machines that decide the languages to concatenate:

$$\begin{aligned}M &= (\text{make-ndfa } S_M \ \Sigma_M \ A \ F_M \ \delta_M) \\N &= (\text{make-ndfa } S_N \ \Sigma_N \ R \ F_N \ \delta_N)\end{aligned}$$

FSA and Regular Expressions

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- We need to construct an ndfa that decides $L = L(M) \circ L(N)$

FSA and Regular Expressions

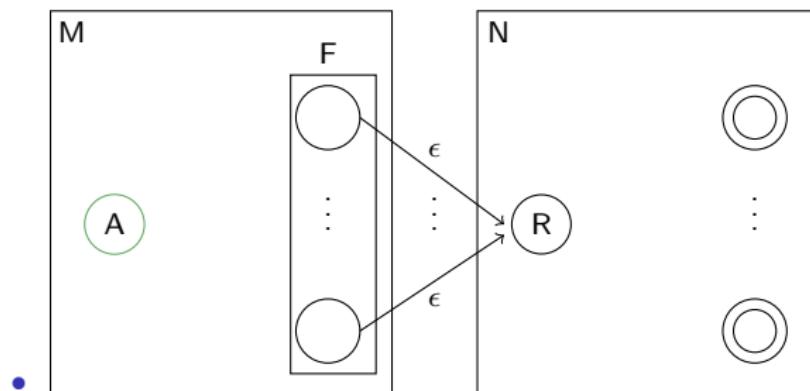
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- We need to construct an ndfa that decides $L = L(M) \circ L(N)$



- Illustrate concat-viz using closure-algorithms.rkt

FSA and Regular Expressions

- `;; ndfa ndfa → ndfa`
`;; Purpose: Construct ndfa for the concatenation of the languages of the`
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`(define (concat-fsa M N)`

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- ```
;; Tests for concat-fsa
(define ab*-o-a-aUb-b* (concat-fsa ab* a-aUb-b*))
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(check-accept? ab*-o-a-aUb-b* '(a b a a b) '(a b b b a a))
(check-equal? (sm-testequiv? ab*-o-a-aUb-b* (sm-concat ab* a-aUb-b*)) #t)

(check-reject? ab*-o-aab* '() '(a b a) '(a a b b a a))
(check-accept? ab*-o-aab* '(a b b a a b b) '(a a a))
(check-equal? (sm-testequiv? ab*-o-aab* (sm-concat ab* aab*)) #t)
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;; Assume: The intersection of the states is empty
(define (concat-fsa M N)
 (let* [(new-start (sm-start M))
```

- ```
; Tests for concat-fsa
(define ab*-o-a-aUb-b* (concat-fsa ab* a-aUb-b*))
(define ab*-o-aab* (concat-fsa ab* aab*))

• (check-reject? ab*-o-a-aUb-b* '() '(b b b) '(a a b a b))
  (check-accept? ab*-o-a-aUb-b* '(a b a a b) '(a b b b a a))
  (check-equal? (sm-testequiv? ab*-o-a-aUb-b* (sm-concat ab* a-aUb-b*)) #t)

  (check-reject? ab*-o-aab* '() '(a b a) '(a a b b a a))
  (check-accept? ab*-o-aab* '(a b b a a b b) '(a a a))
  (check-equal? (sm-testequiv? ab*-o-aab* (sm-concat ab* aab*)) #t)
```

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

- ```
;; ndfa ndfa → ndfa
;; Purpose: Construct ndfa for the concatenation of the languages of the
;; given ndfas
;; Assume: The intersection of the states is empty
(define (concat-fsa M N)
 (let* [(new-start (sm-start M))
 (new-sigma (remove-duplicates (append (sm-sigma M) (sm-sigma N)))))
```
- 
- 

- ```
;; Tests for concat-fsa
(define ab*-o-a-aUb-b* (concat-fsa ab* a-aUb-b*))
(define ab*-o-aab* (concat-fsa ab* aab*))
```
- ```
(check-reject? ab*-o-a-aUb-b* '() '(b b b) '(a a b a b))
(check-accept? ab*-o-a-aUb-b* '(a b a a b) '(a b b b a a))
(check-equal? (sm-testequiv? ab*-o-a-aUb-b* (sm-concat ab* a-aUb-b*)) #t)

(check-reject? ab*-o-aab* '() '(a b a) '(a a b b a a))
(check-accept? ab*-o-aab* '(a b b a a b b) '(a a a))
(check-equal? (sm-testequiv? ab*-o-aab* (sm-concat ab* aab*)) #t)
```

# FSA and Regular Expressions

Regular  
Expressions

Deterministic  
Finite  
Automata

Nondeterministic  
Finite  
Automata

Finite-State  
Automata and  
Regular  
Expressions

Regular  
Grammars

Pumping  
Theorem for  
Regular  
Languages

- `;; ndfa ndfa → ndfa`  
`;; Purpose: Construct ndfa for the concatenation of the languages of the`  
`;; given ndfas`  
`;; Assume: The intersection of the states is empty`  
`(define (concat-fsa M N)`
  - `(let* [(new-start (sm-start M))`
  - `(new-sigma (remove-duplicates (append (sm-sigma M) (sm-sigma N))))`
  - `(new-states (append (sm-states M) (sm-states N))))`

- `;; Tests for concat-fsa`  
`(define ab*-o-a-aUb-b* (concat-fsa ab* a-aUb-b*))`  
`(define ab*-o-aab* (concat-fsa ab* aab*))`
- `(check-reject? ab*-o-a-aUb-b* '() '(b b b) '(a a b a b))`  
`(check-accept? ab*-o-a-aUb-b* '(a b a a b) '(a b b b a a))`  
`(check-equal? (sm-testequiv? ab*-o-a-aUb-b* (sm-concat ab* a-aUb-b*)) #t)`  
  
`(check-reject? ab*-o-aab* '() '(a b a) '(a a b b a a))`  
`(check-accept? ab*-o-aab* '(a b b a a b b) '(a a a))`  
`(check-equal? (sm-testequiv? ab*-o-aab* (sm-concat ab* aab*)) #t)`

# FSA and Regular Expressions

- ```
;; ndfa ndfa → ndfa
;; Purpose: Construct ndfa for the concatenation of the languages of the
;; given ndfas
;; Assume: The intersection of the states is empty
(define (concat-fsa M N)
  (let* [(new-start (sm-start M))
         (new-sigma (remove-duplicates (append (sm-sigma M) (sm-sigma N))))
         (new-states (append (sm-states M) (sm-states N)))
         (new-finals (sm-finals N))]
```
- ```
;; Tests for concat-fsa
(define ab*-o-a-aUb-b* (concat-fsa ab* a-aUb-b*))
(define ab*-o-aab* (concat-fsa ab* aab*))

• (check-reject? ab*-o-a-aUb-b* '() '(b b b) '(a a b a b))
 (check-accept? ab*-o-a-aUb-b* '(a b a a b) '(a b b b a a))
 (check-equal? (sm-testequiv? ab*-o-a-aUb-b* (sm-concat ab* a-aUb-b*)) #t)

 (check-reject? ab*-o-aab* '() '(a b a) '(a a b b a a))
 (check-accept? ab*-o-aab* '(a b b a a b b) '(a a a))
 (check-equal? (sm-testequiv? ab*-o-aab* (sm-concat ab* aab*)) #t)
```

# FSA and Regular Expressions

Regular  
Expressions

Deterministic  
Finite  
Automata

Nondeterministic  
Finite  
Automata

Finite-State  
Automata and  
Regular  
Expressions

Regular  
Grammars

Pumping  
Theorem for  
Regular  
Languages

- ```
;; ndfa ndfa → ndfa
;; Purpose: Construct ndfa for the concatenation of the languages of the
;; given ndfas
;; Assume: The intersection of the states is empty
(define (concat-fsa M N)
  (let* [(new-start (sm-start M))
         (new-sigma (remove-duplicates (append (sm-sigma M) (sm-sigma N))))
         (new-states (append (sm-states M) (sm-states N)))
         (new-finals (sm-finals N))
         (new-rules (append (sm-rules M)
                            (sm-rules N)
                            (map (λ (f) (list f EMP (sm-start N)))
                                 (sm-finals M))))]
    ;; Tests for concat-fsa
    (define ab*-o-a-aUb-b* (concat-fsa ab* a-aUb-b*))
    (define ab*-o-aab* (concat-fsa ab* aab*))

    (check-reject? ab*-o-a-aUb-b* '() '(b b b) '(a a b a b))
    (check-accept? ab*-o-a-aUb-b* '(a b a a b) '(a b b b a a))
    (check-equal? (sm-testequiv? ab*-o-a-aUb-b* (sm-concat ab* a-aUb-b*)) #t)

    (check-reject? ab*-o-aab* '() '(a b a) '(a a b b a a))
    (check-accept? ab*-o-aab* '(a b b a a b b) '(a a a))
    (check-equal? (sm-testequiv? ab*-o-aab* (sm-concat ab* aab*)) #t)
```

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

- `;; ndfa ndfa → ndfa`
 `;; Purpose: Construct ndfa for the concatenation of the languages of the`
 `;; given ndfas`
 `;; Assume: The intersection of the states is empty`
`(define (concat-fsa M N)`
 - `(let* [(new-start (sm-start M))`
 - `(new-sigma (remove-duplicates (append (sm-sigma M) (sm-sigma N))))`
 - `(new-states (append (sm-states M) (sm-states N)))`
 - `(new-finals (sm-finals N))`
 - `(new-rules (append (sm-rules M)`
 `(sm-rules N)`
 `(map (λ (f) (list f EMP (sm-start N)))`
 `(sm-finals M))))]`
 - `(make-ndfa new-states new-sigma new-start new-finals new-rules)))`
 - `;; Tests for concat-fsa`
`(define ab*-o-a-aUb-b* (concat-fsa ab* a-aUb-b*))`
`(define ab*-o-aab* (concat-fsa ab* aab*))`
 - `(check-reject? ab*-o-a-aUb-b* '() '(b b b) '(a a b a b))`
`(check-accept? ab*-o-a-aUb-b* '(a b a a b) '(a b b b a a))`
`(check-equal? (sm-testequiv? ab*-o-a-aUb-b* (sm-concat ab* a-aUb-b*)) #t)`
 - `(check-reject? ab*-o-aab* '() '(a b a) '(a a b b a a))`
`(check-accept? ab*-o-aab* '(a b b a a b b) '(a a a))`
`(check-equal? (sm-testequiv? ab*-o-aab* (sm-concat ab* aab*)) #t)`

FSA and Regular Expressions

- Define three machines as follows:

$$M = (\text{make-ndfa } S \ \Sigma \ Z \ F \ \delta)$$
$$N = (\text{make-ndfa } S' \ \Sigma' \ Z' \ F' \ \delta')$$
$$U = (\text{concat-fsa } M \ N) = (\text{make-ndfa } S'' \ \Sigma'' \ Z'' \ F'' \ \delta'')$$

- Let $L = L(M) \circ L(N)$
- We proceed to prove that $L = L(U)$

FSA and Regular Expressions

Lemma

$$w \in L \Leftrightarrow w \in L(U)$$

- (\Rightarrow) We need to show that $w \in L \Rightarrow w \in L(U)$

FSA and Regular Expressions

Lemma

$$w \in L \Leftrightarrow w \in L(U)$$

- (\Rightarrow) We need to show that $w \in L \Rightarrow w \in L(U)$
- Assume $w \in L$
- This means $w = xy$, where $x \in L(M)$ and $y \in L(N)$
- By construction of U , the following is a valid computation:
 $(xy \text{ } S'') \vdash^*_{U'} (y \text{ } R) \vdash (y \text{ } z') \vdash^*_{U'} ((\text{ }) \text{ } T)$, where $R \in F$ and $T \in F'$
- By construction of U , $F'' = F'$
- Therefore, $w \in L(U)$

FSA and Regular Expressions

Lemma

$$w \in L \Leftrightarrow w \in L(U)$$

- (\Rightarrow) We need to show that $w \in L \Rightarrow w \in L(U)$
- Assume $w \in L$
- This means $w = xy$, where $x \in L(M)$ and $y \in L(N)$
- By construction of U , the following is a valid computation:
 $(xy \ S'') \vdash^*_{U'} (y \ R) \vdash (y \ z') \vdash^*_{U'} ((\ T)$, where $R \in F$ and $T \in F'$
- By construction of U , $F'' = F'$
- Therefore, $w \in L(U)$
- (\Leftarrow) We need to show that $w \in L(U) \Rightarrow w \in L$

FSA and Regular Expressions

Lemma

$$w \in L \Leftrightarrow w \in L(U)$$

- (\Rightarrow) We need to show that $w \in L \Rightarrow w \in L(U)$
- Assume $w \in L$
- This means $w = xy$, where $x \in L(M)$ and $y \in L(N)$
- By construction of U , the following is a valid computation:
 $(xy \text{ } S'') \vdash^*_{U'} (y \text{ } R) \vdash (y \text{ } Z') \vdash^*_{U'} ((\text{ }) \text{ } T)$, where $R \in F$ and $T \in F'$
- By construction of U , $F'' = F'$
- Therefore, $w \in L(U)$
- (\Leftarrow) We need to show that $w \in L(U) \Rightarrow w \in L$
- Assume $w \in L(U)$
- By construction of U , this means that for $w = xy$ the following computation is valid:
 $(xy \text{ } S'') \vdash^*_{U'} (y \text{ } R) \vdash (y \text{ } Z') \vdash^*_{U'} ((\text{ }) \text{ } T)$, where $R \in F$ and $T \in F'$
- This implies that $x \in L(M)$ and $y \in L(N)$
- Thus, $w \in L$

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

**Finite-State
Automata and
Regular
Expressions**

Regular
Grammars

Pumping
Theorem for
Regular
Languages

Lemma

$$w \notin L \Leftrightarrow w \notin L(U)$$

FSA and Regular Expressions

Lemma

$$w \notin L \Leftrightarrow w \notin L(U)$$

- (\Rightarrow) We need to show that $w \notin L \Rightarrow w \notin L(U)$

FSA and Regular Expressions

Lemma

$$w \notin L \Leftrightarrow w \notin L(U)$$

- (\Rightarrow) We need to show that $w \notin L \Rightarrow w \notin L(U)$
- Assume $w \notin L$
- This means $w \neq xy$, where $x \in L(M)$ and $y \in L(N)$
- By construction, all possible computations of U on w either do not reach a final state by consuming w or do not consume all of w
- In both cases, w is rejected
- Therefore, $w \notin L(U)$.

FSA and Regular Expressions

Lemma

$$w \notin L \Leftrightarrow w \notin L(U)$$

- (\Rightarrow) We need to show that $w \notin L \Rightarrow w \notin L(U)$
- Assume $w \notin L$
- This means $w \neq xy$, where $x \in L(M)$ and $y \in L(N)$
- By construction, all possible computations of U on w either do not reach a final state by consuming w or do not consume all of w
- In both cases, w is rejected
- Therefore, $w \notin L(U)$.
- (\Leftarrow) We need to show that $w \notin L(U) \Rightarrow w \notin L$

FSA and Regular Expressions

Lemma

$$w \notin L \Leftrightarrow w \notin L(U)$$

- (\Rightarrow) We need to show that $w \notin L \Rightarrow w \notin L(U)$
- Assume $w \notin L$
- This means $w \neq xy$, where $x \in L(M)$ and $y \in L(N)$
- By construction, all possible computations of U on w either do not reach a final state by consuming w or do not consume all of w
- In both cases, w is rejected
- Therefore, $w \notin L(U)$.
- (\Leftarrow) We need to show that $w \notin L(U) \Rightarrow w \notin L$
- Assume $w \notin L(U)$
- By construction, this means that w is rejected because U consumes w and does not reach a final state or U is unable to consume w
- This implies that w cannot be written as xy , where $x \in L(M)$ and $y \in L(N)$
- Thus, $w \notin L$

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

Theorem

The languages accepted by finite-state machines are closed concatenation.

- The proof follows from the two previous lemmas

FSA and Regular Expressions

- HOMEWORK: 5, 7, 8

FSA and Regular Expressions

Theorem

The languages accepted by finite-state machines are closed under Kleene star.

- Let the following be the machine that decides the language to be Kleene starred:

$M = (\text{make-ndfa } S \ \Sigma \ A \ F \ \delta)$

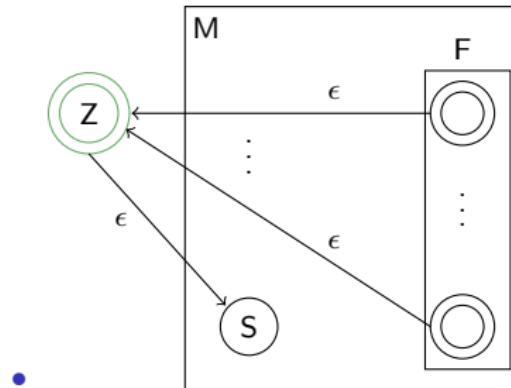
- We need to construct an ndfa that decides $L = L(M)^*$

FSA and Regular Expressions

Theorem

The languages accepted by finite-state machines are closed under Kleene star.

- Let the following be the machine that decides the language to be Kleene starred:
 $M = (\text{make-ndfa } S \Sigma A F \delta)$
- We need to construct an ndfa that decides $L = L(M)^*$



- Illustrate kleenestar-viz using closure-algorithms.rkt

FSA and Regular Expressions

- `;; ndfa → ndfa`
`;; Purpose: Construct ndfa for the Kleene star of given ndfa`
`(define (kstar-fsa M)`

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

- ```
;; ndfa → ndfa
;; Purpose: Construct ndfa for the Kleene star of given ndfa
(define (kstar-fsa M)
```
- ```
;; Tests for kstar-fsa
(define a-aUb-b** (kstar-fsa a-aUb-b*))
(define ab** (kstar-fsa ab*))

(check-reject? a-aUb-b** '(b b b) '(a b a b a a a a))
(check-accept? a-aUb-b** '() '(a a a a b b b b) '(a a b a a b b a a))
(check-equal? (sm-testequiv? a-aUb-b** (sm-kleenestar a-aUb-b*)) #t)

