Lecture 9

CIS 341: COMPILERS

Announcements

- HW3: LLVM lite
  - Available on the course web pages.
  - Due: Weds., February 23rd at 11:59:59pm

START EARLY!!

- Midterm: March 3rd
  - In class
  - One-page, letter-sized, double-sided "cheat sheet" of notes permitted
  - See examples of previous exams on the web pages

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

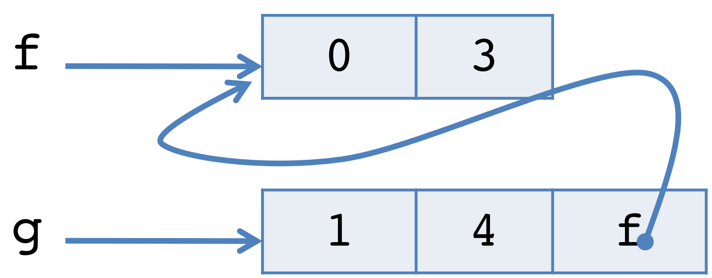
- ML datatypes can also carry data:

```
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:
```

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

DATATYPES IN THE LLVM IR

Structured Data in LLVM

- LLVM's IR is uses types to describe the structure of data.

```
t ::=
    void
    i1 | i8 | i64              N-bit integers
    [<#elts> x t]              arrays
    fty                        function types
    {t1, t2, … , tn}           structures
    t*                         pointers
    %Tident                    named (identified) type

fty ::=              Function Types
    t (t1, .., tn)             return, argument types
```

- <#elts> is an integer constant >= 0
- Structure types can be named at the top level:

```
%T1 = type {t1, t2, … , tn}
```

  – Such structure types can be recursive

Example LL Types

- An array of 341 integers: `[ 341 x i64]`
- A two-dimensional array of integers: `[ 3 x [ 4 x i64 ] ]`
- Structure for representing arrays with their length:

```
{ i64 , [0 x i64] }
```

  - There is no array-bounds check; the static type information is only used for calculating pointer offsets.
- C-style linked lists (declared at the top level):

```
%Node = type { i64, %Node*}
```

- Structs from the C program shown earlier:

```
%Rect = { %Point, %Point, %Point, %Point }
%Point = { i64, i64 }
```

getelementptr

- LLVM provides the getelementptr instruction to compute pointer values
  - Given a pointer and a "path" through the structured data pointed to by that pointer, getelementptr computes an address
  - This is the abstract analog of the X86 LEA (load effective address). It does not access memory.
  - It is a "type indexed" operation, since the size computations depend on the type

```
insn ::= …
       |  getelementptr t* %val, t1 idx1, t2 idx2 ,…
```

- Example: access the x component of the first point of a rectangle:

```
%tmp1 = getelementptr %Rect* %square, i32 0, i32 0
%tmp2 = getelementptr %Point* %tmp1, i32 0, i32 0
```

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
  …
}
```

LLVMlite notes

- Real LLVM requires that constants appearing in getelementptr be declared with type i32:

```
%struct = type { i64, [5 x i64], i64}

@gbl = global %struct {i64 1,
   [5 x i64] [i64 2, i64 3, i64 4, i64 5, i64 6], i64 7}



