CSc 453

Compilers and Systems Software

4 : Lexical Analysis II

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Implementing Automata

NFAs and DFAs can be hard-coded using this pattern:

```
state := start state
c := first char
while (true) {
   case state of {
      1:     case c of {
                char1 :  {
                   c := nextChar();
                   state := new state; }
      2:     case c of {
                char2 :  {
                   c := nextChar();
                   state := new state; }
                char3 :  {
                   return; /* accept */}}}
```

Implementing Automata...

- We can also encode the transitions directly into a transition table:

	next state			
state	$\texttt{char}_1$	$\texttt{char}_2$	other	**Accepting**
1	2			
2	2	2	[3]	
3				$\surd$

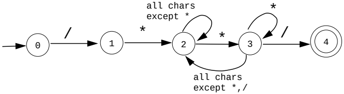
- States in brackets don't consume their inputs. Accepting states are indicated by a $\surd$. Empty entries represent error states.

Implementing Automata...

- Given the table, we can write an interpreter to perform lexical analysis of any DFA:

```
state := 1
c := first char
while not ACCEPT[state] do {
   newstate := NEXTSTATE[state,c]
   if ADVANCE[state,c] then
      c := nextChar()
   state := newstate
}
if ACCEPT[state] then accept;
```

Table-driven C Comments



state	/	*	other	Accepting
0	1			
1		2		
2	2	3	2	
3	4	3	2	
4				√

Table-driven C Comments...

```
class Comments {
    public static final int SLASH = 0;
    public static final int STAR  = 1;
    public static final int OTHER = 2;
    public static final int END   = 3;

    static int[][] NEXTSTATE = {
    //    "/"     "*"      other
        { 1,     -1,     -1},
        {-1,      2,     -1},
        { 2,      3,      2},
        { 4,      3,      2},
        {-1,     -1,     -1}
    };
```

Table-driven C Comments...

```
static boolean[] ACCEPT =
    {false,false,false,false,true};

static boolean[][] ADVANCE = {
//   "/"        "*"        other
    {true,      true,      true},
    {true,      true,      true},
    {true,      true,      true},
    {true,      true,      true},
    {true,      true,      true}
};
```

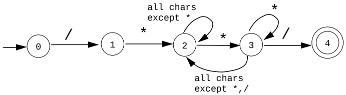
Table-driven C Comments...

```
static String input;
static int current = -1;

static int nextChar() {
    int ch;
    current++;
    if (current >= input.length()) return END;
    switch (input.charAt(current)) {
       case '/' : { ch = SLASH; break;}
       case '*' : { ch = STAR; break;}
       default  : { ch = OTHER; break;}
    }
    return ch;
}
```

Table-driven C Comments...

```
public static boolean interpret () {
    int state = 0;
    int c = nextChar();
    while ((c != END) && (state>=0) && !ACCEPT[state]) {
        int newstate = NEXTSTATE[state][c];
        if (ADVANCE[state][c])
           c = nextChar();
        state = newstate;
    }
    return (state>=0) && ACCEPT[state];
}

public static void main (String[] args) {
   input = args[0];
   boolean result = interpret();
}
```

Hard-coded C Comments



- Let's do the same thing again, but this time we will hard-code the interpreter using switch-statements.
- nextChar and the constant declarations are the same as for the previous program.

Hard-coded C Comments...

```
class Comments {
// Declarations of SLASH,STAR,OTHER,END, and nextChar().
   public static boolean interpret() {
      int state = 0;
      int ch = nextChar();
      while(true) {
         switch (state) {
             case -1 :
                 return false;
             case 0  :
                switch (ch) {
                   case SLASH:ch=nextChar();state=1;break;
                   default   :return false;
                }
                break;
```

```
case 1 :
   switch (ch) {
      case STAR: ch=nextChar(); state=2;
                 break;
      default  : return false;
   }
   break;
case 2 :
   switch (ch) {
      case SLASH: ch=nextChar(); state=2;
                  break;
      case STAR : ch=nextChar(); state=3;
                  break;
      case OTHER: ch=nextChar(); state=2;
                  break;
      default   : return false;
   }
   break;
```

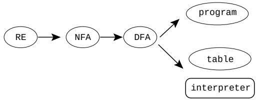
Hard-coded C Comments...

```
            case 3 :
               switch (ch) {
                  case SLASH: ch=nextChar(); state=4;
                              break;
                  case STAR : ch=nextChar(); state=3;
                              break;
                  case OTHER: ch=nextChar(); state=2;
                              break;
                  default   : return false;
               }
               break;
            case 4 :
               return (ch == END);
         }
      }
   }
```

From REs to NFAs

From REs to NFAs

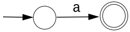
- We will describe our tokens using REs, convert these to an NFA, convert this to a DFA, and finally code this into a program or a table to be interpreted:



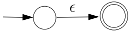
- We will next show how to construct an NFA from a regular expression. This algorithm is called Thompson's Construction (after Ken Thompson of Bell Labs).

