Scanners

Scanners

- Sometimes called *lexers*
- Recall: scanners break input stream up into a set of tokens
  - Identifiers, reserved words, literals, etc.
- What do we need to know?
  - How do we define tokens?
  - How can we recognize tokens?
  - How do we write scanners?

Regular expressions

- Regular sets: set of strings defined by regular expressions
  - Strings are regular sets (with one element): purdue 3.14159
    - So is the empty string: λ (sometimes use ε instead)
  - Concatentations of regular sets are regular: purdue3.14159
    - To avoid ambiguity, can use ( ) to group regexps together
  - A choice between two regular sets is regular, using |: (purdue|3.14159)
  - 0 or more of a regular set is regular, using *: (purdue)*
  - Some other notation used for convenience:
    - Use Not to accept all strings *except* those in a regular set
    - Use ? to make a string optional: x? equivalent to (x|λ)
    - Use + to mean 1 or more strings from a set: x+ equivalent to xx*
    - Use [ ] to present a range of choices: [1-3] equivalent to (1|2|3)

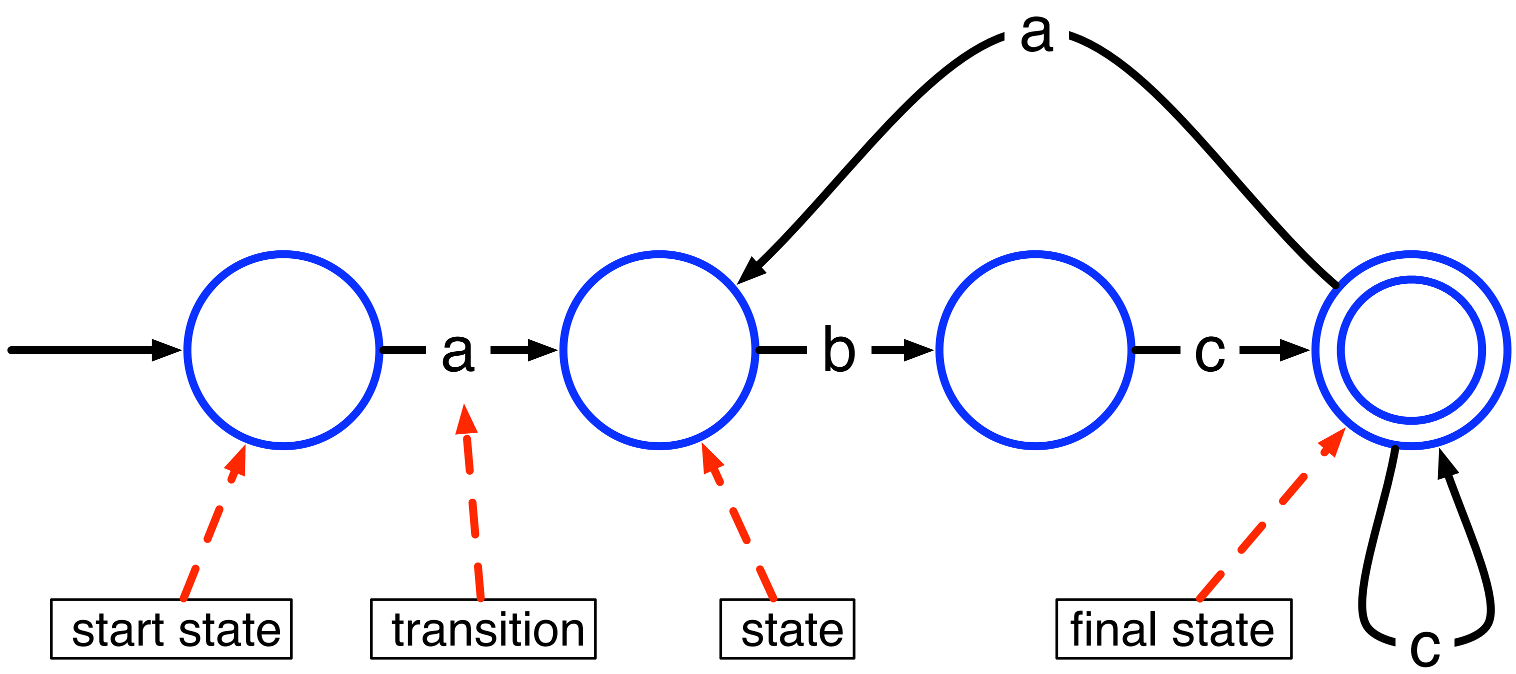
Examples of regular expressions

- Numbers: D = [0-9]+
- Words: L = [A-Za-z]+
- Literals (integers or floats): -?D+(.D*)?
- Identifiers: (_|L)(_|L|D)*
- Comments (as in Micro): -- Not(\n)*\n
- More complex comments (delimited by ##, can use # inside comment): ##((#|λ)Not(#))*##

