Lecture 9

CIS 341: COMPILERS

Announcements

- HW3: LLVM lite
  - Available on the course web pages.
  - Due: Monday, Feb. 26th at 11:59:59pm
  - Only one group member needs to submit
  - Three submissions per group

START EARLY!!

- TODAY @ 4:30 – *The Programmer*
  - 20 minute documentary about the women behind ENIAC
  - Wu & Chen Auditorium
  - Free Food!

DATATYPES IN THE LLVM IR

GEP Example*

```
struct RT {
     int A;
     int B[10][20];
     int C;
}
struct ST {
     struct RT X;
     int Y;
     struct RT Z;
}
int *foo(struct ST *s) {
  return &s[1].Z.B[5][13];
}
```

1. `%s` is a pointer to an (array of) %`ST` structs, suppose the pointer value is ADDR

2. Compute the index of the 1st element by adding `size_ty(%ST)`.

3. Compute the index of the `Z` field by adding `size_ty(%RT)` + `size_ty(i32)` to skip past `X` and `Y`.

4. Compute the index of the `B` field by adding `size_ty(i32)` to skip past `A`.

5. Index into the 2d array.

```
%RT = type { i32, [10 x [20 x i32]], i32 }
%ST = type { %RT, i32, %RT }
define i32* @foo(%ST* %s) {
entry:
     %arrayidx = getelementptr %ST* %s, i32 1, i32 2, i32 1, i32 5, i32 13
     ret i32* %arrayidx
}
```

Final answer: ADDR + `size_ty(%ST)` + `size_ty(%RT)` + `size_ty(i32)` + `size_ty(i32)` + `5*20*size_ty(i32)` + `13*size_ty(i32)`

*adapted from the LLVM documentaion: see http://llvm.org/docs/LangRef.html#getelementptr-instruction

getelementptr

- GEP *never* dereferences the address it's calculating:
  - GEP only produces pointers by doing arithmetic
  - It doesn't actually traverse the links of a datastructure

- To index into a deeply nested structure, need to "follow the pointer" by loadingfrom the computed pointer
  - See list.ll from HW3

Compiling Datastructures via LLVM

1. Translate high level language types into an LLVM representation type.
   - For some languages (e.g. C) this process is straight forward
     - The translation simply uses platform-specific alignment and padding
   - For other languages, (e.g. OO languages) there might be a fairly complex elaboration.
     - e.g. for Ocaml, arrays types might be translated to pointers to length-indexed structs.

     ⟦int array⟧ = `{ i32, [0 x i32]}*`
2. Translate accesses of the data into getelementptr operations:
   - e.g. for Ocaml array size access:
     ⟦length a⟧ =

```
%1 = getelementptr {i32, [0xi32]}* %a, i32 0, i32 0
```

Bitcast

- What if the LLVM IR's type system isn't expressive enough?
  - e.g. if the source language has subtyping, perhaps due to inheritance
  - e.g. if the source language has polymorphic/generic types

- LLVM IR provides a `bitcast` instruction
  - This is a form of (potentially) unsafe cast. Misuse can cause serious bugs (segmentation faults, or silent memory corruption)

```
%rect2 = type { i64, i64 }           ; two-field record
%rect3 = type { i64, i64, i64 }      ; three-field record

define @foo() {
  %1 = alloca %rect3      ; allocate a three-field record
  %2 = bitcast %rect3* %1 to %rect2*    ; safe cast
  %3 = getelementptr %rect2* %2, i32 0, i32 1  ; allowed
  …
}
```

Lexical analysis, tokens, regular expressions, automata

LEXING

Compilation in a Nutshell

Source Code
(Character stream)

