CSE 401 – Compilers

Lecture 4: Implementing Scanners
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Winter 2013

Agenda

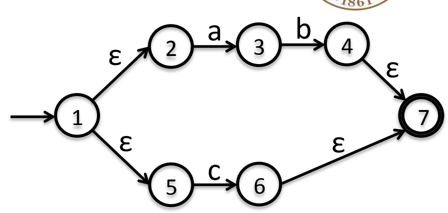
- Last week we covered regular expressions and finite automata.
- Today, we'll finish our final example (NFA to DFA conversion) and then talk about how scanners are implemented.
- Wednesday, we'll begin our discussion of parsing.

Announcements

- Part 1 of the project (the scanner) will be released tomorrow morning.
  - If you or your partner haven't emailed the course staff to let us know your team, do so TODAY.
  - If you haven't been able to find a partner, email me and I'll pair you up with someone else who hasn't.
    - You can also check the discussion board – there have been a few posts by people looking for partners.
  - We currently have an even number of students (54), so everyone should be able to have a partner.

Example

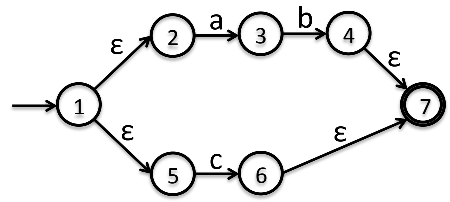
- Convert NFA to a DFA:



Step 1: Find ε closure of start state: {1,2,5}

Example

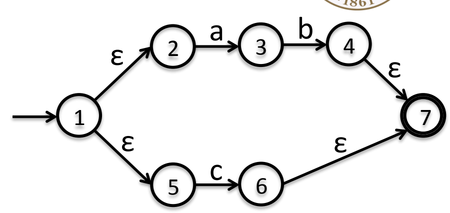
- Convert NFA to a DFA:

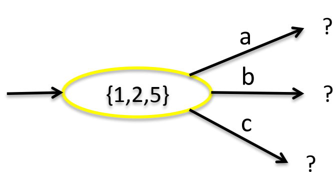


Step 2: Make a new DFA state corresponding to this ε closure. Mark it as unvisited (yellow in this diagram).

Example

- Convert NFA to a DFA:

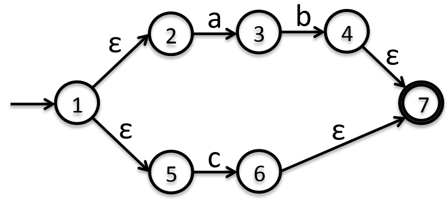


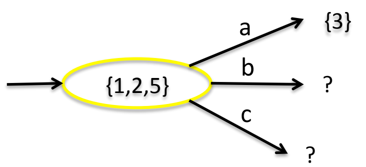


Loop: As long as there are unvisited DFA nodes, pick one. Consider transitions from its corresponding NFA states for every symbol in the alphabet.

Example

- Convert NFA to a DFA:

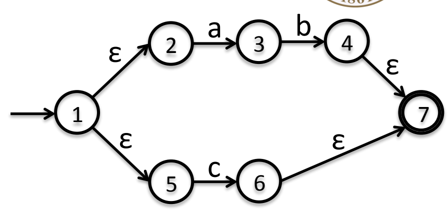


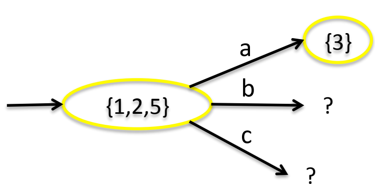


Only transition on ‘a’ from 1,2, or 5 is to 3.

