Programming Languages and Compilers (CS 421)

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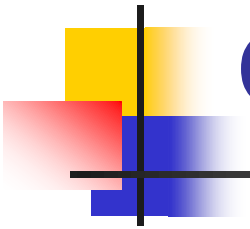
http://courses.engr.illinois.edu/cs421/

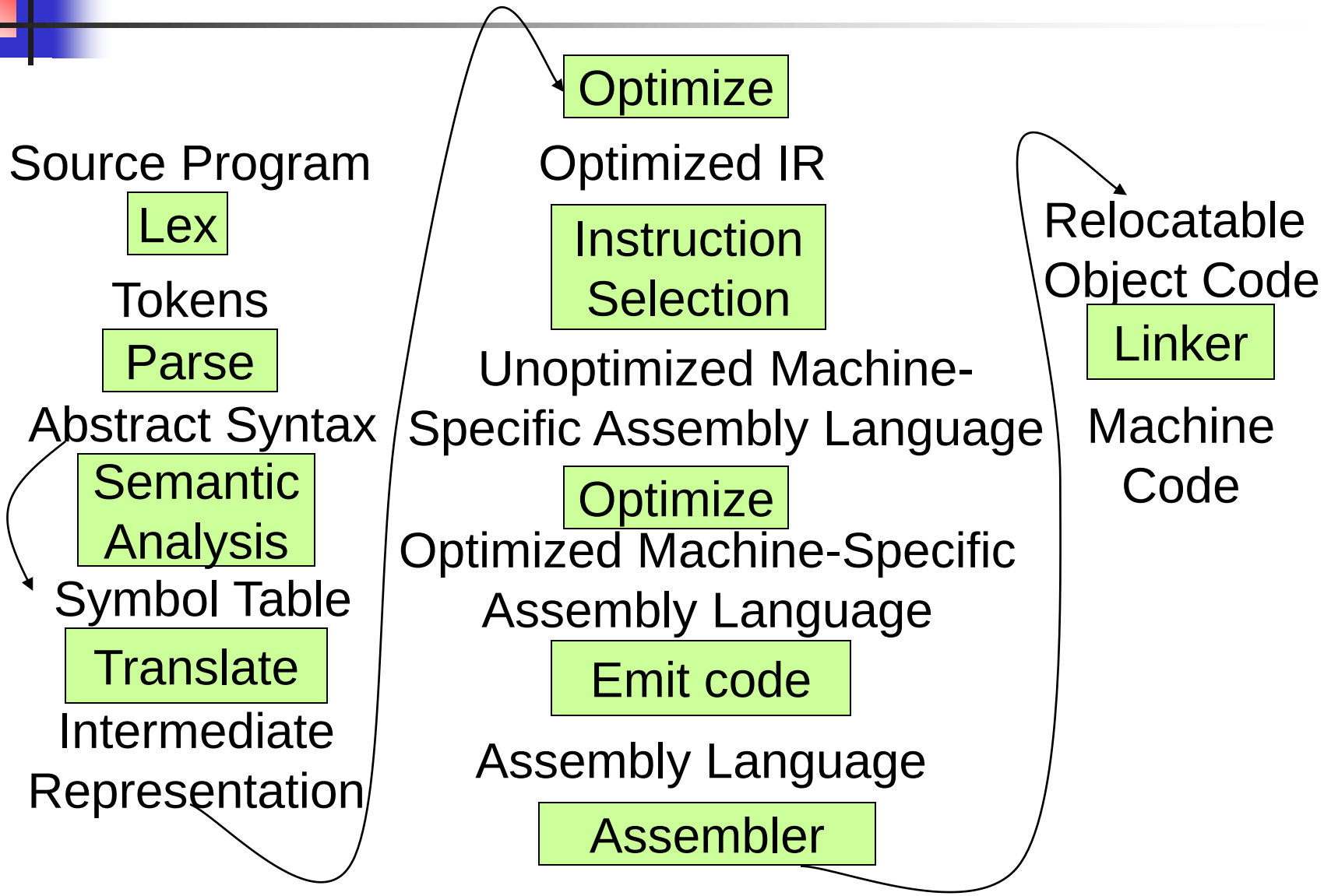
Based in part on slides by Mattox Beckman, as updated by Vikram Adve, Gul Agha, Elsa Gunter, and Dennis Griffith



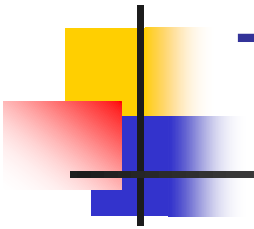
Compilers: Big Picture

- We want to turn strings (code) into computer-readable instructions
- Done in phases
- Turn strings into abstract syntax trees (lex and parse)
- Translate abstract syntax trees into executable instructions (interpret or compile)

Major Phases of a Compiler

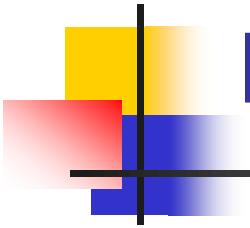


Modified from “Modern Compiler Implementation in ML”, by Andrew Appel



Talking About Languages

- Language Syntax and Semantics
- Syntax
  - DFAs and NFAs
  - Grammars
- Semantics
  - Natural Semantics
  - Transition Semantics



Language Syntax

- Syntax describes which strings of symbols are meaningful expressions in a language
- It takes more than syntax to understand a language; need meaning (semantics) too
- Syntax is the starting point

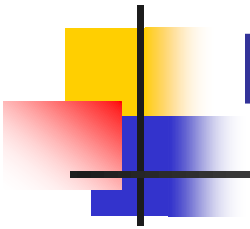
Syntax of English Language

- Pattern 1

Subject	Verb
David	*sings*
The dog	*barked*
Susan	*yawned*

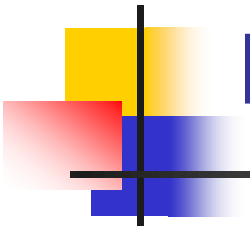
- Pattern 2

Subject	Verb	Direct Object
David	*sings*	*ballads*
The professor	*wants*	*to retire*
The jury	*found*	*the defendant guilty*



