Lecture 9

# EECS 483: COMPILER CONSTRUCTION

# Announcements

- HW2: Grades posted
- HW3: LLVM lite
  - Due: Next Tuesday at 11:59:59pm
  - Some people are still looking for partners on Piazza!

***START EARLY!!***

- Midterm: Tuesday, March 12$^{th}$
  - 7-9pm, DOW 1013 and 1014 (seat assignments will be announced later)
  - One-page, letter-sized, double-sided "cheat sheet" of notes permitted
  - See examples of previous exams on the web pages
  - March 11 will be review/office hours, no lecture.

# TAGGED DATATYPES

# C-style Enumerations / ML-style datatypes

- In C:

```
enum Day {sun, mon, tue, wed, thu, fri, sat} today;
```

- In ML:

```
type day = Sun | Mon | Tue | Wed | Thu | Fri | Sat
```

- Associate an integer *tag* with each case: `sun` = 0, `mon` = 1, …
  - C lets programmers choose the tags

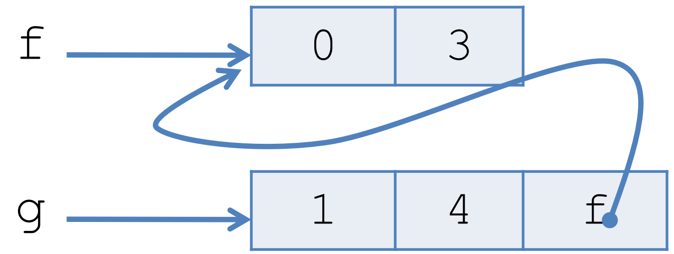
- ML datatypes can also carry data:

```
type foo = Bar of int | Baz of int * foo
```

- Representation: a `foo` value is a pointer to a pair: (tag, data)
- Example: tag(`Bar`) = 0, tag(`Baz`) = 1

  ⟦`let f = Bar(3)`⟧ =

  ⟦`let g = Baz(4, f)`⟧ =



# Switch Compilation

- Consider the C statement:

```
switch (e) {
    case sun: s1; break;
    case mon: s2; break;
    …
    case sat: s3; break;
}
```

- How to compile this?
  - What happens if some of the break statements are omitted? (Control falls through to the next branch.)

# Cascading `if`s and Jumps

⟦`switch(e) {case tag1: s1; case tag2 s2; …}`⟧ =

- Each `$tag1…$tagN` is just a constant int tag value.
- Note: ⟦break;⟧ (within the switch branches) is:
  `br %merge`

```
    %tag = ⟦e⟧;
    br label %l1
l1: %cmp1 = icmp eq %tag, $tag1
    br %cmp1 label %b1, label %merge
b1: ⟦s1⟧
    br label %l2

l2: %cmp2 = icmp eq %tag, $tag2
    br %cmp2 label %b2, label %merge
b2: ⟦s2⟧
    br label %l3
…
lN: %cmpN = icmp eq %tag, $tagN
    br %cmpN label %bN, label %merge
bN: ⟦sN⟧
    br label %merge

merge:
```

# Cascading `ifs` and Jumps

⟦`switch(e) {case tag1: s1; case tag2 s2; …}`⟧ =

- Each `$tag1`…`$tagN` is just a constant int tag value.
- Note: ⟦break;⟧ (within the switch branches) is: `br %merge`

```
    %tag = ⟦e⟧;
    br label %l1
l1: %cmp1 = icmp eq %tag, $tag1
    br %cmp1 label %b1, label %l2
b1: ⟦s1⟧
    br label %b2

l2: %cmp2 = icmp eq %tag, $tag2
    br %cmp2 label %b2, label %l3
b2: ⟦s2⟧
    br label %b3
…
lN: %cmpN = icmp eq %tag, $tagN
    br %cmpN label %bN, label %merge
bN: ⟦sN⟧
    br label %merge

merge:
```

# Alternatives for Switch Compilation

- Nested if-then-else works OK in practice if # of branches is small
  - (e.g. < 16 or so).
- For more branches, use better datastructures to organize the jumps:
  - Create a table of pairs (v1, branch_label) and loop through
  - Or, do binary search rather than linear search
  - Or, use a hash table rather than binary search
- One common case: the tags are dense in some range [min…max]
  - Let N = max – min
  - Create a branch table Branches[N] where Branches[i] = branch_label for tag i.
  - Compute tag = ⟦e⟧ and then do an *indirect jump*: J Branches[tag]
- Common to use heuristics to combine these techniques.

