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 LITTLE): -- Not(\n)*\n
- More complex comments (delimited by ##, can use # inside comment): ##((#|λ)Not(#))*##

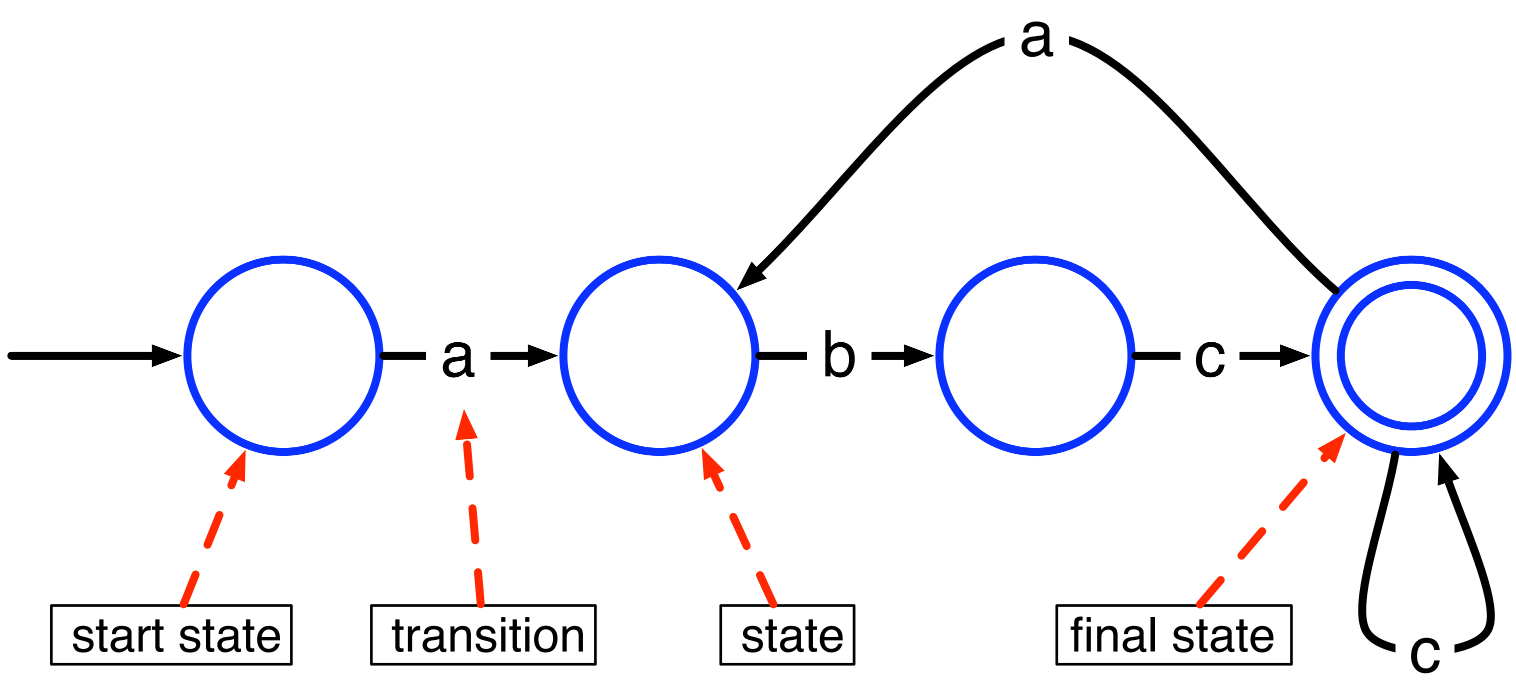
How do we build a scanner?