Thompson's Construction

- Each piece of a regular expression is turned into a part of an NFA.
- Each part is glued together (using ϵ-transitions) into a complete automaton.
- An RE matching the character a translates into

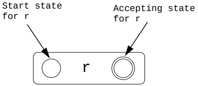


- An RE matching ϵ translates into

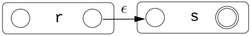


Thompson's Construction – Concatenation

- We represent an RE component `r` by the figure:

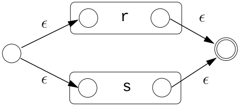


- An RE matching the regular expression `r` followed by the regular expression `s` (`rs`) translates into



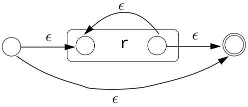
Thompson's Construction – Alternation

- The regular expression `r|s` translates into



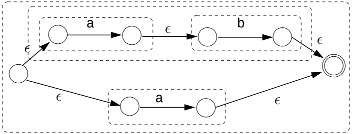
Thompson's Construction – Repetition

- The regular expression `r*` translates into



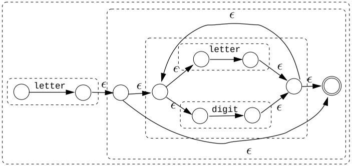
Thompson's Construction – Example I

- The regular expression `ab|a` translates into



Thompson's Construction – Example II

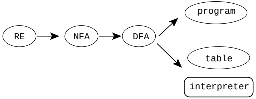
- The regular expression `letter(letter|digit)*` translates into



From NFA to DFA

From NFA to DFA

- We now know how to translate a regular expression into an NFA, and how to translate a DFA into code. The missing piece is how to translate an NFA into a DFA.



From NFA to DFA...

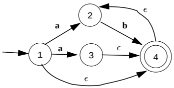
- Each state in the DFA corresponds to a set of states in the NFA.
- The DFA will be in state

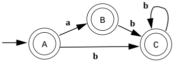
  2,3,4

  if the NFA could have been in any of the states

  2, 3, 4.
- After reading $a_1 a_2 \cdots a_n$ the DFA is in a a state that represents the states the NFA could be in after seeing the input $a_1 a_2 \cdots a_n$.

From NFA to DFA. . .





- Ⓐ in the DFA represents the set of states {①, ②, ④} in the NFA. These are the states the FAs could be in before any input is consumed (the start states).
- Ⓑ in the DFA represents the set of states {②, ③, ④} in the NFA. These are the states we can get to on the symbol a from Ⓐ.

From NFA to DFA. . .

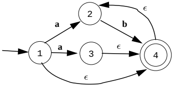
We need three functions:

1. ϵ-`closure`(T) is the set of NFA states reachable from some NFA state s in T on ϵ-transitions alone. This is essentially a graph exploration algorithm that finds the nodes in a graph reachable from a griven node.
2. `move`(T,a) is the set of NFA states to which there is a transition on input symbol a from some NFA state $s \in T$.
3. `SubsetConstruction`(N) returns a DFA D=(`Dstates`,`Dtrans`) corresponding to NFA N.

ϵ-closure(T)

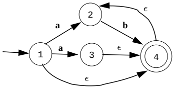
```
procedure ϵ-closure(T)
   push all states in T onto stack
   C := T
   while stack is not empty do
      t := pop(stack)
      for each edge t -ϵ-> u do
         if u is not in C then
            C := C ∪ u
            push(stack, u)
   return C
```

ϵ-closure(T) – Example



- ϵ-closure(①) = {①, ②, ④}
- ϵ-closure(②) = {②}
- ϵ-closure(④) = {②, ④}
- ϵ-closure({③, ④}) = {②, ③, ④}

move(T,a) – Example

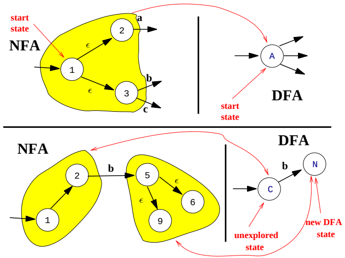


- move$(\{①\}, a) = \{②, ③\}$
- move$(\{②, ③\}, b) = \{④\}$

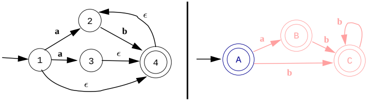
SubsetConstruction(N)

```
procedure SubsetConstruction(NFA N)
   Dstates := {ϵ-closure(s₀)}
   Dtrans := {}
   repeat
      T := an unexplored state in Dstates
      for each input symbol a do
         U := ϵ-closure(move(T,a))
         if U is not in Dstates then
            Dstates := Dstates ∪ U
         Dtrans := Dtrans ∪ (T -a-> U)
   until all states have been explored
   return (Dstates,Dtrans)
```

NFA⇒DFA

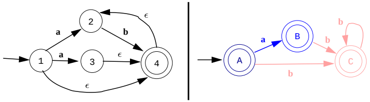


SubsetConstruction(N) – Example



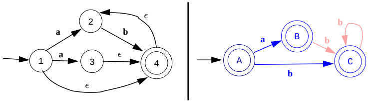
1. ϵ-closure$(①) = \{①, ②, ④\} = Ⓐ$
   - Ⓐ will be the DFA's start state.

