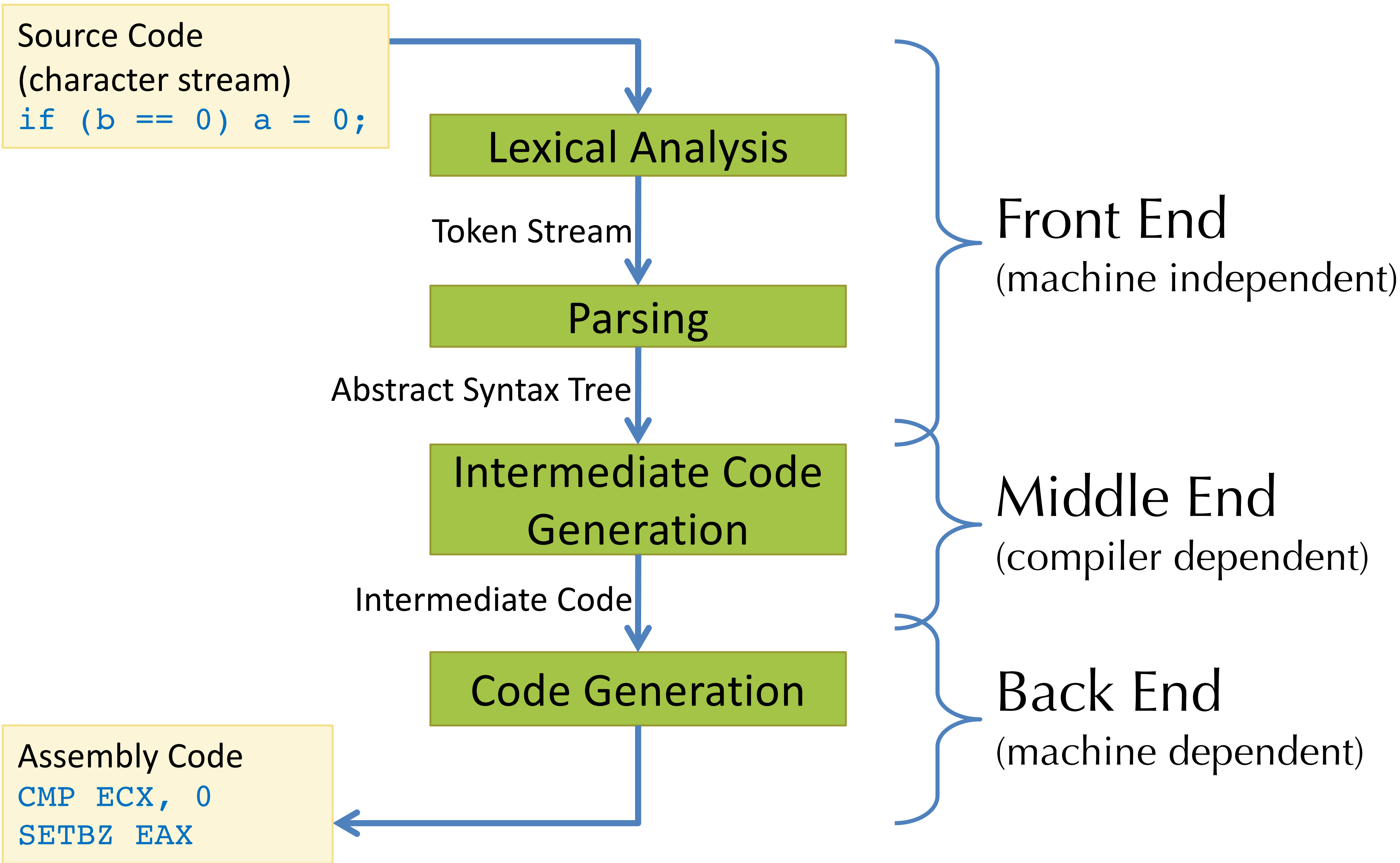
Lecture 9

COMPILER DESIGN

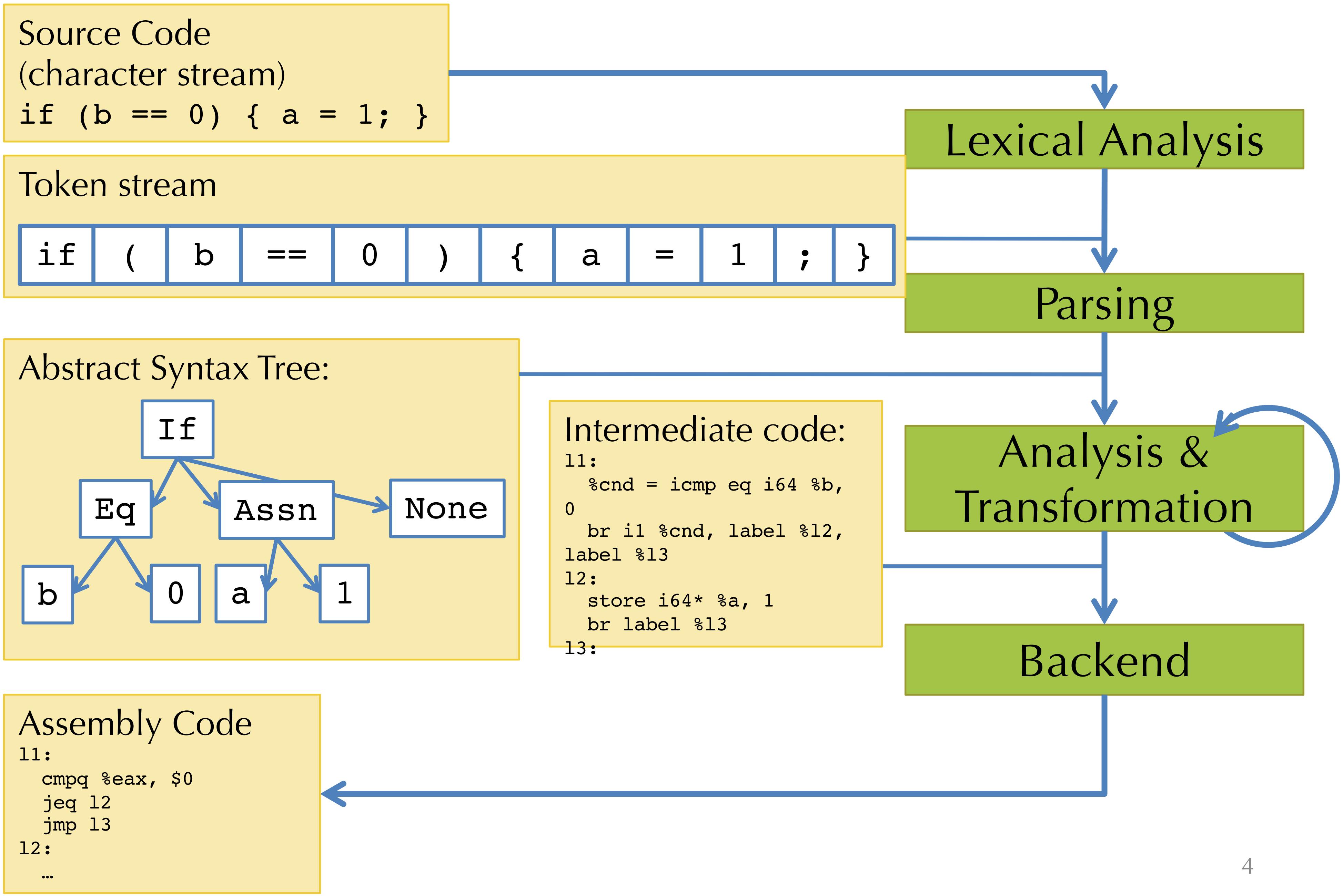
(Simplified) Compiler Structure



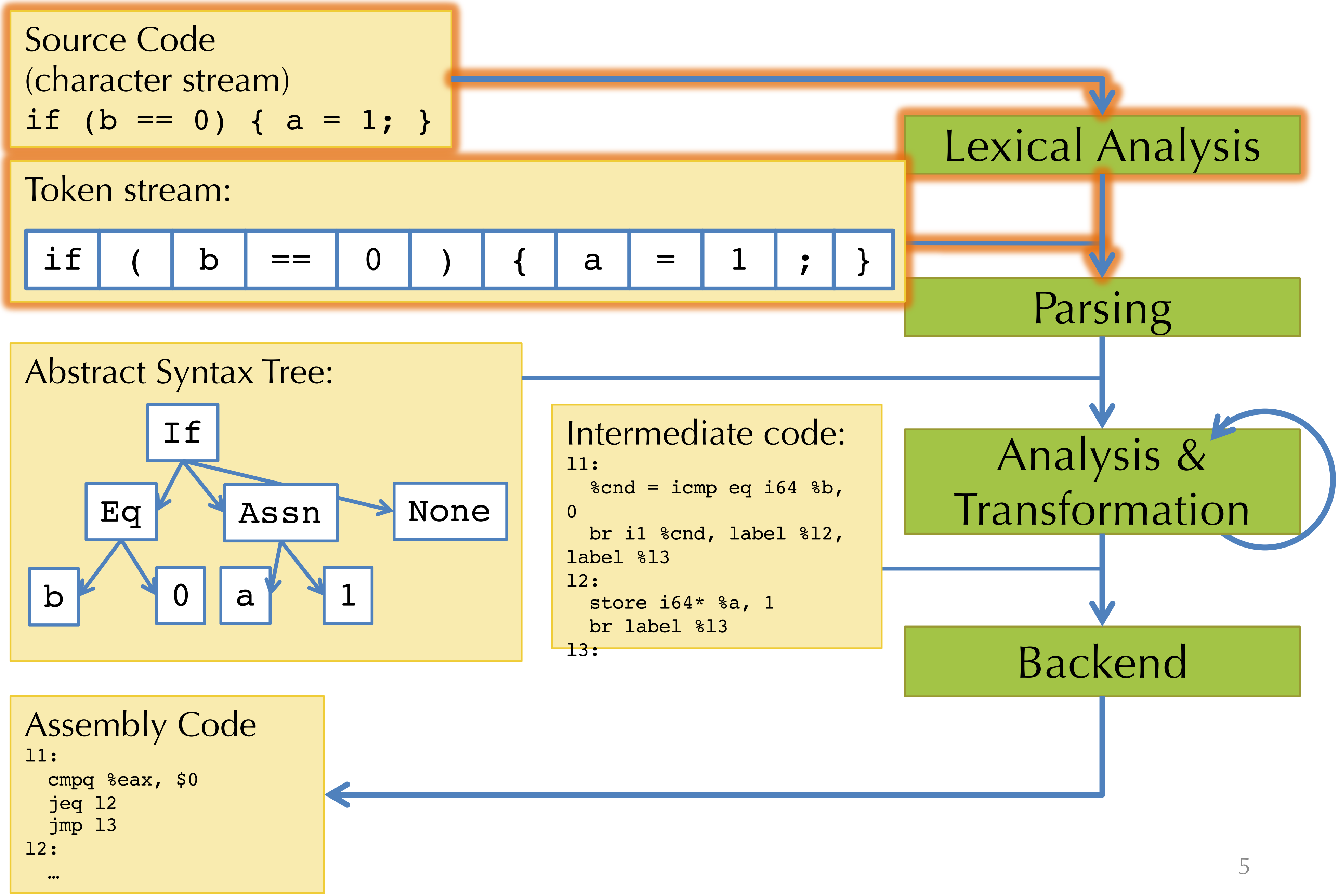
Lexical analysis, tokens, regular expressions, automata

LEXING

Compilation in a Nutshell



Today: Lexing



First Step: Lexical Analysis