(check-reject? ab** '(b) '(b b b))
(check-accept? ab** '() '(a a a a) '(a b a b b a b b b))
(check-equal? (sm-testequiv? ab** (sm-kleenestar ab*)) #t)
```

FSA and Regular Expressions

- `;; ndfa → ndfa`
`;; Purpose: Construct ndfa for the Kleene star of given ndfa`
`(define (kstar-fsa M)`
- `(let* [(new-start (gen-state (sm-states M)))
 (new-sigma (sm-sigma M))`
- `;; Tests for kstar-fsa`
`(define a-aUb-b** (kstar-fsa a-aUb-b*))`
`(define ab** (kstar-fsa ab*))`

`(check-reject? a-aUb-b** '(b b b) '(a b a b a a a))`
`(check-accept? a-aUb-b** '() '(a a a a b b b) '(a a b a a b b a a))`
`(check-equal? (sm-testequiv? a-aUb-b** (sm-kleenestar a-aUb-b*)) #t)`

`(check-reject? ab** '(b) '(b b b))`
`(check-accept? ab** '() '(a a a a) '(a b a b b a b b))`
`(check-equal? (sm-testequiv? ab** (sm-kleenestar ab*)) #t)`

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

- `;; ndfa → ndfa`
`;; Purpose: Construct ndfa for the Kleene star of given ndfa`
`(define (kstar-fsa M)`
- `(let* [(new-start (gen-state (sm-states M)))`
`(new-sigma (sm-sigma M))`
- `(new-states (cons new-start (sm-states M)))`
`(new-finals (cons new-start (sm-finals M))))`
- `;; Tests for kstar-fsa`
`(define a-aUb-b** (kstar-fsa a-aUb-b*))`
`(define ab** (kstar-fsa ab*))`

`(check-reject? a-aUb-b** '(b b b) '(a b a b a a a a))`
`(check-accept? a-aUb-b** '() '(a a a a b b b b) '(a a b a a b b a a))`
`(check-equal? (sm-testequiv? a-aUb-b** (sm-kleenestar a-aUb-b*)) #t)`

`(check-reject? ab** '(b) '(b b b))`
`(check-accept? ab** '() '(a a a a) '(a b a b b a b b b))`
`(check-equal? (sm-testequiv? ab** (sm-kleenestar ab*)) #t)`

FSA and Regular Expressions

- `;; ndfa → ndfa`
`;; Purpose: Construct ndfa for the Kleene star of given ndfa`
`(define (kstar-fsa M)`
- `(let* [(new-start (gen-state (sm-states M)))`
`(new-sigma (sm-sigma M))`
- `(new-states (cons new-start (sm-states M)))`
`(new-finals (cons new-start (sm-finals M)))`
- `(new-rules (cons (list new-start EMP (sm-start M))`
`append (sm-rules M)`
`(map (λ (f) (list f EMP new-start))`
`(sm-finals M)))))]`
- `;; Tests for kstar-fsa`
`(define a-aUb-b**-* (kstar-fsa a-aUb-b*))`
`(define ab**-* (kstar-fsa ab*))`

`(check-reject? a-aUb-b**-* '(b b b) '(a b a b a a a))`
`(check-accept? a-aUb-b**-* '() '(a a a a b b b b) '(a a b a a b b a a))`
`(check-equal? (sm-testequiv? a-aUb-b**-* (sm-kleenestar a-aUb-b*)) #t)`

`(check-reject? ab**-* '(b) '(b b b))`
`(check-accept? ab**-* '() '(a a a a) '(a b a b b a b b))`
`(check-equal? (sm-testequiv? ab**-* (sm-kleenestar ab*)) #t)`

FSA and Regular Expressions

- `;; ndfa → ndfa`
`;; Purpose: Construct ndfa for the Kleene star of given ndfa`
`(define (kstar-fsa M)`
- `(let* [(new-start (gen-state (sm-states M)))`
`(new-sigma (sm-sigma M))`
- `(new-states (cons new-start (sm-states M)))`
`(new-finals (cons new-start (sm-finals M)))`
- `(new-rules (cons (list new-start EMP (sm-start M))`
`append (sm-rules M)`
`(map (λ (f) (list f EMP new-start))`
`(sm-finals M)))))]`
- `(make-ndfa new-states new-sigma new-start new-finals new-rules)))`
- `;; Tests for kstar-fsa`
`(define a-aUb-b** (kstar-fsa a-aUb-b*))`
`(define ab** (kstar-fsa ab*))`

`(check-reject? a-aUb-b** '(b b b) '(a b a b a a a))`
`(check-accept? a-aUb-b** '() '(a a a a b b b b) '(a a b a a b b a a))`
`(check-equal? (sm-testequiv? a-aUb-b** (sm-kleenestar a-aUb-b*)) #t)`

`(check-reject? ab** '(b) '(b b b))`
`(check-accept? ab** '() '(a a a a) '(a b a b b a b b))`
`(check-equal? (sm-testequiv? ab** (sm-kleenestar ab*)) #t)`

FSA and Regular Expressions

- Define two machines as follows:

$M = (\text{make-ndfa } S \ \Sigma \ Z \ F \ \delta)$

$U = (\text{kstar-fsa } M) = (\text{make-ndfa } S' \ \Sigma' \ Z' \ F' \ \delta')$

FSA and Regular Expressions

- Define two machines as follows:

$$M = (\text{make-ndfa } S \ \Sigma \ Z \ F \ \delta)$$
$$U = (\text{kstar-fsa } M) = (\text{make-ndfa } S' \ \Sigma' \ Z' \ F' \ \delta')$$

- Let $L = L(M)^*$
- We proceed to prove that $L = L(U)$

FSA and Regular Expressions

Lemma

$$w \in L \Leftrightarrow w \in L(U)$$

- (\Rightarrow) We need to show that $w \in L \Rightarrow w \in L(U)$

FSA and Regular Expressions

Lemma

$$w \in L \Leftrightarrow w \in L(U)$$

- (\Rightarrow) We need to show that $w \in L \Rightarrow w \in L(U)$
- Assume $w \in L$. This means that $w = w_1 w_2 \dots w_n$, where $w_i \in L(M)$
- By construction of U , the following is a computation on w :
 $((w_1 w_2 \dots w_n \ S') \vdash^* \$ \ U \$ ((w_2 \dots w_n) \ Y_1) \vdash^* _U ((\dots w_n) \ Y_2) \vdash^* _U (\dots Y_n),$ where $Y_i \in F'$
- Therefore, $w \in L(U)$

FSA and Regular Expressions

Lemma

$$w \in L \Leftrightarrow w \in L(U)$$

- (\Rightarrow) We need to show that $w \in L \Rightarrow w \in L(U)$
- Assume $w \in L$. This means that $w = w_1 w_2 \dots w_n$, where $w_i \in L(M)$
- By construction of U , the following is a computation on w :
 $((w_1 w_2 \dots w_n \ S') \vdash^* \$ \ U \$ ((w_2 \dots w_n) \ Y_1) \vdash^* _U ((\dots w_n) \ Y_2) \vdash^* _U (\dots Y_n),$ where $Y_i \in F'$
- Therefore, $w \in L(U)$
- (\Leftarrow) We need to show that $w \in L(U) \Rightarrow w \in L$

FSA and Regular Expressions

Lemma

$$w \in L \Leftrightarrow w \in L(U)$$

- (\Rightarrow) We need to show that $w \in L \Rightarrow w \in L(U)$
- Assume $w \in L$. This means that $w = w_1 w_2 \dots w_n$, where $w_i \in L(M)$
- By construction of U , the following is a computation on w :
 $((w_1 w_2 \dots w_n \ S') \vdash^* \$ \ U \$ ((w_2 \dots w_n) \ Y_1) \vdash^* _U ((\dots w_n) \ Y_2) \vdash^* _U (\dots) \ Y_n),$ where $Y_i \in F'$
- Therefore, $w \in L(U)$
- (\Leftarrow) We need to show that $w \in L(U) \Rightarrow w \in L$
- Assume $w \in L(U)$
- This means that $w = w_1 w_2 \dots w_n$ such that:
 $((w_1 \dots w_n) \ S') \vdash^* _U ((w_2 \dots w_n) \ Y_1) \vdash^* _U ((w_3 \dots w_n) \ Y_2) \dots ((w_n) \ Y_{n-1}) \vdash^* _U (\dots) \ Y_n),$ where $Y_i \in F'$
- By construction of U , F' contains S' and F
- This means that w is the concatenation of zero or more words in $L(M)$
- Thus, $w \in L$

FSA and Regular Expressions

Lemma

$$w \notin L \Leftrightarrow w \notin L(U)$$

- (\Rightarrow)
- We need to show that $w \notin L \Rightarrow w \notin L(U)$

FSA and Regular Expressions

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$$w \notin L \Leftrightarrow w \notin L(U)$$

- (\Rightarrow)
- We need to show that $w \notin L \Rightarrow w \notin L(U)$
- Assume $w \notin L$
- This means that $w \neq w_1 w_2 \dots w_n$, where $w_i \in L(M)$
- By construction of U , the processing of w can occur in two ways
- The first, w is consumed and U does not end in a final state
- The second, w cannot be completely consumed
- In both cases, w is rejected
- Thus, $w \notin L(U)$.

FSA and Regular Expressions

Lemma

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- We need to show that $w \notin L \Rightarrow w \notin L(U)$
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FSA and Regular Expressions

Lemma

$$w \notin L \Leftrightarrow w \notin L(U)$$

- (\Rightarrow)
 - We need to show that $w \notin L \Rightarrow w \notin L(U)$
 - Assume $w \in L$
 - This means that $w = w_1 w_2 \dots w_n$, where $w_i \in L(M)$
 - By construction of U , the processing of w can occur in two ways
 - The first, w is consumed and U does not end in a final state
 - The second, w cannot be completely consumed
 - In both cases, w is rejected
 - Thus, $w \notin L(U)$.
- (\Leftarrow) We need to show that $w \notin L(U) \Rightarrow w \notin L$
 - Assume $w \notin L(U)$
 - This means that $w \neq w_1 w_2 \dots w_n$ such that:
 $((w_1 \dots w_n) \ S') \vdash^*_{\cal U} ((w_2 \dots w_n) \ Y_1) \vdash^*_{\cal U} ((w_3 \dots w_{n-1}) \ Y_2) \dots ((w_n) \ Y_{n-1}) \vdash^*_{\cal U} (\) \ Y_n$, where $Y_i \in F'$
 - By construction of U , F' contains S' and F
 - This means that w is not the concatenation of zero or more words in $L(M)$
 - Thus, $w \notin L$

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

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Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

Theorem

The languages accepted by finite-state machines are closed under Kleene star.

- The proof follows from the previous two lemmas

FSA and Regular Expressions

- HOMEWORK: 10, 11
- QUIZ: 9

FSA and Regular Expressions

Theorem

The languages accepted by finite-state machines are closed under complement.

- Let M be a dfa. The complement of $L(M)$ is defined as follows:

$$\bar{L}(M) = \{w \mid w \notin L(M)\}$$

FSA and Regular Expressions

Theorem

The languages accepted by finite-state machines are closed under complement.

- Let M be a dfa. The complement of $L(M)$ is defined as follows:
$$\bar{L}(M) = \{w \mid w \notin L(M)\}$$
- The complement of $L(M)$ is the language that contains all words not in $L(M)$

FSA and Regular Expressions

Theorem

The languages accepted by finite-state machines are closed under complement.

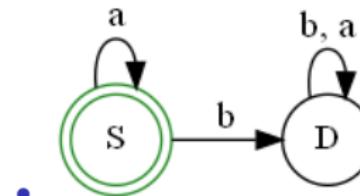
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- Given that M is a dfa, this suggests inverting the roles of M 's states

FSA and Regular Expressions

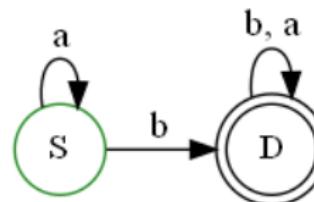
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- Let M be a dfa. The complement of $L(M)$ is defined as follows:
 $\bar{L}(M) = \{w \mid w \notin L(M)\}$
- The complement of $L(M)$ is the language that contains all words not in $L(M)$
- Given that M is a dfa, this suggests inverting the roles of M 's states



- Reversing the roles of the states yields:



- Illustrate complement-viz using closure-algorithms.rkt

FSA and Regular Expressions

- `;; dfa → dfa`
`;; Purpose: Construct a dfa for the complement of given dfa's language`
`(define (complement-fsa M)`

- `;; dfa → dfa`
;; Purpose: Construct a dfa for the complement of given dfa's language
`(define (complement-fsa M)`

```

;; Tests for complement-fsa
(define not-a* (complement-fsa a*))
(define not-EVEN-A-ODD-B (complement-fsa EVEN-A-ODD-B))

(check-reject? not-a* '() '(a a a))
(check-accept? not-a* '(a a b) '(b b a a b))
(check-equal? (sm-testequiv? not-a* (sm-complement a*)) #t)

(check-reject? not-EVEN-A-ODD-B '(b) '(a a b) '(b b a b a))
(check-accept? not-EVEN-A-ODD-B '() '(b b a a) '(a a b b a b))
(check-equal? (sm-testequiv? not-EVEN-A-ODD-B
                               (sm-complement EVEN-A-ODD-B))
              #t)

```

FSA and Regular Expressions

- `;; dfa → dfa`
`;; Purpose: Construct a dfa for the complement of given dfa's language`
`(define (complement-fsa M)`
 - `(let* [(new-finals (filter (λ (s) (not (member s (sm-finals M))))
 (sm-states M)))]`
-
- `;; Tests for complement-fsa`
`(define not-a* (complement-fsa a*))`
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`(check-reject? not-a* '() '(a a a))`
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`(check-equal? (sm-testequiv? not-a* (sm-complement a*)) #t)`

`(check-reject? not-EVEN-A-ODD-B '(b) '(a a b) '(b b a b a))`
`(check-accept? not-EVEN-A-ODD-B '() '(b b a a) '(a a b b a b))`
`(check-equal? (sm-testequiv? not-EVEN-A-ODD-B
 (sm-complement EVEN-A-ODD-B))`
`#t)`

FSA and Regular Expressions

- ```

• ;; dfa → dfa
;; Purpose: Construct a dfa for the complement of given dfa's language
(define (complement-fsa M)

• (let* [(new-finals (filter (λ (s) (not (member s (sm-finals M))))))

 (sm-states M))]

• (make-dfa (sm-states M)
 (sm-sigma M)
 (sm-start M)
 new-finals
 (sm-rules M)
 'no-dead)))

• ;; Tests for complement-fsa
(define not-a* (complement-fsa a*))
(define not-EVEN-A-ODD-B (complement-fsa EVEN-A-ODD-B))

(check-reject? not-a* '() '(a a a))
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(check-equal? (sm-testequiv? not-EVEN-A-ODD-B
 (sm-complement EVEN-A-ODD-B))
 #t)

```

# FSA and Regular Expressions

- Define two machines as follows:

$M = (\text{make-dfa } S \Sigma Z F \delta)$

$U = (\text{complement-fsa } M) = (\text{make-ndfa } S \Sigma Z F' \delta)$

- Let  $L = \bar{L}(M)$
- We proceed to prove that  $L = L(U)$

# FSA and Regular Expressions

## Lemma

$$w \in L \Leftrightarrow w \notin L(U)$$

- ( $\Rightarrow$ )
- We need to show that  $w \in L \Rightarrow w \notin L(U)$

# FSA and Regular Expressions

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- ( $\Rightarrow$ )
- We need to show that  $w \in L \Rightarrow w \notin L(U)$
- Assume  $w \in L$
- Given that  $M$  is a dfa, the following is the computation performed on  $w$ :  
 $((w) S) \vdash^*_M ((\cdot) Q)$ , where  $Q \in F$
- By construction of  $U$ ,  $Q \notin F'$  and  $M$  performs the same computation moving from  $S$  to  $Q$  by consuming  $w$
- Therefore,  $w \notin L(U)$

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  - Assume  $w \in L$
  - Given that  $M$  is a dfa, the following is the computation performed on  $w$ :  
 $((w) S) \vdash_M^* ((Q), \text{ where } Q \in F)$
  - By construction of  $U$ ,  $Q \notin F'$  and  $M$  performs the same computation moving from  $S$  to  $Q$  by consuming  $w$
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  - Assume  $w \notin L(U)$
  - This means that  $U$  performs the following computation on  $w$ :  
 $((w) S) \vdash_U^* ((Q), \text{ where } Q \notin F')$
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# FSA and Regular Expressions

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## Theorem

*The languages accepted by finite-state machines are closed under complement.*

- The proof follows from the previous two lemmas

# FSA and Regular Expressions

- HOMEWORK: 12, 14

# FSA and Regular Expressions

## Theorem

*The languages decided by finite-state automatas are closed under intersection.*

- $M = (\text{make-ndfa } S_M \Sigma_M A F_M \delta_M)$   
 $N = (\text{make-ndfa } S_N \Sigma_N R F_N \delta_N)$
- We need to construct an ndfa that accepts and only accepts the words in  $L(M) \cap L(N)$

# FSA and Regular Expressions

## Theorem

*The languages decided by finite-state automata are closed under intersection.*

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 $N = (\text{make-ndfa } S_N \ \Sigma_N \ R \ F_N \ \delta_N)$
- We need to construct an ndfa that accepts and only accepts the words in  $L(M) \cap L(N)$
- Consider the following facts from set theory:
$$\Sigma^* - B = \{w \mid w \in \Sigma^* \wedge w \notin B\}$$
$$\Sigma^* - A = \{w \mid w \in \Sigma^* \wedge w \notin A\}$$
- All possible words in  $\Sigma^*$  that are not in  $B$  and all possible words in  $\Sigma^*$  that are not in  $A$

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$$\Sigma^* - B = \{w \mid w \in \Sigma^* \wedge w \notin B\}$$
$$\Sigma^* - A = \{w \mid w \in \Sigma^* \wedge w \notin A\}$$
- All possible words in  $\Sigma^*$  that are not in  $B$  and all possible words in  $\Sigma^*$  that are not in  $A$
- Consider the union of these two sets:
$$\{\Sigma^* - B\} \cup \{\Sigma^* - A\} = \{w \mid w \notin A \wedge w \notin B\}$$
- What words are not contained in this union?

# FSA and Regular Expressions

## Theorem

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- Consider the union of these two sets:
$$\{\Sigma^* - B\} \cup \{\Sigma^* - A\} = \{w \mid w \notin A \wedge w \notin B\}$$
- What words are not contained in this union?
- It is exactly the elements that are in both A and B

# FSA and Regular Expressions

## Theorem

*The languages decided by finite-state automata are closed under intersection.*

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- All possible words in  $\Sigma^*$  that are not in B and all possible words in  $\Sigma^*$  that are not in A
- Consider the union of these two sets:

$$\{\Sigma^* - B\} \cup \{\Sigma^* - A\} = \{w \mid w \notin A \wedge w \notin B\}$$

- What words are not contained in this union?
- It is exactly the elements that are in both A and B
- We may define the language for the machine we wish to implement as follows:

$$\begin{aligned}L(M) \cap L(N) &= \Sigma^* - \{\{\Sigma^* - L(M)\} \cup \{\Sigma^* - L(N)\}\} \\&= \Sigma^* - \{\bar{L}(M) \cup \bar{L}(N)\}\end{aligned}$$

- Illustrate intersection-viz using closure-algorithms.rkt

# FSA and Regular Expressions