Finite automata

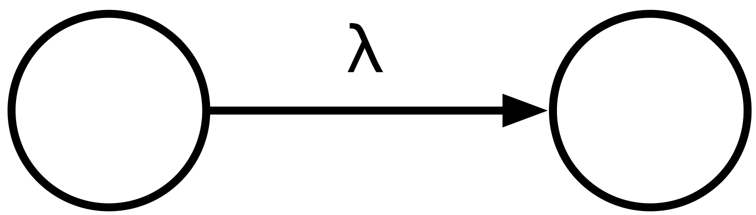
- Finite state machine which will only *accept* a string if it is in the set defined by the regular expression

(a b c+)+



λ transitions

- Transitions between states that aren't triggered by seeing another character
  - Can *optionally* take the transition, but do not have to
  - Can be used to link states together



Non-deterministic FA

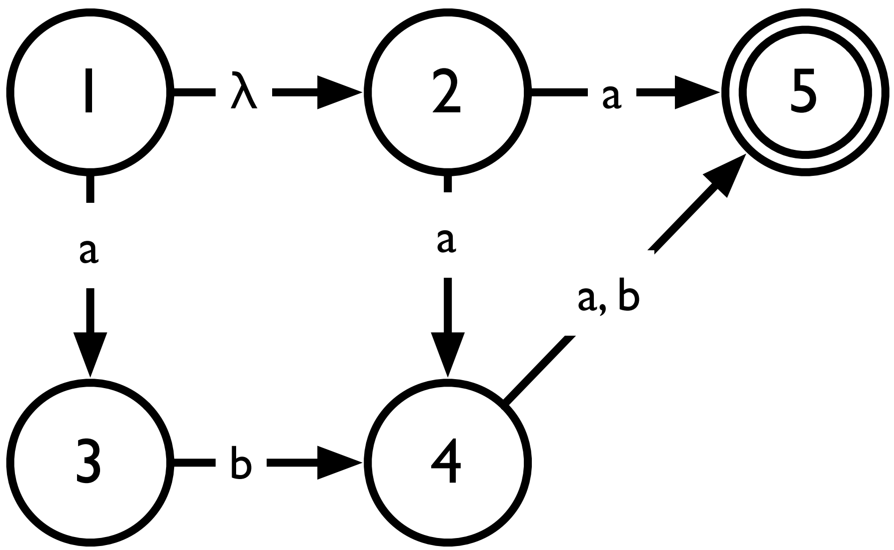
- Note that if a finite automaton has a λ-transition in it, it may be *non-deterministic* (do we take the transition? or not?)
  - More precisely, FA is non-deterministic if, from one state reading a single character could result in transition to multiple states
- How do we deal with non-deterministic finite automata (NFAs)?

“Running” an NFA

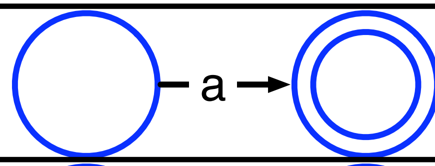
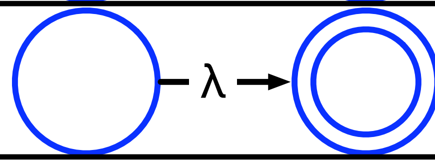
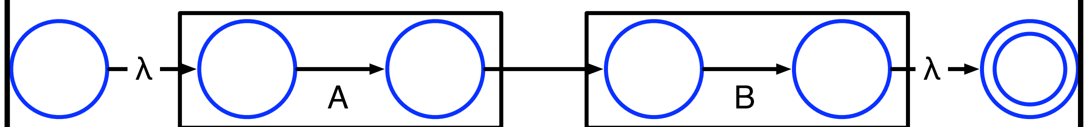
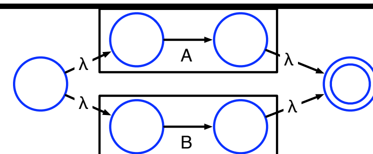
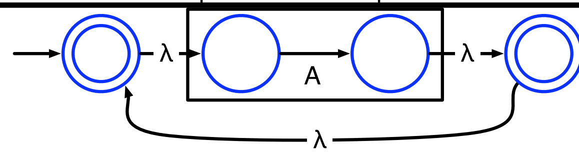
- Intuition: take every possible path through an NFA
  - Essentially, parallel execution of NFA
  - Maintain a “pointer” that tracks the current state
  - Every time there is a choice, “split” the pointer, and have one pointer follow each choice
  - Track each pointer simultaneously
    - If a pointer gets stuck, stop tracking it
    - If any pointer reaches an accept state at the end of input, accept

Example

- How does this NFA handle the string "aba"?