- Change the ***character stream*** “`if (b == 0) a = 1;`” into ***tokens***

`if`	`(`	`b`	`==`	`0`	`)`	`{`	`a`	`=`	`1`	`;`	`}`

```
IF; LPAREN; Ident(“b”); EQEQ; Int(0); RPAREN; LBRACE;
Ident(“a”); EQ; Int(1); 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: `(* Compiler Design: 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, 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

Tricky/Fun Examples

- (Early) FORTRAN
  - Whitespace insignificant, so VAR1 same as VA   R1
  - Then, how about

    DO 5 I = 1,25 (looping)

    DO 5 I = 1.25 (assignment)

- C++
  - Template syntax: Foo<Bar>
  - Stream syntax: cin >> x
  - But, how about nested templates

    Foo<Bar<Bazz>>

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 $(\varepsilon|R)$
  - ['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

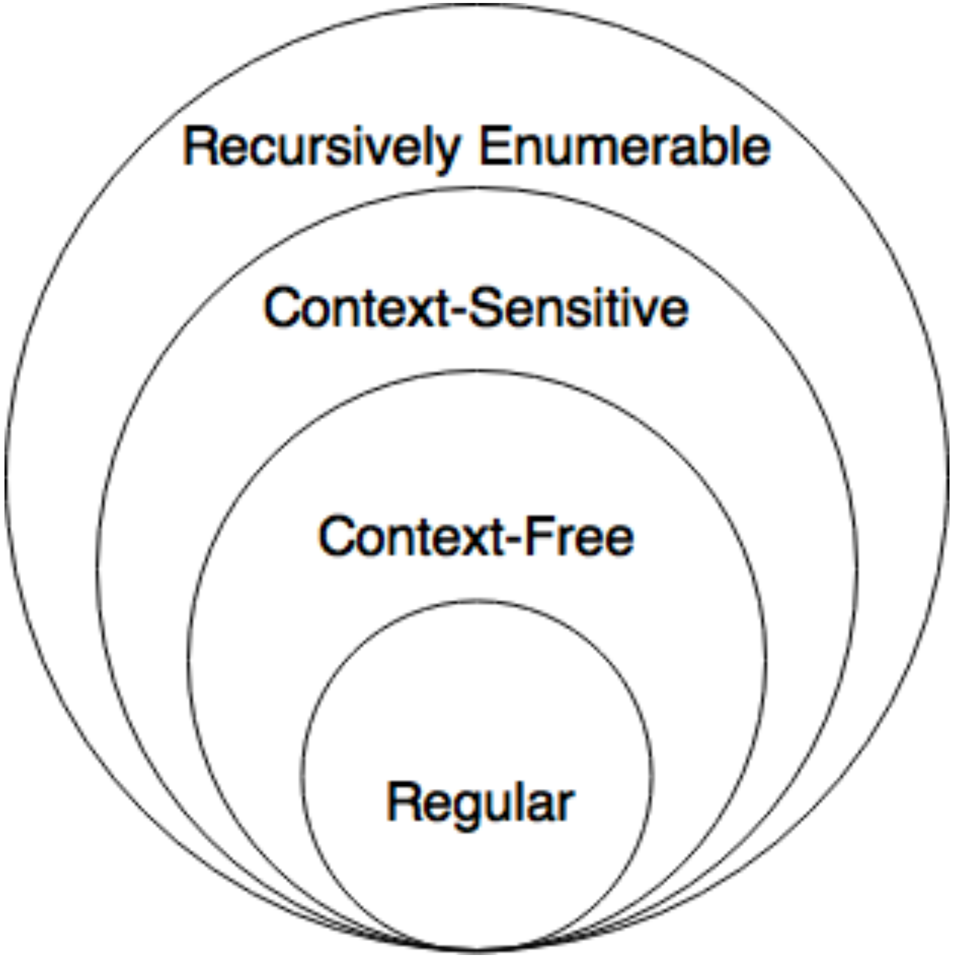
Example Regular Expressions

- 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 is useful to be able to *name* regular expressions

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

Chomsky Hierarchy



How to Match?