# ML-style Pattern Matching

- ML-style match statements are like C's switch statements except:
  - Patterns can bind variables
  - Patterns can nest

```
match e with
| Bar(z) -> e1
| Baz(y, Bar(w)) -> e2
| _ -> e3
```

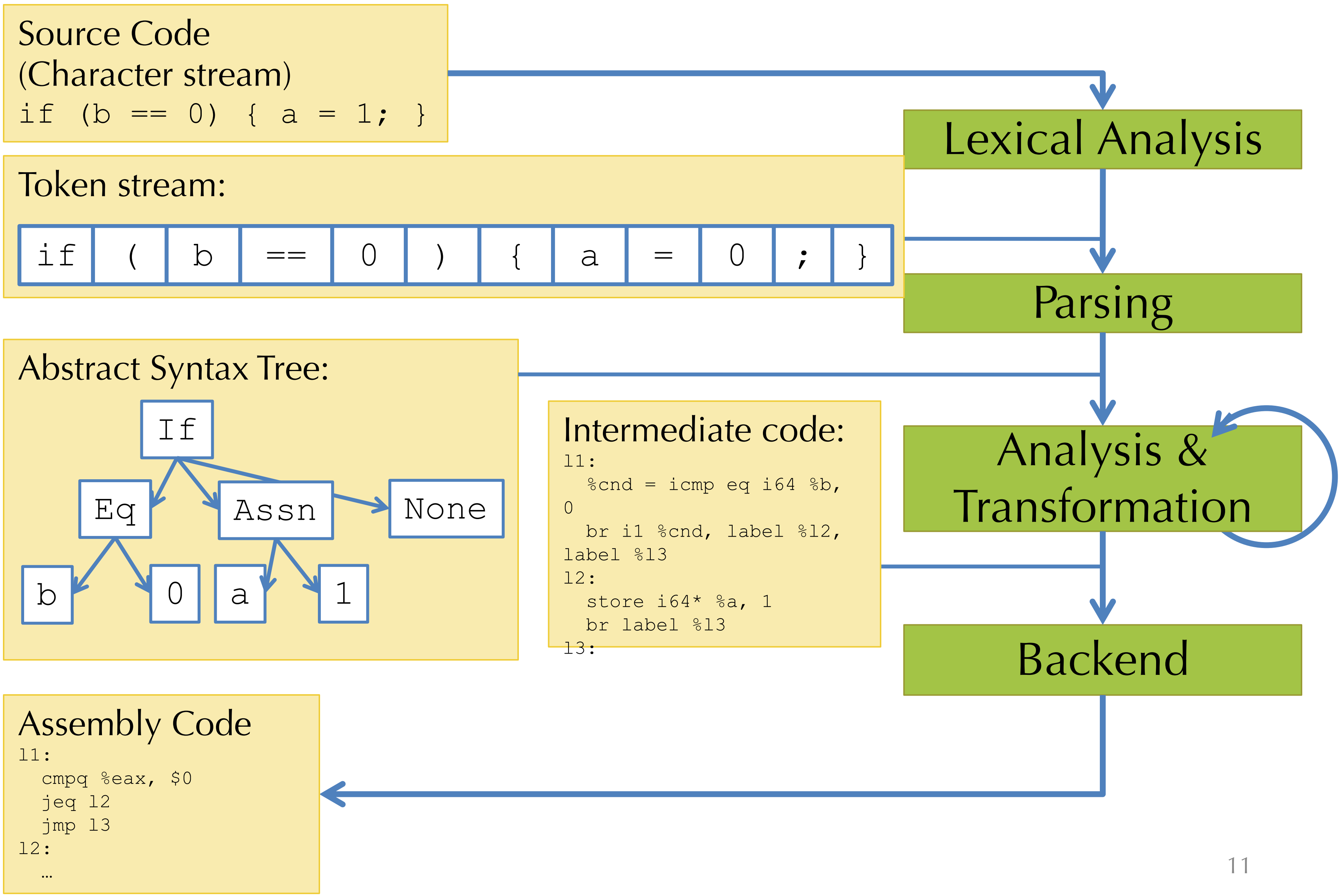
```
match e with
| Bar(z) -> e1
| Baz(y, tmp) ->
    (match tmp with
      | Bar(w) -> e2
      | Baz(_, _) -> e3)
```