Elements of Syntax

- Character set – previously always ASCII, now often 64bit character sets
- Keywords – usually reserved
- Special constants – cannot assign values
- Identifiers – can assign values
- Operator symbols
- Delimiters (parentheses, braces, brackets)
- Blanks (aka white space)



Elements of Syntax

- Expressions

  if ... then begin ... ; ... end else begin ... ; ... end

- Type expressions

  $typexpr_1$ -> $typexpr_2$

- Declarations (in functional languages)

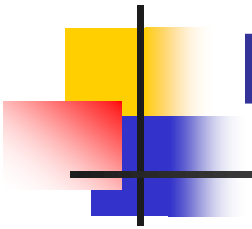
  let $pattern_1$ = $expr_1$ in *expr*

- Statements (in imperative languages)

  a = b + c

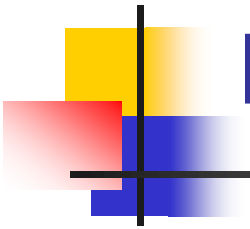
- Subprograms

  let $pattern_1$ = let rec inner = … in *expr*



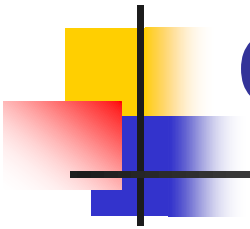
Elements of Syntax

- Modules
- Interfaces
- Classes (for object-oriented languages)



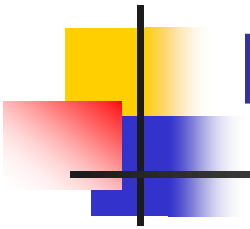
Formal Language Descriptions

- Regular expressions, regular grammars, finite state automata
- Context-free grammars, BNF grammars, syntax diagrams
- Whole family more of grammars and automata – covered in automata theory



Grammars

- Grammars are formal descriptions of which strings over a given character set are in a particular language
- Language designers write grammar
- Language implementers use grammar to know what programs to accept
- Language users use grammar to know how to write legitimate programs



Regular Expressions

- Simple kind of formal grammar
- Start with a given character set ("alphabet") – **a, b, c**…
- Each character is a regular expression
  - Meaning: set of the one one-letter string of that character

Regular Expressions

- If **x** and **y** are regular expressions, then **xy** is a regular expression
  - Meaning: set of all strings made from first a string described by **x** then a string described by **y**

If **x**={a,ab} and **y**={c,d} then **xy** ={ac,ad,abc,abd}.

- If **x** and **y** are regular expressions, then **x** $\vee$ **y** is a regular expression
  - Meaning: set of strings described by either **x** or **y**

If **x**={a,ab} and **y**={c,d} then **x** $\vee$ **y**={a,ab,c,d}

Regular Expressions

- If **x** is a regular expression, then so is **(x)**
  - Meaning is the same as **x** (helps disambiguate)

- If **x** is a regular expression, then so is **x***
  - Meaning: set of strings made from concatenating zero or more strings from **x**

  If **x** = {a,ab}

  then **x*** = {"",a,ab,aa,aab,abab,aaa,aaab,…}

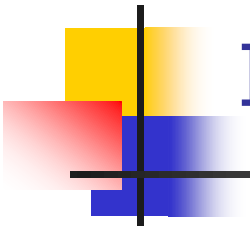
- **ε**
  - Meaning: {""}, set containing the empty string

Example Regular Expressions

- **(0∨1)*1**
  - The set of all strings of **0**'s and **1**'s ending in 1, **{1, 01, 11,…}**
- **a*b(a*)**
  - The set of all strings of a's and b's with exactly one b
- **((01) ∨(10))***
  - ?
- Regular expressions (equivalently, regular grammars) used for *lexing*, breaking strings into recognized words

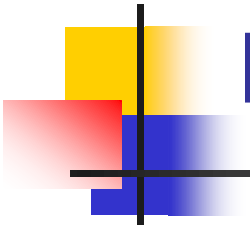
Example: Lexing

- Regular expressions good for describing lexemes (words) in a programming language
  - Identifier = (a $\vee$ b $\vee$ … $\vee$ z $\vee$ A $\vee$ B $\vee$ … $\vee$ Z) (a $\vee$ b $\vee$ … $\vee$ z $\vee$ A $\vee$ B $\vee$ … $\vee$ Z $\vee$ 0 $\vee$ 1 $\vee$ … $\vee$ 9)*
  - Digit = (0 $\vee$ 1 $\vee$ … $\vee$ 9)
  - Number = 0 $\vee$ (1 $\vee$ … $\vee$ 9)(0 $\vee$ … $\vee$ 9)* $\vee$ ~ (1 $\vee$ … $\vee$ 9)(0 $\vee$ … $\vee$ 9)*
  - Keywords: if = if, while = while,…