define void @foo() {
  %1 = getelementptr %struct* @gbl, i32 0, i32 0
  …
}
```

- LLVMlite ignores the i32 annotation and treats these as i64 values
  – we keep the i32 annotation in the syntax to retain compatibility with the clang compiler

see HW3 and README

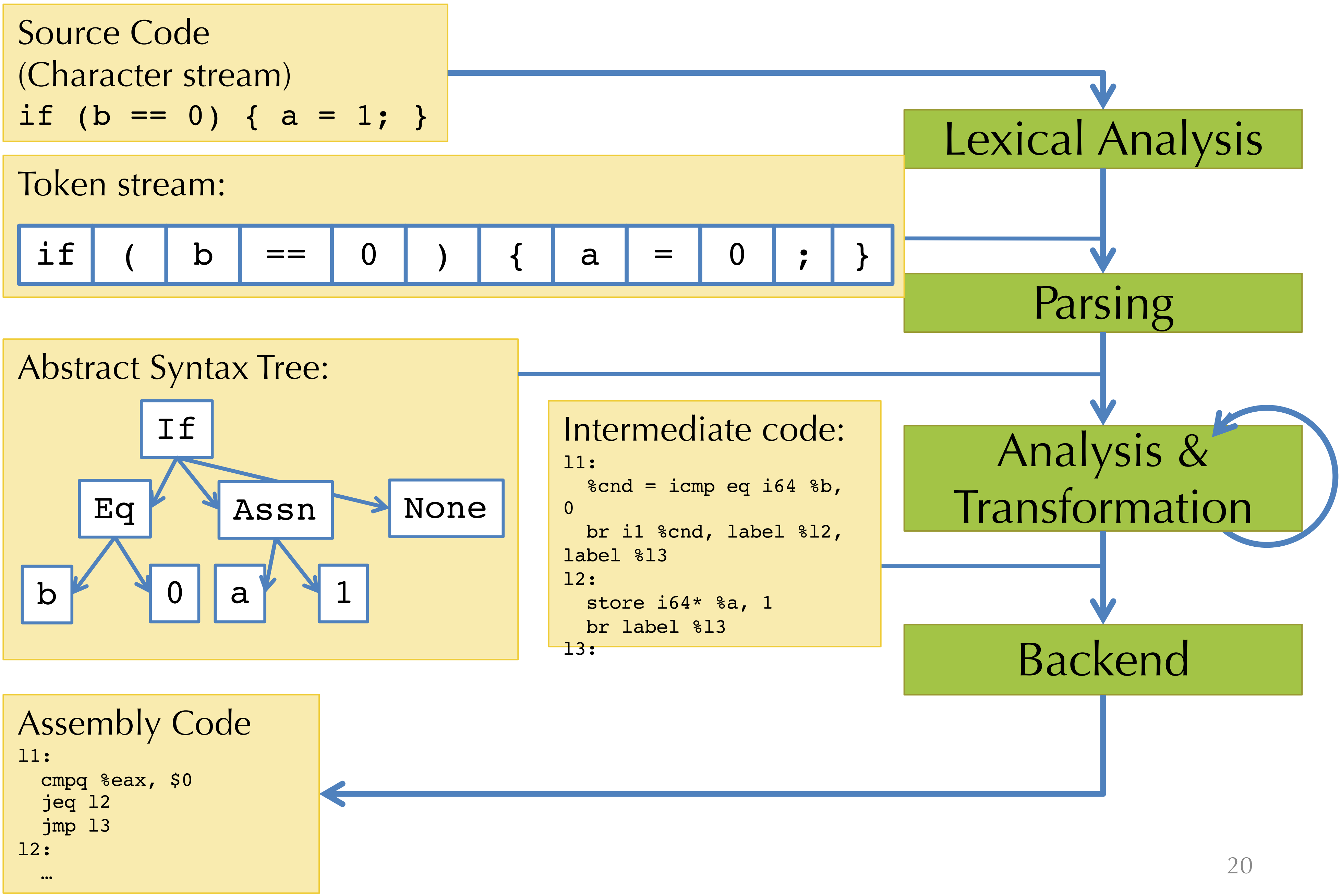
ll.ml, using oatc, clang, etc.

TOUR OF HW 3

Lexical analysis, tokens, regular expressions, automata

LEXING

Compilation in a Nutshell



Today: Lexing

Source Code
(Character stream)

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

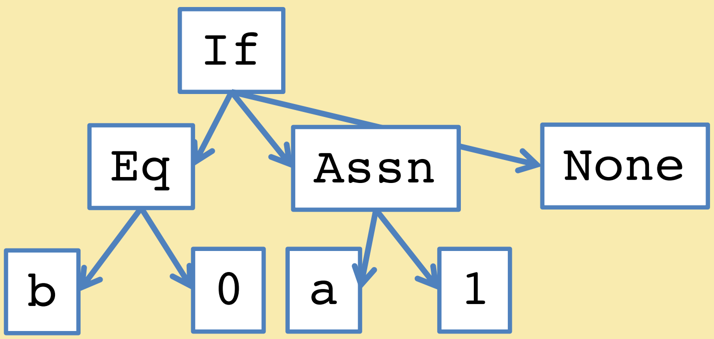
Lexical Analysis

Token stream:

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

Parsing

Abstract Syntax Tree:



Analysis & Transformation

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:
```