Building a FA from a regexp

Expression	FA
a	
λ	
AB	
A|B	
A*	

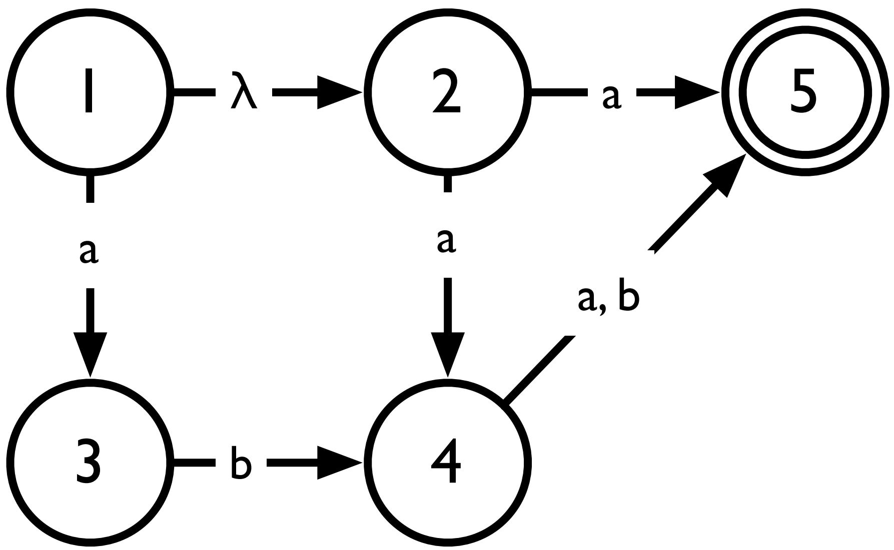
Mini-exercise: how do we build an FA that accepts Not(A)?

NFAs to DFAs

- Can convert NFAs to *deterministic* finite automata (DFAs)
  - No choices — never a need to "split" pointers
- Initial idea: simulate NFA for all possible inputs, any time there is a new configuration of pointers, create a state to capture it
  - Pointers at states 1, 3 and 4 → new state {1, 3, 4}
- Trying all possible inputs is impractical; instead, for any new state, explore all possible *next* states (that can be reached with a single character)
- Process ends when there are no new states found
- Algorithm on page 82 of textbook
- This can result in very large DFAs!

Example

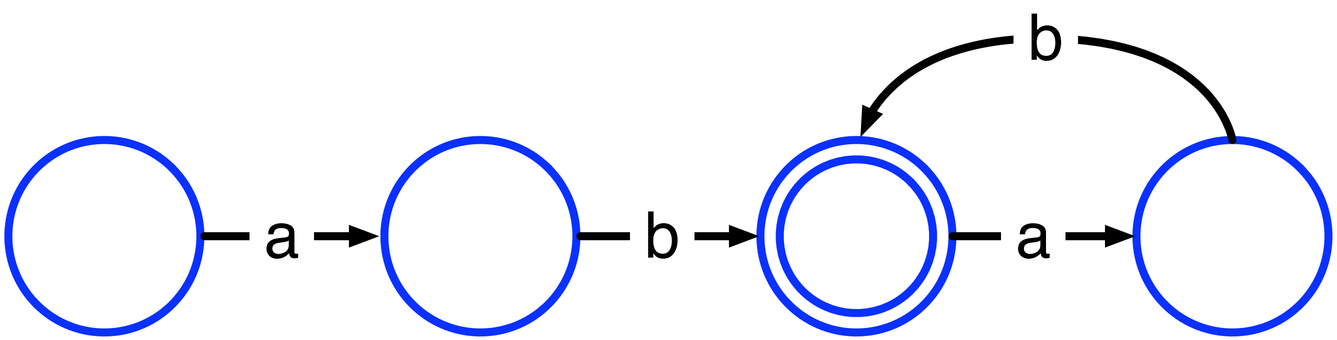
- Convert the following into a DFA



DFA reduction

- DFAs built from NFAs are not necessarily optimal
  - May contain many more states than is necessary