Implementing Regular Expressions

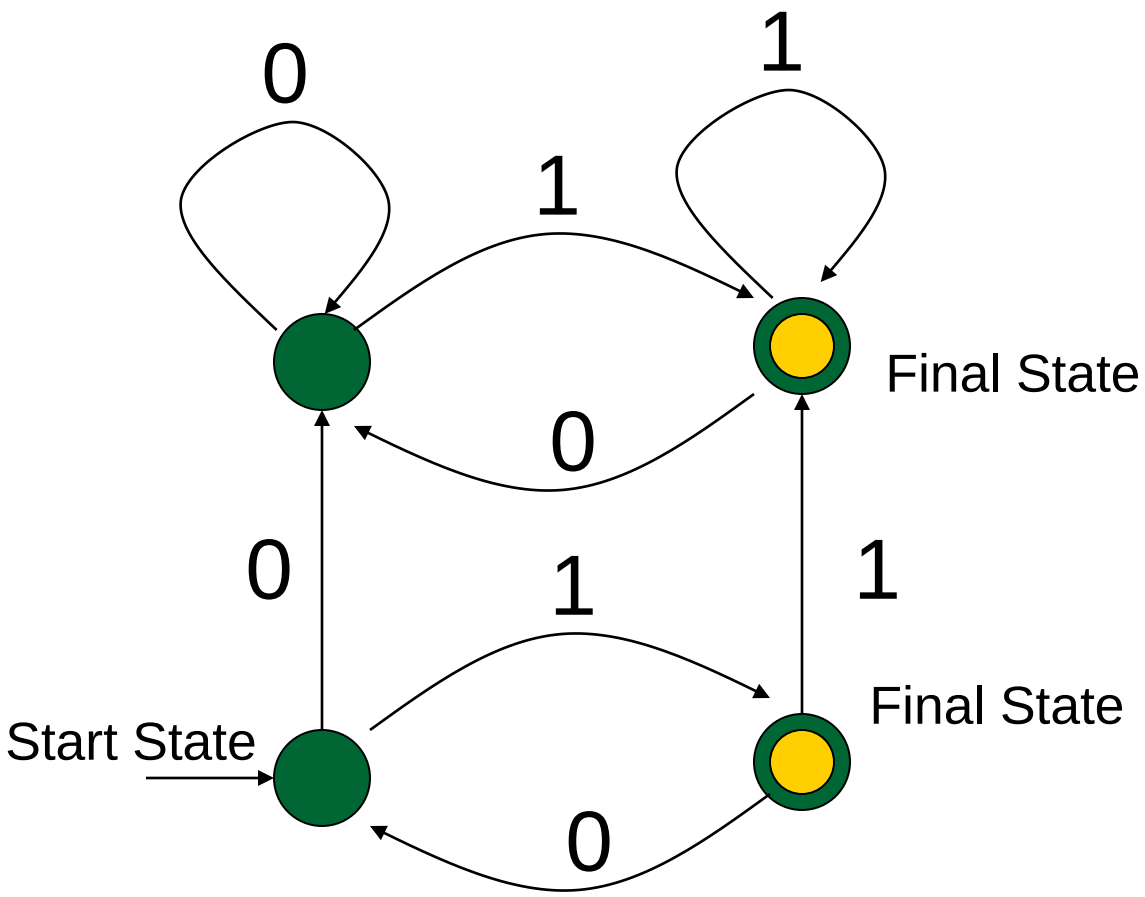
- Good for answering "what are all the strings in the language?"
- Not so good for answering "is this particular string in the language?"
- Problems with Regular Expressions
  - which option to choose
  - how many repetitions to make
- Solution: finite state automata

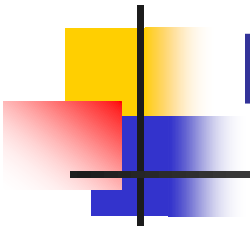


Finite State Automata

- A finite state automata over an alphabet is:
  - a directed graph
  - a finite set of states defined by the nodes
  - edges are labeled with elements of the alphabet, or empty string; they define state transitions
  - some nodes marked as final
  - one node marked as start state

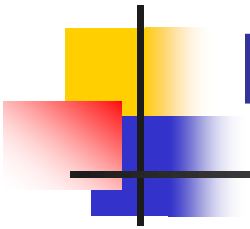
Example FSA





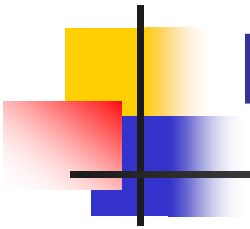
Deterministic FSAs

- A *deterministic* automata (DFA) has for every state *exactly one* edge for each letter
  - No edge labeled with ε
- In general automata may be *non-deterministic* (NFA)
  - NFA also allows edges labeled by ε
- DFAs are a specific kind of NFA



DFA Language Recognition

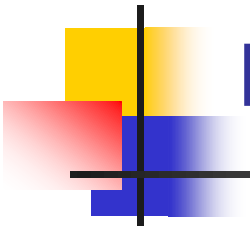
- Think of recognition as a board game: DFA is board
- You have the string as a deck of cards, one letter on each card
- Start by placing marker on the start state



DFA Language Recognition

- Move marker from one state to next along edge indicated by top card in deck; discard top card

- When you run out of cards,
  - if you are in a final state, you win; string is in language
  - if you are not in a final state, you lose; string is not in language

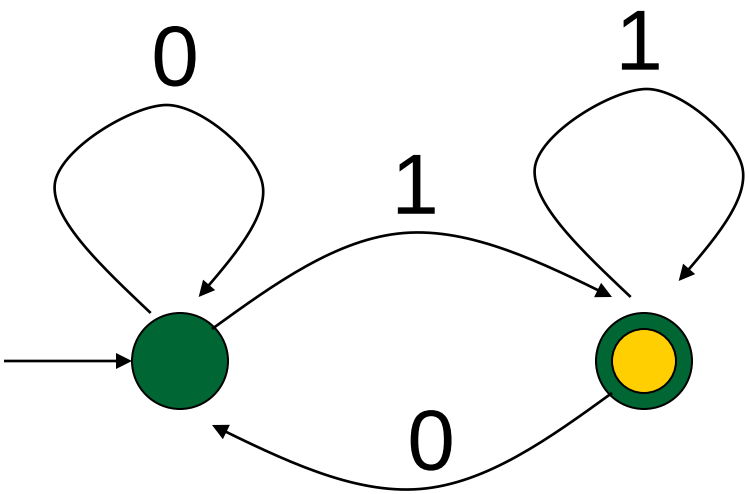


DFA Language Recognition Summary

- Given a string over alphabet
- Start at start state
- Move over edge labeled with first letter to new state
- Remove first letter from string
- Repeat until string is gone
- If end in final state then string in language