Backend

Assembly Code

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

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: `(* 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
  - $R_1 \mid R_2$ 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'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 2^{nd} 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: `R1,…,Rn` , one per token.
- Each token has an attached "action" `Ai` (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 `(R1|…|Rn)*`
  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

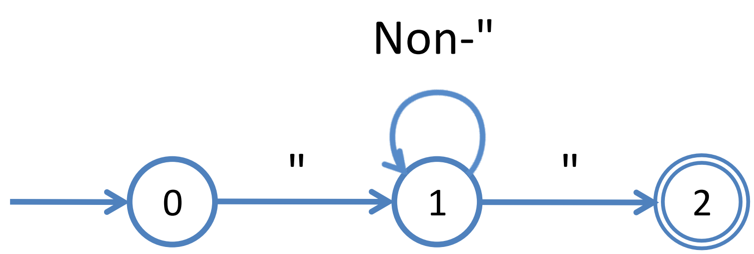
- Other approaches:
  - Brzozowski derivatives
  - Idea: directly manipulate the (abstract syntax of) the regular expression
  - Compute partial "derivatives"
    - Regular expression that is "left-over" after seeing the next character
  - Elegant, purely functional, implementation
  - (very cool!)

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:

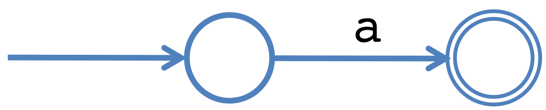


RE to Finite Automaton?

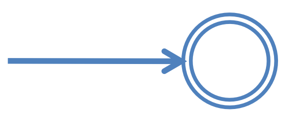
- Can we build a finite automaton for every regular expression?
  - Yes! Recall CIS 262 for the complete theory…

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

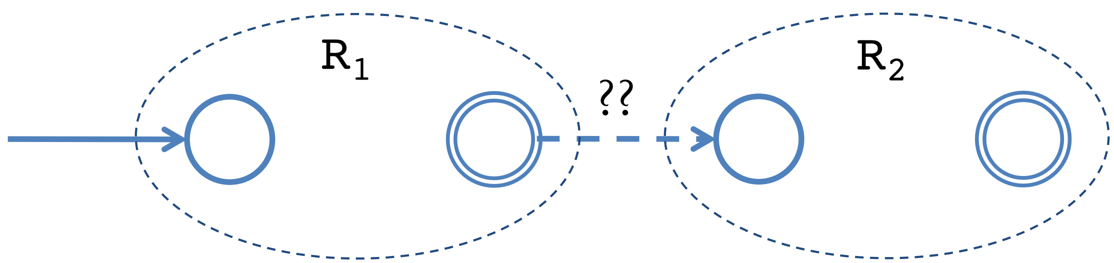
`'a'`



ε



R_1R_2

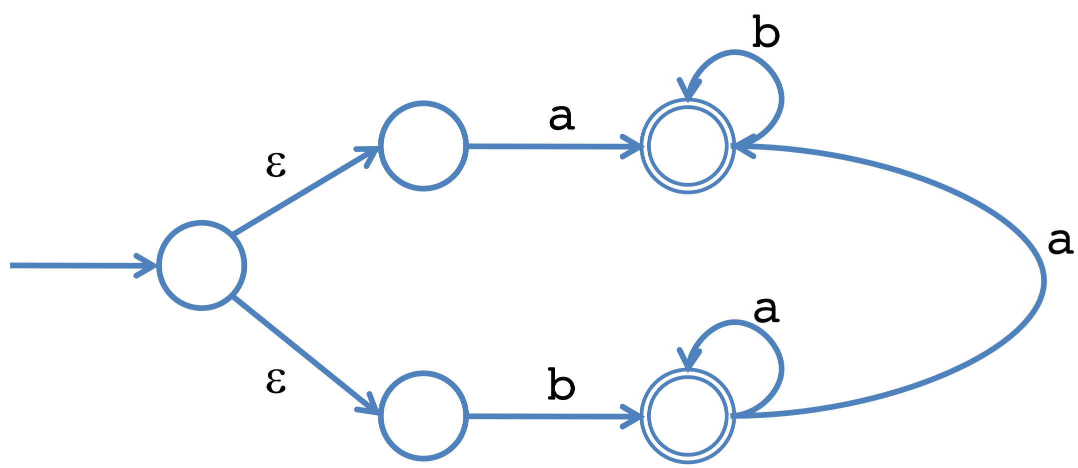


What about?