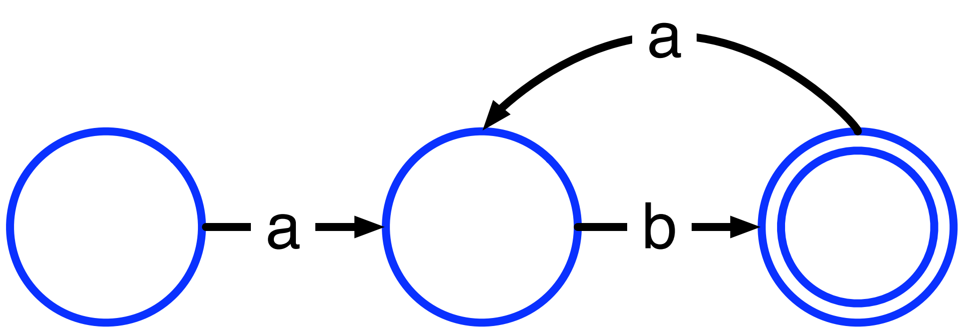
(ab)+ ≡ (ab)(ab)*



DFA reduction

- DFAs built from NFAs are not necessarily optimal
  - May contain many more states than is necessary

$$(ab)+ \equiv (ab)(ab)^*$$

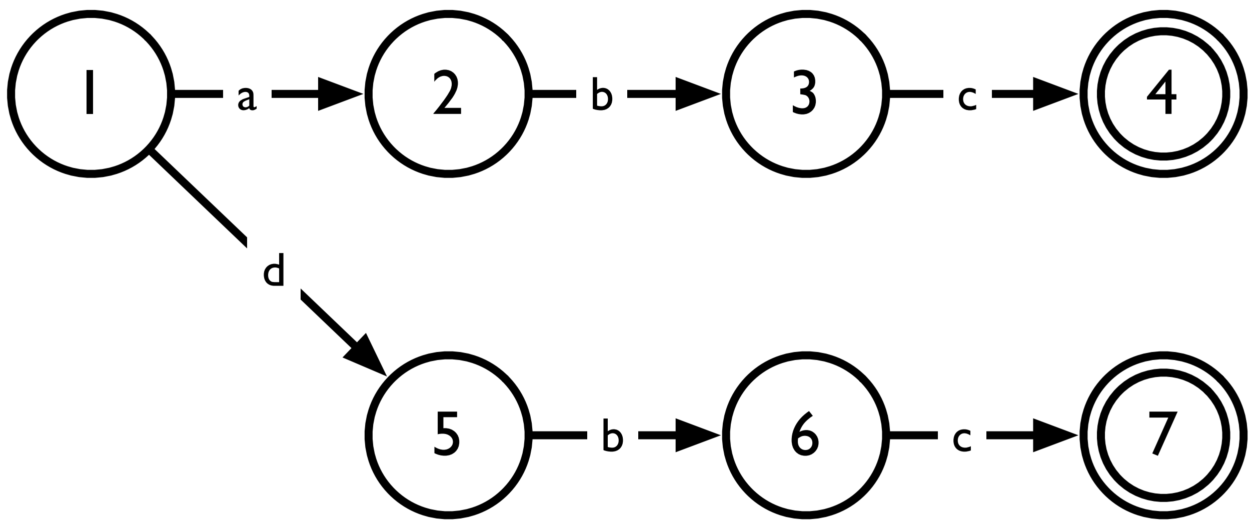


DFA reduction

- Intuition: merge equivalent states
  - Two states are equivalent if they have the same transitions to the same states
- Basic idea of optimization algorithm
  - Start with two big nodes, one representing all the final states, the other representing all other states
  - Successively split those nodes whose transitions lead to nodes in the original DFA that are in different nodes in the optimized DFA
  - See algorithm on page 85 of textbook