Example

- Convert NFA to a DFA:

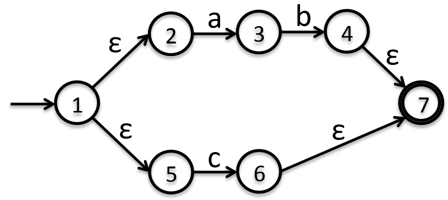


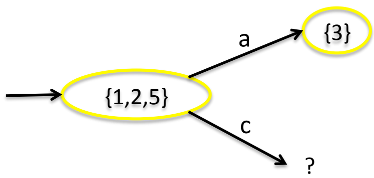


ε closure of {3} is just 3 (no ε transitions), so {1,2,5} transitions to {3} on ‘a’. This DFA state does not exist yet, so make it and mark it unvisited.

Example

- Convert NFA to a DFA:

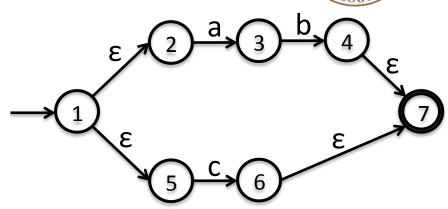


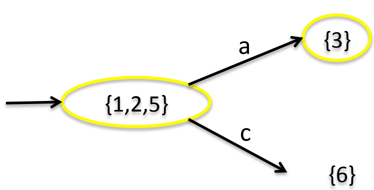


No transitions from 1, 2, or 5 on symbol 'b'.

Example

- Convert NFA to a DFA:

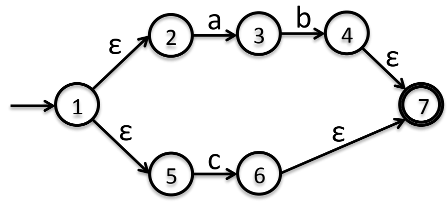


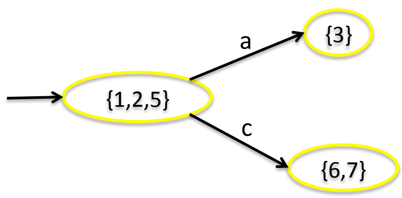


Only transition from 1, 2, or 5 on 'c' is to 6.

Example

- Convert NFA to a DFA:

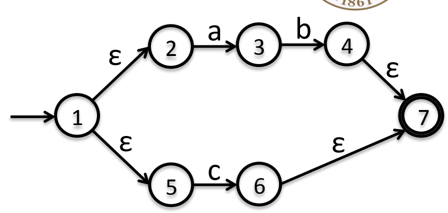


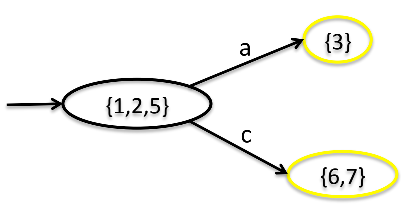


Epsilon closure of {6} is {6,7}, so {1,2,5} transitions to {6,7} on ‘c’. This doesn’t exist, so create and mark unvisited.

Example

- Convert NFA to a DFA:

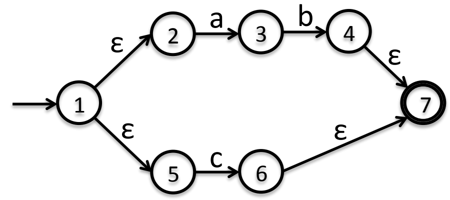


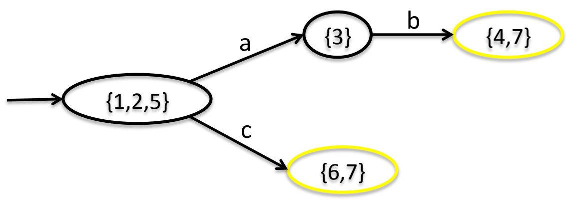


Done with {1,2,5}. Mark as visited (black in our diagram).