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

if	x	=	0

or as

ifx	=	0

- Thus, regular expressions alone can be ambiguous

- We 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

How to Match?

- Conflicts: tokens whose regular expressions have a shared prefix

  Keyword

  `"if"`

  Identifier

  `(['a'-'z']|['A'-'Z'])(['0'-'9']|'_'|['a'-'z']|['A'-'Z'])*`

- How to resolve?
  - 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 Generator

- 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. After matching a (longest) token, 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

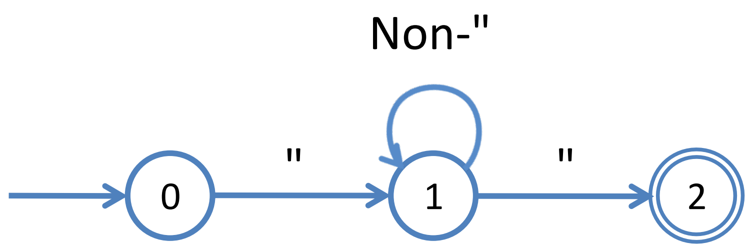
- Other approaches
  - Brzozowski derivatives
  - Idea: directly manipulate the (abstract syntax of) the regular expression
  - Compute partial "derivatives"
    - Regular expression that is "left-over" after seeing the next character
  - Elegant, purely functional, implementation

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

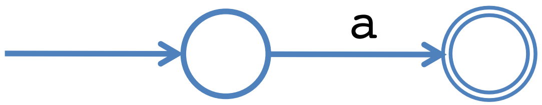


RE to Finite Automaton?

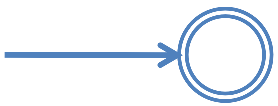
- Can we build a finite automaton for every regular expression?
  - Yes!

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

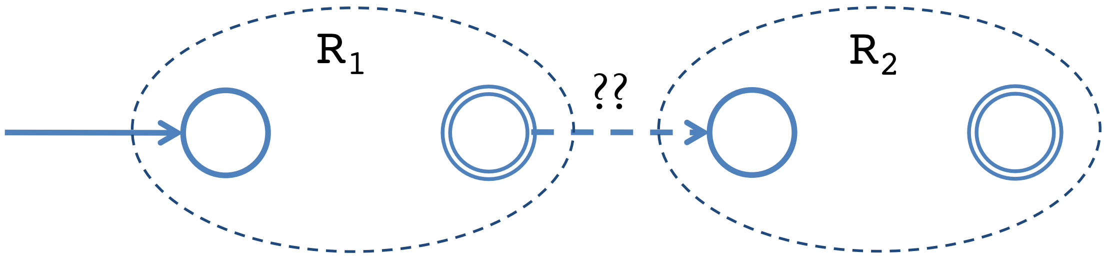
'a'



ε



R_1R_2



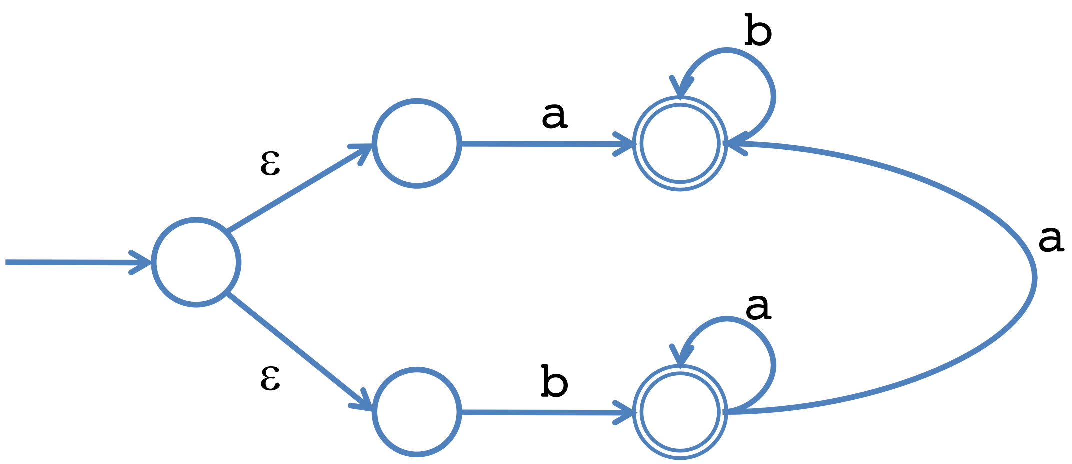
What about?