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

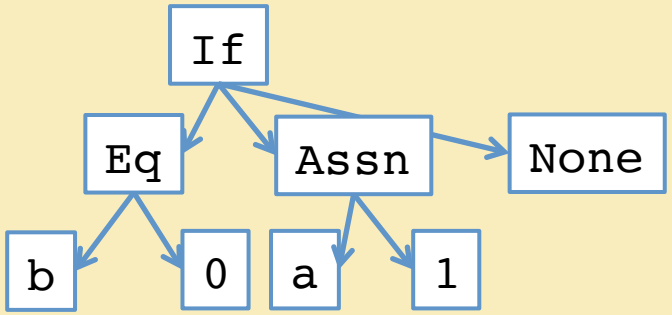
Lexical Analysis

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:
```

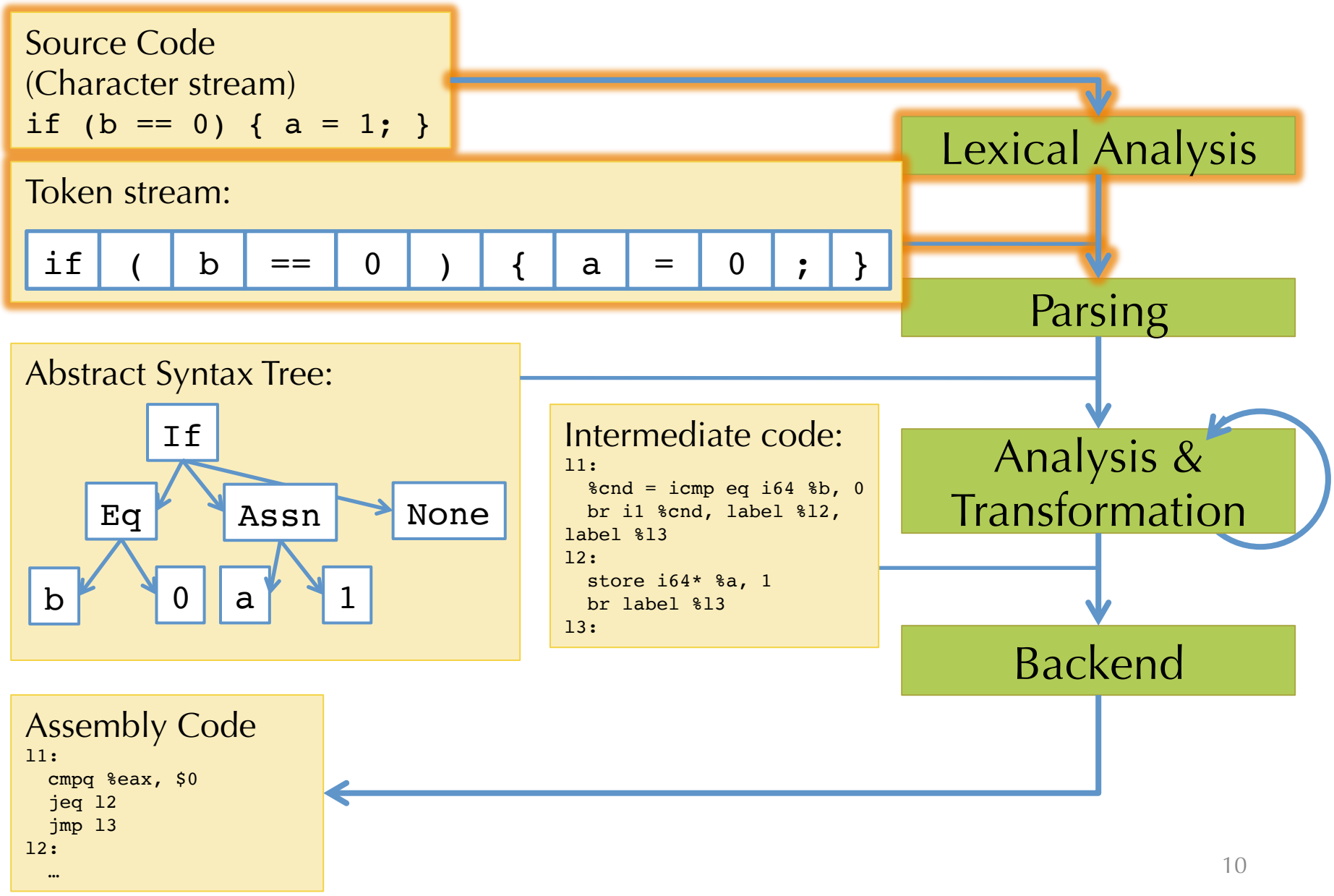
Analysis & Transformation

Backend

Assembly Code

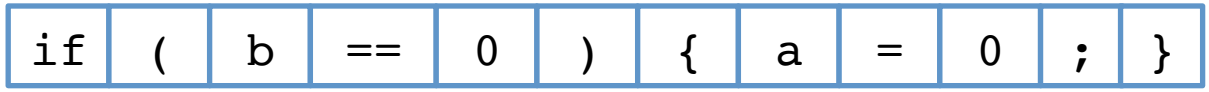
```
l1:
  cmpq %eax, $0
  jeq l2
  jmp l3
l2:
  …
```

Today: Lexing



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: `(* CIS341: 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: | `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