$R_1 \mid R_2$

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



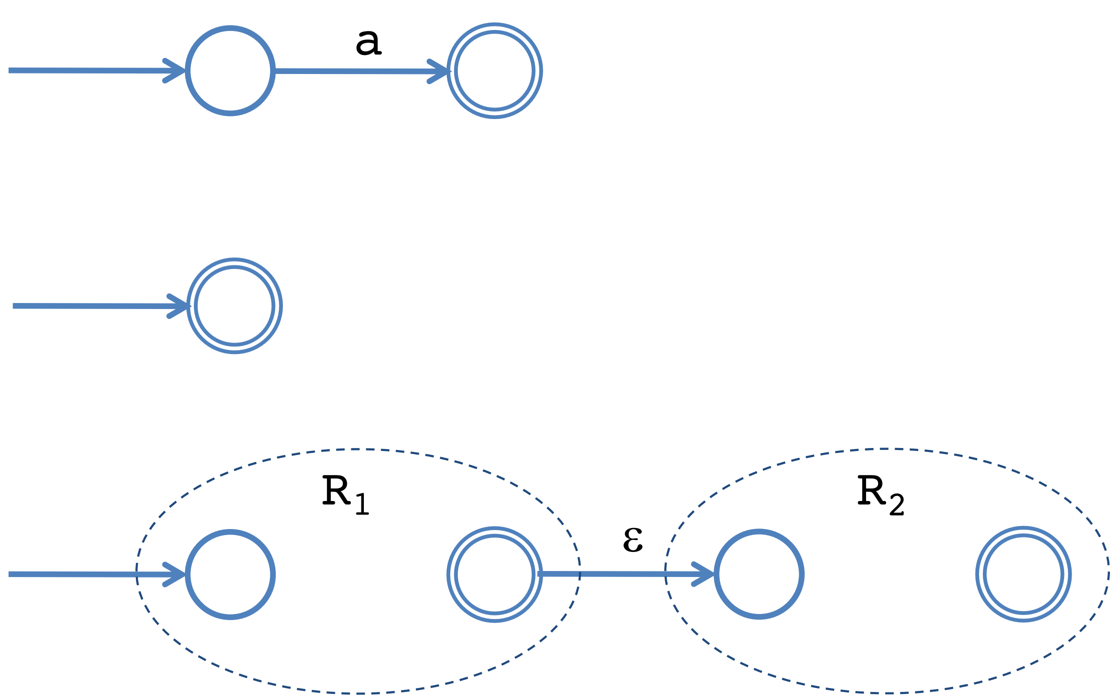
RE to NFA?

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

'a'