- ```
;; ndfa ndfa → ndfa
;; Purpose: Construct an ndfa for the intersection of the languages of the
;;           given ndfas
(define (intersect-fsa M N)
```

FSA and Regular Expressions

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;; Purpose: Construct an ndfa for the intersection of the languages of the
;; given ndfas
(define (intersect-fsa M N)
```
- ```
; Tests for intersect-fsa
(define ab*-intersect-a-aUb-b* (intersect-fsa ab* a-aUb-b*))
(define a-aUb-b*-intersect-EVEN-A-ODD-B (intersect-fsa a-aUb-b*
                                              EVEN-A-ODD-B))

(check-reject? ab*-intersect-a-aUb-b* '() '(a b b a) '(a b))
;; L(ab*-intersect-a-aUb-b*) = ∅
(check-equal? (sm-testequiv? ab*-intersect-a-aUb-b* (sm-intersection ab* a-aUb-b*)) #t)

(check-reject? a-aUb-b*-intersect-EVEN-A-ODD-B '() '(b b) '(a a b b))
(check-accept? a-aUb-b*-intersect-EVEN-A-ODD-B '(a a b) '(a a b b b))
(check-equal? (sm-testequiv? a-aUb-b*-intersect-EVEN-A-ODD-B
                           (sm-intersection a-aUb-b* EVEN-A-ODD-B))
              #t)
```

FSA and Regular Expressions

- ```
;; ndfa ndfa → ndfa
;; Purpose: Construct an ndfa for the intersection of the languages of the
;; given ndfas
(define (intersect-fsa M N)
```
- ```
(let* [(notM (complement-fsa (ndfa2dfa M)))
        (notN (complement-fsa (ndfa2dfa N)))]
  (complement-fsa (ndfa2dfa (sm-union notM notN))))
  sm-union does not assume intersection of states is empty
```
- ```
;; Tests for intersect-fsa
(define ab*-intersect-a-aUb-b* (intersect-fsa ab* a-aUb-b*))
(define a-aUb-b*-intersect-EVEN-A-ODD-B (intersect-fsa a-aUb-b*
 EVEN-A-ODD-B))

(check-reject? ab*-intersect-a-aUb-b* '() '(a b b a) '(a b))
;; L(ab*-intersect-a-aUb-b*) = ∅
(check-equal? (sm-testequiv? ab*-intersect-a-aUb-b* (sm-intersection ab* a-aUb-b*)) #t)

(check-reject? a-aUb-b*-intersect-EVEN-A-ODD-B '() '(b b) '(a a b b))
(check-accept? a-aUb-b*-intersect-EVEN-A-ODD-B '(a a b) '(a a b b b))
(check-equal? (sm-testequiv? a-aUb-b*-intersect-EVEN-A-ODD-B
 (sm-intersection a-aUb-b* EVEN-A-ODD-B))
 #t)
```

# FSA and Regular Expressions

- ```

• ;; ndfa ndfa → ndfa
• ;; Purpose: Construct an ndfa for the intersection of the languages of the
• ;; given ndfas
• (define (intersect-fsa M N)
•   (let* [(notM (complement-fsa (ndfa2dfa M)))
•          (notN (complement-fsa (ndfa2dfa N)))]
•        (complement-fsa (ndfa2dfa (sm-union notM notN))))))
•     sm-union does not assume intersection of states is empty
•   (complement-fsa (ndfa->dfa (sm-union notM notN)))))

• ;; Tests for intersect-fsa
(define ab*-intersect-a-aUb-b* (intersect-fsa ab* a-aUb-b*))
(define a-aUb-b*-intersect-EVEN-A-ODD-B (intersect-fsa a-aUb-b*
                                                       EVEN-A-ODD-B))

(check-reject? ab*-intersect-a-aUb-b* '() '(a b b a) '(a b))
;; L(ab*-intersect-a-aUb-b*) = ∅
(check-equal? (sm-testequiv? ab*-intersect-a-aUb-b* (sm-intersection ab* a-aUb-b*)) #t)

(check-reject? a-aUb-b*-intersect-EVEN-A-ODD-B '() '(b b) '(a a b b))
(check-accept? a-aUb-b*-intersect-EVEN-A-ODD-B '(a a b) '(a a b b))
(check-equal? (sm-testequiv? a-aUb-b*-intersect-EVEN-A-ODD-B
                           (sm-intersection a-aUb-b* EVEN-A-ODD-B))
              #t)

```

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- Define three machines as follows:

$$M = (\text{make-ndfa } S \ \Sigma \ Z \ F \ \delta)$$

$$N = (\text{make-ndfa } S' \ \Sigma' \ Z' \ F' \ \delta')$$

$$U = (\text{intersect-fsa } M \ N) = (\text{make-ndfa } S'' \ \Sigma'' \ Z'' \ F'' \ \delta'')$$

- Let $L = L(M) \cap L(N)$
- We proceed to prove that $L = L(U)$

FSA and Regular Expressions

Lemma

$$w \in L \Leftrightarrow w \in L(U)$$

- (\Rightarrow) We need to show that $w \in L \Rightarrow w \in L(U)$

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Lemma

$$w \in L \Leftrightarrow w \in L(U)$$

- (\Rightarrow) We need to show that $w \in L \Rightarrow w \in L(U)$
- Assume $w \in L$
- This means that $w \in L(M)$ and $w \in L(N)$
- Therefore, $w \in (\Sigma^* - \{\bar{L}(M) \cup \bar{L}(N)\})$
- By construction of U , $w \in L(U)$

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

Lemma

$$w \in L \Leftrightarrow w \in L(U)$$

- (\Rightarrow) We need to show that $w \in L \Rightarrow w \in L(U)$
- Assume $w \in L$
- This means that $w \in L(M)$ and $w \in L(N)$
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- By construction of U , $w \in L(U)$
- (\Leftarrow) We need to show that $w \in L(U) \Rightarrow w \in L$

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

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- (\Leftarrow) We need to show that $w \in L(U) \Rightarrow w \in L$
- Assume $w \in L(U)$
- By U 's construction, $w \in (\Sigma^* - \{\bar{L}(M) \cup \bar{L}(N)\})$
- Therefore, $w \in L(M)$ and $w \in L(N)$
- Thus, $w \in L$

FSA and Regular Expressions

Lemma

$$w \notin L \Leftrightarrow w \notin L(U)$$

- (\Rightarrow) We need to show that $w \notin L \Rightarrow w \notin L(U)$

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
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$$w \notin L \Leftrightarrow w \notin L(U)$$

- (\Rightarrow) We need to show that $w \notin L \Rightarrow w \notin L(U)$
- Assume $w \notin L$
- This means that $w \notin L(M)$ or $w \notin L(N)$
- Therefore, $w \notin (\Sigma^* - \{\bar{L}(M) \cup \bar{L}(N)\})$
- By construction of U , $w \notin L(U)$

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

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FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

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- Assume $w \notin L$
- This means that $w \notin L(M)$ or $w \notin L(N)$
- Therefore, $w \notin (\Sigma^* - \{\bar{L}(M) \cup \bar{L}(N)\})$
- By construction of U , $w \notin L(U)$
- (\Leftarrow) We need to show that $w \notin L(U) \Rightarrow w \notin L$
- Assume $w \notin L(U)$
- By U 's construction, $w \notin (\Sigma^* - \{\bar{L}(M) \cup \bar{L}(N)\})$
- Therefore, $w \notin L(M)$ or $w \notin L(N)$
- Thus, $w \notin L$

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

Theorem

The languages decided by finite-state automata are closed under intersection.

- The proof follows from the previous two lemmas

FSA and Regular Expressions

- HOMEWORK: 15
- Quiz: 16 (due in 1 week)

FSA and Regular Expressions

- Is there a finite-state machine for the language of any regular expression?

FSA and Regular Expressions

- Is there a finite-state machine for the language of any regular expression?
- Is there a regular expression for any language decided by a finite-state machine?

FSA and Regular Expressions

- Is there a finite-state machine for the language of any regular expression?
- Is there a regular expression for any language decided by a finite-state machine?
- Our goal: establish the equivalence of finite-state machines and regular expressions

FSA and Regular Expressions

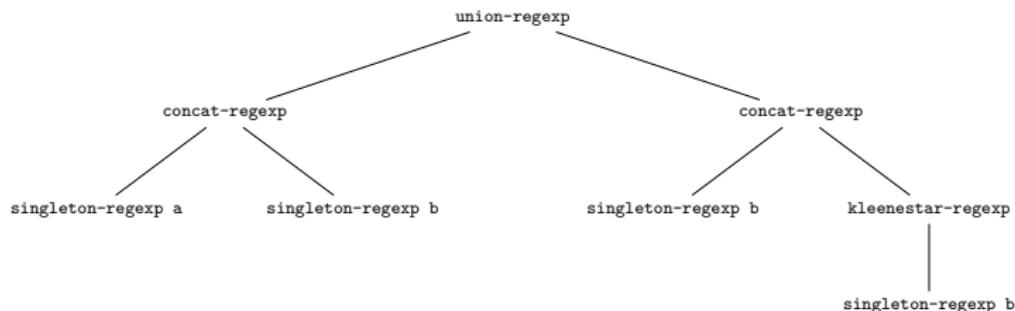
- We start by proving that there is a finite-state machine that decides the language of a regular expression

FSA and Regular Expressions

- We start by proving that there is a finite-state machine that decides the language of a regular expression
- Think about the structure of a regular expression
- A regular expression may be thought of as a tree
- The empty regular expression and the singleton regular expressions are leaves
- The concatenation, union, and Kleene star regular expressions are interior nodes

FSA and Regular Expressions

- We start by proving that there is a finite-state machine that decides the language of a regular expression
- Think about the structure of a regular expression
- A regular expression may be thought of as a tree
- The empty regular expression and the singleton regular expressions are leaves
- The concatenation, union, and Kleene star regular expressions are interior nodes
- $ab \cup bb^*$



- A regular expression may be processed using structural recursion

FSA and Regular Expressions

- To build an `ndfa`, a regular expression, e , and the language's alphabet, Σ , are needed

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

FSA and Regular Expressions

- To build an `ndfa`, a regular expression, e , and the language's alphabet, Σ , are needed
- The subtype of the given regular expression is determined and the appropriate `ndfa` is constructed

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

FSA and Regular Expressions

- To build an `ndfa`, a regular expression, e , and the language's alphabet, Σ , are needed
- The subtype of the given regular expression is determined and the appropriate `ndfa` is constructed
- If the subtype is an empty regular expression then an `ndfa` that only accepts empty is returned.

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

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- To build an `ndfa`, a regular expression, e , and the language's alphabet, Σ , are needed
- The subtype of the given regular expression is determined and the appropriate `ndfa` is constructed
- If the subtype is an empty regular expression then an `ndfa` that only accepts empty is returned.
- If the subtype is a singleton regular expression for $x \in \Sigma$ then an `ndfa` that only accepts x is returned

FSA and Regular Expressions

- To build an `ndfa`, a regular expression, e , and the language's alphabet, Σ , are needed
- The subtype of the given regular expression is determined and the appropriate `ndfa` is constructed
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- If the subtype is a union regular expression then closure under union is used

FSA and Regular Expressions

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- If the subtype is a union regular expression then closure under union is used
- If the subtype is a concatenation regular expression then closure under concatenation is used

FSA and Regular Expressions

- To build an `ndfa`, a regular expression, e , and the language's alphabet, Σ , are needed
- The subtype of the given regular expression is determined and the appropriate `ndfa` is constructed
- If the subtype is an empty regular expression then an `ndfa` that only accepts empty is returned.
- If the subtype is a singleton regular expression for $x \in \Sigma$ then an `ndfa` that only accepts x is returned
- If the subtype is a union regular expression then closure under union is used
- If the subtype is a concatenation regular expression then closure under concatenation is used
- If the subtype is a Kleene star regular expression then closure under Kleene star is used
- Illustrate using `regexp2ndfa.rkt`

FSA and Regular Expressions

- `; ; regexp alphabet → ndfa Purpose: Build ndfa for given regexp
(define (regexp->ndfa e sigma)`

FSA and Regular Expressions

- ;; Tests for reg-exp->ndfa
(define e (empty-regexp)) (define a (singleton-regexp "a"))
(define b (singleton-regexp "b"))
(define ab (concat-regexp a b)) (define aa (concat-regexp a a))
(define abUe (union-regexp ab e))
(define abUaa (union-regexp ab aa))
(define aa-* (kleenestar-regexp aa))
(define abUaa-* (kleenestar-regexp abUaa))

FSA and Regular Expressions

- ```
;; Tests for reg-exp->ndfa
(define e (empty-regexp)) (define a (singleton-regexp "a"))
(define b (singleton-regexp "b"))
(define ab (concat-regexp a b)) (define aa (concat-regexp a a))
(define abUe (union-regexp ab e))
(define abUaa (union-regexp ab aa))
(define aa-* (kleenestar-regexp aa))
(define abUaa-* (kleenestar-regexp abUaa))
```
- ```
(define Me  (regexp->ndfa e '(a b)))
(define Ma  (regexp->ndfa a '(a b)))
(define Mb  (regexp->ndfa b '(a b)))
(define Mab (regexp->ndfa ab '(a b)))
(define Maa (regexp->ndfa aa '(a b)))
(define MabUMe (regexp->ndfa abUe '(a b)))
(define MabUaa (regexp->ndfa abUaa '(a b)))
(define Maa-* (regexp->ndfa aa-* '(a b)))
(define MabUaa-* (regexp->ndfa abUaa-* '(a b)))
```

FSA and Regular Expressions

- ```
;; Tests for reg-exp->ndfa
(define e (empty-regexp)) (define a (singleton-regexp "a"))
(define b (singleton-regexp "b"))
(define ab (concat-regexp a b)) (define aa (concat-regexp a a))
(define abUe (union-regexp ab e))
(define abUaa (union-regexp ab aa))
(define aa-* (kleenestar-regexp aa))
(define abUaa-* (kleenestar-regexp abUaa))
```
- ```
(define Me  (regexp->ndfa e '(a b)))
(define Ma  (regexp->ndfa a '(a b)))
(define Mb  (regexp->ndfa b '(a b)))
(define Mab (regexp->ndfa ab '(a b)))
(define Maa (regexp->ndfa aa '(a b)))
(define MabUMe (regexp->ndfa abUe '(a b)))
(define MabUaa (regexp->ndfa abUaa '(a b)))
(define Maa-* (regexp->ndfa aa-* '(a b)))
(define MabUaa-* (regexp->ndfa abUaa-* '(a b)))
```
- ```
(check-reject? Me '(a)) (check-accept? Me '())
(check-reject? Ma '(b)) (check-accept? Ma '(a))
(check-reject? Mab ') (check-accept? Mab '(a b))
(check-reject? Maa '(b a a))
(check-accept? Maa '(a a))
(check-reject? MabUMe '(a b a a) '(b b))
(check-accept? MabUMe '() '(a b))
(check-reject? MabUaa '(a b b b) '(b a b))
(check-accept? MabUaa '(a a) '(a b))
(check-reject? Maa-* '(a b) '(a a a))
(check-accept? Maa-* '(a a) '(a a a a a))
(check-reject? MabUaa-* '(a b a) '(b b b))
(check-accept? MabUaa-* '() '(a a a a a b))
```

# FSA and Regular Expressions

- ;; regexp alphabet → ndfa Purpose: Build ndfa for given regexp

```
(define (regexp->ndfa e sigma)
 (let* [(st-pairs (foldl (λ (s acc) from-to state pairs
 (let* [(used-st-names (flatten acc))
 (from-state (gen-state used-st-names))
 (to-state (gen-state (cons from-state used-st-names)))
 (cons (list from-state to-state) acc)))
 '()
 (cons EMP sigma)))
 (simple-tbl (map (λ (p a) (list a
 singleton machines (make-ndfa p
 sigma
 (first p)
 (list (second p))
 (list (list (first p) a (second p)))))

 st-pairs
 (cons EMP sigma))))]
```

# FSA and Regular Expressions

- `;; regexp alphabet → ndfa Purpose: Build ndfa for given regexp`  
`(define (regexp->ndfa e sigma)`  
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 (from-state (gen-state used-st-names))  
 (to-state (gen-state (cons from-state used-st-names)))  
 (cons (list from-state to-state) acc))  
 ()  
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 (list (second p))  
 (list (list (first p) a (second p))))  
 st-pairs  
 (cons EMP sigma))))]  
 (cond [(empty-regexp? e) (second (assoc EMP simple-tbl))]`

# FSA and Regular Expressions

- `;; regexp alphabet → ndfa Purpose: Build ndfa for given regexp`  
`(define (regexp->ndfa e sigma)`  
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 sigma  
 (first p)  
 (list (second p))  
 (list (list (first p) a (second p))))  
 st-pairs  
 (cons EMP sigma))))]  
• (cond [ (empty-regexp? e) (second (assoc EMP simple-tbl)) ]  
• [ (singleton-regexp? e)  
 (second (assoc (string->symbol (singleton-regexp-a e)) simple-tbl)) ]`

# FSA and Regular Expressions

- `;; regexp alphabet → ndfa Purpose: Build ndfa for given regexp`  
`(define (regexp->ndfa e sigma)`  
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 (list (list (first p) a (second p))))  
 st-pairs  
 (cons EMP sigma))))])`  
 `(cond [(empty-regexp? e) (second (assoc EMP simple-tbl))]  
 [(singleton-regexp? e)  
 (second (assoc (string->symbol (singleton-regexp-a e)) simple-tbl))]  
 [(concat-regexp? e)  
 (let* [(M (regexp->ndfa (concat-regexp-r1 e) sigma))  
 (N (sm-rename-states (sm-states M)  
 (regexp->ndfa (concat-regexp-r2 e) sigma)))]  
 (concat-fsa M N))])`