Example. . .



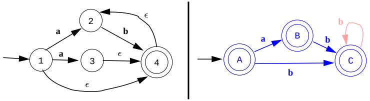
2. $\epsilon\text{-}\mathtt{closure}(\mathtt{move}(\textcircled{A}, a)) =$
$\epsilon\text{-}\mathtt{closure}(\mathtt{move}(\{\textcircled{1}, \textcircled{2}, \textcircled{4}\}, a)) = \epsilon\text{-}\mathtt{closure}(\{\textcircled{2}, \textcircled{3}\}) =$
$\{\textcircled{2}, \textcircled{3}, \textcircled{4}\} = \textcircled{B}$
   - We add the transition $\textcircled{A} \xrightarrow{a} \textcircled{B}$

Example. . .



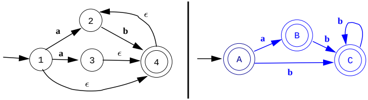
3. $\epsilon\text{-}\mathtt{closure}(\mathtt{move}(\textcircled{A}, b)) =$
$\epsilon\text{-}\mathtt{closure}(\mathtt{move}(\{\textcircled{1}, \textcircled{2}, \textcircled{4}\}, b)) = \epsilon\text{-}\mathtt{closure}(\{\textcircled{4}\}) =$
$\{\textcircled{2}, \textcircled{4}\} = \textcircled{C}$
   - We add the transition $\textcircled{A} \xrightarrow{b} \textcircled{C}$

Example. . .



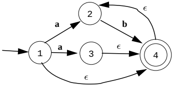
4. $\epsilon\text{-}\mathtt{closure}(\mathtt{move}(\textcircled{B}, b)) =$
$\epsilon\text{-}\mathtt{closure}(\mathtt{move}(\{\textcircled{2}, \textcircled{3}, \textcircled{4}\}, b)) = \epsilon\text{-}\mathtt{closure}(\{\textcircled{4}\}) =$
$\{\textcircled{2}, \textcircled{4}\} = \textcircled{C}$
   - We add the transition $\textcircled{B} \xrightarrow{b} \textcircled{C}$

Example. . .

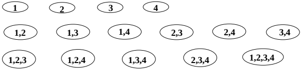


5. $\epsilon\text{-}\mathtt{closure}(\mathtt{move}(\textcircled{C}, b)) = \epsilon\text{-}\mathtt{closure}(\mathtt{move}(\{\textcircled{2}, \textcircled{4}\}, b)) =$
$\epsilon\text{-}\mathtt{closure}(\{\textcircled{2}, \textcircled{4}\}) = \{\textcircled{2}, \textcircled{4}\} = \textcircled{C}$
   - We add the transition $\textcircled{C} \xrightarrow{b} \textcircled{C}$

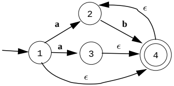
Example, Take 2



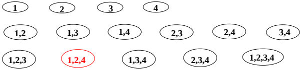
- A slightly different approach is to generate the power-set of the set of NFA states, and then add all the edges we get from ϵ-`closure()`.



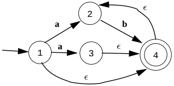
Example, Take 2. . .



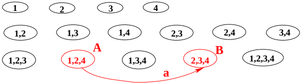
- On ϵ we can go to states ①, ②, ④ which becomes our start state, Ⓐ.



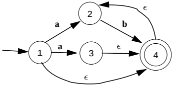
Example, Take 2. . .



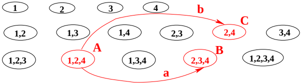
- From states ①, ②, ④ we can go to states ②, ③, ④ on an **a**.



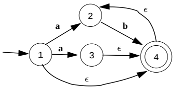
Example, Take 2. . .



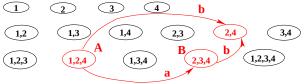
- From states ①, ②, ④ we can go to states ②, ④ on a **b**.



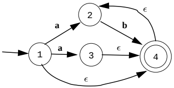
Example, Take 2...



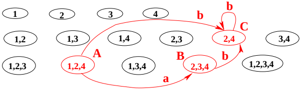
- From states 2, 3, 4 we can go to states 2, 4 on a **b**.