- Compilation strategy:
  - "Flatten" nested patterns into matches against one constructor at a time.
  - Compile the match against the tags of the datatype as for C-style switches.
  - Code for each branch additionally must copy data from ⟦e⟧ to the variables bound in the patterns.
- There are many opportunities for optimization, many papers about "pattern-match compilation"
  - Many of these transformations can be done at the AST level

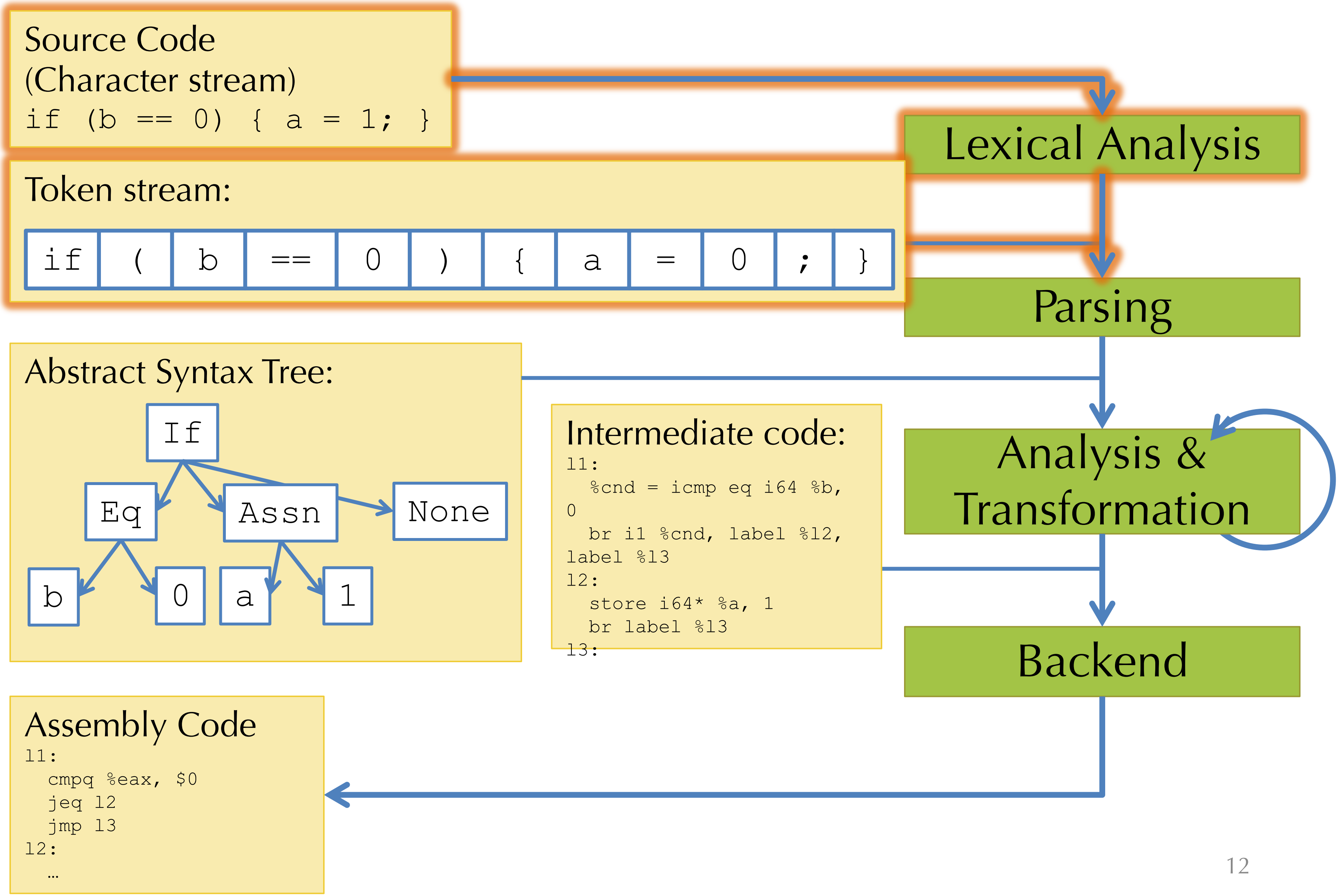
Lexical analysis, tokens, regular expressions, automata