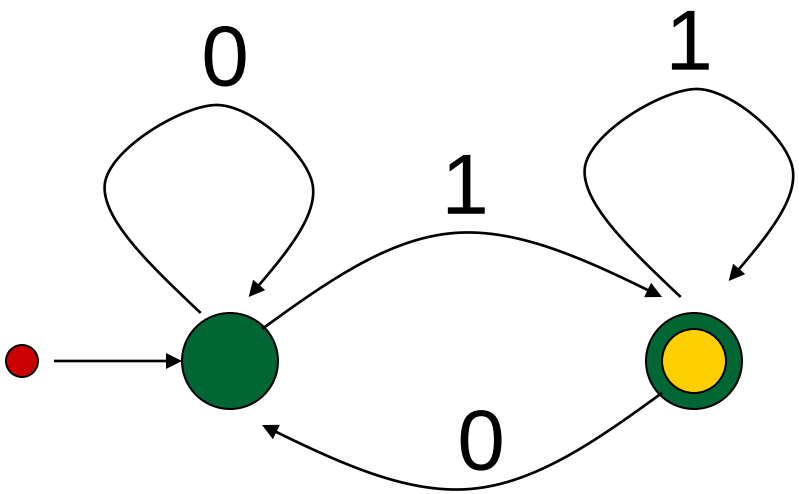
Example DFA

- Regular expression: (0 $\vee$ 1)* 1
- Deterministic FSA



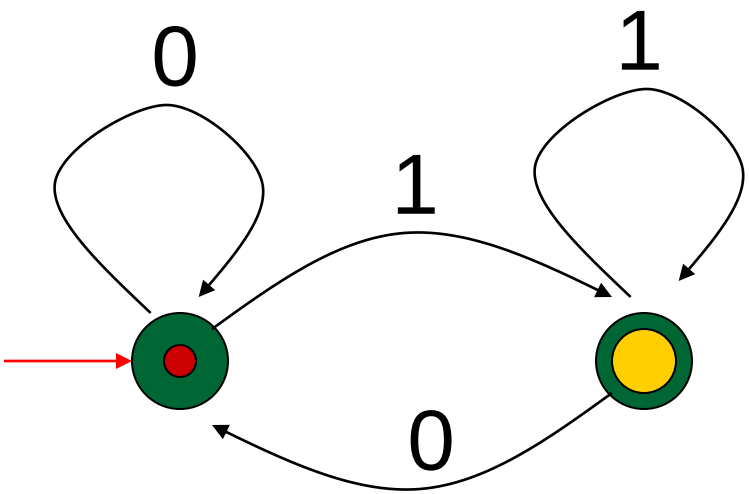
Example DFA

- Regular expression: (0 $\vee$ 1)* 1
- Accepts string 0 1 1 0 1



Example DFA

- Regular expression: (0 $\vee$ 1)* 1
- Accepts string 0 1 1 0 1 ?



Example DFA

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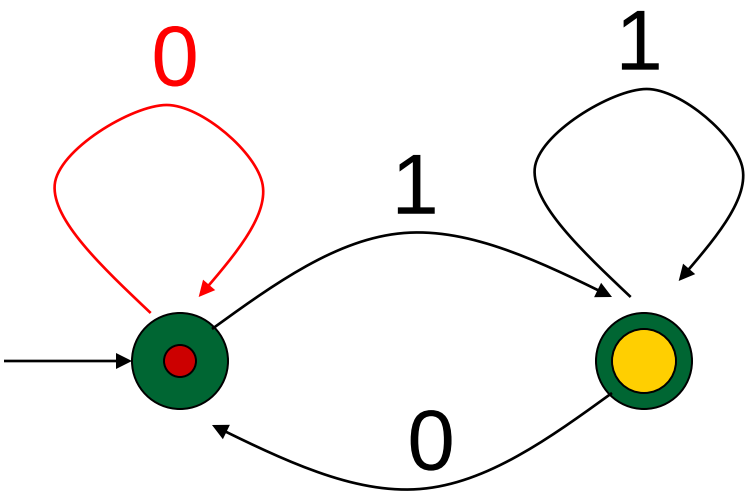

Example DFA

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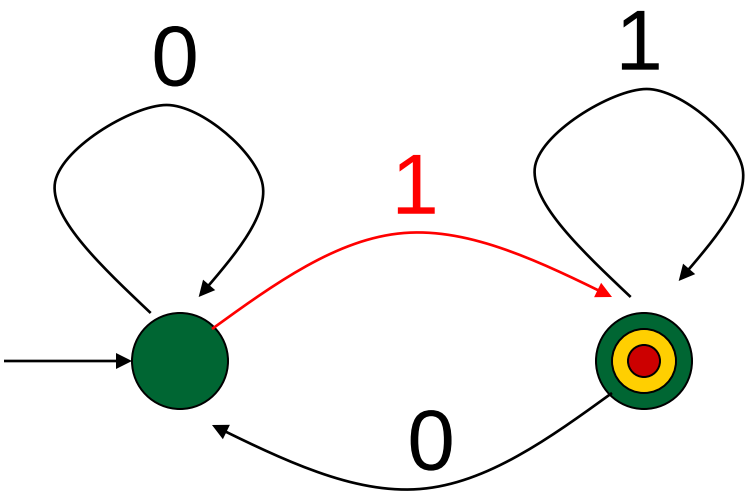

Example DFA

- Regular expression: (0 $\vee$ 1)* 1
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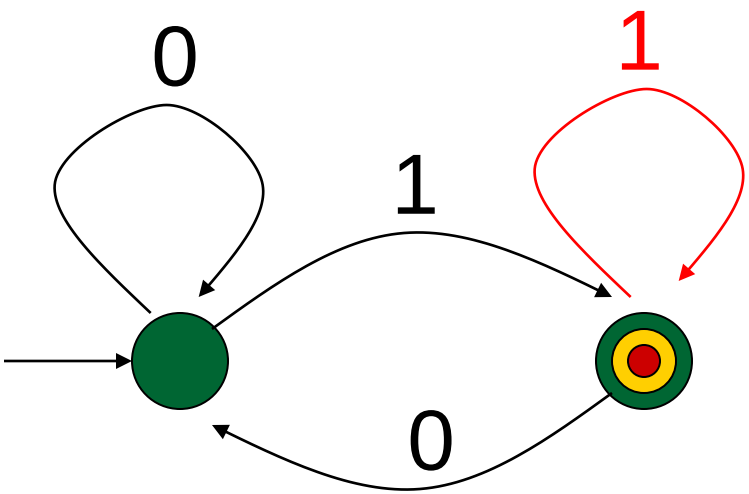

