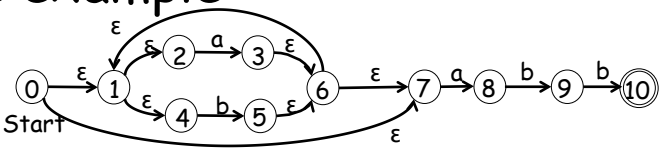
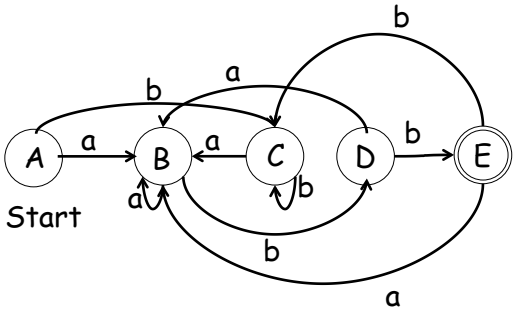
Revisit the example



ε-closure(0)={0, 1, 2, 4, 7} = A
Trans(A, a) = {1, 2, 3, 4, 6, 7, 8} = B
Trans(A, b) = {1, 2, 4, 5, 6, 7} = C
Trans(B, a) = {1, 2, 3, 4, 6, 7, 8} = B
Trans(B, b) = {1, 2, 4, 5, 6, 7, 9} = D
Trans(C, a) = {1, 2, 3, 4, 6, 7, 8} = B
Trans(C, b) = {1, 2, 4, 5, 6, 7} = C
Trans(D, a) = {1, 2, 3, 4, 6, 7, 8} = B
Trans(D, b) = {1, 2, 4, 5, 6, 7, 10} = E (mark as end state because 10 is included)
Trans(E, a) = {1, 2, 3, 4, 6, 7, 8} = B
Trans(E, b) = {1, 2, 4, 5, 6, 7} = C

1

Transformed DFA



2

Minimizing the DFA

- Insight
  - Identify equivalent state sets if all states have the same transitions
  - Merge equivalent states as a new state in the refined DFA

3

Minimizing the DFA

Initially partition the state set into two groups:

(1) Group I: the states with only final states, and

(2) Group II: the states with only non-final states

for each group G do

partition G into subgroups such that for any states s and t in G, for all input symbols, they have transitions to states in the same group

replace G with identified subgroups

4

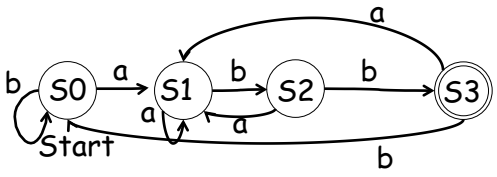
Revisit the example

Initially, two partitions:
G1 = {E}, G2 = {A, B, C, D}
G1 cannot be further partitioned
Trans(G2, a) = {B} $\subseteq$ G2
Trans(G2, b) = {C, D, E}, the resulting set does not belong to the same group
partition G2 into {A, B, C}=G3, {D}=G4
Trans(G3, a) = {B} $\subseteq$ G3
Trans(G3, b) = {C, D}, the resulting set does not belong to the same group
Partition G3 into {A, C} = G5, {B} = G6
Trans(G5, a) = {B} = G6
Trans(G5, b) = {C} $\subseteq$ G5
Therefore, the resulting partition is:
{A, C}, {B}, {D}, {E}

State	Input symbol	
	a	b
A	B	C
B	B	D
C	B	C
D	B	E
E	B	C

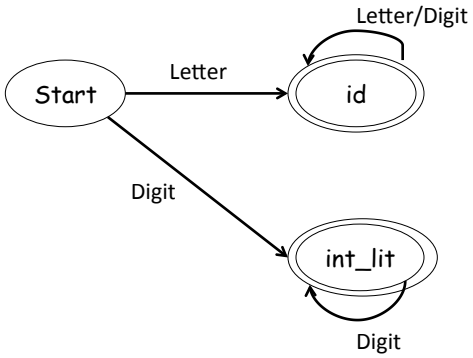
5

Refined DFA



6

State Transition Diagram (DFA)



7

Constructing the Lexical Analysis

- Convenient utility subprograms:
  - **`getChar`** - gets the next character of input, puts it in **`nextChar`**, determines its class and puts the class in **`charClass`**
  - **`addChar`** - puts the character from **`nextChar`** into the place the token is being accumulated: **`nextToken`**

8

Implementation Pseudo-code

```
static TOKEN nextToken;

static CHAR_CLASS charClass;

void lex() {
  getChar();
  switch (charClass) {
    case LETTER:
      addChar();
      getChar();
      while (charClass == LETTER || charClass ==
   DIGIT)
      {
        addChar();
        getChar();
      }
      return; //nextToken = ID
```

9

Implementation (Cont'd)

```
…
case DIGIT:
      addChar();
      getChar();
      while (charClass == DIGIT) {
        addChar();
        getChar();
      }
      return;//nextToken = INT_LIT
default: report error();
  }  /* End of switch */
}  /* End of function lex */
```

10

Key Points about Scanner

- Nearly universal rule
  - Always take the longest possible token from the input
    - foobar is never parsed to foo or fooba
- Regular expressions "**generate**" a regular language, while DFAs "**recognize**" it

11

Parser

- By analogy to RE and DFAs, a context-free grammar (CFG) is a **generator** for a context-free language, while a parser is a language **recognizer**
- Responsibilities
  - Generate a parse tree, report syntax errors if any