# LEXING

# Compilation in a Nutshell



# Today: Lexing



# First Step: Lexical Analysis

- Change the *character stream* “`if (b == 0) a = 0;`” into *tokens*:

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| if | ( | b | == | 0 | ) | { | a | = | 0 | ; | } |

```
IF; LPAREN; Ident(“b”); EQEQ; Int(0); RPAREN; LBRACE;
Ident(“a”); EQ; Int(0); SEMI; RBRACE
```

- Token: data type that represents indivisible “chunks” of text:
  - Identifiers: `a   y11  elsex   _100`
  - Keywords: `if   else   while`
  - Integers: `2   200   -500    5L`
  - Floating point: `2.0    .02    1e5`
  - Symbols: `` +   *   `   {   }   (   )   ++   <<   >>   >>> ``
  - Strings: `“x”    “He said, \”Are you?\””`
  - Comments: `(* 483: Project 1 … *)   /* foo */`

- Often delimited by *whitespace* (‘ ‘, \t, etc.)
  - In some languages (e.g. Python or Haskell) whitespace is significant

How hard can it be?
handlex0.ml and handlex.ml

# DEMO: HANDLEX

# Lexing By Hand

- How hard can it be?
  - Tedious and painful!

- Problems:
  - Precisely define tokens
  - Matching tokens simultaneously
  - Reading too much input  (need look ahead)
  - Error handling
  - Hard to compose/interleave tokenizer code
  - Hard to maintain

# PRINCIPLED SOLUTION TO LEXING

# Regular Expressions

- Regular expressions precisely describe sets of strings.
- A regular expression R has one of the following forms:
  - ε — Epsilon stands for the empty string
  - `'a'` — An ordinary character stands for itself
  - $R_1 \mid R_2$ — Alternatives, stands for choice of $R_1$ or $R_2$
  - $R_1R_2$ — Concatenation, stands for $R_1$ followed by $R_2$
  - `R*` — Kleene star, stands for *zero or more* repetitions of `R`
- *Useful extensions:*
  - `"foo"` — Strings, equivalent to `'f''o''o'`
  - `R+` — One or more repetitions of `R`, equivalent to `RR*`
  - `R?` — Zero or one occurrences of `R`, equivalent to `(ε|R)`
  - `['a'-'z']` — One of `a` or `b` or `c` or … `z`, equivalent to `(a|b|…|z)`
  - `[^'0'-'9']` — Any character except `0` through `9`
  - `R as x` — Name the string matched by `R` as `x`

# Example Regular Expressions

- Recognize the keyword "if": `"if"`
- Recognize a digit: `['0'-'9']`
- Recognize an integer literal: `'-'?['0'-'9']+`
- Recognize an identifier:
  `(['a'-'z']|['A'-'Z'])(['0'-'9']|'_'|['a'-'z']|['A'-'Z'])*`

- In practice, it's useful to be able to *name* regular expressions:

```
let lowercase = ['a'-'z']
let uppercase = ['A'-'Z']
let character = uppercase | lowercase
```

# How to Match?

- Consider the input string: `ifx = 0`
  - Could lex as:

| | | | |
|---|---|---|---|
| `if` | `x` | `=` | `0` |

or as:

| | | |
|---|---|---|
| `ifx` | `=` | `0` |

- Regular expressions alone are ambiguous, need a rule for choosing between the options above
- Most languages choose "longest match"
  - So the 2nd option above will be picked
  - Note that only the first option is "correct" for parsing purposes

- Conflicts: arise due to two tokens whose regular expressions have a shared prefix
  - Ties broken by giving some matches higher priority
  - Example: keywords have priority over identifiers
  - Usually specified by order the rules appear in the lex input file

# Lexer Generators

- Reads a list of regular expressions: $R_1, \ldots, R_n$, one per token.
- Each token has an attached "action" $A_i$ (just a piece of code to run when the regular expression is matched):

```
rule token = parse
| '-'?digit+                  { Int (Int32.of_string (lexeme lexbuf)) }
| '+'                         { PLUS }
| 'if'                        { IF }
| character (digit|character|'_')*        { Ident (lexeme lexbuf) }
| whitespace+                         { token lexbuf }
```

token
regular expressions

actions

- Generates scanning code that:
  1. Decides whether the input is of the form $(R_1|\ldots|R_n)*$
  2. Whenever the scanner matches a (longest) token, it runs the associated action

lexlex.mll

# DEMO: OCAMLLEX

# Implementation Strategies

- Most Tools: lex, ocamllex, flex, etc.:
  - Table-based
  - Deterministic Finite Automata (DFA)
  - Goal: Efficient, compact representation, high performance