Example

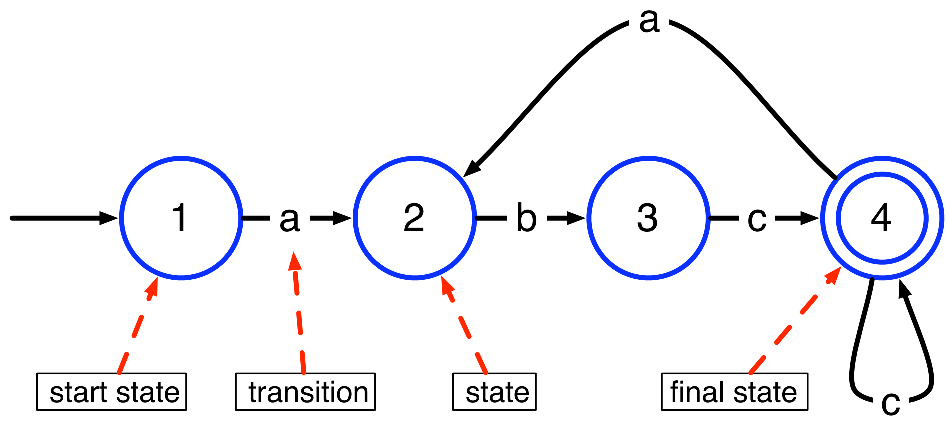
- Simplify the following



Transition tables

- Table encoding states and transitions of FA
  - 1 row per state, 1 column per possible character
  - Each entry: if automaton in a particular state sees a character, what is the next state?

State	Character		
	a	b	c
1	2		
2		3	
3			4
4	2		4



Finite automata program

- Using a transition table, it is straightforward to write a program to recognize strings in a regular language

```
state = initial_state; //start state of FA
while (true) {
   next_char = getc();
   if (next_char == EOF) break;
   next_state = T[state][next_char];
   if (next_state == ERROR) break;
   state = next_state;
}
if (is_final_state(state))
   //recognized a valid string
else
   handle_error(next_char);
```

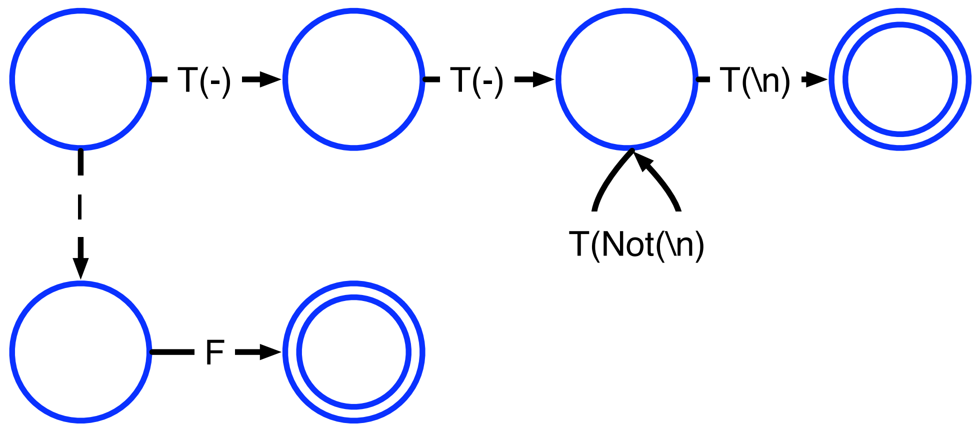
Alternate implementation

- Here's how we would implement the same program "conventionally"

```
next_char = getc();
while (next_char == 'a') {
   next_char = getc();
   if (next_char != 'b') handle_error(next_char);
   next_char = getc();
   if (next_char != 'c') handle_error(next_char);
   while (next_char == 'c') {
      next_char = getc();
      if (next_char == EOF) return; //matched token
      if (next_char == 'a') break;
      if (next_char != 'c') handle_error(next_char);
   }
}
handle_error(next_char);
```