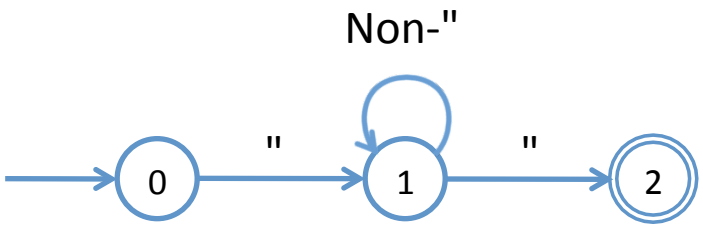
- Other approaches:
  - Brzozowski derivatives
  - Idea: directly manipulate the (abstract syntax of) the regular expression
  - Compute partial "derivatives"
    - Regular expression that is "left-over" after seeing the next character
  - Elegant, purely functional, implementation
  - (very cool!)

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:



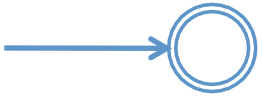
RE to Finite Automaton?

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

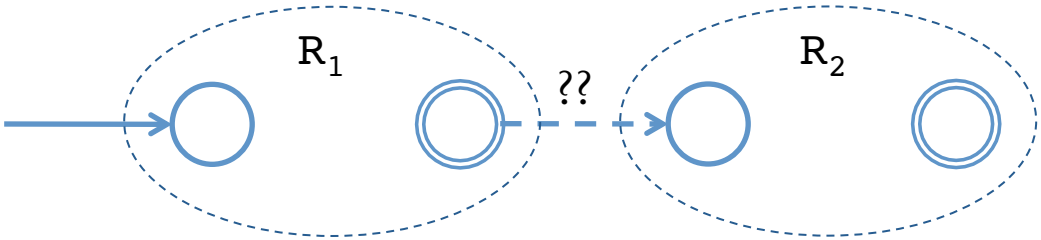