Example DFA

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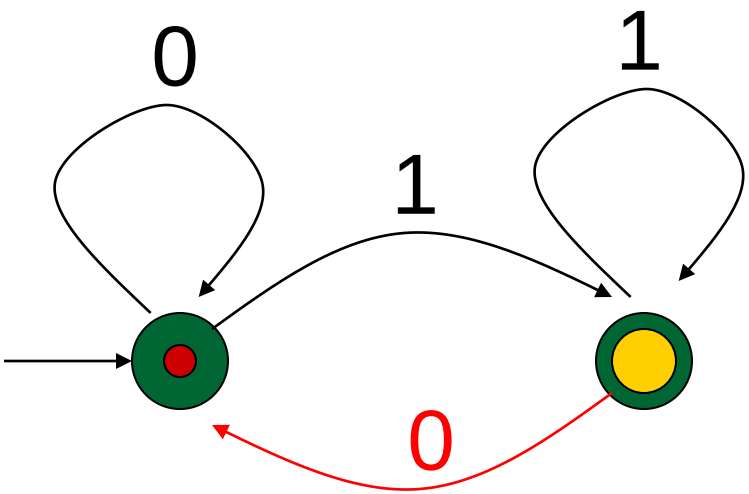

Example DFA

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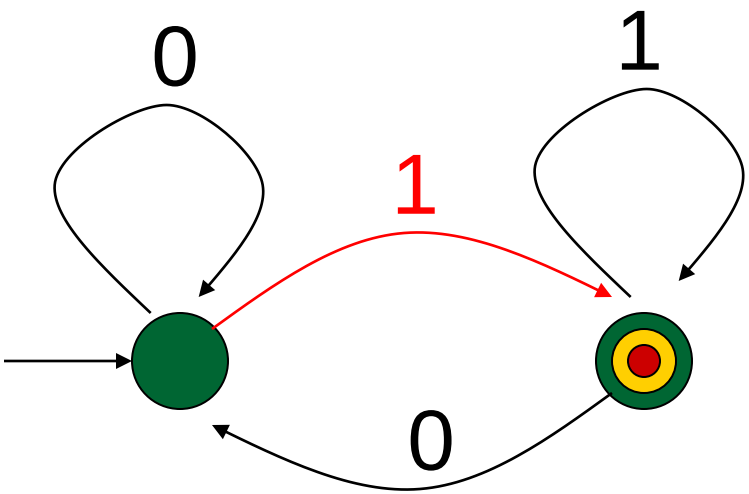
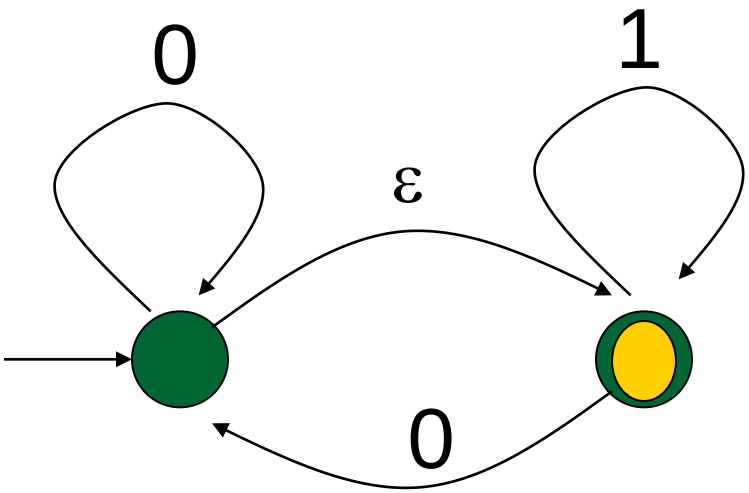


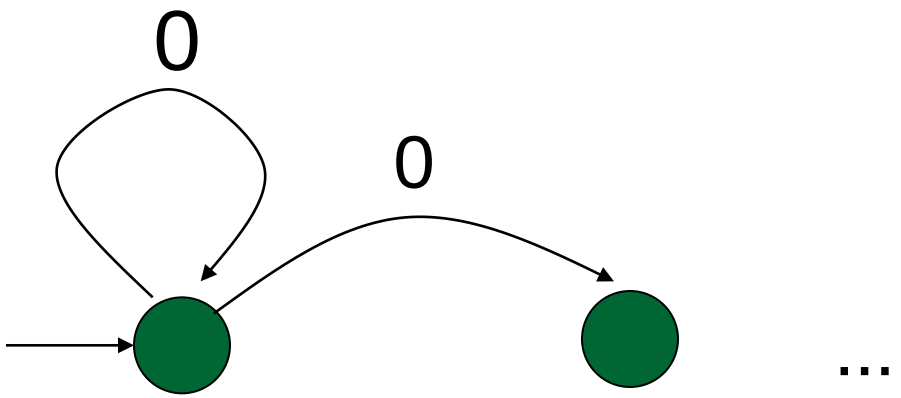
Non-deterministic FSA

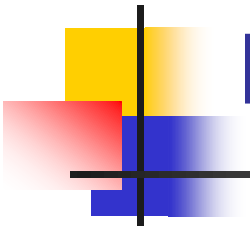
- NFA generalizes DFA in two ways:
- Include edges labeled by ε
  - Allows process to non-deterministically change state



Non-deterministic FSAs

- Each state can have zero, one, or more edges labeled by each letter
  - Given a letter, non-deterministically choose an edge to use



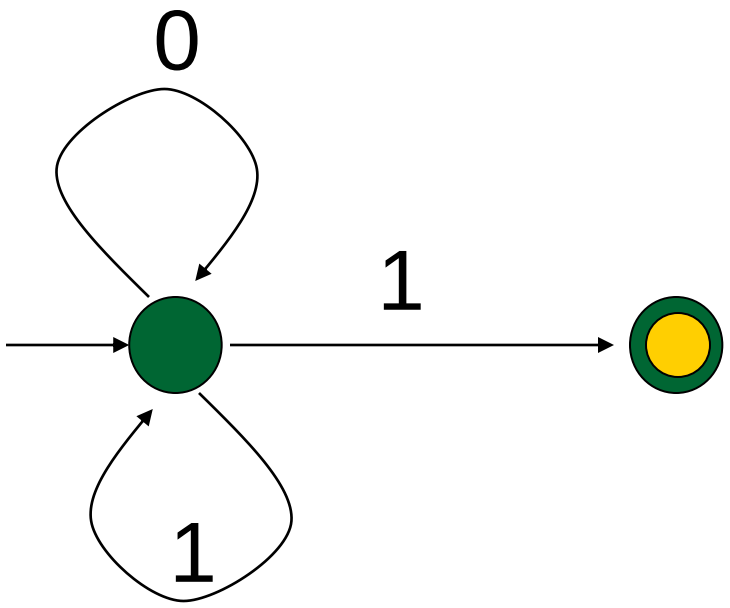


NFA Language Recognition

- Play the same game as with DFA
- Free move: move across an edge with empty string label without discarding card
- When you run out of letters, if you are in final state, you win; string is in language
- You can take one or more moves back and try again
- If you've tried all possible paths without success, then you lose; string not in language