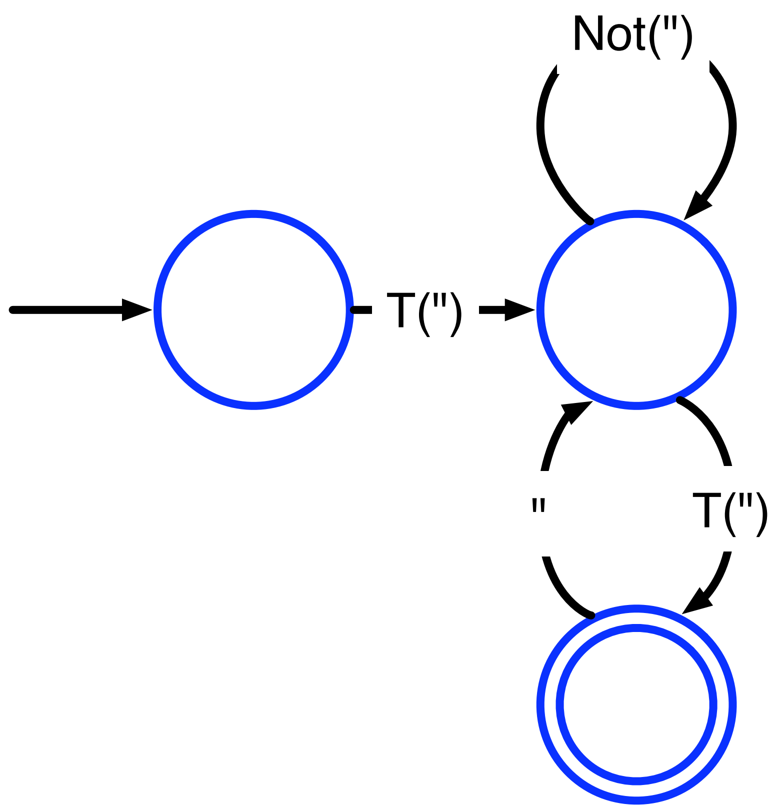
Transducers

- Simple extension of a FA which also outputs the recognized string
- Recognized characters are output; everything else is discarded
  - Annotate transitions:
    - T(x): "toss" x
    - x: "save" x
- Example: DFA to recognize comments and "if" token



Example: Transducer for strings

- Recognize quoted strings
- Can use double quotation marks (“”) within string to produce a quotation mark
- (“ (Not(”) | “”)* ”)
- Examples:
  - “ECE 468”
    - ➡ ECE 468
  - “Scanning is ““fun”” ”
    - ➡ Scanning is “fun”



Practical Consderations

Or: what do I have to worry about if I'm actually going to write a scanner?

Handling reserved words

- Keywords can be written as regular expressions. However, this leads to a big blowup in FA size
  - Consider writing a regular expression that accepts identifiers which *cannot* be if, while, do, for, etc.
- Usually better to specify reserved words as "exceptions"
  - Capture them using the identifier regexp, and then decide if the token corresponds to a reserved word

Generating symbol table entries

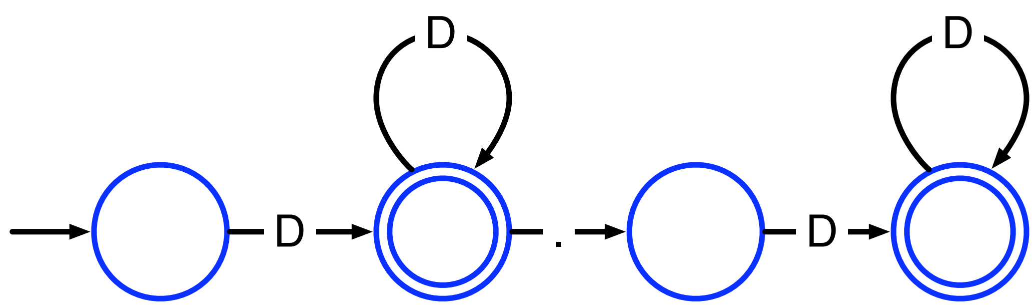
- In simple languages, the scanner can build the symbol table directly
- In more complex languages, with complicated scoping rules, this needs to be handled by the parser

Lookahead

- Up until now, we have only considered matching an entire string to see if it is in a regular language
- What if we want to match multiple tokens from a file?
  - Distinguish between `int a` and `inta`
  - We need to *look ahead* to see if the next character belongs to the current token
  - If it does, we can continue
  - If it doesn't, the next character becomes part of the next token

Multi-character lookahead

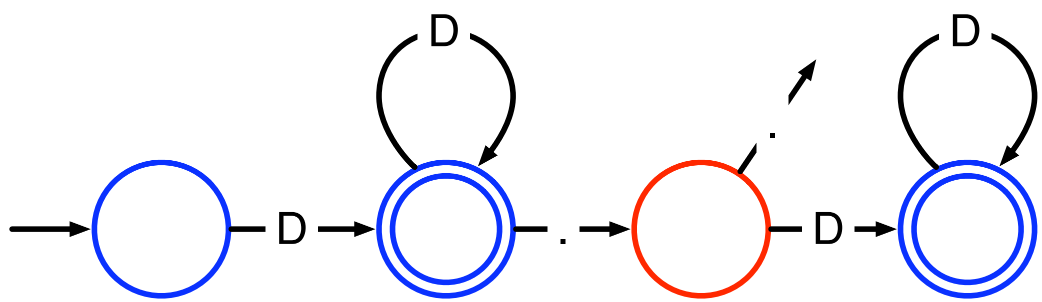
- Sometimes, a scanner will need to look ahead more than one character to distinguish tokens
- Examples
  - Fortran: DO I = 1,100 (loop) vs. DO I = 1.100 (variable assignment)
  - Pascal: 23.85 (literal) vs. 23..85 (range)