12

Two Classes of Grammars

- Left-to-right, Leftmost derivation (LL)
- Left-to-right, Rightmost derivation (LR)
- We can build parsers for these grammars that run in linear time

13

Grammar Comparison

LL	LR
E -> T E' E' -> + T E' | ε T -> F T' T' -> * F T' | ε F -> id	E -> E + T | T T -> T * F | F F -> id

14

Two Categories of Parsers

- LL(1) Parsers
  - L: scanning the input from left to right
  - L: producing a leftmost derivation
  - 1: using one input symbol of lookahead at each step to make parsing action decisions
- LR(1) Parsers
  - L: scanning the input from left to right
  - R: producing a rightmost derivation **in reverse**
  - 1: the same as above

15

Two Categories of Parsers

- LL(1) parsers (predicative parsers)
  - Top down
    - Build the parse tree from the root
    - Find a left most derivation for an input string
- LR(1) parsers (shift-reduce parsers)
  - Bottom up
    - Build the parse tree from leaves
    - Reducing a string to the start symbol of a grammar

16

Top-down parsing algorithms

- Recursive predictive parsing
  - Recursive-descent parsing
- Non-recursive predictive parsing
  - LL(1): Table-driven parsing

17

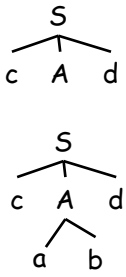
Motivating Example

- Consider the grammar
  S -> cAd
  A -> ab | a
- Input string: w = cad
- How to build a parse tree top-down?

18

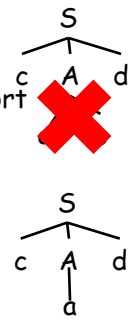
Recursive-Descent Parsing

- Initially create a tree containing a single node S (the start symbol)
- Apply the S-rule to see whether the first token matches
  - If matches, expand the tree
    - Apply the A-rule to the leftmost nonterminal A
      - Since the first token matches both alternatives (A1 and A2), randomly pick one (e.g., A1) to apply



19

Recursive-Descent Parsing



- Since the third token d does not match b, report failure and go back to A to try another alternative
- Rollback to the state before applying A1 rule, and then apply the alternative rule
- The third token matches, so parsing is successfully done

20

Recursive-Descent Parsing Algorithm

Suppose we have a scanner which generates the next token as needed.
Given a string, the parsing process starts with the start symbol rule:

```
if there is only one RHS then
    for each terminal in the RHS
        compare it with the next input token
        if they match, then continue
        else report an error
    for each nonterminal in the RHS
        call its corresponding subprogram and try match
        if no match is found, then report an error
else // there is more than one RHS
    choose the RHS based on the next input token (the lookahead)
    for each chosen RHS
        call the corresponding subprogram and try match
    if no match is found, then report an error
```

21

Constructing Parser

- Utility program
  - `match(…)` sees what it expects to see, and do corresponding processing

22

An Example (one RHS)

```
/* Function expr Parses strings in the language
   generated by the rule:
<expr> → <term> {(+ | -) <term>}      */

void expr() {
/* Parse the first term */
   term();

/* As long as the next token is + or -, call lex to
   get the next token, and parse the next term */

   while (nextToken == PLUS_CODE ||
          nextToken == MINUS_CODE){
     lex();
     term();
   }
}
```

23

Another Example (multiple RHS)

```
/* Function factor Parses strings in the
  language generated by the rule:
     <factor> -> id  |  (<expr>)  */
 void factor() {
   if (nextToken == ID_CODE) {
     lex();
  }
   else if (nextToken == LEFT_PAREN_CODE) {
     lex();
      expr();
      if (nextToken == RIGHT_PAREN_CODE) {
         lex();
      }
      else
        error();
   }
   else error(); /* Neither RHS matches */
 }
```

24

Key points about recursive-descent parsing

- Recursive-descent parsing may require backtracking
- LL(1) does not allow backtracking
  - By only looking at the next input token, we can always precisely decide which rule to apply
- By carefully designing a grammar, i.e., LL(1) grammar, we can avoid backtracking

25

Two Obstacles to LL(1)-ness

- Left recursion
  - E.g., id_list -> id_list_prefix ;
    id_list_prefix -> id_list_prefix, id | id
  - When the next token is id, which rule should we apply?
- Common prefixes
  - E.g., A -> ab | a
  - When the next token is a, which rule should we apply?

26

LL(1) Grammar

- Grammar which can be processed with LL(1) parser
- Non-LL grammar can be converted to LL(1) grammar via:
  - Left-recursion elimination
  - Left factoring by extracting common prefixes

27

Left-Recursion Elimination

- Replace left-recursion with right-recursion

id_list -> id_list_prefix ;
id_list_prefix -> id_list_prefix, id | id

=>

id_list -> id id_list_tail
id_list_tail -> ; | , id id_list_tail

28

Left Factoring

- Extract the common prefixes, and introduce new nonterminals as needed

  A -> ab | a

  =>

  A -> aB

  B -> b | ε

29

Non-LL Languages

- Simply eliminating left recursion and common prefixes is not guaranteed to make LL(1)
- An example in Pascal:

  stmt -> if condition then_clause else_clause
  | other_stmt

  then_clause -> then stmt

  else_clause -> else stmt | ε
- How to parse "if C1 then if C2 then S1 else S2" ?

30

Non-LL Languages

- Define "disambiguating rule", use it together with ambiguous grammar to parse top-down
  - E.g., in the case of a conflict between two possible productions, the one to use is the one that occurs first, textually in the grammar
  - to pair the else with the nearest then
- "Disambiguating rule" can be also defined for bottom-up parsing

31