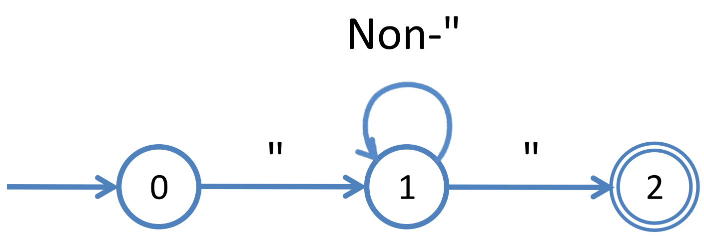
- Other approaches:
  - Brzozowski derivatives
  - Idea: directly manipulate the (abstract syntax of) the regular expression
  - Compute partial “derivatives”
    - Regular expression that is “left-over” after seeing the next character
  - Elegant, purely functional, implementation
  - (very cool!)

# Finite Automata

- Consider the regular expression: `'"' [^'"']*'"'`
- An automaton (DFA) can be represented as:
  - A transition table:

| | " | Non-" |
|---|---|---|
| 0 | 1 | ERROR |
| 1 | 2 | 1 |
| 2 | ERROR | ERROR |

  - A graph:

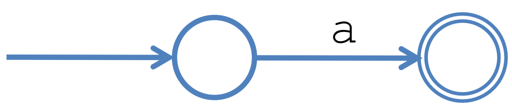


# RE to Finite Automaton?

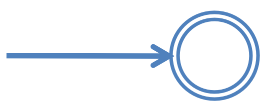
- Can we build a finite automaton for every regular expression?
  - Yes! Recall CIS 262 for the complete theory…

- Strategy: consider every possible regular expression (by induction on the structure of the regular expressions):

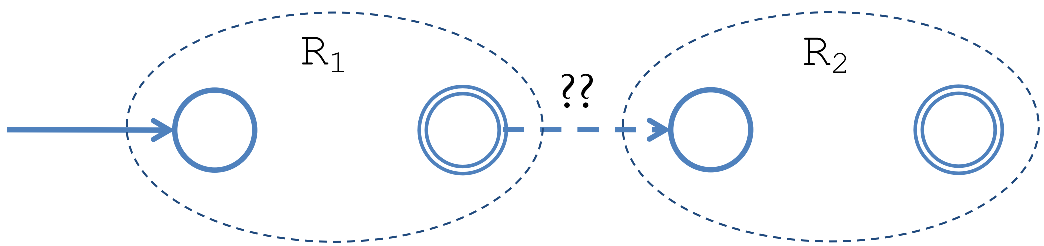
'a'




ε



$R_1R_2$

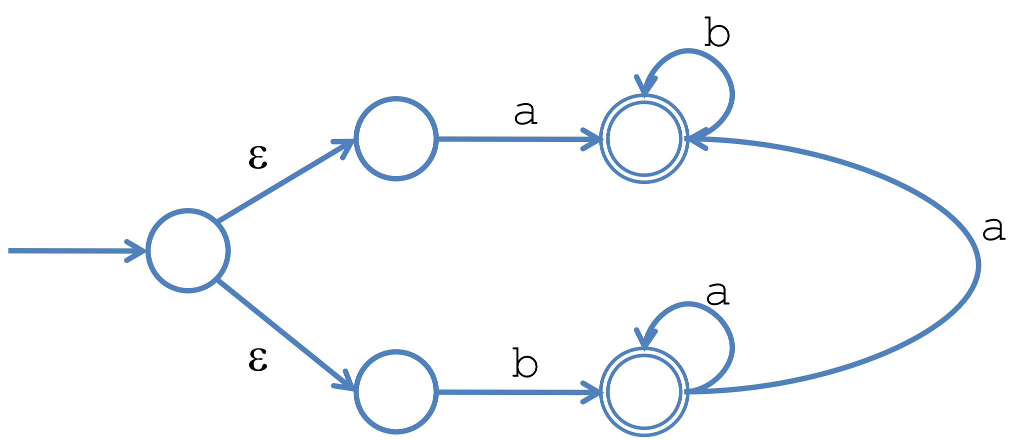



What about?