Example

- Convert NFA to a DFA:

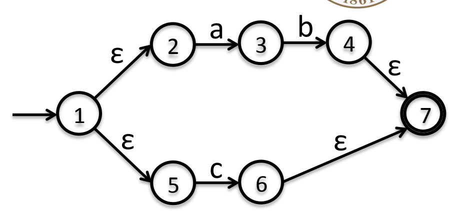


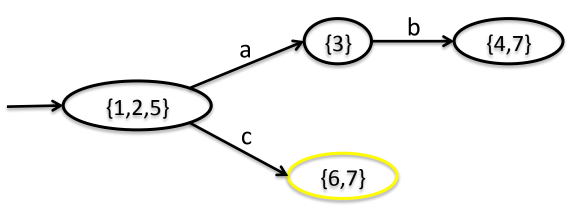


Repeat for another unvisited node ({3}). Creates {4,7}.

Example

- Convert NFA to a DFA:

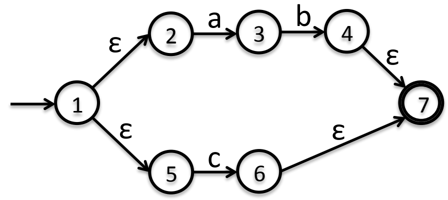


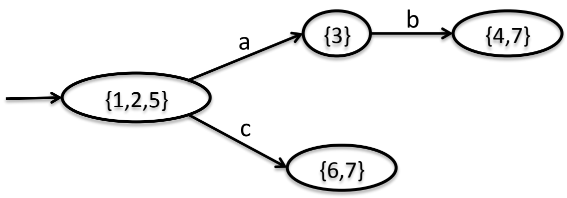


Repeat for unvisited node ({4,7}). No transitions.

Example

- Convert NFA to a DFA:

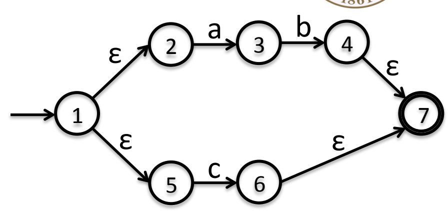


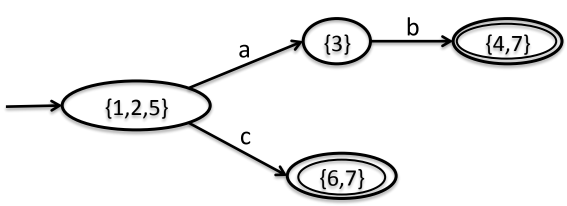


Repeat for unvisited node {6,7}. No transitions.

Example

- Convert NFA to a DFA:





No more unvisited nodes. Mark as final all states which include an NFA final state in their set.

Building a Scanner

- We've seen the theory (RE to NFA to DFA), but how is this converted to practice?
- A scanner needs to take an input stream and convert it to tokens.
  - Following the "longest match" principle – i.e., build the longest legal token starting at the current input position. Then repeat.
- General idea:
  - Create an RE for every token type. E.g., an RE for +, and RE for integers, etc.
  - Build a DFA for the union of the REs
  - Modify DFA implementation to recognize the longest matching substring (rather than only accepting the whole string).
    - This is sometimes free/unnecessary for certain DFAs
  - Repeatedly invoke (typically by the parser to obtain next token).

Scanning DFA

- How does this modified DFA work?
  - Must not just accept, but accept *and* tell us which RE generated the string (i.e., which token we found).
  - Identify the token by the final state we end in.
    - What if our DFA final state corresponds to multiple REs from the original?
    - This can happen if text matches *multiple tokens*. E.g., "for" may match the `for` keyword RE and the identifier RE. Compiler writer must define priority order (e.g., keywords > IDs).
  - Must also find longest match – may get this for free…
    - If needed, run DFA until no more transitions. If not in a final state, backtrack to last seen final state. Not always necessary.