- Strategy: consider every possible regular expression (by induction on the structure of the regular expressions):

'a'

ε



R_1R_2

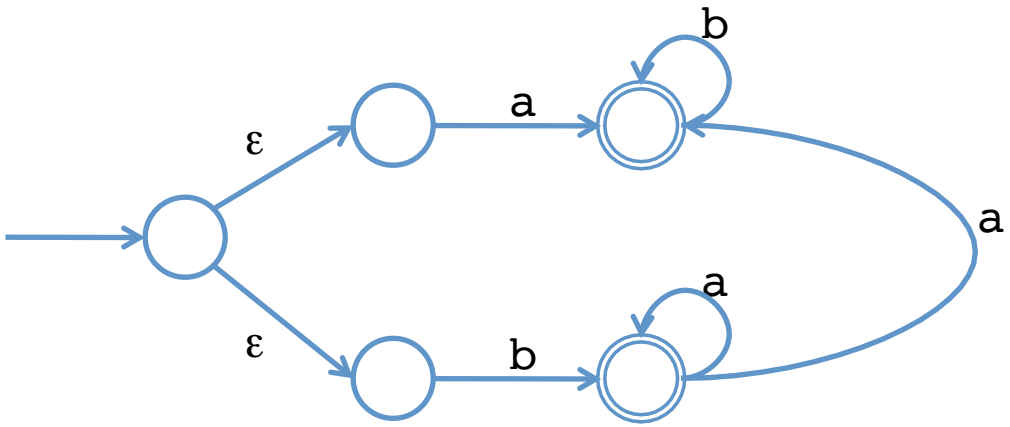


What about?

$R_1 \mid R_2$

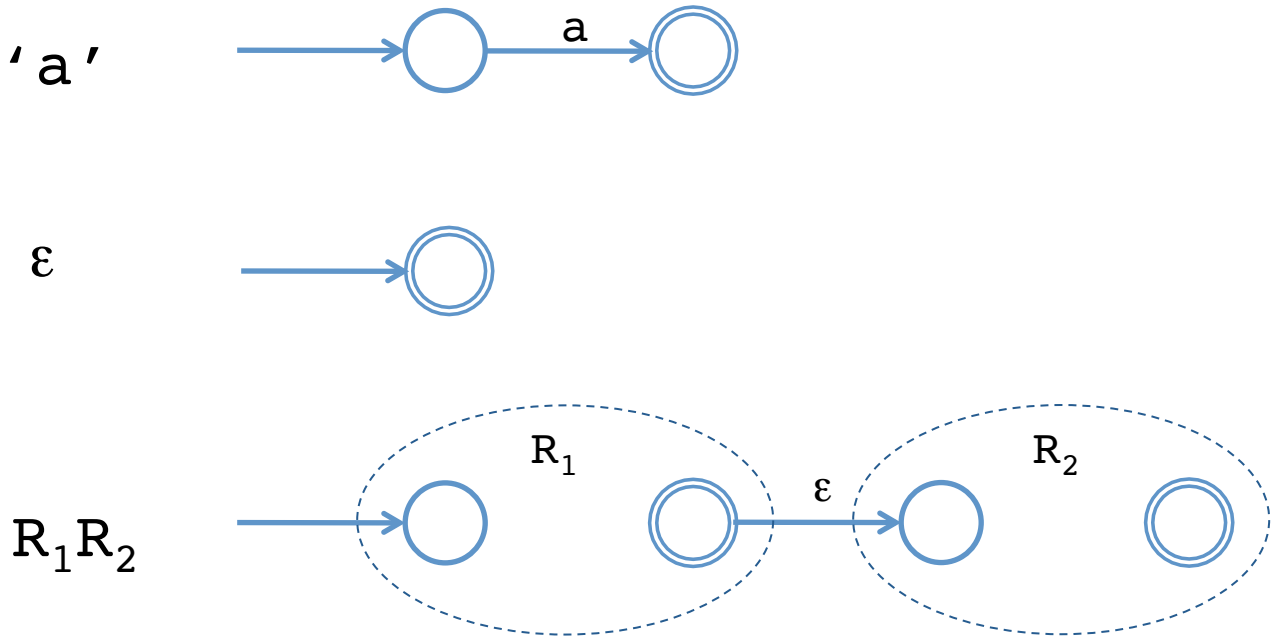
Nondeterministic Finite Automata

- 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?

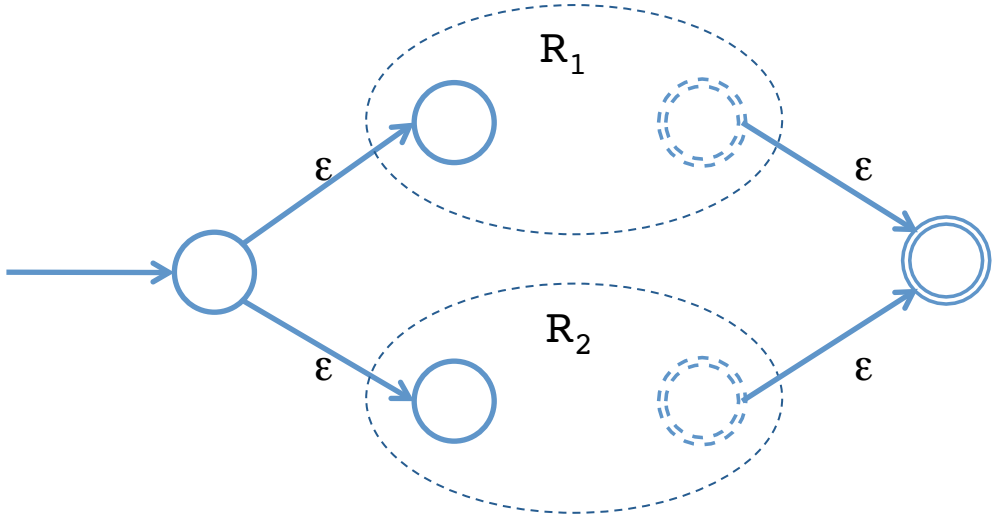
- Converting regular expressions to NFAs is easy.
- Assume each NFA has one start state, unique accept state



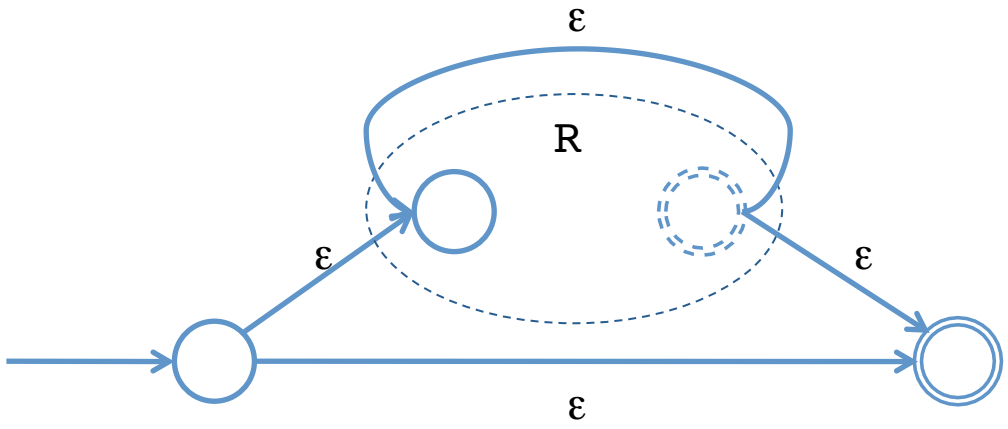
RE to NFA (cont'd)