$R_1 \mid R_2$

# Nondeterministic Finite Automata

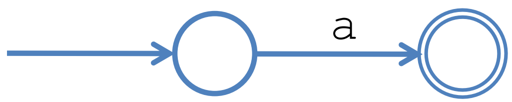
- A finite set of states, a start state, and accepting state(s)
- Transition arrows connecting states
  - Labeled by input symbols
  - Or ε (which does not consume input)
- *Nondeterministic*: two arrows leaving the same state may have the same label



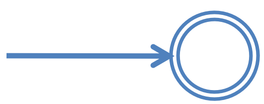
# RE to NFA?

- Converting regular expressions to NFAs is easy.
- Assume each NFA has one start state, unique accept state

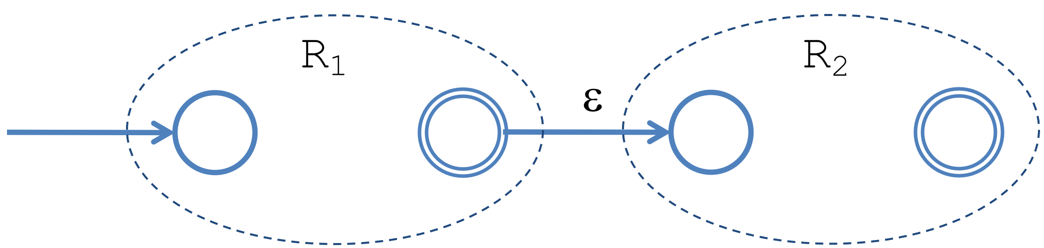
'a'




ε



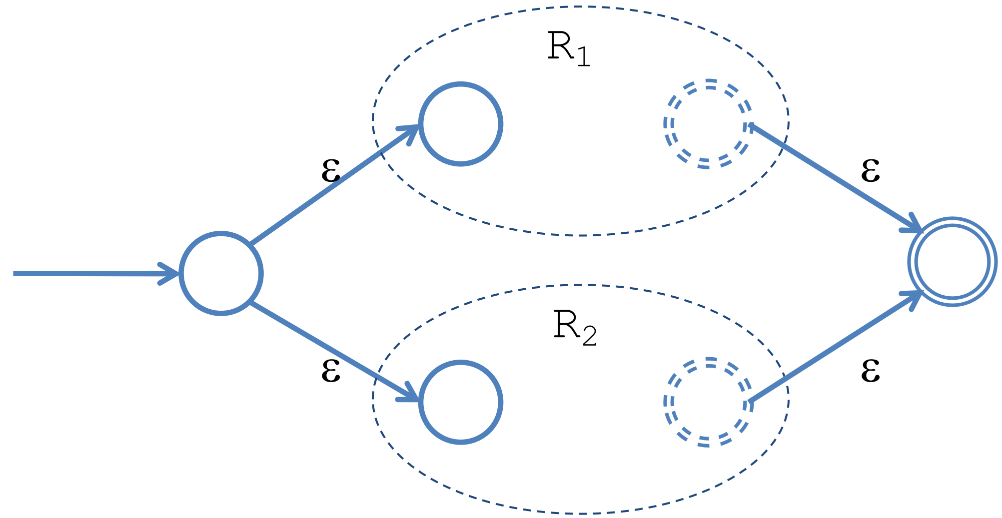
$R_1R_2$



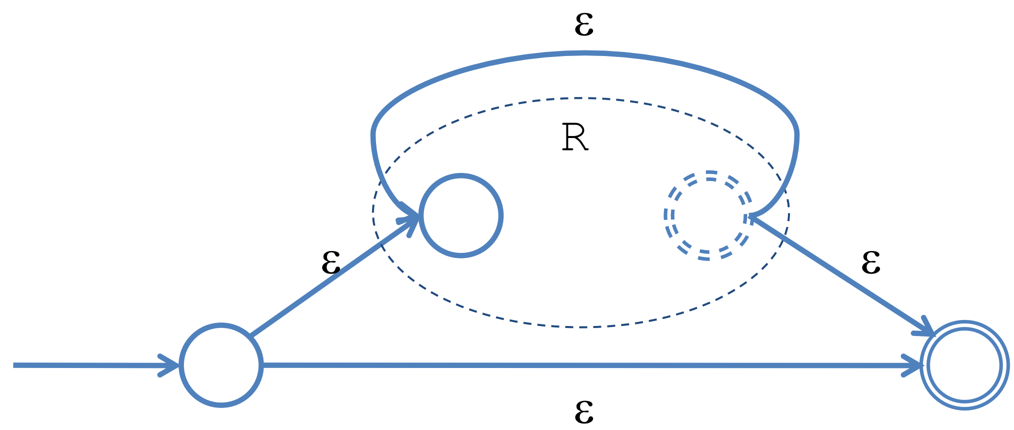
# RE to NFA (cont'd)

