Lecture 10

CS 131: COMPILERS

Announcements

- HW3: LLVM lite
  - Available on Blackboard.
  - Due: November 6th at 11:59:59pm

it is too late to
START EARLY!!

- Midterm: November 19th (tentative)
  - In class
  - One-page, letter-sized, double-sided "cheat sheet" of notes permitted
  - See Piazza / Blackboard for previous exams

Lexical analysis, tokens, regular expressions, automata

LEXING

Compilation in a Nutshell

Source Code
(Character stream)
if (b == 0) { a = 1; }

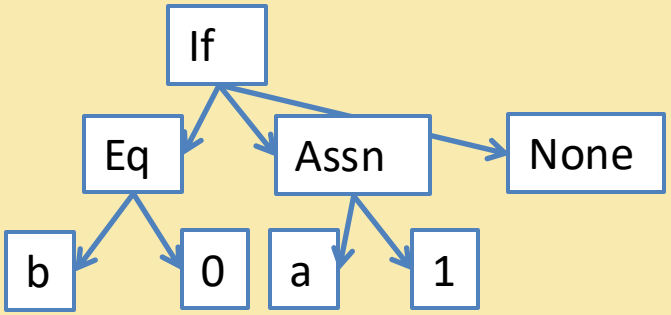
Lexical Analysis

Token stream:

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

Parsing

Abstract Syntax Tree:



Intermediate code:

```
l1:
  %cnd = icmp eq i64 %b, 0
  br i1 %cnd, label %l2, label %l3
l2:
  store i64* %a, 1
  br label %l3
l3:
```

Analysis & Transformation

Backend

Assembly Code

```
l1:
  cmpq %eax, $0
  jeq l2
  jmp l3
l2:
  …
```

Today: Lexing

Source Code
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Lexical Analysis

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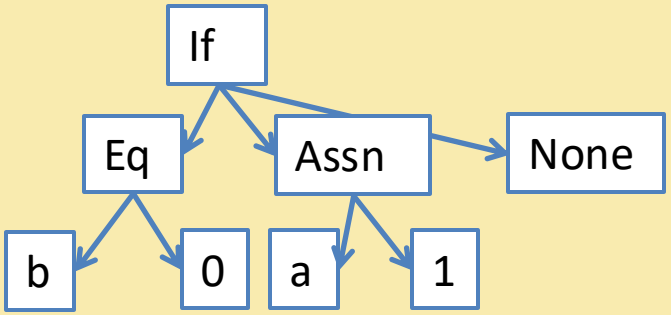

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  …
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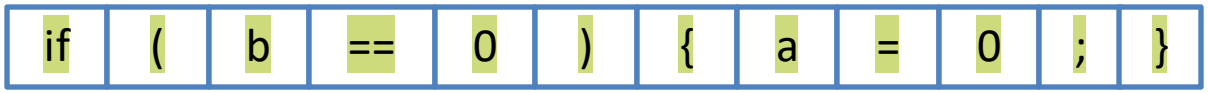
First Step: Lexical Analysis

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



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: (* CS131: 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 | 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

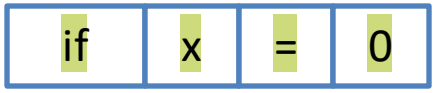
Example Regular Expressions

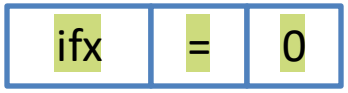
- Recognize the keyword “if”: ”if”
- Recognize a digit: ['0'-'9']
- Recognize an integer literal: '-'?['0'-'9']+
- Recognize an identifier:
  (['a'-'z']|['A'-'Z'])(['0'-'9']|'_'|['a'-'z']|['A'-'Z'])*

- 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: 

or as: 

- Regular expressions alone are ambiguous: they 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

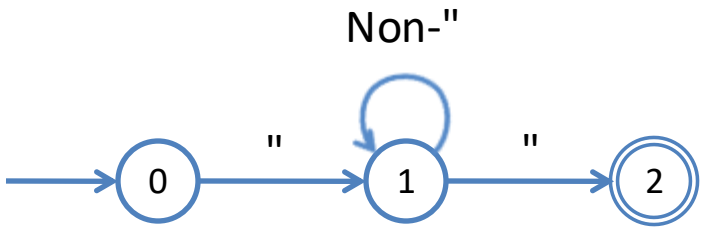
- Other approaches:
  - Brzozowski derivatives
  - Idea: directly manipulate the (abstract syntax of) the regular expression
  - Compute partial "derivatives"
    - Regular expression that is "left-over" after seeing the next character
  - Elegant, purely functional, implementation
  - (very cool!)

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?