$R_1 | R_2$

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*

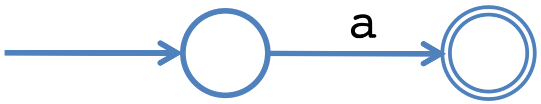
  Two arrows leaving the same state may have the same label



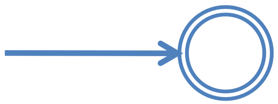
RE to NFA?

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

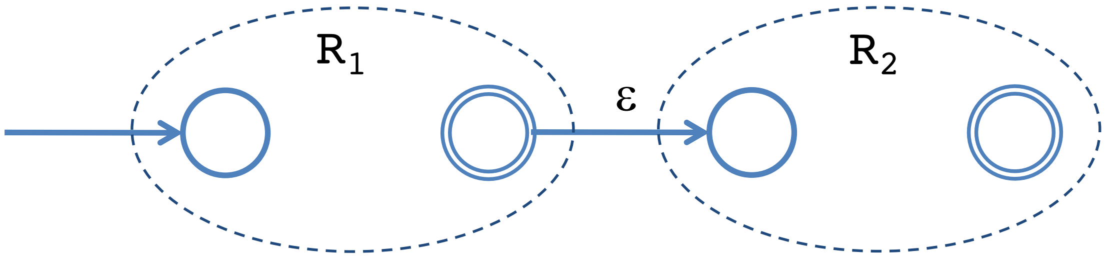
'a'



ε



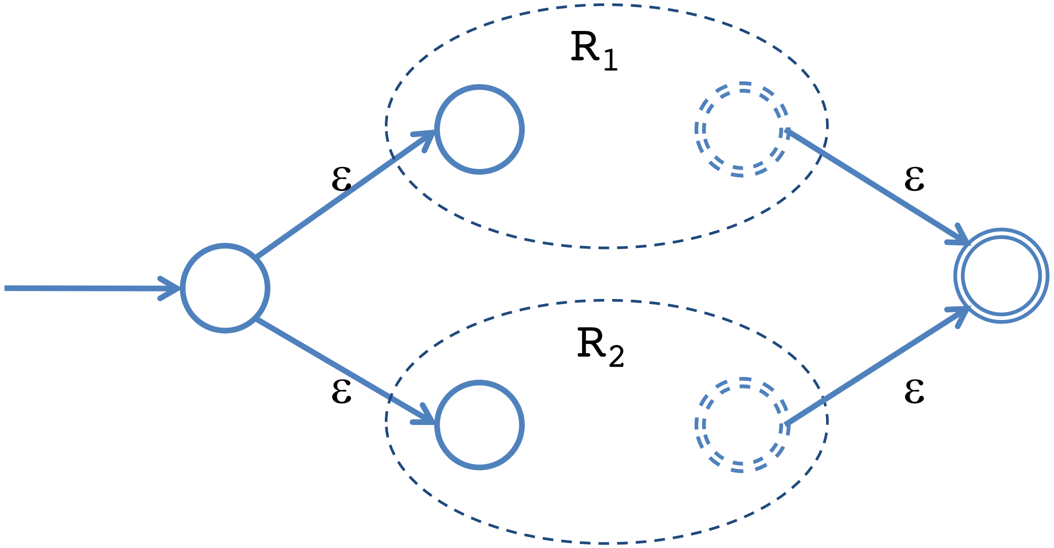
R_1R_2



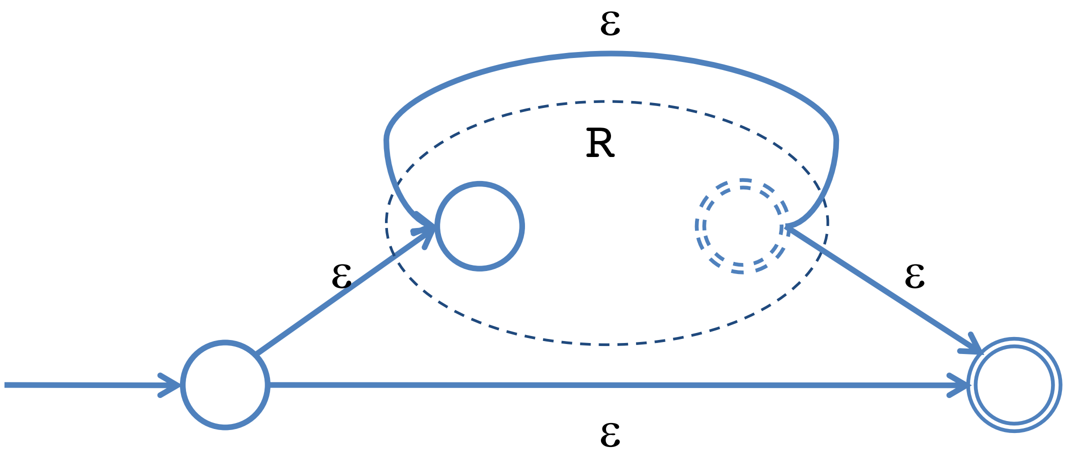
RE to NFA (cont'd)

- Sums and Kleene stars are easy with NFAs

$R_1 | R_2$



R*



DFA vs. NFA