- Sums and Kleene star are easy with NFAs

$R_1 \mid R_2$




$R^*$



# DFA versus NFA

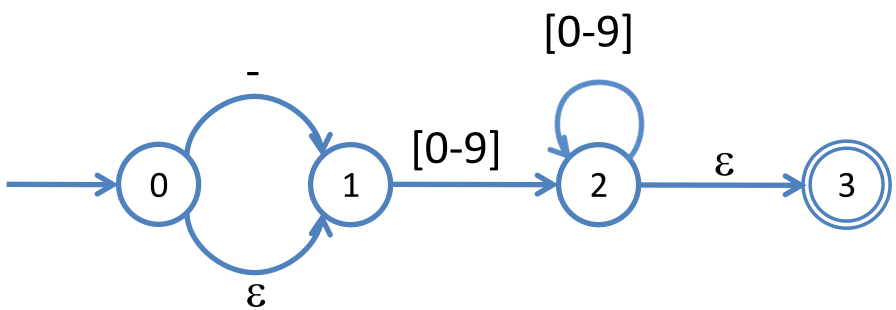
- DFA:
  - Action of the automaton for each input is fully determined
  - Automaton accepts if the input is consumed upon reaching an accepting state
  - Obvious table-based implementation

- NFA:
  - Automaton potentially has a choice at every step
  - Automaton accepts an input string if there *exists* a way to reach an accepting state
  - Less obvious how to implement efficiently

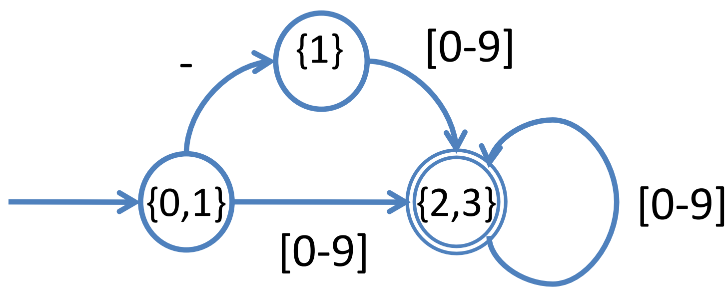
# NFA to DFA conversion (Intuition)

- Idea: Run all possible executions of the NFA "in parallel"
- Keep track of a set of possible states: "finite fingers"
- Consider: `-?[0-9]+`

- NFA representation:




- DFA representation:



# Summary of Lexer Generator Behavior

- Take each regular expression $R_i$ and it's action $A_i$
- Compute the NFA formed by $(R_1 \mid R_2 \mid \ldots \mid R_n)$
  - Remember the actions associated with the accepting states of the $R_i$
- Compute the DFA for this big NFA
  - There may be multiple accept states (why?)
  - A single accept state may correspond to one or more actions (why?)
- Compute the minimal equivalent DFA
  - There is a standard algorithm due to Myhill & Nerode
- Produce the transition table
- Implement longest match:
  - Start from initial state
  - Follow transitions, remember last accept state entered (if any)
  - Accept input until no transition is possible (i.e. next state is "ERROR")
  - Perform the highest-priority action associated with the last accept state; if no accept state there is a lexing error

# Lexer Generators in Practice

- Many existing implementations: lex, Flex, Jlex, ocamllex, …
  - For example ocamllex program
    - see lexlex.mll, olex.mll, piglatin.mll on course website
- Error reporting:
  - Associate line number/character position with tokens
  - Use a rule to recognize '\n' and increment the line number
  - The lexer generator itself usually provides character position info.
- Sometimes useful to treat comments specially
  - Nested comments: keep track of nesting depth
- Lexer generators are usually designed to work closely with parser generators…