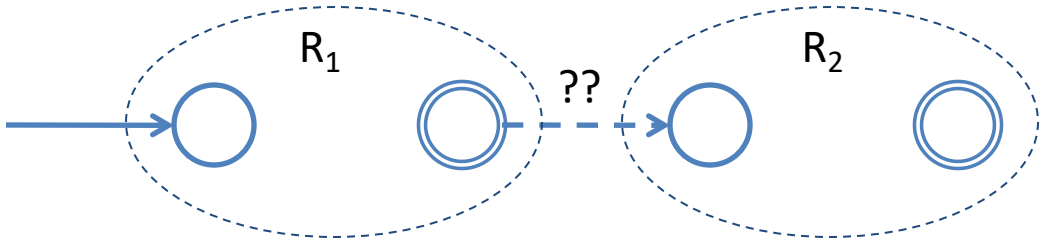
- Can we build a finite automaton for every regular expression?
  - Yes!

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

'a'

ε

R_1R_2

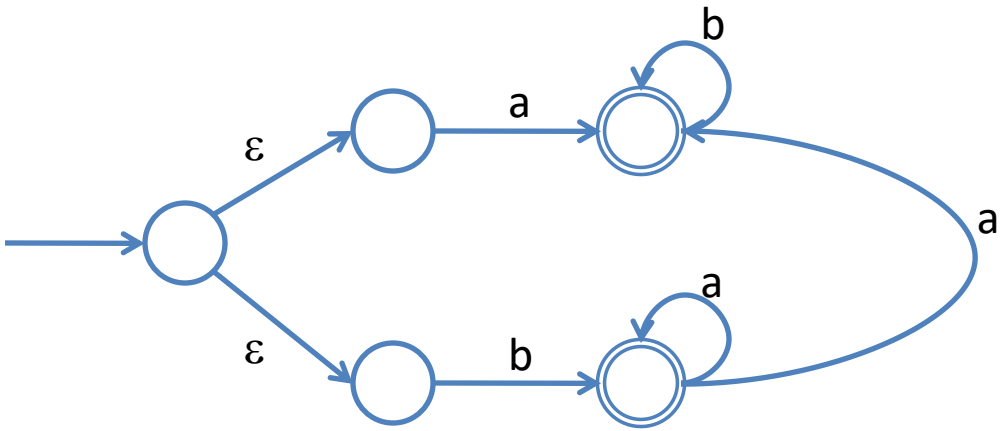


What about?

$R_1 | R_2$

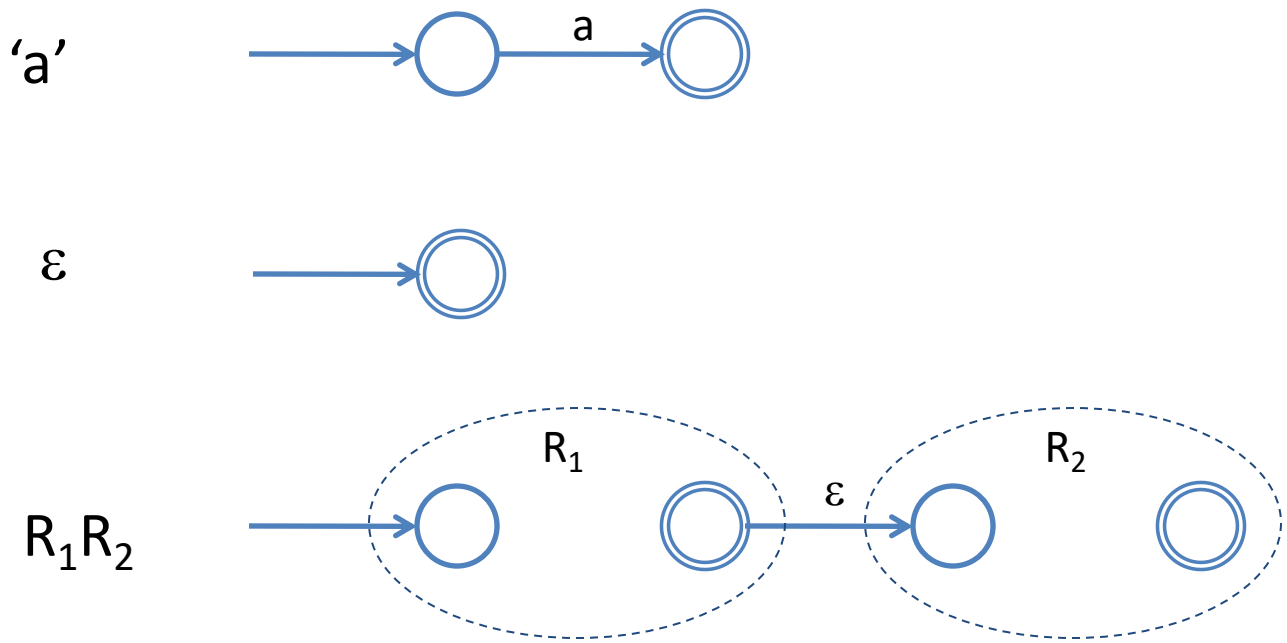
Nondeterministic Finite Automata

- 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?