# FSA and Regular Expressions

- ```

• • ;; regexp alphabet → ndfa Purpose: Build ndfa for given regexp
  (define (regexp->ndfa e sigma)
    (let* [(st-pairs (foldl (λ (s acc) from-to state pairs
                                (let* [(used-st-names (flatten acc))
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            (simple-tbl (map (λ (p a) (list a
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                                                          sigma
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            [(concat-regexp? e)
             (let* [(M (regexp->ndfa (concat-regexp-r1 e) sigma))
                    (N (sm-rename-states (sm-states M)
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               (concat-fsa M N))]
            [(union-regexp? e)
             (let* [(M (regexp->ndfa (union-regexp-r1 e) sigma))
                    (N (sm-rename-states (sm-states M)
                                         (regexp->ndfa (union-regexp-r2 e) sigma)))]
               (union-fsa M N))])

```

FSA and Regular Expressions

- ;; regexp alphabet → ndfa Purpose: Build ndfa for given regexp

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(define (regexp->ndfa e sigma)
  (let* [(st-pairs (foldl (λ (s acc) from-to state pairs
                           (let* [(used-st-names (flatten acc))
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                                  (cons (list from-state to-state) acc)))
                           '()
                           (cons EMP sigma)))
        (simple-tbl (map (λ (p a) (list a
                                         singleton machines           (make-ndfa p
                                                               sigma
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                                                               (list (second p))
                                                               (list (list (first p) a (second p)))))
                         st-pairs
                         (cons EMP sigma)))]
```
- (cond [(empty-regexp? e) (second (assoc EMP simple-tbl))]
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 (second (assoc (string->symbol (singleton-regexp-a e)) simple-tbl))]
- [(concat-regexp? e)
 (let* [(M (regexp->ndfa (concat-regexp-r1 e) sigma)
 (N (sm-rename-states (sm-states M)
 (regexp->ndfa (concat-regexp-r2 e) sigma)))]
 (concat-fsa M N))]
- [(union-regexp? e)
 (let* [(M (regexp->ndfa (union-regexp-r1 e) sigma)
 (N (sm-rename-states (sm-states M)
 (regexp->ndfa (union-regexp-r2 e) sigma)))]
 (union-fsa M N))]
- [else (kstar-fsa (regexp->ndfa (kleenestar-regexp-r1 e)
 sigma))]))]

FSA and Regular Expressions

- we shall prove that `regexp->ndfa` is correct
- Given that `regexp->ndfa` uses structural recursion on a binary tree, the proof is by induction on the height of the binary tree

FSA and Regular Expressions

Theorem

L is a regular language $\Rightarrow L$ is decided by a finite-state machine.

- Assume L is regular

FSA and Regular Expressions

Theorem

L is a regular language $\Rightarrow L$ is decided by a finite-state machine.

- Assume L is regular
- This means that there is a regular expression, R , that defines L
- Let Σ be the alphabet for the language of R
- We prove by induction on the height of R that (`regexp->ndfa R Σ`) builds an `ndfa` for L

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

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- Base Case: $h = 0$
- If h is zero then R must be an empty or a singleton regular expression

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

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Theorem for
Regular
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- Let Σ be the alphabet for the language of R
- We prove by induction on the height of R that `(regexp->ndfa R Σ)` builds an ndfa for L
- Base Case: $h = 0$
- If h is zero then R must be an empty or a singleton regular expression
- If R is the empty regular expression the `(regexp->ndfa R Σ)` returns an ndfa that only accepts EMP

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

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Theorem for
Regular
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- Assume L is regular
- This means that there is a regular expression, R , that defines L
- Let Σ be the alphabet for the language of R
- We prove by induction on the height of R that $(\text{regexp-} \rightarrow \text{ndfa } R \ \Sigma)$ builds an ndfa for L
- Base Case: $h = 0$
- If h is zero then R must be an empty or a singleton regular expression
- If R is the empty regular expression the $(\text{regexp-} \rightarrow \text{ndfa } R \ \Sigma)$ returns an ndfa that only accepts EMP
- If R is $(\text{singleton-regexp } a)$ then $(\text{regexp-} \rightarrow \text{ndfa } R \ \Sigma)$ returns an ndfa that only accepts a , where $a \in \Sigma$.
- This establishes the base case

FSA and Regular Expressions

Theorem

L is a regular language $\Rightarrow L$ is decided by a finite-state machine.

- Inductive Step:
- Assume: $(\text{regexp} \rightarrow \text{ndfa } R \Sigma)$ returns an ndfa that decides L for $h = k$
- Show: $(\text{regexp} \rightarrow \text{ndfa } R \Sigma)$ returns an ndfa that decides L for $h = k+1$

FSA and Regular Expressions

Theorem

L is a regular language $\Rightarrow L$ is decided by a finite-state machine.

- Inductive Step:
- Assume: $(\text{regexp} \rightarrow \text{ndfa } R \Sigma)$ returns an ndfa that decides L for $h = k$
- Show: $(\text{regexp} \rightarrow \text{ndfa } R \Sigma)$ returns an ndfa that decides L for $h = k+1$
- $h \geq 0 \Rightarrow h+1 \geq 1 \Rightarrow$ union, a concatenation, or a Kleene star regexp

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L is a regular language $\Rightarrow L$ is decided by a finite-state machine.

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- Show: $(\text{regexp} \rightarrow \text{ndfa } R \Sigma)$ returns an ndfa that decides L for $h = k+1$
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- We analyze each regular expression subtype independently:

FSA and Regular Expressions

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- Inductive Step:
- Assume: $(\text{regexp-} \rightarrow \text{ndfa } R \Sigma)$ returns an ndfa that decides L for $h = k$
- Show: $(\text{regexp-} \rightarrow \text{ndfa } R \Sigma)$ returns an ndfa that decides L for $h = k+1$
- $h \geq 0 \Rightarrow h+1 \geq 1 \Rightarrow$ union, a concatenation, or a Kleene star regexp
- We analyze each regular expression subtype independently:
- $(\text{union-regexp } S T) (\text{regexp-} \rightarrow \text{ndfa } R \Sigma)$ returns

```
(let* [(M (regexp->ndfa (union-regexp-r1 e) sigma))
        (N (sm-rename-states
            (sm-states M)
            (regexp->ndfa (union-regexp-r2 e) sigma)))]
    (union-fsa M N))
```
- $(\text{union-regexp-r1 } e)$'s and $(\text{union-regexp-r2 } e)$'s height is at most k
- By IH, recursive calls return ndfas for the language of each
- Closure under union, union-fsa returns ndfa for their union

FSA and Regular Expressions

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L is a regular language $\Rightarrow L$ is decided by a finite-state machine.

- Inductive Step:

- Assume: $(\text{regexp-} \rightarrow \text{ndfa } R \Sigma)$ returns an ndfa that decides L for $h = k$
- Show: $(\text{regexp-} \rightarrow \text{ndfa } R \Sigma)$ returns an ndfa that decides L for $h = k+1$
- $h \geq 0 \Rightarrow h+1 \geq 1 \Rightarrow$ union, a concatenation, or a Kleene star regexp
- We analyze each regular expression subtype independently:
- $(\text{union-regexp } S T) (\text{regexp-} \rightarrow \text{ndfa } R \Sigma)$ returns

```
(let* [(M (regexp->ndfa (union-regexp-r1 e) sigma))
       (N (sm-rename-states
            (sm-states M)
            (regexp->ndfa (union-regexp-r2 e) sigma)))]
      (union-fsa M N))
```

- $(\text{union-regexp-r1 } e)$'s and $(\text{union-regexp-r2 } e)$'s height is at most k
- By IH, recursive calls return ndfas for the language of each
- Closure under union, union-fsa returns ndfa for their union
- $(\text{concat-regexp } S T) (\text{regexp-} \rightarrow \text{ndfa } R \Sigma)$ returns

```
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            (sm-states M)
            (regexp->ndfa (concat-regexp-r2 e) sigma)))]
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```

- By IH, the recursive calls return ndfas for $L(r1)$ and $L(r2)$
- Closure under concat, concat-fsa returns an ndfa for their concat

FSA and Regular Expressions

Theorem

L is a regular language $\Rightarrow L$ is decided by a finite-state machine.

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```

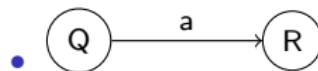
- By IH, the recursive calls return ndfas for $L(r1)$ and $L(r2)$
- Closure under concat, concat-fsa returns an ndfa for their concat
- $(\text{regexp-} \rightarrow \text{ndfa } R \Sigma)$ returns
- $(\text{kstar-fsa } (\text{regexp-} \rightarrow \text{ndfa } (\text{kleenestar-regexp-r1 } e) \sigma))$
- By IH, the recursive call returns an ndfa, N , for its language
- Closure under Kleene star, kstar-fsa returns an ndfa for $*$
- \square

FSA and Regular Expressions

- To create a regular expression for the language of an ndfa, a regular expression is needed that generates all words that take the given machine from its start state to any its final states
- This means that a regular expression is needed from any state, Q, to any state, R, that is reachable from Q

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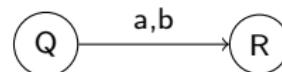


- Regular expression is needed for the part of the word that takes the machine from Q to R
- A singleton regular expression is needed for the rule (Q a R):

`(singleton-regexp "a")`

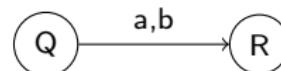
FSA and Regular Expressions

- There can be more than one transition from Q to R:



FSA and Regular Expressions

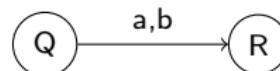
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- The machine can move from Q to R on a a or on a b

FSA and Regular Expressions

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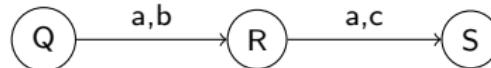


- The machine can move from Q to R on a a or on a b
- A union-regexp is needed:

```
(union-regexp (singleton-regexp "a")
              (singleton-regexp "b"))
```

FSA and Regular Expressions

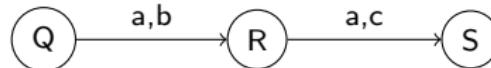
- More than two connected nodes:



- S is reachable from Q
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FSA and Regular Expressions

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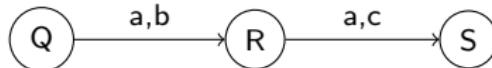


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FSA and Regular Expressions

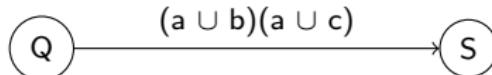
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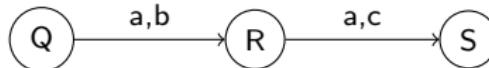


- R may be ripped out, along with the transitions into and out of it
- Substitute with a transition from Q to S that concatenates the regular expressions:



FSA and Regular Expressions

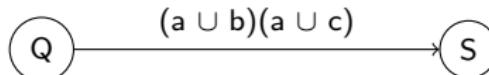
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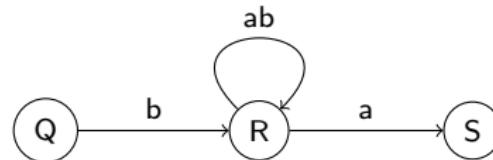


- The needed regular expression:

```
(concat-regexp (union-regexp (singleton-regexp a)
                               (singleton-regexp b))
               (union-regexp (singleton-regexp a)
                           (singleton-regexp c)))
```

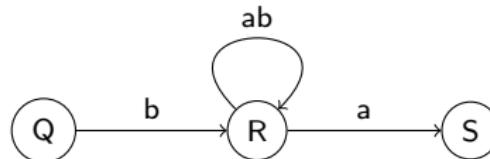
FSA and Regular Expressions

- The intermediate node R may have a loop on it:

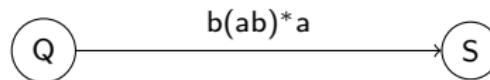


FSA and Regular Expressions

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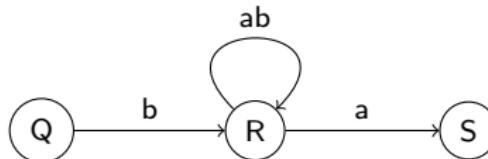


- To rip out the intermediate state the regular expression must generate the part of the word that takes the machine from Q to R, then generates zero or more times the part of the word that takes the machine from R to R, and finally generates the part of the word that takes the machine from R to S
- A Kleene star regular expression is needed:

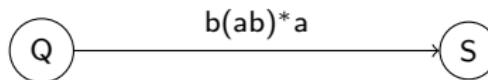


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- The needed regular expression is:

```
(concat-regexp
  (singleton-regexp "b")
  (concat-regexp
    (kleenestar-regexp
      (concat-regexp (singleton-regexp "a")
                    (singleton-regexp "b")))
    (singleton-regexp "a")))
```

FSA and Regular Expressions

- Given an NFA the goal is to construct a regular expression for all transition diagram paths from the start state to all reachable final states

FSA and Regular Expressions

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- Initial digraph has all the machine's states as nodes and the edges are labeled with a regular expression for what is consumed by a transition between two states

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- In addition, the initial directed graph has two extra nodes representing a new start state and a new and only final state
- There is an ϵ -transition from the new start state to the machine's start state and there are ϵ -transitions from every machine final state to the new final state

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- The process starts by collapsing multiple edges between two nodes into one labeled with a union regular expression
- At each step, this graph is collapsed by ripping out a node
- Ripping out a state may result in multiple edges between nodes and these are collapsed before moving on
- After all machine states are ripped out the graph has been collapsed to two states (the new start state and the new final state) with a single edge between them
- The label on that edge is the regular expression for the machine's language

FSA and Regular Expressions

- To rip out a state, S , the graph's edges are partitioned into 4 subsets:

not- s -edges *The list of edges that are not into nor out of S*
into- s -edges *The list of non-loop edges that are into S*
outof- s -edges *The list of non-loop edges that are out of S*
self-edges *The list of self-loop edges on S*

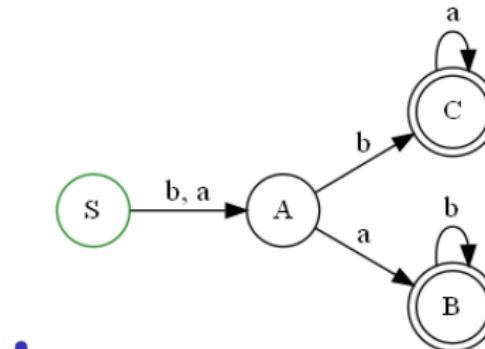
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- A new graph is constructed using not-s-edges and the new edges created using the other 3 sets of edges
- If S has a self-loop new edges are created for each incoming edge using the outgoing edges
- Each new edge is from the start node of the incoming node to the destination node of an outgoing edge
- The edge's label is a concatenation regular expression for the label of the incoming edge, the Kleene star of the self-loop label, and the label of an outgoing edge

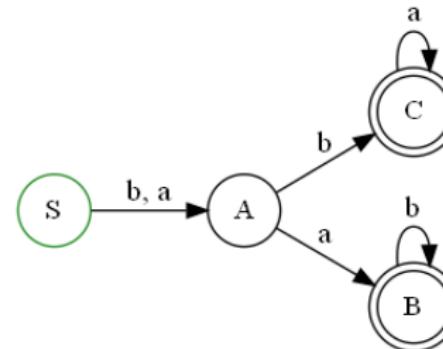
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- The edge's label is a concatenation regular expression for the label of the incoming edge, the Kleene star of the self-loop label, and the label of an outgoing edge
- If S does not have a self-loop new edges are also created for each incoming edge using the outgoing edges
- Each new edge is from the start node of the incoming node to the destination node of an outgoing edge
- The edge's label is a concatenation regular expression for the label of the incoming edge and the label of an outgoing edge

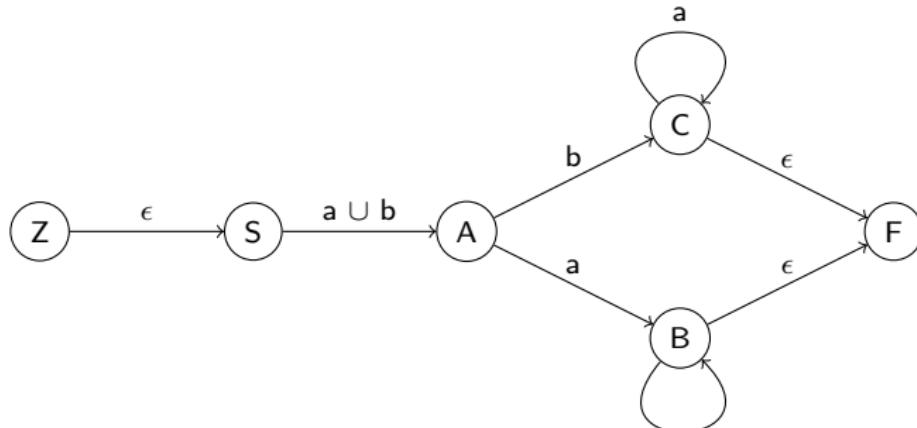
FSA and Regular Expressions



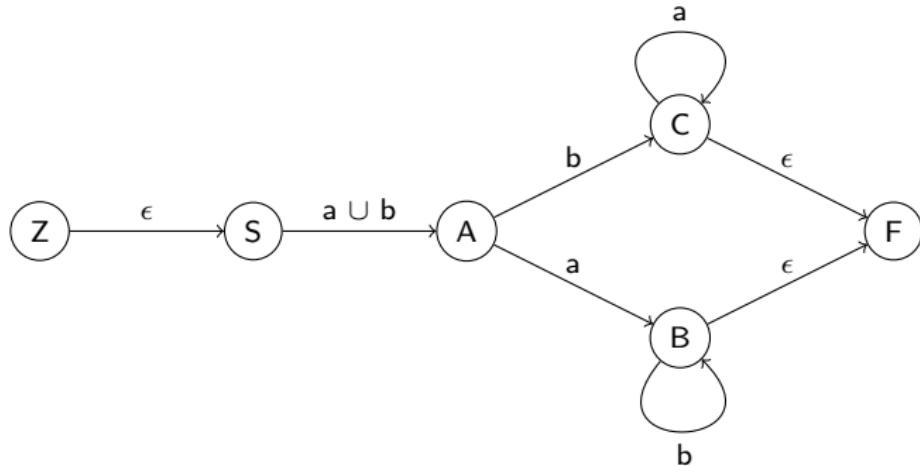
FSA and Regular Expressions



- Initial Graph collapse multiple edges between nodes:

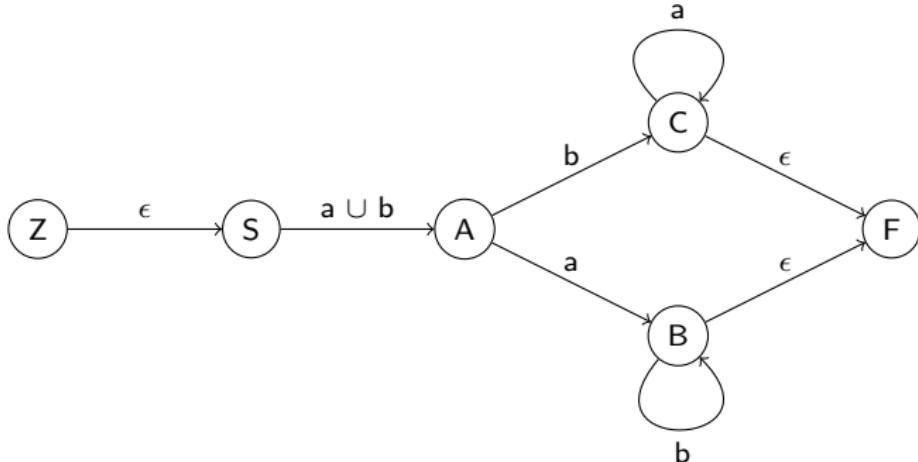


FSA and Regular Expressions



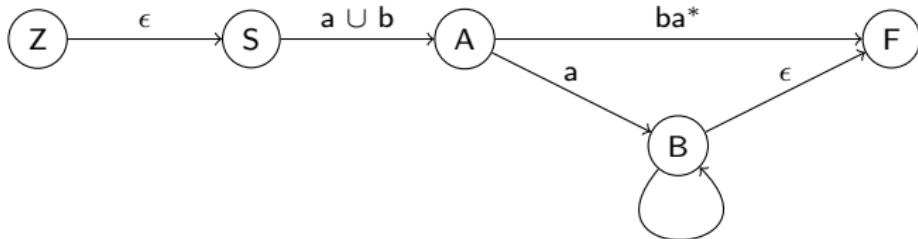
- To collapse the graph, at each step a node is ripped out
 - The order in which they are ripped out does not matter

FSA and Regular Expressions

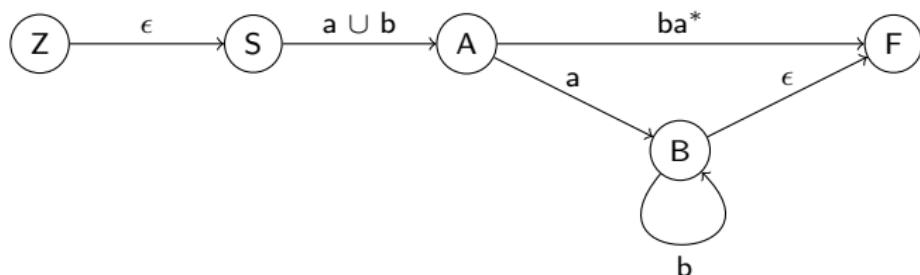


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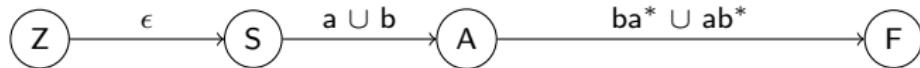
- To collapse the graph, at each step a node is ripped out
- The order in which they are ripped out does not matter
- Let us start by ripping out C:



FSA and Regular Expressions



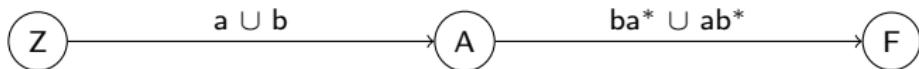
- Let us now rip out B:



FSA and Regular Expressions



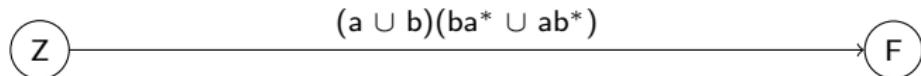
- Let's rip out S:



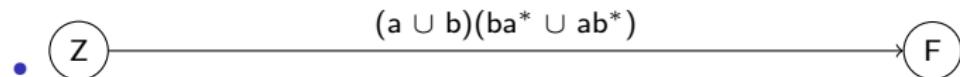
FSA and Regular Expressions



- Let's rip out A:

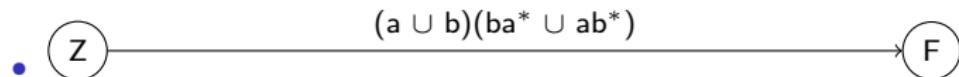


FSA and Regular Expressions



- All nodes for machine states ripped out

FSA and Regular Expressions



- All nodes for machine states ripped out
- ```
(concat-regexp
 (union-regexp (singleton-regexp "a")
 (singleton-regexp "b")))
 (union-regexp
 (concat-regexp
 (singleton-regexp "b")
 (kleenestar-regexp (singleton-regexp "a"))))
 (concat-regexp
 (singleton-regexp "a")
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```

# FSA and Regular Expressions

- The discussion so far has assumed that  $L(M) \neq \emptyset$

# FSA and Regular Expressions

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- If the language of the given machine is empty then the collapsed graph will have no edges
- This is a problem because there is no regular expression for generating no words

# FSA and Regular Expressions

- The discussion so far has assumed that  $L(M) \neq \emptyset$
- If the language of the given machine is empty then the collapsed graph will have no edges
- This is a problem because there is no regular expression for generating no words
- To address this problem FSM introduces a new regular expression constructor, `null-regexp`, to represent a language with no words
- Illustrate `ndfa2regexp-viz` using `ndfa2regexp.rkt`

# FSA and Regular Expressions

- ```
;; Data Definitions
;;
;; A node is a symbol
;;
;; An edge, (list node regexp node), has a beginning
;; node, a regular expression for its label, and
;; destination node.
;;
;; A directed graph, dgraph, is a (listof edge)
```

FSA and Regular Expressions

- To test the constructor EVEN-A-ODD-B and the following machines are used:

```
; ; L =  
(define EMPTY (make-ndfa '(S) '(a b) 'S '() '()))  
  
; ; L = ab* U ba*  
(define aUb-ba*Uab*  
  (make-ndfa  
    '(S A B C)  
    '(a b)  
    'S  
    '(B C)  
    '(((S a A) (S b A) (A a B) (A b C) (B b B) (C a C))))  
  
; ; L = b*  
(define b* (make-ndfa `,(DEAD S A)  
                      '(a b)  
                      'S  
                      '(A)  
                      `((S ,EMP A) (S a ,DEAD) (A b A))))
```

FSA and Regular Expressions

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;; Assume: Transition diagram of machine is connected digraph
`(define (ndfa2regexp m)`

FSA and Regular Expressions

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- `;; Tests for ndfa2regexp`
`(define b*-regexp (ndfa2regexp b*))`
`(define ba*Uab*-regexp (ndfa2regexp ba*Uab*))`
`(define EVEN-A-ODD-B-regexp (ndfa2regexp EVEN-A-ODD-B))`

`(check-equal? (printable-regexp (ndfa2regexp NULL)) "∅") ;; null-regexp cannot gen words`
`(check-accept? b* (gen-regexp-word b*-regexp))`

`(check-accept? ba*Uab* (gen-regexp-word ba*Uab*-regexp))`
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`(gen-regexp-word ba*Uab*-regexp)`
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-
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`(gen-regexp-word ba*Uab*-regexp))`

`(check-accept? EVEN-A-ODD-B (gen-regexp-word EVEN-A-ODD-B-regexp))`
`(gen-regexp-word EVEN-A-ODD-B-regexp)`
`(gen-regexp-word EVEN-A-ODD-B-regexp)`
`(gen-regexp-word EVEN-A-ODD-B-regexp))`

FSA and Regular Expressions

- `;; ndfa → regexp` Purpose: Create a regexp from the given ndfa
;; Assume: Transition diagram of machine is connected digraph
`(define (ndfa2regexp m)`
 - `(let* [(new-start (gen-state (sm-states m)))`
 - `(new-final (gen-state (sm-states m)))`
 - `(init-dgraph (make-dgraph`
 - `(cons (list new-start EMP (sm-start m))`
 - `(append`
 - `(map (λ (f) (list f EMP new-final)) (sm-finals m))`
 - `(sm-rules m))))`
-
- `;; Tests for ndfa2regexp`
`(define b*-regexp (ndfa2regexp b*))`
`(define ba*Uab*-regexp (ndfa2regexp ba*Uab*))`
`(define EVEN-A-ODD-B-regexp (ndfa2regexp EVEN-A-ODD-B))`

`(check-equal? (printable-regexp (ndfa2regexp NULL)) "∅") ;; null-regexp cannot gen words`
`(check-accept? b* (gen-regexp-word b*-regexp))`

`(check-accept? ba*Uab* (gen-regexp-word ba*Uab*-regexp))`
`(gen-regexp-word ba*Uab*-regexp)`
`(gen-regexp-word ba*Uab*-regexp)`
`(gen-regexp-word ba*Uab*-regexp))`

`(check-accept? EVEN-A-ODD-B (gen-regexp-word EVEN-A-ODD-B-regexp))`
`(gen-regexp-word EVEN-A-ODD-B-regexp)`
`(gen-regexp-word EVEN-A-ODD-B-regexp)`
`(gen-regexp-word EVEN-A-ODD-B-regexp))`

FSA and Regular Expressions

- `;; ndfa → regexp` Purpose: Create a regexp from the given ndfa
 `;; Assume: Transition diagram of machine is connected digraph`
`(define (ndfa2regexp m)`
 - `(let* [(new-start (gen-state (sm-states m)))`
 - `(new-final (gen-state (sm-states m)))`
 - `(init-dgraph (make-dgraph`
 - `(cons (list new-start EMP (sm-start m))`
 - `(append`
 - `(map (λ (f) (list f EMP new-final)) (sm-finals m))`
 - `(sm-rules m))))`
 - `(collapsed-dgraph`
 - `(rip-out-nodes (sm-states m) (remove-multiple-edges init-dgraph)))`
- `;; Tests for ndfa2regexp`
`(define b*-regexp (ndfa2regexp b*))`
`(define ba*Uab*-regexp (ndfa2regexp ba*Uab*))`
`(define EVEN-A-ODD-B-regexp (ndfa2regexp EVEN-A-ODD-B))`

`(check-equal? (printable-regexp (ndfa2regexp NULL)) "∅") ;; null-regexp cannot gen words`
`(check-accept? b* (gen-regexp-word b*-regexp))`

`(check-accept? ba*Uab* (gen-regexp-word ba*Uab*-regexp))`
`(gen-regexp-word ba*Uab*-regexp)`
`(gen-regexp-word ba*Uab*-regexp)`
`(gen-regexp-word ba*Uab*-regexp))`

`(check-accept? EVEN-A-ODD-B (gen-regexp-word EVEN-A-ODD-B-regexp))`
`(gen-regexp-word EVEN-A-ODD-B-regexp)`
`(gen-regexp-word EVEN-A-ODD-B-regexp)`
`(gen-regexp-word EVEN-A-ODD-B-regexp))`

FSA and Regular Expressions

- `;; ndfa → regexp` Purpose: Create a regexp from the given ndfa
 `;; Assume: Transition diagram of machine is connected digraph`
`(define (ndfa2regexp m)`
 - `(let* [(new-start (gen-state (sm-states m)))`
 - `(new-final (gen-state (sm-states m)))`
 - `(init-dgraph (make-dgraph`
 - `(cons (list new-start EMP (sm-start m))`
 - `(append`
 - `(map (λ (f) (list f EMP new-final)) (sm-finals m))`
 - `(sm-rules m))))`
 - `(collapsed-dgraph`
 - `(rip-out-nodes (sm-states m) (remove-multiple-edges init-dgraph)))`
 - `(if (empty? collapsed-dgraph)`
 - `(null-regexp)`
 - `(simplify-regexp (second (first collapsed-dgraph))))`
 - `;; Tests for ndfa2regexp`
`(define b*-regexp (ndfa2regexp b*))`
`(define ba*Uab*-regexp (ndfa2regexp ba*Uab*))`
`(define EVEN-A-ODD-B-regexp (ndfa2regexp EVEN-A-ODD-B))`

`(check-equal? (printable-regexp (ndfa2regexp NULL)) "∅") ;; null-regexp cannot gen words`
`(check-accept? b* (gen-regexp-word b*-regexp))`

`(check-accept? ba*Uab* (gen-regexp-word ba*Uab*-regexp))`
`(gen-regexp-word ba*Uab*-regexp)`
`(gen-regexp-word ba*Uab*-regexp)`
`(gen-regexp-word ba*Uab*-regexp))`

`(check-accept? EVEN-A-ODD-B (gen-regexp-word EVEN-A-ODD-B-regexp))`
`(gen-regexp-word EVEN-A-ODD-B-regexp)`
`(gen-regexp-word EVEN-A-ODD-B-regexp)`
`(gen-regexp-word EVEN-A-ODD-B-regexp))`

FSA and Regular Expressions

- `;; (listof ndfa-rule) → dgraph`
`;; Purpose: Create a dgraph from the given ndfa`
`(define (make-dgraph lor)`

FSA and Regular Expressions

- ```
;; (listof ndfa-rule) → dgraph
;; Purpose: Create a dgraph from the given ndfa
(define (make-dgraph lor)
```
- ```
;; Tests for make-dgraph
(check-equal? (make-dgraph '()) '())
(check-equal?
 (make-dgraph `((S ,EMP A) (S a ,DEAD) (A b A)))
 (list (list 'S (empty-regexp) 'A)
       (list 'S (singleton-regexp "a") 'ds)
       (list 'A (singleton-regexp "b") 'A)))
(check-equal?
 (make-dgraph `((S a A) (S b A) (A a B) (A b C) (B b B) (C a C)))
 (list (list 'S (singleton-regexp "a") 'A)
       (list 'S (singleton-regexp "b") 'A)
       (list 'A (singleton-regexp "a") 'B)
       (list 'A (singleton-regexp "b") 'C)
       (list 'B (singleton-regexp "b") 'B)
       (list 'C (singleton-regexp "a") 'C))))
```

FSA and Regular Expressions

- ```
;; (listof ndfa-rule) → dgraph
;; Purpose: Create a dgraph from the given ndfa
(define (make-dgraph lor)
 (map (λ (r) (if (eq? (second r) EMP)
 (list (first r) (empty-regexp) (third r))
 (list (first r)
 (singleton-regexp (symbol->string (second r)))
 (third r))))
 lor))
 ;; Tests for make-dgraph
 (check-equal? (make-dgraph '()) '())
 (check-equal?
 (make-dgraph `((S ,EMP A) (S a ,DEAD) (A b A)))
 (list (list 'S (empty-regexp) 'A)
 (list 'S (singleton-regexp "a") 'ds)
 (list 'A (singleton-regexp "b") 'A)))
)
 (check-equal?
 (make-dgraph `((S a A) (S b A) (A a B) (A b C) (B b B) (C a C)))
 (list (list 'S (singleton-regexp "a") 'A)
 (list 'S (singleton-regexp "b") 'A)
 (list 'A (singleton-regexp "a") 'B)
 (list 'A (singleton-regexp "b") 'C)
 (list 'B (singleton-regexp "b") 'B)
 (list 'C (singleton-regexp "a") 'C)))
)
)
```

# FSA and Regular Expressions

- ```
;; dgraph → dgraph
;; Purpose: Collapse multiple edges between nodes
;; Accumulator Invariant: g = the unprocessed graph
(define (remove-multiple-edges g)
```

FSA and Regular Expressions

Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

- ```
;; dgraph → dgraph
;; Purpose: Collapse multiple edges between nodes
;; Accumulator Invariant: g = the unprocessed graph
(define (remove-multiple-edges g))
```
- ```
;; Tests for remove-multiple-edges
(check-equal? '() '())
(check-equal?
 (remove-multiple-edges `((S ,(singleton-regexp "a") A)
                           (S ,(singleton-regexp "b") A)
                           (A ,(singleton-regexp "a") A)))
 `((S
      ,(union-regexp (singleton-regexp "a") (singleton-regexp "b"))
      A)
    (A ,(singleton-regexp "a") A)))
```

FSA and Regular Expressions

- ```
;; dgraph → dgraph
;; Purpose: Collapse multiple edges between nodes
;; Accumulator Invariant: g = the unprocessed graph
(define (remove-multiple-edges g)
 (if (empty? g)
 '()
```
- ```
;; Tests for remove-multiple-edges
(check-equal? '() '())
(check-equal?
  (remove-multiple-edges `((S ,(singleton-regexp "a") A)
                           (S ,(singleton-regexp "b") A)
                           (A ,(singleton-regexp "a") A)))
  `((S
      ,(union-regexp (singleton-regexp "a") (singleton-regexp "b"))
      A)
    (A ,(singleton-regexp "a") A)))
```

FSA and Regular Expressions

- ```
;; dgraph → dgraph
;; Purpose: Collapse multiple edges between nodes
;; Accumulator Invariant: g = the unprocessed graph
(define (remove-multiple-edges g)

 • (if (empty? g)
 '()

 • (let* [(curr-edge (first g))
 (from-state (first curr-edge))
 (to-state (third curr-edge))
 (to-collapse (filter (λ (e) (and (eq? (first e) from-state)
 (eq? (third e) to-state)))
 g))
 (remaining-g (filter (λ (e) (not (member e to-collapse))) g))]
 (cons (list from-state (collapse-edges to-collapse) to-state)
 (remove-multiple-edges remaining-g)))))