- Idea: represent each token as a regular expression
  - Match token if regular expression matches
  - Big problem: string of characters can have multiple tokens
- Simpler problem for now: decide if a regular expression matches the entire string

Finite automata

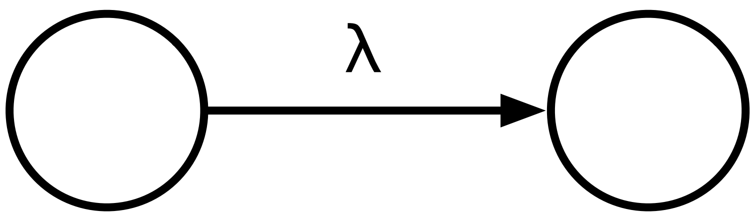
- Finite state machine which will only *accept* a string if it is in the set defined by the regular expression

(a b c+)+



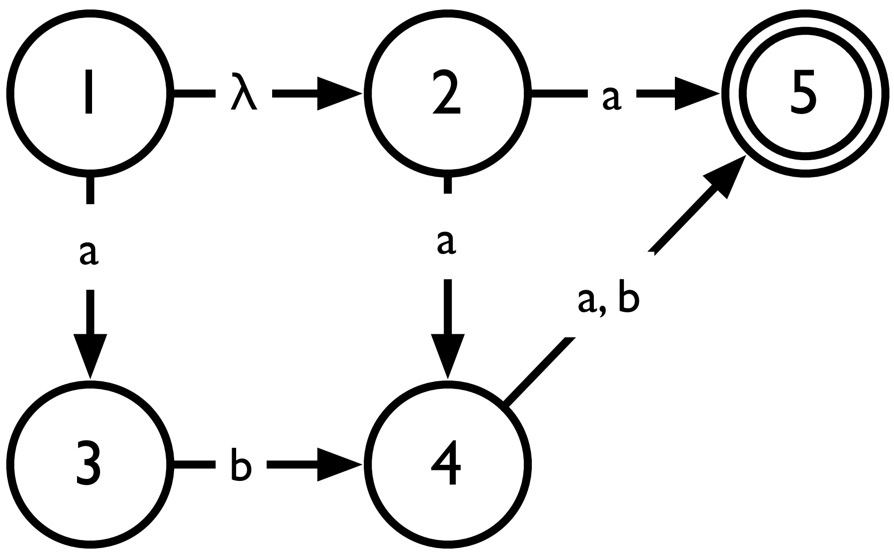
λ transitions

- 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 FAs (NFAs)

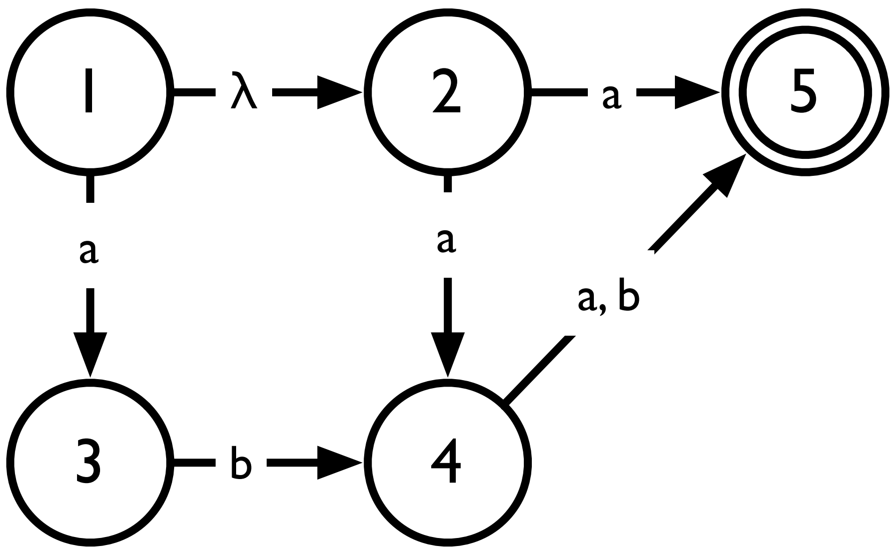
- What happens when we have an FA that offers multiple choices?
  - FA is *non-deterministic* if, from one state reading a single character could result in transition to multiple states
  - If a finite automaton has a λ-transition in it, it may be non-deterministic (do we take the transition? or not?)