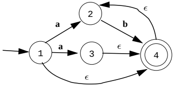
Example, Take 2...



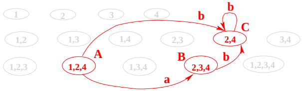
- From states 2, 4 we can go to states 2, 4 on a **b**.



Example, Take 2...



- Finally, removing unreachable states gives us our DFA.



Keywords

Keywords revisited

- For a language with many keywords (Ada-95 has 98, COBOL has hundreds), the transition table can be large.
- We can remove all keywords from the transition table and instead analyze them as `IDENT`s.
- When an IDENT is found we look it up in a special table to see if it is, in fact, a reserved word.
- We can use a regular hash-table, of course, but if we're concerned about speed we can use a minimal perfect hash-table. This is a static table and related lookup routines that have been optimized for a particular static set of words.

Keywords revisited...

- For example, we could build this perfect hash-table for the words `LUCA`, `MODULA-2`, `OBERON`:

0	LUCA
1	MODULA-2
2	
3	OBERON

```
int hash(String s) {return s[0]-'L';}
boolean member(String s) {return table[hash(s)] = s;}
```

- In this case we use the first character of the string as the hash-value.
- This is not a minimal table, there's one wasted entry.

Using Unix gperf

- `gperf` (http://www.gnu.org/manual/gperf-2.7) is a Unix program that takes a list of keywords as input and returns a perfect hash-table (and related search routines) as output.
- From the `gperf` manual:

The perfect hash function generator gperf reads a set of "keywords" from a keyfile. It attempts to derive a perfect hashing function that recognizes a member of the static keyword set with at most a single probe into the lookup table. If gperf succeeds in generating such a function it produces a pair of C source code routines that perform hashing and table lookup recognition.

Using Unix gperf...

- The following command

  ```
  > echo "BEGIN\nEND" | gperf -L ANSI-C
  ```

  generates the C program below.

```
/* ANSI-C code produced by gperf version 2.7 */
#define TOTAL_KEYWORDS 2
#define MIN_WORD_LENGTH 3
#define MAX_WORD_LENGTH 5
#define MIN_HASH_VALUE 3
#define MAX_HASH_VALUE 5
```

Using Unix gperf...

```
static unsigned int hash (
   register const char *str, register unsigned int len) {
   static unsigned char asso_values[] =  {
      6, 6, 6, 6, 6, 6, 6, 6, 6, 6,
      6, 6, 6, 6, 6, 6, 6, 6, 6, 6,
      6, 6, 6, 6, 6, 6, 6, 6, 6, 6,
      6, 6, 6, 6, 6, 6, 6, 6, 6, 6,
      6, 6, 6, 6, 6, 6, 6, 6, 6, 6,
      6, 6, 6, 6, 6, 6, 6, 6, 6, 6,
      6, 6, 6, 6, 6, 6, 0, 6, 0, 0,
    <--- Lots more stuff like this --->
    };
  return len + asso_values[(unsigned char)str[len - 1]] +
         asso_values[(unsigned char)str[0]];
}
```

```
const char * in_word_set (
   register const char *str,
   register unsigned int len) {
   static const char * wordlist[] =  {
      "", "", "", "END", "", "BEGIN"};

  if (len<=MAX_WORD_LENGTH && len>=MIN_WORD_LENGTH) {
      register int key = hash (str, len);
      if (key <= MAX_HASH_VALUE && key >= 0) {
          register const char *s = wordlist[key];
          if (*str == *s && !strcmp (str + 1, s + 1)) retu
      }
  }
  return 0;
}
```

- In this particular case, the hash function only looks at the first and last characters of the string, as well as the string length.

Summary

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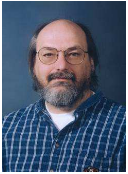
- The problem with table-driven methods is that the tables can easily get huge. Much work has gone into constructing table-compression algorithms, and data structures for sparse tables. See the Dragon book for details.
- There are also many algorithms for minimizing the number of states in a DFA. See Louden, pp. 72–74.

Readings and References

- Read Louden, pp. 31–80.
- Or, read the Dragon book, pp. 83–140.



- An interview with Ken Thompson: http://www.computer.org/computer/thompson.htm.
- His Turing award lecture (*Reflections on Trusting Trust*): http://www.acm.org/classics/sep95/.
- The next slide shows how you insert a Trojan Horse in the C compiler.

Reflections on Trusting Trust

```
compile (String S)
   if (we're compiling "login.c")
      GENERATE_CODE(
         if (user=="collberg" && passwd="D. Troi")
            login_ok = true
      )
   if (we're compiling "gcc.c")
      GENERATE_CODE(
         if (we're compiling "login.c")
            GENERATE_CODE(
               if (user=="collberg" && passwd="D. Troi")
                  login_ok = true
            )
      )
```