Putting it together

- A scanner is a DFA that finds the next token each time it is called (and advances the input pointer to the token's end).
- Every "final" state of a DFA emits (returns) a token.
- For example:
  - **==** becomes <equal> (not <assign> <assign>)
  - **(** becomes <leftParen>
  - **private** becomes <private>
- Compiler writer (you!) choose the token names
- Also, there may be additional data associated with tokens … `\r\n` might count lines; all tokens might include line #; integer literals include value; etc.

DFA => Code, by Hand

- Option 1: One procedure per DFA state
  - Reads in a character, and uses a switch statement to determine the next state to call
  - Final states return token.
- Options 2: Single procedure for DFA, switch based on first character
  - We'll see an example of this in a few slides.
- Pros
  - Fairly straightforward to write.
  - If written well, can be faster than generated scanners (particularly option 2).
  - Can handle any weird language corner cases that don't map perfectly to the RE/NFA/DFA model.
  - Readable code (mostly).
- Cons
  - A lot of tedious work – thus, error prone.

DFA => code, automatic

- Option 1: use a tool to generate table driven scanner
  - Rows: states of DFA
  - Columns: input characters
  - Entries: action
    - Go to next state
    - Accept token, go to start state
    - Error
- Pros
  - Convenient – just feed it the token regular expressions
  - Exactly matches specification you give it, if tool correct
- Cons
  - "Magic"
  - Sometimes language constructs don't map perfectly to FA model
  - Not efficient

DFA => code, automatic

- Option 2: use tool to generate direct-coded scanner
  - Transitions embedded in the code, using conditional statements, loops, possibly goto
- Pros
  - Convenient – just feed it the REs
  - Exactly matches specification you give it, if tool correct
  - More efficient than table driven scanners
- Cons
  - "Magic"
  - Code is unreadable
  - Generates *lots* of code (but can be fairly fast)

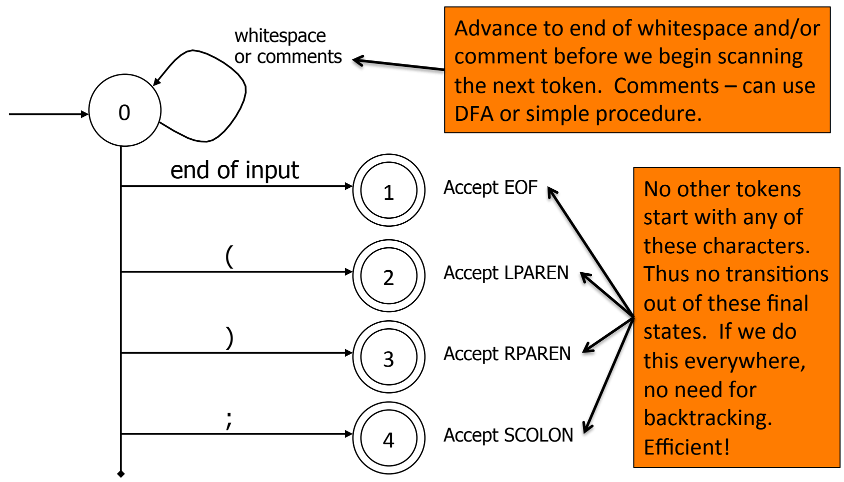
The Real World

- In commercial settings (and most gcc front ends) hand written scanners used more often than not.
  - Especially for larger languages, e.g., C++/Java.
  - Can purchase, e.g., EDG C/C++ front end (used by Cray, Intel, others).
- Why?
  - Fastest
  - Can handle language corner cases – C++ especially bad.
  - Readable/debuggable code.

Example: A hand-written DFA and scanner

- To demonstrate, we'll show a hand-written DFA for some typical programming language constructs
  - Then use to construct a hand-written scanner
- Setting: Scanner is called whenever the parser needs a new token
  - Scanner stores current position in input
  - From there, use a DFA to recognize the longest possible input sequence that makes up a token and return that token; save updated position for next time
- Disclaimer: Example for illustration only – you'll use tools for the course project.
- Credit: Hal Perkins wrote this DFA and code.