Simulating NFAs

- To run NFA, simulate *every* possible path
  - Intuition: *deterministic* FAs (DFAs) have a "pointer" that follows the single path from one state to the next
  - When we come to a non-deterministic choice, we can "split" the pointer into two, one for each path
- Termination conditions
  - If *any* pointer is in an accept state at the end of input, the NFA accepts (intuitively: there was one possible path that took us to the accept state)
  - If *all* pointers enter an error state, the NFA enters the error state (intuitively: no possible path avoids the error state)

Example

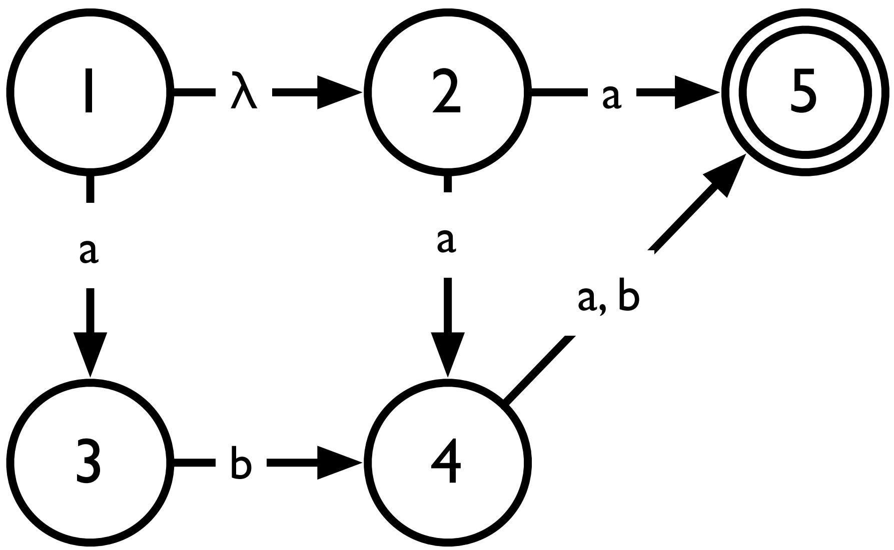


NFAs to DFAs

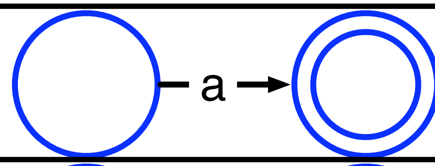
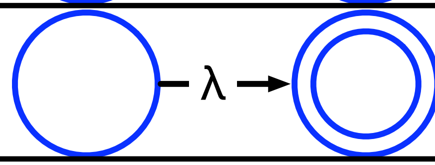
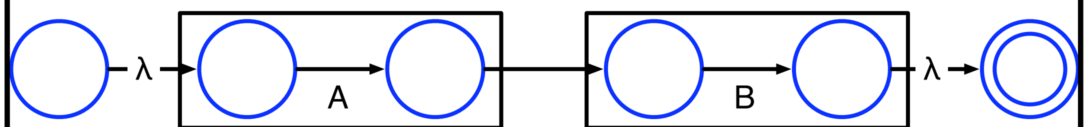
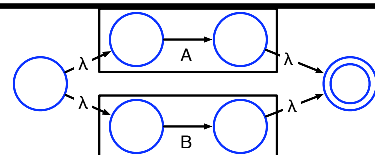
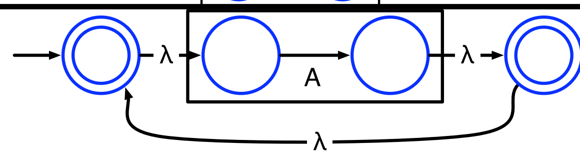
- We can convert NFAs to DFAs!
- Intuition: create new states that express where *every* "pointer" in the NFA is at any given time
  - *Subset construction*
  - Note: this can result in very large DFAs!