- 2 solutions: Backup or special "action" state

Multi-character lookahead

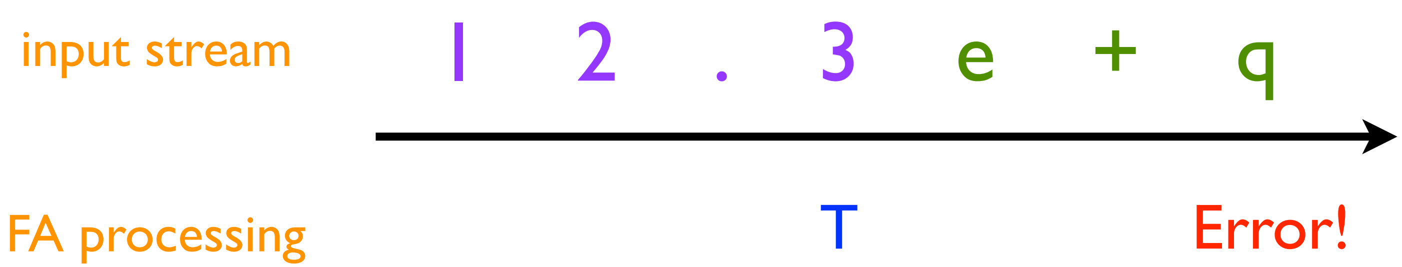
- Sometimes, a scanner will need to look ahead more than one character to distinguish tokens
- Examples
  - Fortran: DO I = 1,100 (loop) vs. DO I = 1.100 (variable assignment)
  - Pascal: 23.85 (literal) vs. 23..85 (range)



- 2 solutions: Backup or special "action" state

General approach

- Remember states (T) that can be final states
- Buffer the characters from then on
- If stuck in a non-final state, back up to T, restore buffered characters to stream
- Example: 12.3e+q



Why can't we do this?

- Just build an FA which recognizes the string

  D+(λ |.D+)(. | ..)D+(λ |.D+) and recognize the final state we are in to determine the token type?

- Note that this will recognize tokens of the form 12.3 and 12..3

Error Recovery

- What do we do if we encounter a lexical error (a character which causes us to take an undefined transition)?
- Two options
  - Delete all currently read characters, start scanning from current location
  - Delete *first* character read, start scanning from second character
    - This presents problems with ill-formatted strings (why?)
    - One solution: create a new regexp to accept runaway strings

Scanner Generators

Scanner generators

- Essentially, tools for converting regular expressions into finite automata
- Two well-known tools
  - ScanGen: a scanner generator that produces transition tables for a finite automaton driver program (as we saw earlier)
  - Lex: generates a scanner directly, makes use of user-written "filter" functions to output tokens

ScanGen

- User defines the input to ScanGen using a file with three sections:
  - Options : ScanGen settings for table optimization, etc.
  - Character classes : define sets of characters (e.g., digits)
  - Token definitions :
    - `Token name { minor major } = regexp`
      - Can include "except" clauses to simplify regexps
      - Can "toss" parts of regexps
  - Sample ScanGen input (for Micro language): page 61 of textbook

ScanGen driver

- Driver routine provides the actual scanner, which will be called by the parser

```
void scanner(codes *major,
             codes *minor,
             char *token_text)
```

- Reads input character stream, drives the finite automaton using the table generated by ScanGen, and returns found tokens

ScanGen tables

- ScanGen produces two tables:
  - State table: next_state[NUM_STATES][NUM_CHARS]
    - Encodes transition table
  - Action table: action[NUM_STATES][NUM_CHARS]
    - Tells the driver when a complete token is recognized (i.e., defines accepting states), and what to do with the "lookahead" character