Scanner DFA Example (1)



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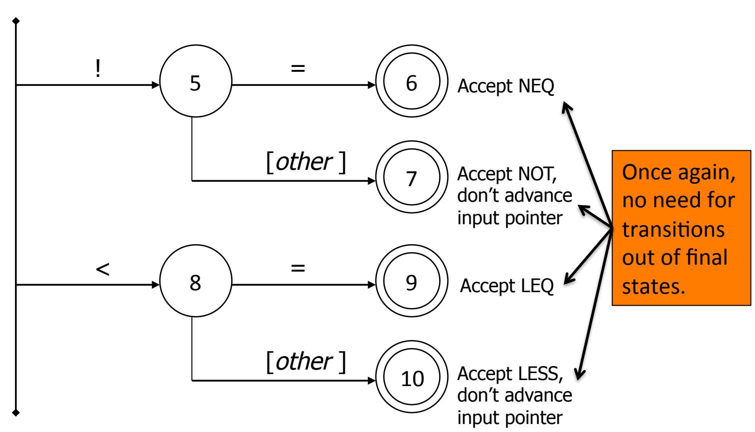
Scanner DFA Example (2)



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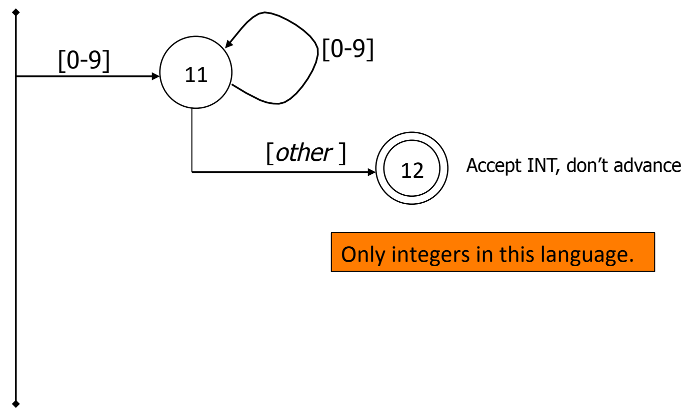
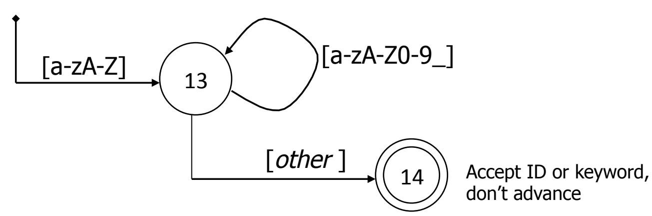
Scanner DFA Example (3)



Only integers in this language.

Scanner DFA Example (4)



- Strategies for handling identifiers vs keywords
  - Hand-written scanner: look up identifiers in table of keywords (good application of perfect hashing–i.e., given knowledge of keys ahead of time, can ensure no collisions.)
  - Machine-generated scanner: generate DFA with appropriate transitions to recognize keywords (> priority than IDs).

Backtracking

- As we saw, backtracking is not necessary in our DFA.
  - More efficient
- In many cases, token syntax can be chosen (and DFA constructed carefully) such that backtracking is rare (or can be avoided entirely).
- Easier to ensure this happens in a hand-written scanner
  - Part of why *well-written* hand-written scanners are the most efficient.