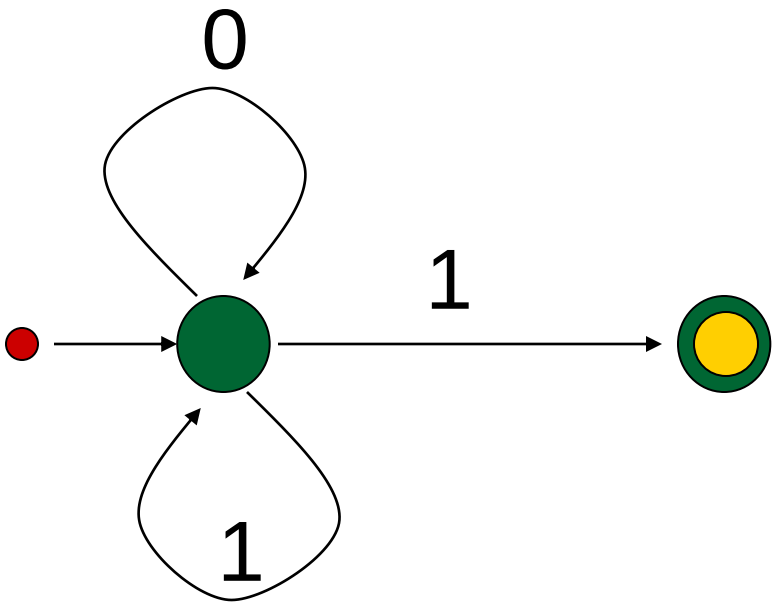
Example NFA

- Regular expression: (0 $\vee$ 1)* 1
- Non-deterministic automata



Example NFA

- Regular expression: (0 $\vee$ 1)* 1
- Accepts string 0 1 1 0 1 ?



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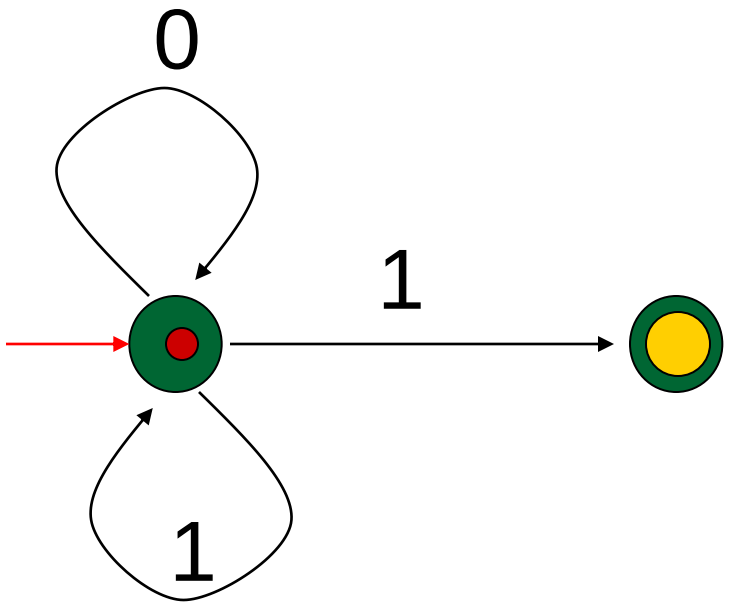

Example NFA

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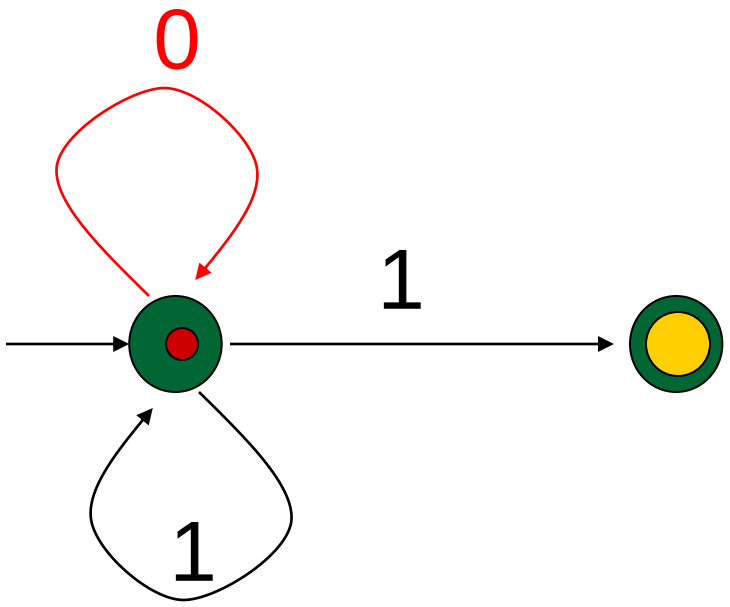
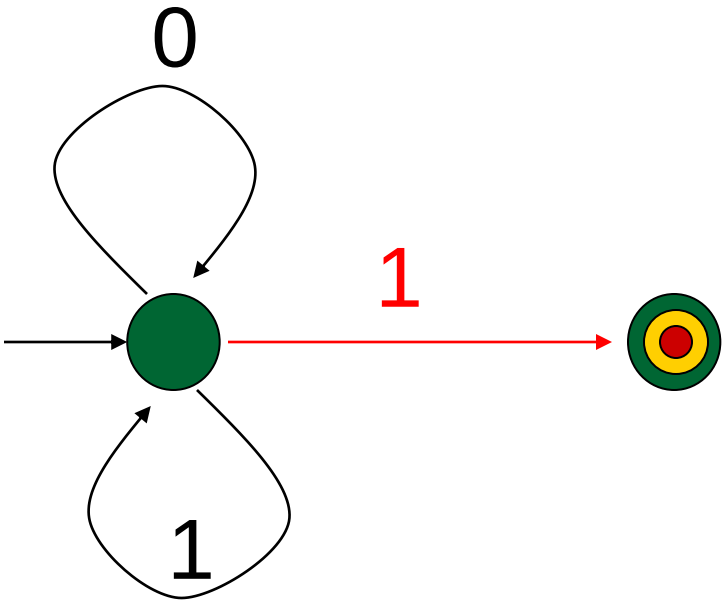