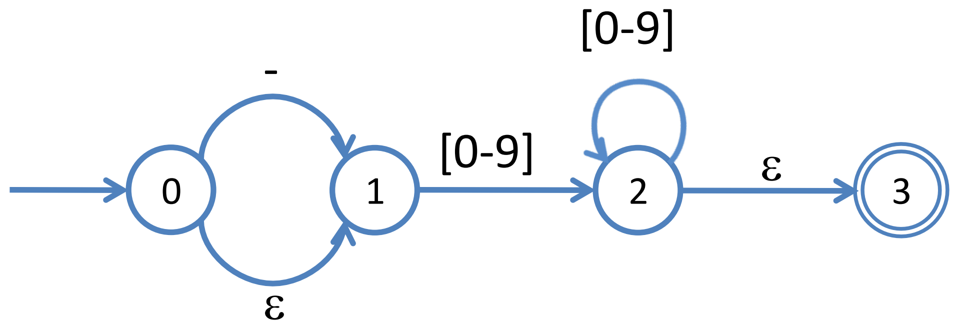
- DFA
  - Action of the automaton for each input is fully determined
  - Accepts if the input is consumed upon reaching an accepting state
  - Obvious table-based implementation

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

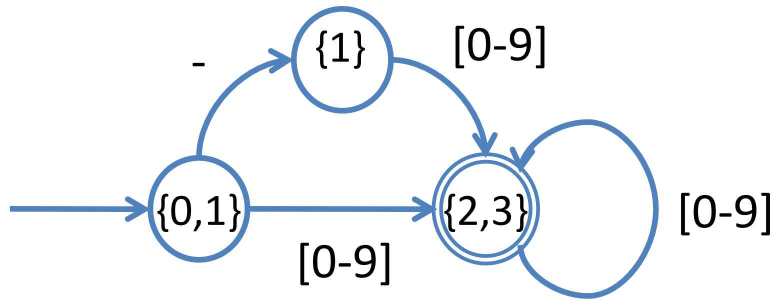
NFA to DFA conversion (Intuition)

- 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 its 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

lexlex.mll, olex.mll, piglatin.mll

DEMO: OCAMLLEX