ε

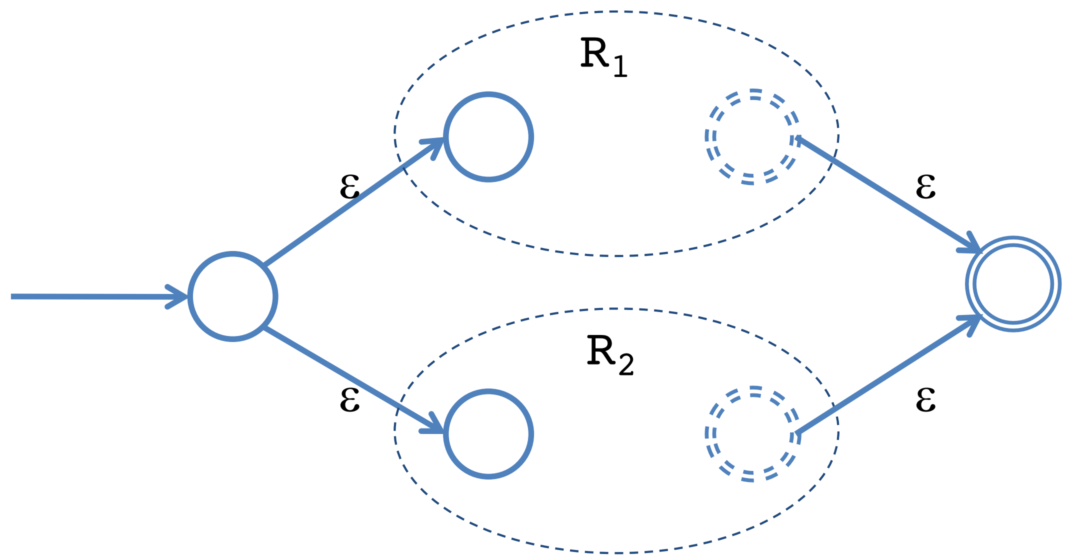
R_1R_2



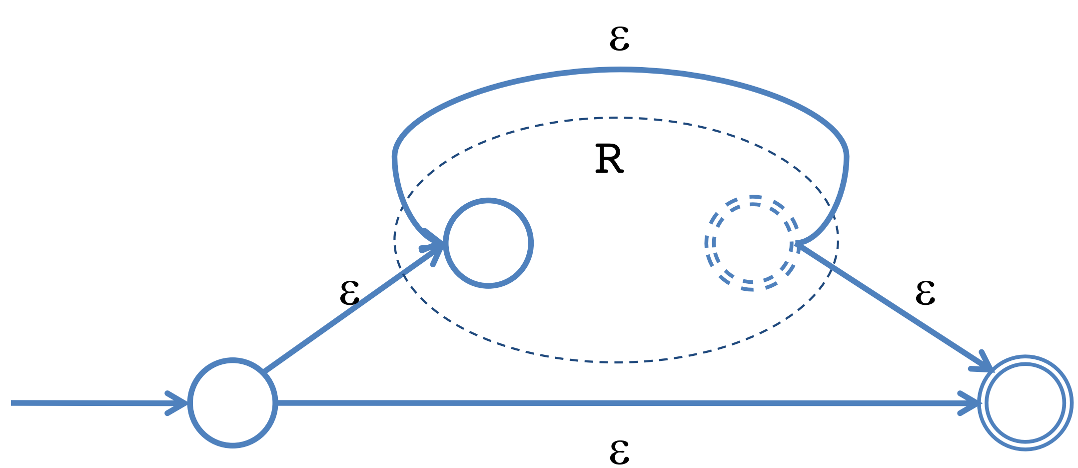
RE to NFA (cont'd)

- Sums and Kleene star are easy with NFAs

$R_1 | R_2$



$R*$



DFA versus NFA

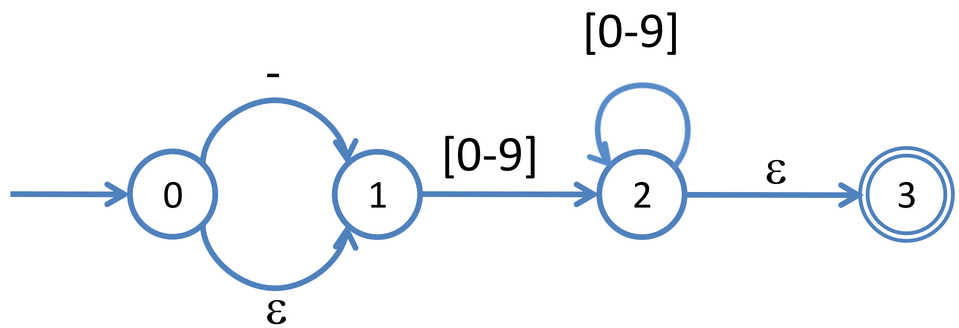
- DFA:
  - Action of the automaton for each input is fully determined
  - Automaton accepts if the input is consumed upon reaching an accepting state
  - Obvious table-based implementation

- 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

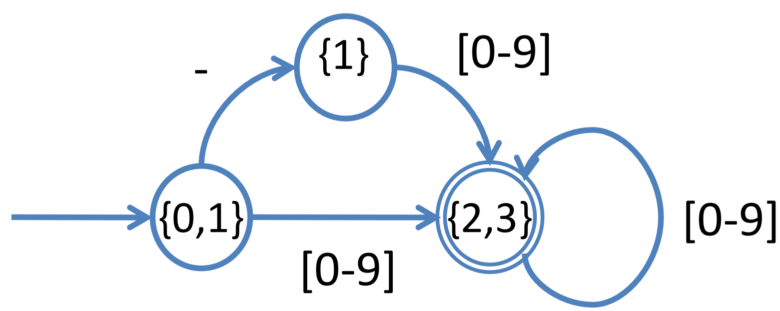
NFA to DFA conversion (Intuition)

- 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