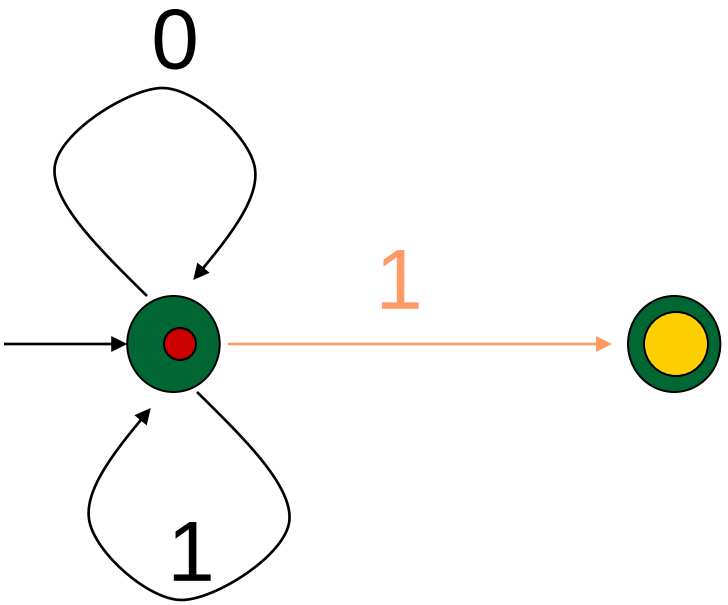
Example NFA

- Regular expression: (0 $\vee$ 1)* 1
- Accepts string ~~0~~ ~~1~~ 1 0 1 ?
- Guess



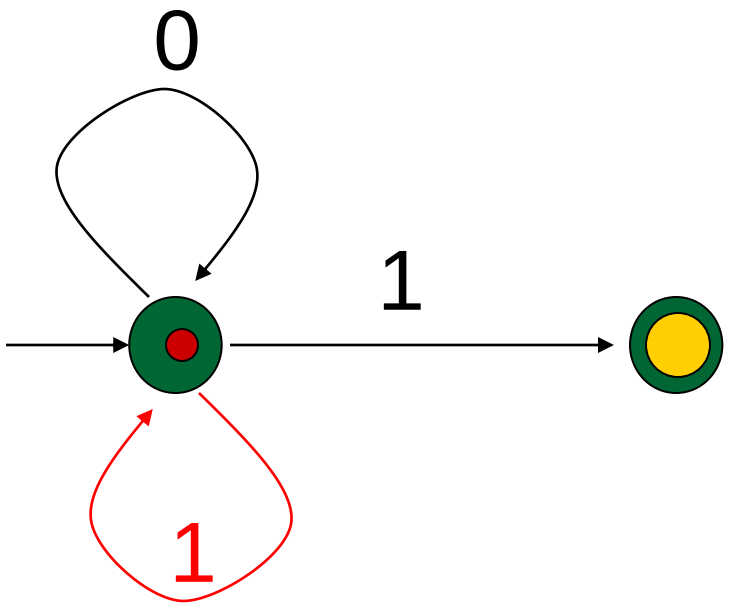
Example NFA

- Regular expression: (0 $\vee$ 1)* 1
- Accepts string ~~0~~ 1 1 0 1 ?
- Backtrack



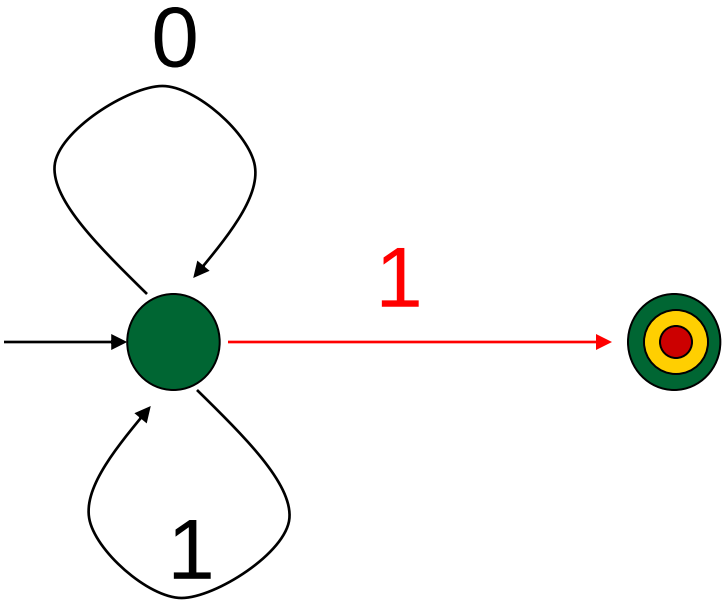
Example NFA

- Regular expression: (0 $\vee$ 1)* 1
- Accepts string 0 1 1 0 1 ?
- Guess again



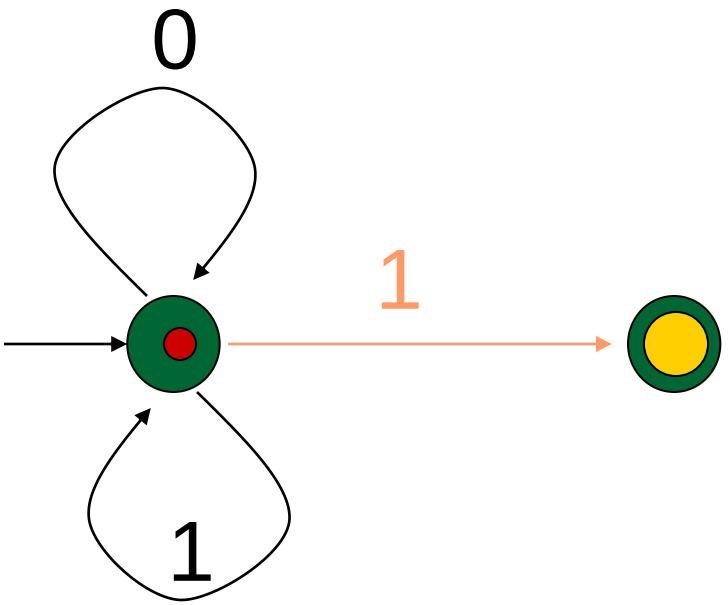
Example NFA

- Regular expression: (0 $\vee$ 1)* 1
- Accepts string ~~0 1 1~~ 0 1 ?
- Guess



Example NFA

- Regular expression: (0 $\vee$ 1)* 1
- Accepts string ~~0~~ ~~1~~ 1 0 1 ?
- Backtrack