Example

- Convert the following into a DFA



Building a FA from a regexp

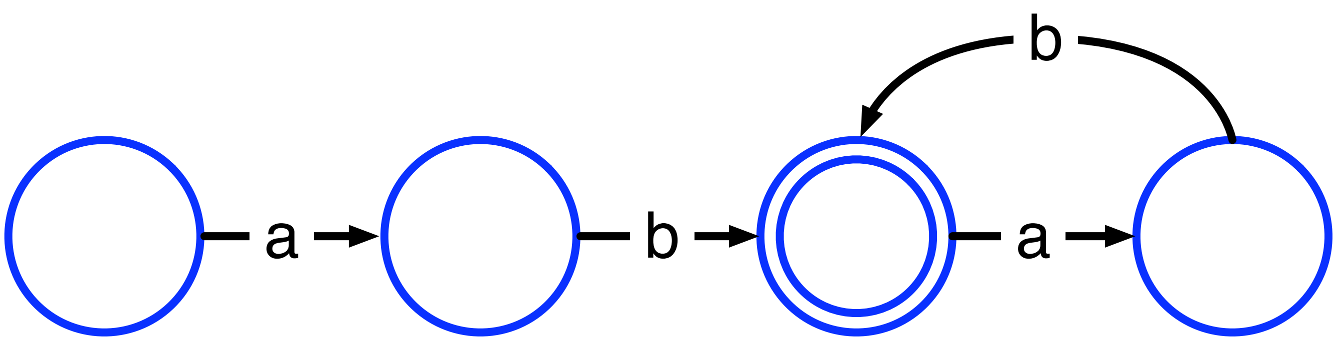
Expression	FA
a	
λ	
AB	
A|B	
A*	

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

DFA reduction

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

(ab)+ ≡ (ab)(ab)*



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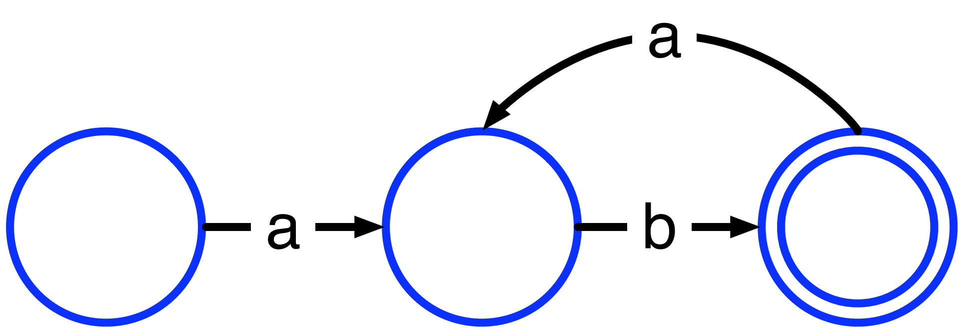
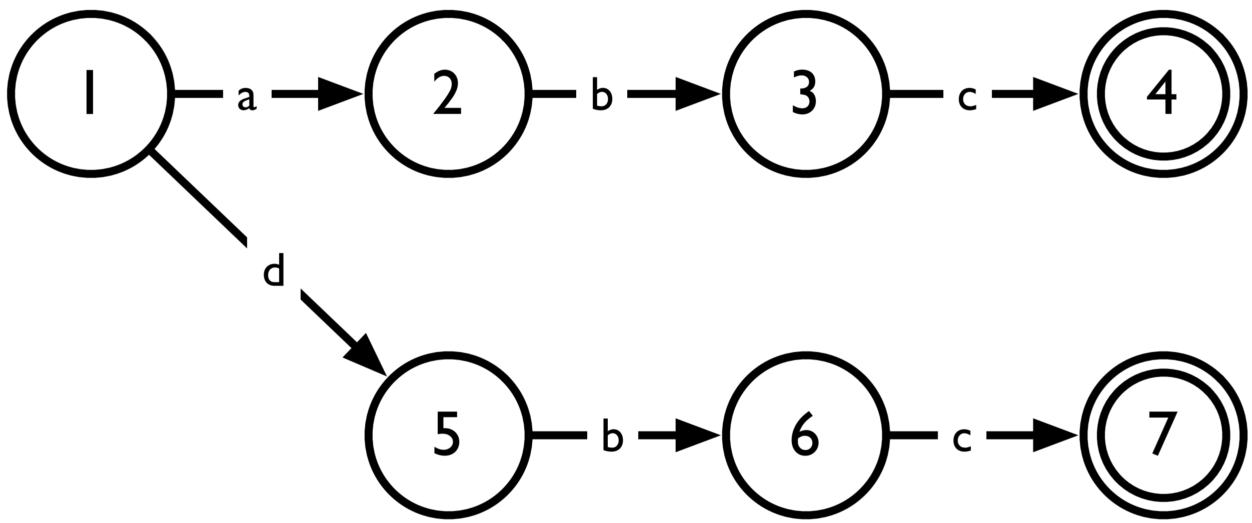