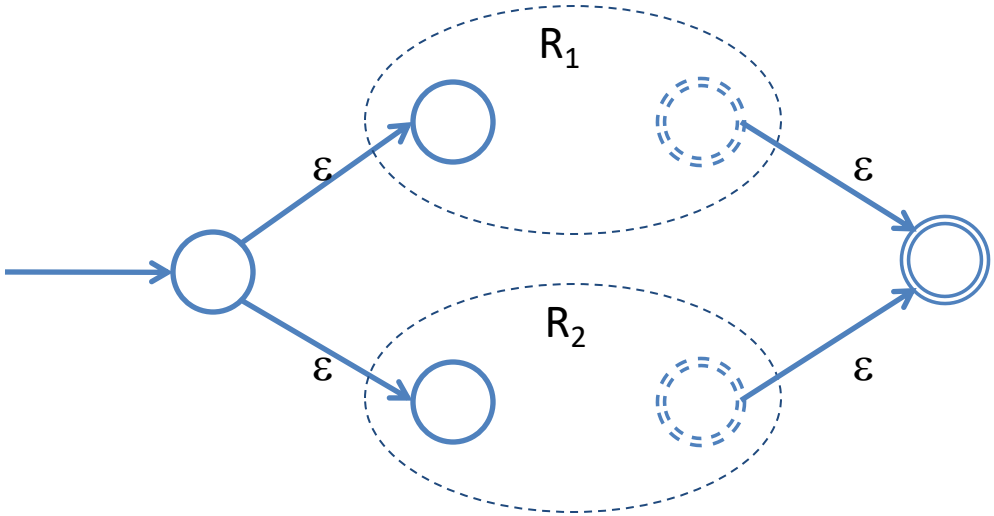
- Converting regular expressions to NFAs is easy.
- Assume each NFA has one start state, unique accept state



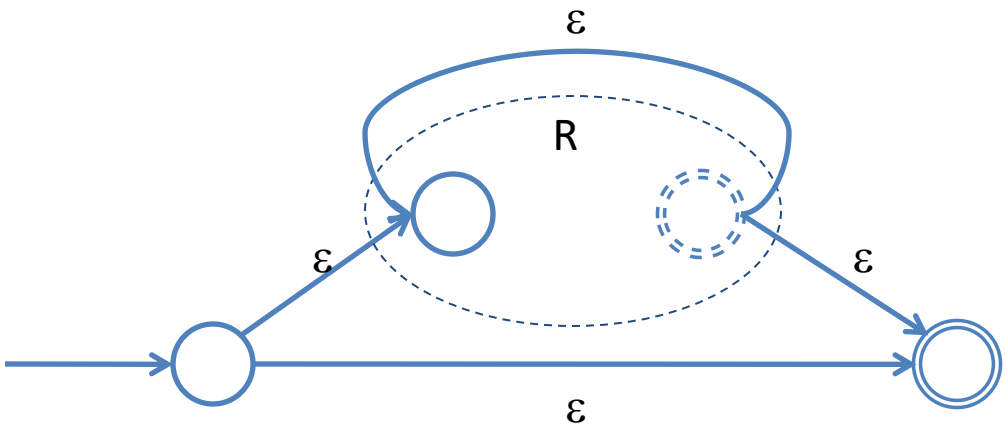
RE to NFA (cont'd)

- Sums and Kleene star are easy with NFAs

$R_1 | R_2$



R^*



DFA versus NFA

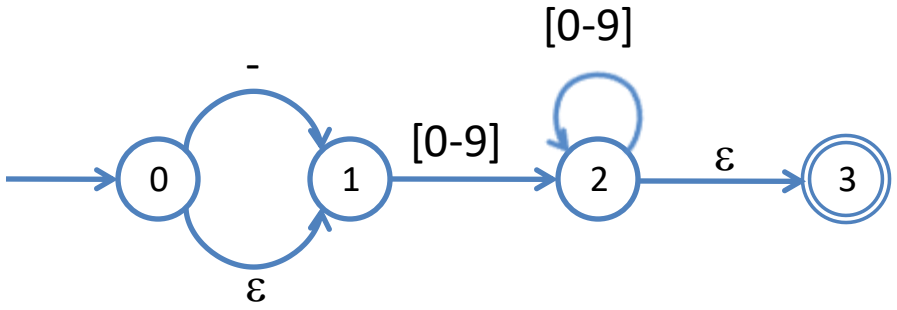
- DFA:
  - Action of the automaton for each input is fully determined
  - Automaton accepts if the input is consumed upon reaching an accepting state
  - Obvious table-based implementation

- 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

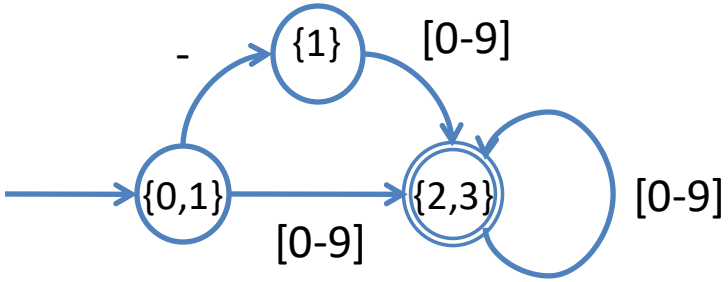
NFA to DFA conversion (Intuition)

- 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…