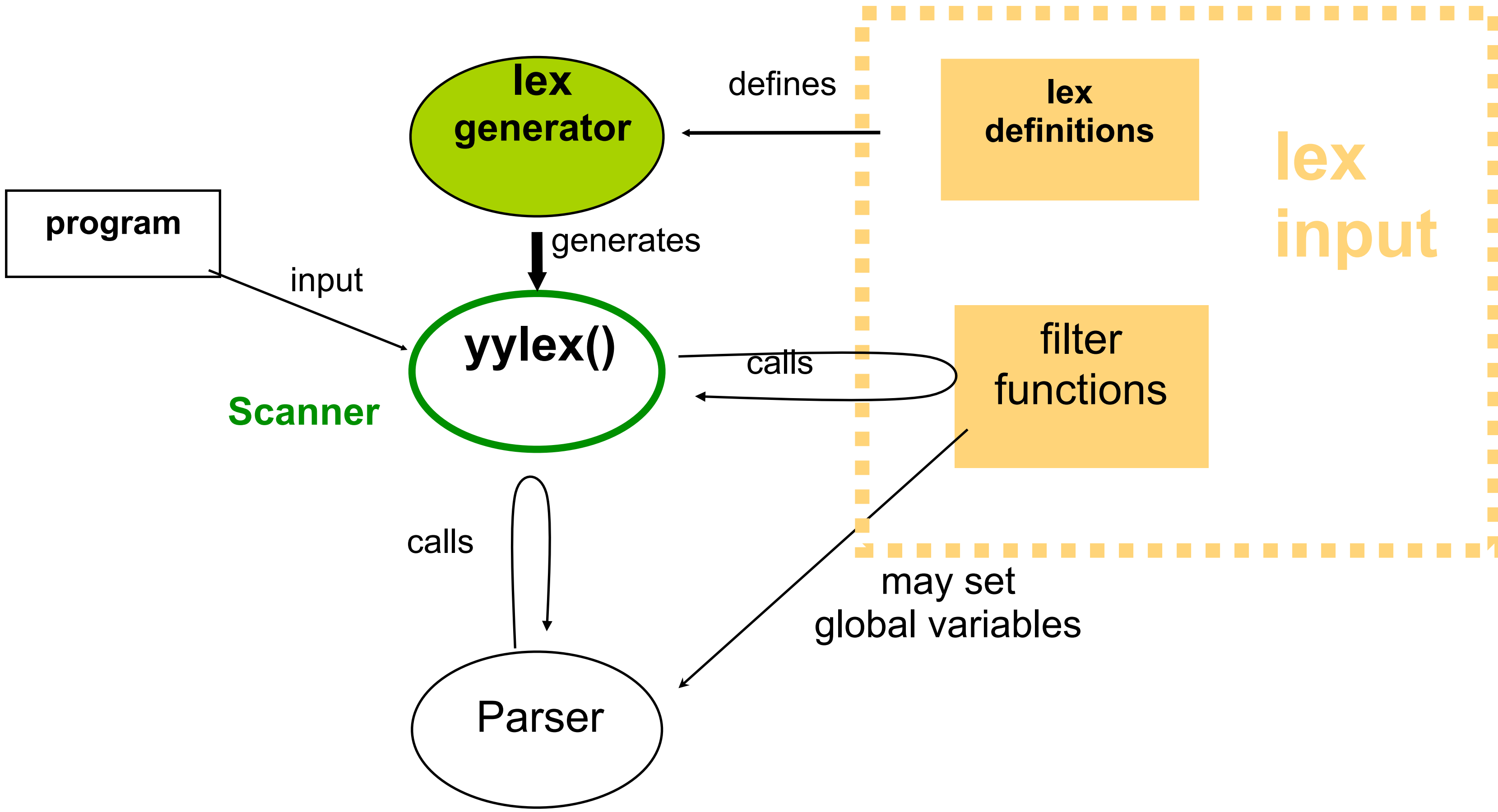
Actions

- Action table has 6 possible values
  - ERROR: scan error
  - MOVEAPPEND: add next character to token string and continue
  - MOVENOAPPEND: "toss" next character and continue
  - HALTAPPEND: add next character to token string and return it (final state)
  - HALTNOAPPEND: "toss" next character and return token (final state)
  - HALTREUSE: put next character back on to input and return token (final state)
- Question: Why no "MOVEREUSE" state?
- Driver program on pages 65–66 of textbook

Lex (Flex)

- Commonly used Unix scanner generator (superseded by Flex)
- Has character classes and regular expressions like ScanGen but some key differences:
  - After each token is matched, calls user-defined "filter" function, which processes identified token before returning it to parser
    - Hence, no "Toss" facility (why?)
  - No exception list
    - Instead, supports matching multiple regexps.
      - Matches longest token (i.e., doesn't think `ifa` is `IF ID(a)`)
      - In case of tie, returns earliest-defined regexp
        - To treat `if` as a reserved word instead of an identifier, define token IF before defining identifiers.

Lex operation



Example of Lex input on page 67 of textbook

Next Time

- We've covered how to tokenize an input program
- But how do we decide what the tokens actually say?
  - How do we recognize that

    IF ID(a) OP(<) ID(b) { ID(a) ASSIGN LIT(5) ; }

    is an if-statement?
- Next time: Parsers