DFA reduction

- 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

Example

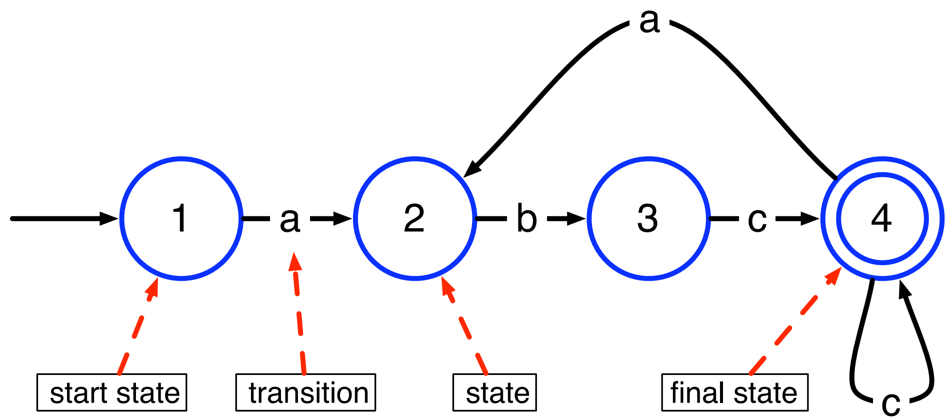
- Simplify the following



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);
```

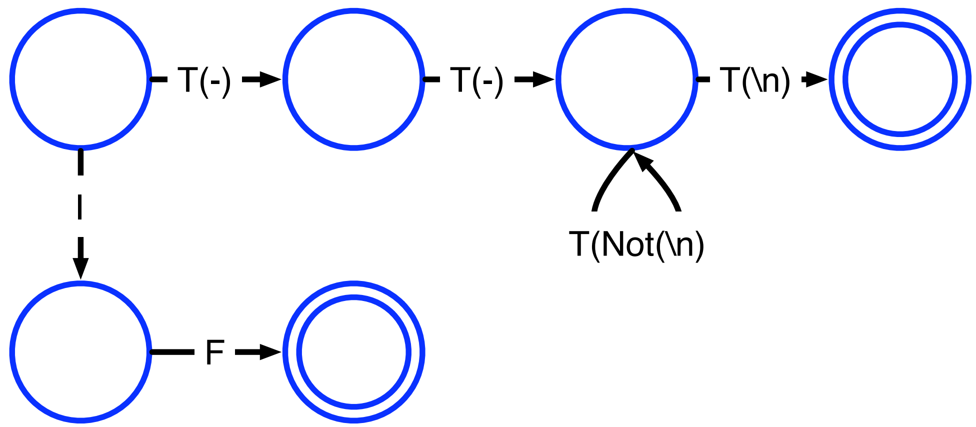
Alternate implementation

- 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);
```