 • ;; Tests for remove-multiple-edges
 (check-equal? '() '())
 (check-equal?
 (remove-multiple-edges `((S ,(singleton-regexp "a") A)
 (S ,(singleton-regexp "b") A)
 (A ,(singleton-regexp "a") A)))
 `((S
 ,(union-regexp (singleton-regexp "a") (singleton-regexp "b"))
 A)
 (A ,(singleton-regexp "a") A))))
```

# FSA and Regular Expressions

- `;; (listof edge) → regexp`  
`;; Purpose: Collapse the given edges into a regexp`  
`(define (collapse-edges loe)`  
 `(cond [(empty? loe) '()]`  
 `[(!empty? (rest loe)) (second (first loe))])`  
 `[else (union-regexp (second (first loe))`  
 `(collapse-edges (rest loe))))]))`  
  
`;; Tests for collapse-edges`  
`(check-equal? (collapse-edges '()) '())`  
`(check-equal? (collapse-edges `((S ,(singleton-regexp "a") S)))`  
 `(singleton-regexp "a")))`  
`(check-equal?`  
 `(collapse-edges `((A ,(singleton-regexp "a") A)`  
 `(A ,(singleton-regexp "b") A)`  
 `(A ,(empty-regexp) A))))`  
`(union-regexp (singleton-regexp "a")`  
 `(union-regexp (singleton-regexp "b")`  
 `(empty-regexp))))`

# FSA and Regular Expressions

- `;; (listof node) dgraph → dgraph`  
;; Purpose: Rip out the given nodes from the given graph  
;; Assume: Given nodes in given graph and g has no multiple edges  
;; between nodes  
`(define (rip-out-nodes lon g)`  
    `(foldr (λ (s g) (rip-out-node s g)) g lon))`  
  
;; Tests for rip-out-nodes  
`(check-equal? (rip-out-nodes '() `((S ,(singleton-regexp "a") A)  
                      (A ,(singleton-regexp "b") B)))`  
    ``((S ,(singleton-regexp "a") A)  
              (A ,(singleton-regexp "b") B)))`  
  
`(check-equal?`  
    `(rip-out-nodes '(A B) `((S ,(singleton-regexp "a") A)  
                      (A ,(singleton-regexp "b") B)  
                      (B ,(singleton-regexp "b") C)))`  
    ``((S  
          ,(concat-regexp (singleton-regexp "a")  
                         (concat-regexp (singleton-regexp "b")  
                              (singleton-regexp "b"))))  
          C)))`

# FSA and Regular Expressions

- `;; state dgraph → dgraph` Purpose: Rip out given node from given graph  
`;; Assume: Given node in given graph and g has no multiple edges between nodes`  
`(define (rip-out-node n g)`

# FSA and Regular Expressions

- ;; Tests for rip-out-node  
(check-equal?  
 (rip-out-node  
 'A  
 `((S ,(singleton-regexp "a") A) (A ,(singleton-regexp "b") B)))  
 `((S  
 ,(concat-regexp (singleton-regexp "a") (singleton-regexp "b"))  
 B)))  
 (check-equal?  
 (rip-out-node  
 'C  
 `((S ,(singleton-regexp "a") A) (S ,(singleton-regexp "b") B)  
 (A ,(singleton-regexp "a") C) (B ,(singleton-regexp "b") C)  
 (C ,(singleton-regexp "a") D) (C ,(singleton-regexp "b") E)))  
 `((S ,(singleton-regexp "a") A)  
 (S ,(singleton-regexp "b") B)  
 (A  
 ,(concat-regexp (singleton-regexp "a") (singleton-regexp "a"))  
 D)  
 (A  
 ,(concat-regexp (singleton-regexp "a") (singleton-regexp "b"))  
 E)  
 (B ,(concat-regexp (singleton-regexp "b") (singleton-regexp "a")) D)  
 (B ,(concat-regexp (singleton-regexp "b") (singleton-regexp "b")) E))))

# FSA and Regular Expressions

- ```
;; state dgraph → dgraph Purpose: Rip out given node from given graph
;; Assume: Given node in given graph and g has no multiple edges between nodes
(define (rip-out-node n g)
  (let*
    [(non (filter (λ (r) (and (not (eq? (third r) n))(not (eq? (first r) n)))) g))
```

FSA and Regular Expressions

- ```
;; state dgraph → dgraph Purpose: Rip out given node from given graph
;; Assume: Given node in given graph and g has no multiple edges between nodes
(define (rip-out-node n g)
 (let*
 [(non (filter (λ (r) (and (not (eq? (third r) n))(not (eq? (first r) n)))) g))
```
- ```
(into-n (filter (λ (r) (and (eq? (third r) n) (not (eq? (first r) n)))) g))
```

FSA and Regular Expressions

- ```
;; state dgraph → dgraph Purpose: Rip out given node from given graph
;; Assume: Given node in given graph and g has no multiple edges between nodes
(define (rip-out-node n g)
 (let*
 [(non (filter (λ (r) (and (not (eq? (third r) n)) (not (eq? (first r) n)))) g))
 (into-n (filter (λ (r) (and (eq? (third r) n) (not (eq? (first r) n)))) g))
 (outof-n (filter (λ (r) (and (eq? (first r) n) (not (eq? (third r) n)))) g))
```
- ```
(into-n (filter (λ (r) (and (eq? (third r) n) (not (eq? (first r) n)))) g))
```
- ```
(outof-n (filter (λ (r) (and (eq? (first r) n) (not (eq? (third r) n)))) g))
```

# FSA and Regular Expressions

- `;; state dgraph → dgraph` Purpose: Rip out given node from given graph  
`;; Assume: Given node in given graph and g has no multiple edges between nodes`  
`(define (rip-out-node n g)`  
 `(let*`  
 `[(non (filter (λ (r) (and (not (eq? (third r) n))(not (eq? (first r) n)))) g))`
  - `(into-n (filter (λ (r) (and (eq? (third r) n) (not (eq? (first r) n)))) g))`
  - `(outof-n (filter (λ (r) (and (eq? (first r) n) (not (eq? (third r) n)))) g))`
  - `(self-edges (filter (λ (r) (and (eq? (first r) n) (eq? (third r) n)))) g))]`
- `(remove-multiple-edges`  
 `(append`  
 `non`

# FSA and Regular Expressions

- `;; state dgraph → dgraph Purpose: Rip out given node from given graph  
;; Assume: Given node in given graph and g has no multiple edges between nodes  
(define (rip-out-node n g)  
 (let*  
 [(non (filter (λ (r) (and (not (eq? (third r) n)) (not (eq? (first r) n)))) g))`
- `(into-n (filter (λ (r) (and (eq? (third r) n) (not (eq? (first r) n)))) g))`
- `(outof-n (filter (λ (r) (and (eq? (first r) n) (not (eq? (third r) n)))) g))`
- `(self-edges (filter (λ (r) (and (eq? (first r) n) (eq? (third r) n)))) g))]`
- `(remove-multiple-edges  
 (append  
 non  
 (if (not (empty? self-edges))  
 (let [(se (first self-edges))]  
 (append-map  
 (λ (into-edge)  
 (map (λ (outof-edge)  
 (list (first into-edge)  
 (concat-regexp  
 (second into-edge)  
 (concat-regexp (kleenestar-regexp (second se))  
 (second outof-edge)))  
 (third outof-edge)))  
 outof-s-edges))  
 into-s-edges))`

# FSA and Regular Expressions

- `;; state dgraph → dgraph` Purpose: Rip out given node from given graph  
`;; Assume: Given node in given graph and g has no multiple edges between nodes`  
`(define (rip-out-node n g)`  
 `(let*`  
 `[(non (filter (λ (r) (and (not (eq? (third r) n)) (not (eq? (first r) n)))) g))`  
  
 `(into-n (filter (λ (r) (and (eq? (third r) n) (not (eq? (first r) n)))) g))`  
 `(outof-n (filter (λ (r) (and (eq? (first r) n) (not (eq? (third r) n)))) g))`  
 `(self-edges (filter (λ (r) (and (eq? (first r) n) (eq? (third r) n)))) g))]`  
  
 `(remove-multiple-edges`  
 `(append`  
 `non`  
 `(if (not (empty? self-edges))`  
 `(let [(se (first self-edges))]`  
 `(append-map`  
 `(λ (into-edge)`  
 `(map (λ (outof-edge)`  
 `(list (first into-edge)`  
 `(concat-regexp`  
 `(second into-edge)`  
 `(concat-regexp (kleenestar-regexp (second se))`  
 `(second outof-edge)))`  
 `(third outof-edge)))`  
 `outof-s-edges))`  
 `into-s-edges))`  
 `(append-map`  
 `(λ (into-edge)`  
 `(map (λ (outof-edge) (list (first into-edge)`  
 `(concat-regexp (second into-edge)`  
 `(second outof-edge)))`  
 `(third outof-edge)))`  
 `outof-s-edges))`  
 `into-s-edges))))))`

# FSA and Regular Expressions

## Theorem

$(\text{ndfa2regexp } m)$  returns a regular expression for  $L(m)$ .

- The proof of correctness requires proving that all functions return the expected value
- To prove that each function is correct assume that the auxiliary functions are correct
- We start with the main function

# FSA and Regular Expressions

## Theorem

$(ndfa2regexp m)$  returns a regular expression for  $L(m)$ .

- New start and final states are generated
- To  $m$ 's rules  $\epsilon$ -transitions are added from the new start state to  $m$ 's start state and from each of  $m$ 's final states to the new final state

# FSA and Regular Expressions

## Theorem

$(ndfa2regexp m)$  returns a regular expression for  $L(m)$ .

- New start and final states are generated
- To  $m$ 's rules  $\epsilon$ -transitions are added from the new start state to  $m$ 's start state and from each of  $m$ 's final states to the new final state
- By assumption, `make-dgraph` creates the correct initial directed graph
- Multiple edges between any pair of nodes are removed by `remove-multiple-edges`
- All the nodes that represent a state in  $m$  are ripped out by `rip-out-nodes` to create the collapsed graph

# FSA and Regular Expressions

## Theorem

$(ndfa2regexp m)$  returns a regular expression for  $L(m)$ .

- New start and final states are generated
- To  $m$ 's rules  $\epsilon$ -transitions are added from the new start state to  $m$ 's start state and from each of  $m$ 's final states to the new final state
- By assumption, `make-dgraph` creates the correct initial directed graph
- Multiple edges between any pair of nodes are removed by `remove-multiple-edges`
- All the nodes that represent a state in  $m$  are ripped out by `rip-out-nodes` to create the collapsed graph
- Observe that the graph meets the assumptions made by `rip-out-nodes`
- These auxiliary functions, by assuming their correctness, return the correct graph for their given input

# FSA and Regular Expressions

## Theorem

*(ndfa2regexp m) returns a regular expression for  $L(m)$ .*

- New start and final states are generated
- To  $m$ 's rules  $\epsilon$ -transitions are added from the new start state to  $m$ 's start state and from each of  $m$ 's final states to the new final state
- By assumption, `make-dgraph` creates the correct initial directed graph
- Multiple edges between any pair of nodes are removed by `remove-multiple-edges`
- All the nodes that represent a state in  $m$  are ripped out by `rip-out-nodes` to create the collapsed graph
- Observe that the graph meets the assumptions made by `rip-out-nodes`
- These auxiliary functions, by assuming their correctness, return the correct graph for their given input
- The collapsed graph is examined to test if it is empty
- If so, `(null-regexp)` is returned because  $L(m)$  is empty

# FSA and Regular Expressions

## Theorem

*(ndfa2regexp m) returns a regular expression for  $L(m)$ .*

- New start and final states are generated
- To  $m$ 's rules  $\epsilon$ -transitions are added from the new start state to  $m$ 's start state and from each of  $m$ 's final states to the new final state
- By assumption, `make-dgraph` creates the correct initial directed graph
- Multiple edges between any pair of nodes are removed by `remove-multiple-edges`
- All the nodes that represent a state in  $m$  are ripped out by `rip-out-nodes` to create the collapsed graph
- Observe that the graph meets the assumptions made by `rip-out-nodes`
- These auxiliary functions, by assuming their correctness, return the correct graph for their given input
- The collapsed graph is examined to test if it is empty
- If so, `(null-regexp)` is returned because  $L(m)$  is empty
- Otherwise, the only edge's regular expression is returned
- This is correct because this regular expression can generate words on all paths from the new start state to the new final state in the initial directed graph

# FSA and Regular Expressions

## Theorem

*(rip-out-nodes l o n g) returns a dgraph resulting from removing the given nodes from the given graph.*

- By assumption, all the given nodes are in the given graph and the given graph does not have multiple edges between nodes

# FSA and Regular Expressions

## Theorem

*(rip-out-nodes lon g)* returns a dgraph resulting from removing the given nodes from the given graph.

- By assumption, all the given nodes are in the given graph and the given graph does not have multiple edges between nodes
- The given list of nodes is traversed using `foldr` to rip out one node at a time
- Initially, `foldr`'s accumulator is the given graph
- For each node, `foldr` creates a new graph by ripping out the next node using `rip-out-node`

# FSA and Regular Expressions

Regular  
Expressions

Deterministic  
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Grammars

Pumping  
Theorem for  
Regular  
Languages

## Theorem

*(rip-out-nodes long) returns a dgraph resulting from removing the given nodes from the given graph.*

- By assumption, all the given nodes are in the given graph and the given graph does not have multiple edges between nodes
- The given list of nodes is traversed using `foldr` to rip out one node at a time
- Initially, `foldr`'s accumulator is the given graph
- For each node, `foldr` creates a new graph by ripping out the next node using `rip-out-node`
- Observe that the graph returned by `rip-out-node` satisfies the assumptions made by this function
- Therefore, the returned graph may be input to `rip-out-node`
- This auxiliary function, by assumption, is correct
- Thus, `rip-out-nodes` returns the correct directed graph after ripping out all the given nodes

# FSA and Regular Expressions

## Theorem

*(rip-out-node n g) returns a dgraph resulting from removing the given node from the given dgraph.*

- By assumption, the given node is in the given graph

# FSA and Regular Expressions

## Theorem

*(rip-out-node n g)* returns a dgraph resulting from removing the given node from the given dgraph.

- By assumption, the given node is in the given graph
- Extracts four mutually exclusive sets of rules:

|                   |                                                         |
|-------------------|---------------------------------------------------------|
| <b>non</b>        | The set of edges that are not into nor out of n         |
| <b>into-n</b>     | The set of edges into n                                 |
| <b>outof-n</b>    | The set of edges out of n                               |
| <b>self-edges</b> | The set of edges that are self-loops on n ← at most one |

# FSA and Regular Expressions

## Theorem

*(rip-out-node n g)* returns a dgraph resulting from removing the given node from the given dgraph.

- By assumption, the given node is in the given graph
- Extracts four mutually exclusive sets of rules:

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**self-edges** The set of edges that are self-loops on n ← at most one

- If there is a self-loop on n, for each edge, i, in into-n a new edge is created using each edge, o, in outof-n that has the following form:

(starting state of i  
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regular expression in i  
(concat-regexp  
(**(kleenestar-regexp regular expression in only self-edge)**  
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- The remaining proofs for auxiliary functions are left as exercises

# FSA and Regular Expressions

- HOMEWORK: 17–19
- QUIZ: 20 (due in a week)

# Regular Grammars

- We know that a dfa decides a regular language by reading one symbol at a time
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# Regular Grammars

- We know that a dfa decides a regular language by reading one symbol at a time
- This suggests that words in the language may be generated one symbol at a time starting with a symbol  $S$
- We have to be able to generate the empty word because it may be part of a regular language
- There are three types of rules in a regular grammar:
  - ①  $S$  generates the empty word (i.e.,  $EMP$ )
  - ② Rules that generate an alphabet member
  - ③ Rules that generate a symbol representing the concatenation of a terminal symbol and a symbol representing a syntactic category.
- The members of the alphabet are the terminal symbols
- The symbols representing syntactic categories are the nonterminals

# Regular Grammars

- Formally:

A regular grammar is an instance of  $(\text{make-rg } N \Sigma R S)$

- $N$  is the set of capital letters in the Roman alphabet representing the nonterminal symbols
- $\Sigma$  is the set of lowercase symbols called the alphabet
- $S$  is the starting nonterminal symbol
- $R$  is the set of generating (or production) rules

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- Each production rule contains a nonterminal followed by an arrow and a symbol
- There are only 3 types of production rules:

$S \rightarrow \epsilon$ , where  $S$  is the starting nonterminal and  $S \in N$

$A \rightarrow a$ , where  $A \in N$  and  $a \in \Sigma$

$A \rightarrow aB$ , where  $A, B \in N$  and  $a \in \Sigma$

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- Observe that each rule generates one terminal symbol at a time
- The language of a grammar  $G$  is denoted as  $L(G)$
- It contains all the words that can be generated using  $G$

# Regular Grammars

- Grammar observers:

(grammar-nts g): Returns a list of g's nonterminal symbols.

(grammar-sigma g): Returns a list of g's terminal symbols.

(grammar-rules g): Returns a list of g's production rules

(grammar-start g): Returns g's starting nonterminal.

(grammar-type g): Returns a symbol for g's grammar type.

(grammar-derive g w): If the given word, w, is in the language of the given grammar then a derivation for w is returned.  
Otherwise, a string indicating that w is not in the language of the given grammar is returned.

- A derivation consists of 1 or more derivation steps
- A derivation step is denoted by  $\rightarrow$
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- A derivation consists of 1 or more derivation steps
- A derivation step is denoted by  $\rightarrow$
- One or more derivation steps is denoted by  $\rightarrow^+$ .
- Testing functions:

(grammar-both-derive g1 g2 w): Tests if both of the given grammars derive the given word.

(grammar-testequiv g1 g2 [natnum]): Tests if the given grammars derive 100 (or the optional number of) randomly generated words. If all tests give the same result true is returned. Otherwise, a list of words that produce different results is returned.

(grammar-test g1 [natnum]): Tests the given grammar with 100 (or the optional number of) randomly generated words. A list of pairs containing a word and the result of attempting to derive the word are returned.

# Regular Grammars

- The Design Recipe for Grammars

- ① Pick a name for the grammar and specify the alphabet
- ② Define each syntactic category and associate each with a nonterminal clearly specifying the starting nonterminal
- ③ Develop the production rules
- ④ Write unit tests
- ⑤ Implement the grammar
- ⑥ Run the tests and redesign if necessary
- ⑦ For each syntactic category design and implement an invariant predicate to determine if a given word satisfies the role of the syntactic category
- ⑧ For words in  $L(G)$  prove that the invariant predicates hold for every derivation step
- ⑨ Prove that  $L = L(G)$

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;; S generates words in a*, starting nonterminal
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  - ;; Syntactic categories documentation  
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    - ` ((S ,ARROW ,EMP)  
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- $S$  generates an arbitrary number of  $a$ s  
`(define (S-INV w) (andmap (λ (l) (eq? l 'a)) w))`

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- To prove that invariants holds for words in the grammar's language, we perform an induction on,  $h$ , the height of the derivation tree
- Consider any derivation tree of height  $h$  that the grammar can generate

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Derivation tree is generated using ( $S \rightarrow \text{EMP}$ ). This means  $w=\text{EMP}$ . Thus,  $S\text{-INV}$  holds.

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**Assume:** Invariants hold for a tree of height  $k$   
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- Inductive Step  
Assume: Invariants hold for a tree of height  $k$   
Show: Invariants hold for a tree of height  $k+1$
- $k \geq 1 \Rightarrow k > 1 \Rightarrow$  The derivation tree is generated using:  
 $(S \rightarrow aS)$   
The height of the derivation tree for the  $S$  on the RHS has height  $\leq k$ . By IH, its yield (i.e., what it generates) is in  $a^*$ . This rule makes the yield for the  $S$  on the LHS  $aa^*$ . Thus,  $S\text{-INV}$  holds.

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This means there is no derivation tree for  $w$ . Assume  $z$  is the longest suffix of  $w$  that only contains  $a$ s. That is,  $w = xsz$ , where  $x \in a^*$  and  $s \in a^*$  EMP. Observe that  $s = b$  and, therefore,  $w = xbz$ . Otherwise, our assumptions are contradicted. Thus,  $w \notin L$ .

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This means  $w$  contains a  $b$ . Given that invariants always hold,  $A^*$  does not generate  $w$ . Thus,  $w \notin L(A^*)$ .

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- 
- ```
(define numb>numa
      (make-cfg
        (list (list 'a 'b)
              ...)))
```
 - ```
'(a b)
```

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  - ;; S: generates words with number of b > number of a, starting nonterminal
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```
  - S generates an arbitrary number of as
- ```
(define (S-INV yield)
  (let [(as (filter (λ (s) (eq? s 'a)) yield))
        (bs (filter (λ (s) (eq? s 'b)) yield))]
    (> (length bs) (length as))))
```
-
- ```
(define (A-INV yield)
 (let [(as (filter (λ (s) (eq? s 'a)) yield))
 (bs (filter (λ (s) (eq? s 'b)) yield))]
 (>= (length bs) (length as))))
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Yield has more bs than as. S-INV holds.