Implementing a Scanner by Hand – Token Representation

- A token is a simple, tagged structure
  - (Compilers written in C/C++ often use a "tagged union" style structure)

```
public class Token {
  public int kind;   // token's lexical class
  public int intVal;// integer value if class = INT
  public String id; // actual identifier if class = ID

  // lexical classes
  public static final int EOF    = 0; // "end of file"
                                      // token
  public static final int ID     = 1; // identifier,
                                      // not keyword
  public static final int INT    = 2; // integer
  public static final int LPAREN = 4; // (
  public static final int SCOLN  = 5; // ;
  public static final int WHILEK = 6; // )
  // etc. etc. etc. …
```

Simple Scanner Example

```
// global state and methods

// next unprocessed input character
static char nextch;

// advance to next input char
void getch() { … }

// skip whitespace and comments
void skipWhitespace() { … }

// input is a letter, digit, or _
boolean isIDChar(char c);
```


Scanner getToken() method

```
// Called by parser to retrieve the next input token
public Token getToken() {
  Token result;

  skipWhiteSpace();

  if (/*no more input*/) {
    result = new Token(Token.EOF); return result;
  }

  switch(nextch) {
    case '(': result = new Token(Token.LPAREN); getch();
              return result;
    case ')': result = new Token(Token.RPAREN); getch();
              return result;
    case ';': result = new Token(Token.SCOLON); getch();
              return result;
    // Repeat for other single character tokens…
```

getToken() (2)

```
case '!': // ! or !=
  getch();
  if (nextch == '=') {
    result = new Token(Token.NEQ); getch();
    return result;
  } else {
    result = new Token(Token.NOT); return result;
  }

case '<': // < or <=
  getch();
  if (nextch == '=') {
    result = new Token(Token.LEQ); getch();
    return result;
  } else {
    result = new Token(Token.LESS); return result;
  }
```


getToken() (3)

```
case '0': case '1': case '2': case '3': case '4':
case '5': case '6': case '7': case '8': case '9':
  // integer constant
  String num = nextch;
  getch();
  while (Character.isdigit(nextch)) {
    num = num + nextch;
    getch();
  }
  result = new Token(Token.INT,
                     Integer(num).intValue());
  return result;
```

getToken() (4)

```
case 'a': … case 'z':
case 'A': … case 'Z':  // id or keyword
  string s = nextch;
  getch();
  while (isIDChar(nextch))  // letter, digit, _
  {
    s = s + nextch; getch();
  }
  if (keywordTable.isKeyword(s)) {
    result = new Token(keywordTable.getKind(s));
  } else {
    result = new Token(Token.ID, s);
  }
  return result;
```


MiniJava Scanner Generation

- We'll use the JFlex tool to automatically create a scanner from a specification file.
- We'll use the CUP tool to automatically create a parser from a specification file.
- Token class is shared by jflex and CUP. Lexical classes (token kinds) are listed in CUP's input file and it generates the token class definition.
- So you'll need to modify both specification files for the scanner portion of your project
  - Parser mods will be small.

JFlex Specification Example

- Open src/Scanner/minijava.jflex in your project starter code. You'll see that a few tokens have already been done for you, to demonstrate how it works, e.g.:

```
"+" { return symbol(sym.PLUS); }
{letter} ({letter}|{digit}|_)* {
  return symbol(sym.IDENTIFIER, yytext());
}
```

- Format is Token RE, followed by code to execute.
- Can define helper abbreviations, e.g.:

```
letter = [a-zA-Z]
digit = [0-9]
```


Specifying the tokens

- Tokens are specified in the CUP file
  - src/Parser/minijava.cup

```
/* Terminals (tokens returned by the scanner) */

/* reserved words: */
terminal DISPLAY;

/* operators: */
terminal PLUS, BECOMES;

/* delimiters: */
terminal LPAREN, RPAREN, SEMICOLON;

/* tokens with values: */
terminal String IDENTIFIER;
```

JFlex Demo!

- Your project starter code has a few tokens defined already. We'll add multiplication.

Coming Attractions

- Starting next lecture: parsing
  - Will do LR parsing first – we need this for the project, then LL (recursive-descent) parsing, which you should also know.
  - May take the rest of January – it's a big topic…
- Sections – more details about using JFlex for your project.
  - The *full* details can be found in the JFlex and CUP documentation.