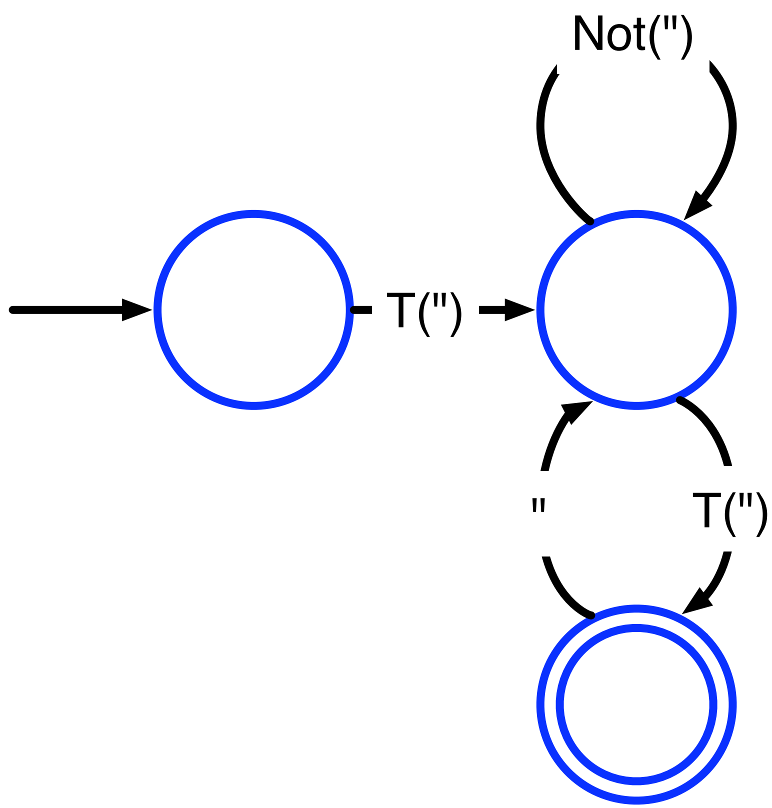
Transducers

- 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:
    - “Compilers”
        - ➡ Compilers
    - “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

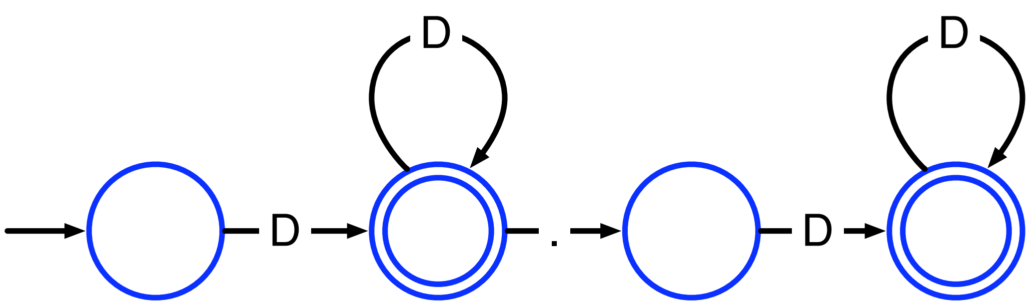
- Keywords can be written as regular expressions. However, this leads to a big blowup in FA size
  - Consider writing a regular expression that accepts identifiers which *cannot* be if, while, do, for, etc.
- Usually better to specify reserved words as "exceptions"
  - Capture them using the identifier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

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

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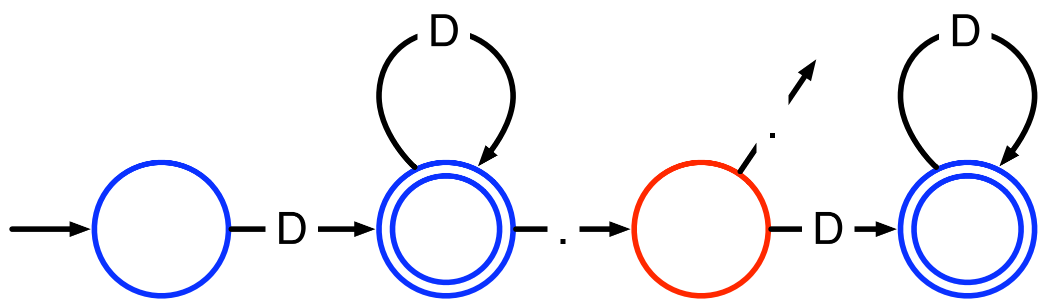
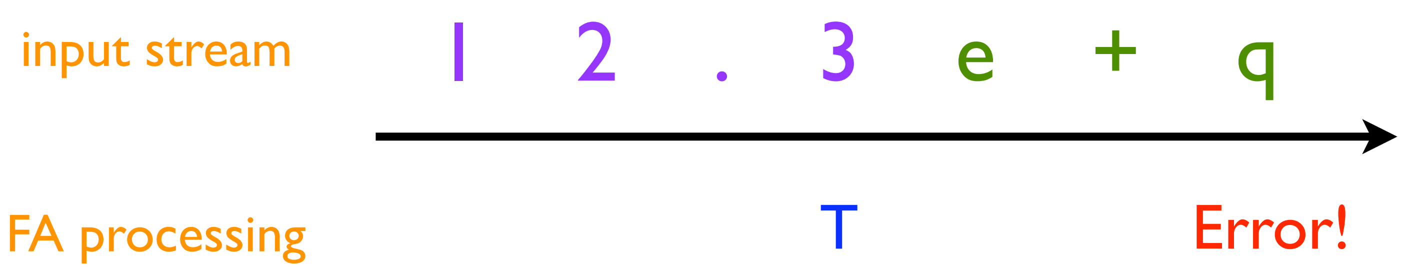