$(A \rightarrow \text{EMP})$

Yield has equal number of bs than as. A-INV holds.

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Assume: Invariants hold for a tree of height k

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The derivation tree for each  $A$  on the RHS is of height  $\leq k$ .  
By, IH each generates num of bs  $\geq$  to num of as. This rules adds a b between the two yields. Thus, S-INV holds.

# Regular Grammars

- $L = \{w \mid w \text{ has more bs than as}\}$

- Base Case:  $h=1$

$(S \rightarrow b)$

Yield has more bs than as. S-INV holds.

$(A \rightarrow \text{EMP})$

Yield has equal number of bs than as. A-INV holds.

- Inductive Step

Assume: Invariants hold for a tree of height  $k$   
Show: Invariants hold for a tree of height  $k+1$

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- $(A \rightarrow bA)$

The derivation tree for  $A$  on the RHS is on height  $\leq k$ . By,  
IH it generates num of bs  $\geq$  to num of as.  
This rules adds a b to the front of its yield. Thus, A-INV holds.

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The derivation tree for each  $A$  on the RHS is of height  $\leq k$ .  
By, IH each generates num of bs  $\geq$  to num of as. This rules adds a b and an a to their yields. Thus, A-INV holds.

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- $L = \{w \mid w \text{ has more bs than as}\}$

- Base Case:  $h=1$

$(S \rightarrow b)$

Yield has more bs than as. S-INV holds.

$(A \rightarrow \text{EMP})$

Yield has equal number of bs than as. A-INV holds.

- Inductive Step

Assume: Invariants hold for a tree of height k

Show: Invariants hold for a tree of height k+1

$k \geq 1 \Rightarrow k+1 \Rightarrow$  The derivation tree is generated using:

- $(S \rightarrow AbA)$

The derivation tree for each A on the RHS is of height  $\leq k$ .

By, IH each generates num of bs  $\geq$  to num of as. This rules adds a b between the two yields. Thus, S-INV holds.

- $(A \rightarrow ba)$

The derivation tree for A on the RHS is on height  $\leq k$ . By,

IH it generates num of bs  $\geq$  to num of as.

This rules adds a b to the front of its yield. Thus, A-INV holds.

- $(A \rightarrow AbAaA)$

The derivation tree for each A on the RHS is of height  $\leq k$ .

By, IH each generates num of bs  $\geq$  to num of as. This rules adds a b and an a to their yields. Thus, A-INV holds.

- $(A \rightarrow AaAbA)$

The derivation tree for each A on the RHS is of height  $\leq k$ .

By, IH each generates num of bs  $\geq$  to num of as. This rules adds an a and an b to their yields. Thus, A-INV holds.

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Given that invariants hold, this means  $w$  has more bs than as. Thus,  $w \in L$ .

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- $w \notin L(\text{numb} > \text{numa}) \Leftrightarrow w \notin L$

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This means that there does not exist a parse tree rooted at  $S$  that yields  $w$ . Given that invariants hold, if  $w$  has more bs than as then  $(S \rightarrow AbA)$  generates it. Therefore,  $w$  must have a number of as  $\leq$  to the number of bs. Thus,  $w \notin L$ .

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- ( $\Leftarrow$ ) Assume  $w \notin L$   
Given that invariants always hold,  $S$  cannot generate  $w$ . Thus,  $w \notin L(\text{numb}>\text{numa})$ .

# Regular Grammars

- Design a regular grammar for:

$$L = \{w \mid \text{the number of } a\text{s in } w \text{ is a multiple of 3}\}$$

# Regular Grammars

- Design a regular grammar for:  
 $L = \{w \mid \text{the number of } a\text{s in } w \text{ is a multiple of 3}\}$
- Name: MULT3-as
- $\Sigma = \{a, b\}$

# Regular Grammars

- Syntactic categories
- $S = \text{words where the number of } a \text{ is } 3n, \text{ starting nonterminal}$

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  - $S = \text{words where the number of } a \text{ is } 3n, \text{ starting nonterminal}$
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- $C = \text{words where the number of } a \text{ is } 3n + 1$
- If  $C$  generates an  $a$  then a word with  $3n$  as must be generated

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- $S = \text{words where the number of } a \text{ is } 3n, \text{ starting nonterminal}$
- If  $a$  is generated by  $S$  then  $3n+2$  as needed
- $(\text{list } 'S \text{ ARROW } \text{EMP})$   
 $(\text{list } 'S \text{ ARROW } 'aB)$   
 $(\text{list } 'S \text{ ARROW } 'bS)$
- $B = \text{words where the number of } a \text{ is } 3n + 2$
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- $(\text{list } 'B \text{ ARROW } 'aC)$   
 $(\text{list } 'B \text{ ARROW } 'bB)$
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- If  $C$  generates an  $a$  then a word with  $3n$  as must be generated
- **Typo in the book.**  
 $(C \text{ ,ARROW } aS)$   
 $(C \text{ ,ARROW } bC)$

# Regular Grammars

- Unit Tests

```
#:rejects '((b b a b b) (b b a b b a) (b b a b a b a a b))
#:accepts '(() (a a a) (b b a a b a b b))
```

# Regular Grammars

- Implementation

```
(define MULT3-as
 (make-rg '(S B C)
 '(a b)
 `((S ,ARROW ,EMP)
 (S ,ARROW aB)
 (S ,ARROW bS)
 (B ,ARROW aC)
 (B ,ARROW bB)
 (C ,ARROW aS)
 (C ,ARROW bC))
 'S
 #:rejects '((b b a b b) (b b a b b a)
 (b b a b a b a a b))
 #:accepts '((() (a a a) (b b a a b a b))))
```

# Regular Grammars

- Implementation

```
(define MULT3-as
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 `((S ,ARROW ,EMP)
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 #:rejects '((b b a b b) (b b a b b a)
 (b b a b a b a a b))
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```

- Run the tests

# Regular Grammars

- > (grammar-test MULT3-as 10)  
'(((b a a a) (S -> bS -> baB -> baaC -> baaaS -> baaa))  
((b a a a a) "(b a a a a) is not in L(G).")  
((a a) "(a a) is not in L(G).")  
((a b a b) "(a b a b) is not in L(G).")  
((a b) "(a b) is not in L(G).")  
((() (S ->  $\epsilon$ ))  
((b) (S -> bS -> b))  
((b b) (S -> bS -> bbS -> bb))  
((b a b a) "(b a b a) is not in L(G).")  
((b a a b a b)  
 (S  
 ->  
 bS  
 ->  
 baB  
 ->  
 baaC  
 ->  
 baabC  
 ->  
 baabaS  
 ->  
 baababS  
 ->  
 baabab)))

- Illustrate derivation with grammar-viz using mult3-as.rkt

# Regular Grammars

- HOMEWORK: 1–5
- HOMEWORK: Prove MULT3-as correct

# Regular Grammars

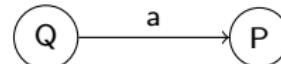
## Theorem

$L \text{ is regular} \Leftrightarrow L \text{ is generated by a regular grammar.}$

- Must be able to build a rg from a dfa
- Must be able to build a dfa from an rg

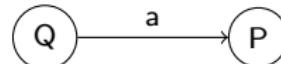
# Regular Grammars

- Building a regular grammar,  $R$ , from,  $D$ , a dfa such that  $L(R) = L(D)$
- D's transition rules always consume an element of the alphabet:



# Regular Grammars

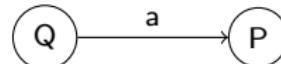
- Building a regular grammar,  $R$ , from,  $D$ , a dfa such that  $L(R) = L(D)$
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- $R$  must have a production rule to produce such an  $a$
- $a$  must be part of the right hand side of the production rule

# Regular Grammars

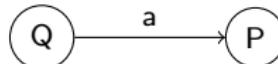
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- We do not know what  $D$  may consume after reaching  $P$ , but whatever it is it must be generated by production rules obtained from transition rules starting at  $P$

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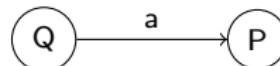
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- We do not know what  $D$  may consume after reaching  $P$ , but whatever it is it must be generated by production rules obtained from transition rules starting at  $P$
- $a$  and anything read after reaching  $P$  must be generated

# Regular Grammars

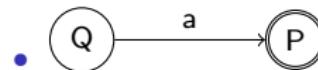
- Building a regular grammar, R, from, D, a dfa such that  $L(R) = L(D)$
- D's transition rules always consume an element of the alphabet:



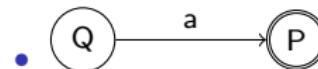
- R must have a production rule to produce such an a
- a must be part of the right hand side of the production rule
- We do not know what D may consume after reaching P, but whatever it is it must be generated by production rules obtained from transition rules starting at P
- a and anything read after reaching P must be generated
- The states of D are the nonterminals of the regular grammar
- From Q an a and whatever is produced by P must be produced:

(list 'Q ARROW 'aP)

# Regular Grammars



# Regular Grammars

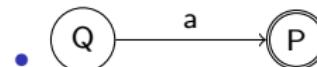


- Two rules when P is a final state

(list 'Q ARROW 'a)

(list 'Q ARROW 'aP)

# Regular Grammars



- Two rules when P is a final state
  - (list 'Q ARROW 'a)
  - (list 'Q ARROW 'aP)
- D's starting state, S, is a final state:  
(list 'S ARROW EMP)

# Regular Grammars

- `;; (listof dfa-rule) (listof state) → (listof rg-rule)`  
;; Purpose: Generate production rules for the given  
;; dfa-rules and the given final states  
`(define (mk-prod-rules mrules mfinals)`

# Regular Grammars

- ```
;; (listof dfa-rule) (listof state) → (listof rg-rule)
;; Purpose: Generate production rules for the given
;;           dfa-rules and the given final states
(define (mk-prod-rules mrules mfinals)
```
- ```
;; Tests for mk-prod-rules
(check-equal? (mk-prod-rules '() '(F G)) '())
(check-equal? (mk-prod-rules '((S a F) (S b R)
 (R a G) (R b R)
 (G a G) (G b G))
 '(F G))
 '((S -> a) (S -> aF) (S -> bR)
 (R -> a) (R -> aG) (R -> bR)
 (G -> a) (G -> aG) (G -> b) (G -> bG)))
```

## Regular Grammars

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• (append-map
  (λ (r)
    (if (not (member (third r) mfinals))
        (list (list (first r) ARROW (los->symbol (rest r))))))

• ;; Tests for mk-prod-rules
(check-equal? (mk-prod-rules '() '(F G)) '())
(check-equal? (mk-prod-rules '((S a F) (S b R)
                                (R a G) (R b R)
                                (G a G) (G b G))
                                ' (F G)))
  '((S -> a) (S -> aF) (S -> bR)
    (R -> a) (R -> aG) (R -> bR)
    (G -> a) (G -> aG) (G -> b) (G -> bG)))
```

Regular Grammars

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 `(if (not (member (third r) mfinals))`
 `(list (list (first r) ARROW (los->symbol (rest r))))`
- `(list (list (first r) ARROW (second r))`
 `(list (first r) ARROW (los->symbol (rest r))))))`
 `mrules))`
- `;; Tests for mk-prod-rules`
`(check-equal? (mk-prod-rules '() '(F G)) '())`
`(check-equal? (mk-prod-rules '((S a F) (S b R)`
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 `'(F G))`
`' ((S -> a) (S -> aF) (S -> bR)`
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 `(G -> a) (G -> aG) (G -> b) (G -> bG)))`

Regular Grammars

-

`;; dfa → rg`

`;; Purpose: Build a rg for the language of the given dfa
;; Assume: dfa states are represented by a single capital letter`

`(define (dfa2rg m)`

Regular Grammars

- $\text{;; dfa} \rightarrow \text{rg}$

;; Purpose: Build a rg for the language of the given dfa
;; Assume: dfa states are represented by a single capital letter
`(define (dfa2rg m)`

- $\text{;; Tests for dfa2rg}$

```
(define SIGMA*-rg (dfa2rg SIGMA*))  
(define EA-0B-rg (dfa2rg EVEN-A-ODD-B))  
  
(check-accept? SIGMA* '() '(a b c) '(c c a b a c))  
(check-derive? SIGMA*-rg '() '(a b c) '(c c a b a c))  
  
(check-reject? EVEN-A-ODD-B '(a b) '(a a b a))  
(check-not-derive? EA-0B-rg '(a b) '(a a b a))  
(check-accept? EVEN-A-ODD-B '(b) '(b a a b b))  
(check-derive? EVEN-A-ODD-B '(b) '(b a a b b))
```

Regular Grammars

- `;; dfa → rg`
 `;; Purpose: Build a rg for the language of the given dfa`
 `;; Assume: dfa states are represented by a single capital letter`
`(define (dfa2rg m)`
 - `(let* [(nts (sm-states m))`
 `(sigma (sm-sigma m))`
 `(startnt (sm-start m))`- `;; Tests for dfa2rg`
`(define SIGMA*-rg (dfa2rg SIGMA*))`
`(define EA-0B-rg (dfa2rg EVEN-A-ODD-B))`

`(check-accept? SIGMA* '() '(a b c) '(c c a b a c))`
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`(check-reject? EVEN-A-ODD-B '(a b) '(a a b a))`
`(check-not-derive? EA-0B-rg '(a b) '(a a b a))`
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`(sigma (sm-sigma m))`
`(startnt (sm-start m))`
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`(check-accept? SIGMA* '() '(a b c) '(c c a b a c))`
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Regular Grammars

- `;; dfa → rg`
 `;; Purpose: Build a rg for the language of the given dfa`
 `;; Assume: dfa states are represented by a single capital letter`
`(define (dfa2rg m)`
- `(let* [(nts (sm-states m))`
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- Convert $G=(\text{make-rg } N \ \Sigma P \ S)$ into, M , a finite-state machine that decides $L(G)$
- The finite-state machine shall simulate a derivation

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- G 's nonterminals are states in M
- Σ is M 's alphabet
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- To simulate a compound production rule:
$$I \rightarrow iJ \dashrightarrow (I \ i \ J)$$

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- Consider:

```
(define a*Ub*-rg    ;; L = a* U b*
  (make-rg '(S A B) '(a b)
            `((S ,ARROW ,EMP) (S ,ARROW aA) (S ,ARROW bB)
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- $S = (\text{cons } 'Z \ (S \ A \ B))$
 $\Sigma = '(a \ b)$
 $A = 'S$
 $F = (\text{list } 'Z)$

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- Consider:

```
(define a*Ub*-rg    ;; L = a* U b*
  (make-rg '(S A B) '(a b)
            `((S ,ARROW ,EMP) (S ,ARROW aA) (S ,ARROW bB)
              (S ,ARROW a) (S ,ARROW b) (A ,ARROW aA)
              (A ,ARROW a) (B ,ARROW bB) (B ,ARROW b))
            'S))
```

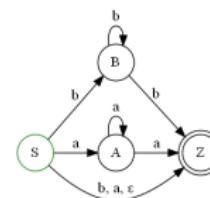
- $S = (\text{cons } 'Z \ (S \ A \ B))$
 $\Sigma = '(a \ b)$
 $A = 'S$
 $F = (\text{list } 'Z)$
- $I \rightarrow i \text{ rules}$ $I \rightarrow iJ \text{ rules}$
 $(S \rightarrow \epsilon)$ $(S \rightarrow aA)$
 $(S \rightarrow a)$ $(S \rightarrow bB)$
 $(S \rightarrow b)$ $(A \rightarrow aA)$
 $(A \rightarrow a)$ $(B \rightarrow bB)$
 $(B \rightarrow b)$

Regular Grammars

- Consider:

```
(define a*Ub*-rg    ;; L = a* U b*
  (make-rg '(S A B) '(a b)
            `((S ,ARROW ,EMP) (S ,ARROW aA) (S ,ARROW bB)
              (S ,ARROW a) (S ,ARROW b) (A ,ARROW aA)
              (A ,ARROW a) (B ,ARROW bB) (B ,ARROW b))
            'S))
```

- $S = (\text{cons } 'Z \ (S \ A \ B))$
- $\Sigma = '(a \ b)$
- $A = 'S$
- $F = (\text{list } 'Z)$
- $I \rightarrow i \text{ rules}$
 - $(S \rightarrow \epsilon)$
 - $(S \rightarrow a)$
 - $(S \rightarrow b)$
 - $(A \rightarrow a)$
 - $(B \rightarrow b)$
- $I \rightarrow iJ \text{ rules}$
 - $(S \rightarrow aA)$
 - $(S \rightarrow bB)$
 - $(A \rightarrow aA)$
 - $(B \rightarrow bB)$



- It is not difficult to see that it decides $L = a^* \cup b^*$

Regular Grammars

- To test the constructor:

```
;; Sample rg
;; L = (a U b U c)*
(define SIGMA*-rg (dfa2rg SIGMA*))
```

```
;; L = w | w has an even number of a and an odd number of b
(define EA-OB-rg (dfa2rg EVEN-A-ODD-B))
```

```
;; L = a* U b*
(define a*Ub*-rg
  (make-rg
    '(S A B)
    '(a b)
    `((S ,ARROW ,EMP) (S ,ARROW aA) (S ,ARROW bB) (S ,ARROW a)
      (S ,ARROW b) (A ,ARROW aA) (A ,ARROW a) (B ,ARROW bB)
      (B ,ARROW b))
    'S))
```

```
;; L = a aba
(define a-aba-rg
  (make-rg
    '(S A B)
    '(a b)
    `((S ,ARROW a) (S ,ARROW aA) (A ,ARROW bB) (B ,ARROW a))
    'S))
```

Regular Grammars

- `;; rg → ndfa`
`;; Purpose: Build a ndfa for the language of the given rg`
`(define (rg2ndfa rg)`

Regular Grammars

- ;; Tests for rg2ndfa
(define SIGMA*-ndfa (rg2ndfa SIGMA*-rg))
(define EA-OB-ndfa (rg2ndfa EA-OB-rg))
(define a*Ub*-ndfa (rg2ndfa a*Ub*-rg))
(define a-aba-ndfa (rg2ndfa a-aba-rg))

(check-derive? SIGMA*-rg '() '(a b c) '(c c a b a c))
(check-accept? SIGMA*-ndfa '() '(a b c) '(c c a b a c))
(check-equal? (sm-testequiv? SIGMA* SIGMA*-ndfa) #t)

(check-not-derive? EA-OB-rg '(a b) '(a a b a))
(check-reject? EA-OB-ndfa '(a b) '(a a b a))
(check-derive? EA-OB-rg '(b) '(b a a b b))
(check-accept? EA-OB-ndfa '(b) '(b a a b b))
(check-equal? (sm-testequiv? EVEN-A-ODD-B EA-OB-ndfa) #t)

(check-not-derive? a*Ub*-rg '(a b) '(a b b a))
(check-reject? a*Ub*-ndfa '(a b) '(a b b a))
(check-derive? a*Ub*-rg '() '(a a a) '(b))
(check-accept? a*Ub*-ndfa '() '(a a a) '(b))

(check-not-derive? a-aba-rg '(b b) '())
(check-reject? a-aba-ndfa '(b b) '())
(check-derive? a-aba-rg '(a b a) '(a))
(check-accept? a-aba-ndfa '(a b a) '(a))

Regular Grammars

- `;; rg → ndfa`

`;; Purpose: Build a ndfa for the language of the given rg`
`(define (rg2ndfa rg)`
 `(let* [(final-state (generate-symbol 'Z (grammar-nts rg)))]`

Regular Grammars

- `;; rg → ndfa`
;; Purpose: Build a ndfa for the language of the given rg
`(define (rg2ndfa rg)`
 `(let* [(final-state (generate-symbol 'Z (grammar-nts rg)))`
 `(states (cons final-state (grammar-nts rg)))`
 `(sigma (grammar-sigma rg))`
 `(start (grammar-start rg))`
 `(finals (list final-state))`

Regular Grammars

- `;; rg → ndfa`
`;; Purpose: Build a ndfa for the language of the given rg`
`(define (rg2ndfa rg)`
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 `(sigma (grammar-sigma rg))`
 `(start (grammar-start rg))`
 `(finals (list final-state)))`
 `(simple-prs (filter`
 `(λ (pr) (= (length (symbol->fsmlos (third pr))) 1))`
 `(grammar-rules rg)))`
 `(cmpnd-prs`
 `(filter (λ (pr) (= (length (symbol->fsmlos (third pr))) 2))`
 `(grammar-rules rg))))`

Regular Grammars

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 `(grammar-rules rg)))`
 `(rules (append`
 `(map (λ (spr)`
 `(list (first spr) (third spr) final-state))`
 `simple-prs)`
 `(map (λ (pr)`
 `(let [(rhs (symbol->fsmlos (third pr)))]`
 `(list (first pr) (first rhs) (second rhs))))`
 `cmpnd-prs))))]`

Regular Grammars

- `;; rg → ndfa`
`;; Purpose: Build a ndfa for the language of the given rg`
`(define (rg2ndfa rg)`
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 `simple-prs)`
 `(map (λ (pr)`
 `(let [[(rhs (symbol->fsmlos (third pr)))]`
 `(list (first pr) (first rhs) (second rhs))))`
 `cmpnd-prs)))]`
 `)`
 `(make-ndfa states sigma start finals rules)))`

Regular Grammars

Lemma

$S \xrightarrow{+} w \Leftrightarrow ((a_1 \dots a_n) A) \vdash^+ (() Q)$, where $Q=Z$ if w ends with a terminal symbol and $Q \in N$ if w ends with a nonterminal

- (\Rightarrow) Assume $S \xrightarrow{+} w$.
- We must show that $(a_1 \dots a_n A) \vdash^+ (() Q)$, where $Q=Z$ if w ends with a terminal symbol and $Q \in N$ if w ends with a nonterminal

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- Induction on, n , the number of steps in the derivation
- Base Case: $n=1$
- The derivation uses only a single production rule
- There are two cases:
- If it is a simple production rule, $(S \rightarrow a)$, then $w=a$. By construction of M , we have that $(S \xrightarrow{} Z) \in \delta$. Therefore, $(a A) \vdash^+ (() Z) = (() Q)$

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- If it is a compound production rule, $(S \rightarrow aK)$, then $w=aK$
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- Inductive Step:
- Assume: $S \xrightarrow{+} w \Rightarrow (a_1 \dots a_k A) \vdash^+ (() Q)$, where $Q=Z$ if w ends with a terminal symbol and $Q \in N$ if w ends with a nonterminal, for $n=k$.
- Show: $S \xrightarrow{+} w \Rightarrow (a_1 \dots a_{k+1} A) \vdash^+ (() Q)$, where $Q=Z$ if w ends with a terminal symbol and $Q \in N$ if w ends with a nonterminal, for $n=k+1$

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- Assume $S \rightarrow^+ w$ for $n=k+1$

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 - Show: $S \rightarrow^+ w \Rightarrow (a_1 \dots a_{k+1} A) \vdash^+ (() Q)$, where $Q=Z$ if w ends with a terminal symbol and $Q \in N$ if w ends with a nonterminal, for $n=k+1$
 - Assume $S \rightarrow^+ w$ for $n=k+1$
 - Given that $k \geq 1$, $k+1 > 1$. This means that the derivation of w is either:
 - $S \rightarrow \dots \rightarrow a_1 \dots a_k U \rightarrow a_1 \dots a_k a_{k+1}$, where $U \in N$
 - $S \rightarrow \dots \rightarrow a_1 \dots a_k U \rightarrow a_1 \dots a_k a_{k+1} V$, where $U, V \in N$

Regular Grammars

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 - Show: $S \rightarrow^+ w \Rightarrow (a_1 \dots a_{k+1} A) \vdash^+ (() Q)$, where $Q=Z$ if w ends with a terminal symbol and $Q \in N$ if w ends with a nonterminal, for $n=k+1$
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 - $S \rightarrow \dots \rightarrow a_1 \dots a_k U \rightarrow a_1 \dots a_k a_{k+1} V$, where $U, V \in N$
 - By inductive hypothesis, we have:
 $((a_1 \dots a_k a_{k+1}) A) \vdash^* ((a_{k+1}) U)$

Regular Grammars

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 - The derivation uses only a single production rule
 - There are two cases:
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 - Show: $S \rightarrow^+ w \Rightarrow (a_1 \dots a_{k+1} A) \vdash^+ (() Q)$, where $Q=Z$ if w ends with a terminal symbol and $Q \in N$ if w ends with a nonterminal, for $n=k+1$
 - Assume $S \rightarrow^+ w$ for $n=k+1$
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 - $S \rightarrow \dots \rightarrow a_1 \dots a_k U \rightarrow a_1 \dots a_k a_{k+1} V$, where $U, V \in N$
 - By inductive hypothesis, we have:
 $((a_1 \dots a_k a_{k+1}) A) \vdash^* ((a_{k+1}) U)$
 - If the last production rule used in the derivation is a simple production rule, $(U \rightarrow a_{k+1})$, then by construction of M , $(U a_{k+1} Z) \in \delta$
 - Therefore, $((a_1 \dots a_k a_{k+1}) A) \vdash^* (() Z) = (() Q)$.

Regular Grammars

Lemma

$S \rightarrow^+ w \Leftrightarrow ((a_1 \dots a_n) A) \vdash^+ (() Q)$, where $Q=Z$ if w ends with a terminal symbol and $Q \in N$ if w ends with a nonterminal

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- Induction on, n , the number of steps in the derivation
- Base Case: $n=1$
 - The derivation uses only a single production rule
 - There are two cases:
 - If it is a simple production rule, $(S \rightarrow a)$, then $w=a$. By construction of M , we have that $(S a Z) \in \delta$. Therefore, $(a A) \vdash^+ (() Z) = (() Q)$
 - If it is a compound production rule, $(S \rightarrow aK)$, then $w=aK$
 - By construction of M , we have that $(S a K) \in \delta$
 - Therefore, $(a A) \vdash^+ (() K) = (() Q)$
- Inductive Step:
 - Assume: $S \rightarrow^+ w \Rightarrow (a_1 \dots a_k A) \vdash^+ (() Q)$, where $Q=Z$ if w ends with a terminal symbol and $Q \in N$ if w ends with a nonterminal, for $n=k$.
 - Show: $S \rightarrow^+ w \Rightarrow (a_1 \dots a_{k+1} A) \vdash^+ (() Q)$, where $Q=Z$ if w ends with a terminal symbol and $Q \in N$ if w ends with a nonterminal, for $n=k+1$
 - Assume $S \rightarrow^+ w$ for $n=k+1$
 - Given that $k \geq 1$, $k+1 > 1$. This means that the derivation of w is either:
 - $S \rightarrow \dots \rightarrow a_1 \dots a_k U \rightarrow a_1 \dots a_k a_{k+1}$, where $U \in N$
 - $S \rightarrow \dots \rightarrow a_1 \dots a_k U \rightarrow a_1 \dots a_k a_{k+1} V$, where $U, V \in N$
 - By inductive hypothesis, we have:
 $((a_1 \dots a_k a_{k+1}) A) \vdash^* ((a_{k+1}) U)$
 - If the last production rule used in the derivation is a simple production rule, $(U \rightarrow a_{k+1})$, then by construction of M , $(U a_{k+1} Z) \in \delta$
 - Therefore, $((a_1 \dots a_k a_{k+1}) A) \vdash^* (() Z) = (() Q)$.
 - If the last production rule used in the derivation is a compound production rule, $(U \rightarrow a_{k+1} V)$, then by construction of M , $(U a_{k+1} V) \in \delta$
 - Therefore, $((a_1 \dots a_k a_{k+1}) A) \vdash^* (() V) = (() Q)$

Regular Grammars

Lemma

$S \xrightarrow{+} w \Leftrightarrow ((a_1 \dots a_n) A) \vdash^+ (() Q)$, where $Q=Z$ if w ends with a terminal symbol and $Q \in N$ if w ends with a nonterminal

- (\Leftarrow) Assume $((a_1 \dots a_n) A) \vdash^+ (() Q)$, where $Q=Z$ if w ends with a terminal symbol and $Q \in N$ if w ends with a nonterminal
- We must show that $S \xrightarrow{+} w$
- Induction on, n , the number of transitions in M's computation

Regular Grammars

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$S \xrightarrow{+} w \Leftrightarrow ((a_1 \dots a_n) A) \vdash^+ (() Q)$, where $Q=Z$ if w ends with a terminal symbol and $Q \in N$ if w ends with a nonterminal

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- We must show that $S \xrightarrow{+} w$
- Induction on, n , the number of transitions in M's computation
- Base Case: $n=1$
- This means that w ends with a terminal
- M's computation is either:
 $(() A) \vdash (() Z) \vee ((a) A) \vdash (() Z)$

Regular Grammars

Lemma

$S \xrightarrow{+} w \Leftrightarrow ((a_1 \dots a_n) A) \vdash^{+} (() Q)$, where $Q=Z$ if w ends with a terminal symbol and $Q \in N$ if w ends with a nonterminal

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- For the first computation, by construction of M , G must have $(S \rightarrow \epsilon)$

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- This means that w ends with a terminal
- M's computation is either:
 $(() A) \vdash (() Z) \vee ((a) A) \vdash (() Z)$
- For the first computation, by construction of M, G must have $(S \rightarrow \epsilon)$
- For the second computation, by construction of M, G must have $(S \rightarrow a)$

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- Given that w is an arbitrary word, M decides L
- Thus, L is regular

Regular Grammars

- HOMEWORK: 9, 10, 11, 12
- QUIZ: 7 (due in a week)

Pumping Theorem for RLs

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- Consider the following language:
$$L = \{a^n b^n \mid n \geq 0\}$$
- On the surface it appears to be a rather simple and uninteresting language

Pumping Theorem for RLs

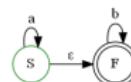
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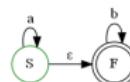
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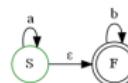
- If we define this machine as $a2n-b2n$ the following tests pass:

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;; Tests for a2n-b2n
(check-equal? (sm-apply a2n-b2n '(b b a a)) 'reject)
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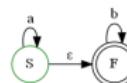
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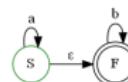
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- To remember an arbitrary number of as the machine needs an arbitrary number of states

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; ; Tests for a2n-b2n
(check-equal? (sm-apply a2n-b2n '(b b a a)) 'reject)
(check-equal? (sm-apply a2n-b2n '()) 'accept)
(check-equal? (sm-apply a2n-b2n '(a b)) 'accept)
(check-equal? (sm-apply a2n-b2n '(a a b b)) 'accept)
(check-equal? (sm-apply a2n-b2n '(a a a b b)) 'accept)
```

- Should this give us confidence that the machine decides L?
- Unfortunately, the answer is an unequivocal no
- The tests are not thorough enough:

```
(check-equal? (sm-apply a2n-b2n '(a a)) 'reject)
(check-equal? (sm-apply a2n-b2n '(b)) 'reject)
(check-equal? (sm-apply a2n-b2n '(a a a b)) 'reject)
```

- These tests fail and this should not happen
- The machine needs to remember the number of as
- To remember an arbitrary number of as the machine needs an arbitrary number of states
- This strongly suggests that L is interesting because it is not a regular language
- In general, how can we tell if a language is not regular?

Pumping Theorem for RLs

- Cycles in the transition diagram of a finite-state machine and Kleene stars in a regular expression suggest that there is a repetitive structure

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Regular
Expressions

Deterministic
Finite
Automata

Nondeterministic
Finite
Automata

Finite-State
Automata and
Regular
Expressions

Regular
Grammars

Pumping
Theorem for
Regular
Languages

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- $xyyz \in L$, $xyyyz \in L$, $xyyyyyz \in L$ and so on are also in the machine's language. The loop is traversed one or more times
- It is also the case that xz is in the machine's language
- Generalize: $xy^iz \in L$, where $i \geq 0$
- If $w \in L$ then we can "pump" up or down on y and still have a word that is in L

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Theorem

For a regular language, L , there is a word length $n \geq 1$ such that any $w \in L$ may be written as $w = xyz$, where $y \neq \epsilon$, $|xy| \leq n$, and $xy^i z \in L$ for $i \geq 0$.

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- $w \in L$ of length greater than or equal to some positive integer, n , may be divided into three parts, x , y and z

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- $w \in L$ of length greater than or equal to some positive integer, n , may be divided into three parts, x , y and z
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- That is, xy must be at the beginning of w
- What is this theorem good for?
- For a concrete $w \in L$ that is long enough we must be able to identify a nonempty y that may safely be repeated an arbitrary number of times and still end with a word in L
- If such a y does not exist then the language is not regular

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- $n = |K|$
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- The first n steps of M 's computation on w are as follows:
 $((a_1 \ a_2 \ \dots \ a_n) \ S) \vdash ((a_2 \dots \ a_n) \ Q_1) \vdash ((a_3 \dots \ a_n) \ Q_2) \vdash \dots \ ((\) \ Q_n)$
- Observe that the computation has $n+1$ configurations

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- Observe that the computation has $n+1$ configurations
- Since M only has n states by the pigeonhole principle there must be a repeated state in the computation: $Q_i = Q_j$
- This means there is a loop in M :
 $((a_i \dots a_j) \ Q_{i-1}) \vdash ((a_{i+1} \dots a_j) \ Q_i) \vdash^* ((\) \ Q_i)$

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- If we define $x = (a_1 \ \dots \ a_{i-1})$, $y = (a_i \ \dots \ a_j)$, and $z = (a_{j+1} \ \dots \ a_n)$ then $xy^iz \in L$
- Finally, observe that $|(a_1 \ \dots \ a_j)| \leq n$ because the loop can contain at most all of M 's states
- Therefore, $|xy| \leq n$

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Theorem

$L = \{a^n b^n \mid n \geq 0\}$ is not regular

- Assume L is regular

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- If it contained any b s then $|xy|$ would be too long
- Thus, $y = a^j$, where $j > 0$
- We may write w as follows:

$$w = xyz = a^{n-j-r} a^j a^r b^n, \text{ where } x = a^{n-j-r} \wedge z = a^r b^n$$

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- If we pump down once the resulting word is $w' = a^{n+1-p}b^n$
- Observe that $n+1-p \leq n$
- Clearly, w' is not in L
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Theorem

$L = \{w \mid w \in (a b)^* \wedge w \text{ has an equal number of } as \text{ and } bs\}$ is not regular

- It's ok not to use the Pumping Theorem
- Use closure properties

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L' = (concat-regexp
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$$\begin{aligned} L' &= (\text{concat-regexp} \\ &\quad (\text{kleenestar-reg-exp} (\text{singleton-regexp } a)) \\ &\quad (\text{kleenestar-reg-exp} (\text{singleton-regexp } b))) \end{aligned}$$

- If L is regular then by closure under intersection $L \cap L'$ is also regular
- However, we have that:
$$L \cap L' = a^n b^n$$
- $a^n b^n$ is not regular
- Therefore, the assumption that L is regular must be wrong

Pumping Theorem for RLs

- HOMEWORK: 2–4, 8–11