- Sums and Kleene star are easy with NFAs

$R_1 \mid R_2$



R^*



DFA versus NFA

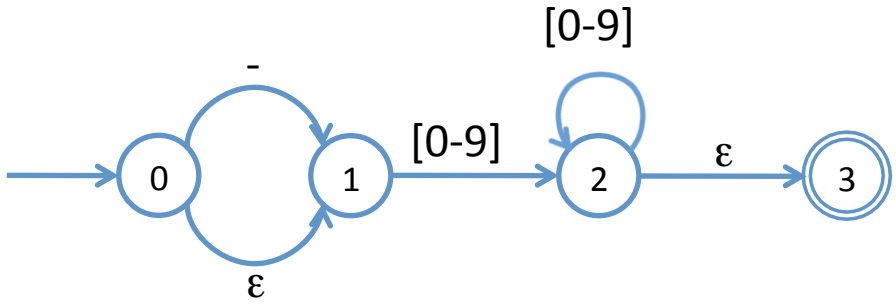
- DFA:
  - Action of the automaton for each input is fully determined
  - Automaton accepts if the input is consumed upon reaching an accepting state
  - Obvious table-based implementation

- 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

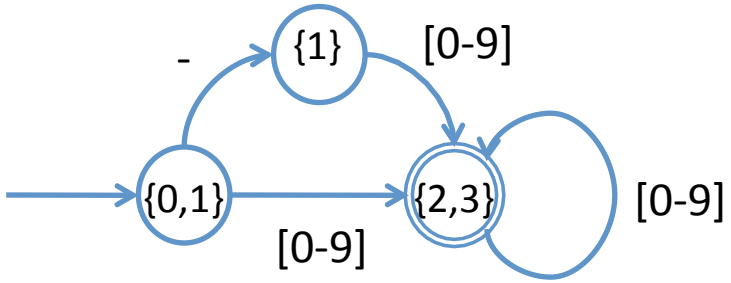
NFA to DFA conversion (Intuition)

- 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…

lexlex.mll, olex.mll, piglatin.mll

DEMO: OCAMLLEX