- 2 solutions: Backup or special "action" state

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 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

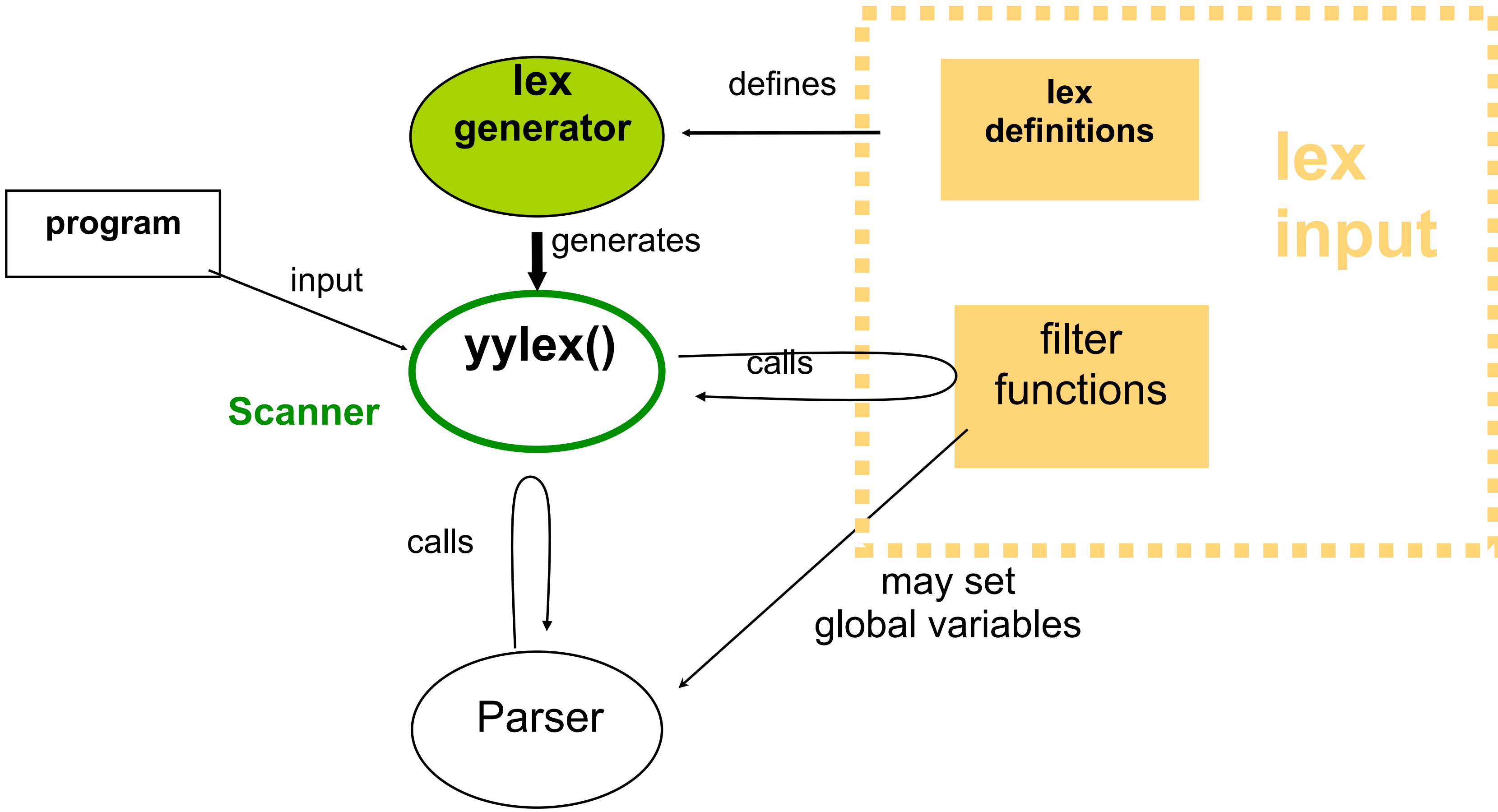
Actions

- 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



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