Example NFA

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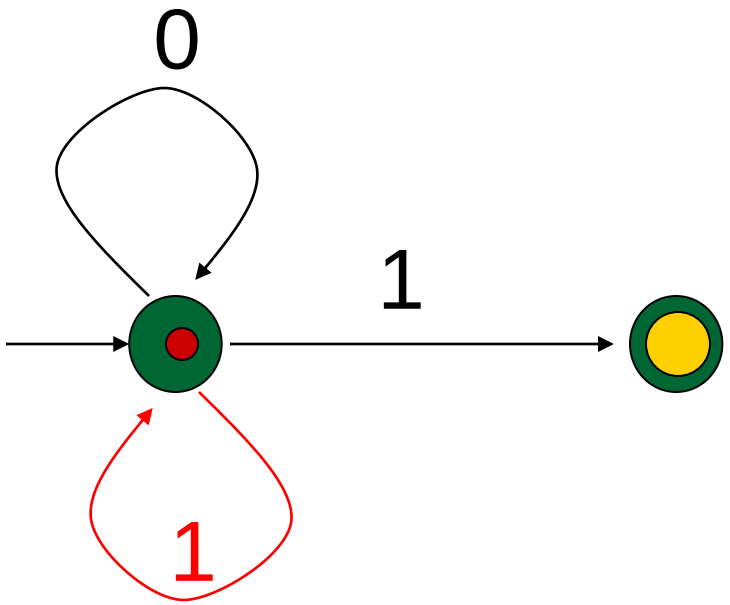
- Guess again



Example NFA

- Regular expression: (0 $\vee$ 1)* 1
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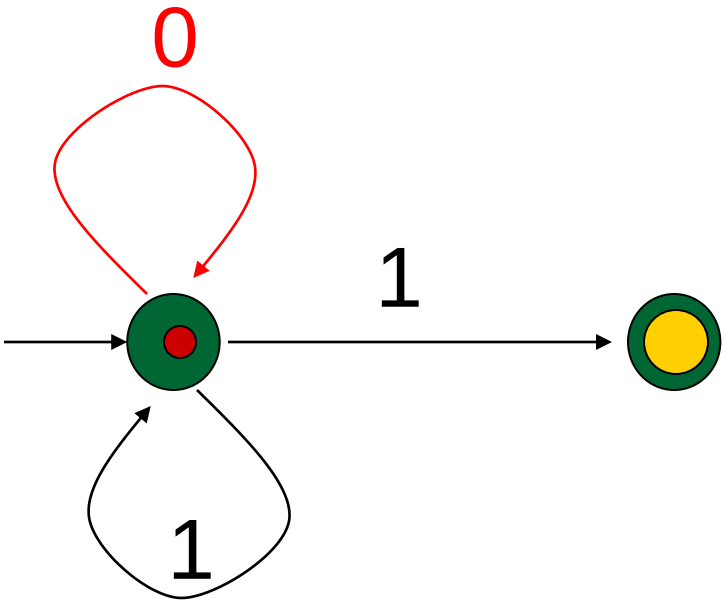
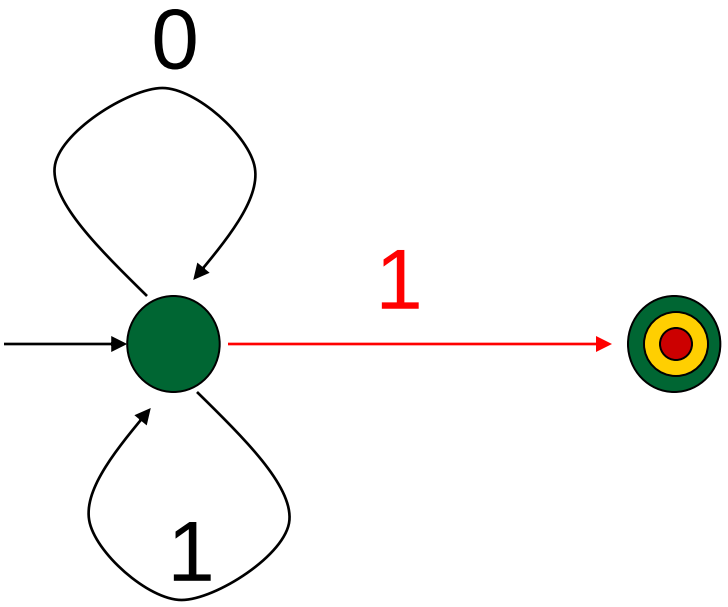
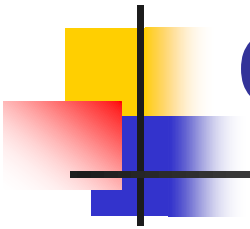


Example NFA

- Regular expression: (0 $\vee$ 1)* 1
- Accepts string ~~0 1 1 0 1~~ ?
- Guess (works this time)





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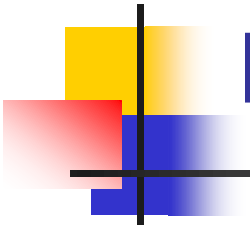
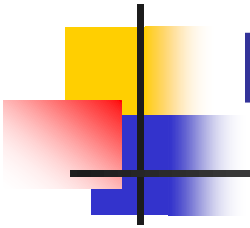
- Turn strings into abstract syntax trees (lex and parse)
- Translate abstract syntax trees into executable instructions (interpret or compile)



Lexing and Parsing

- Converting strings to abstract syntax trees done in two phases
  - **Lexing:** Convert a string (program text) into a list of tokens ("words" of the language)
  - **Parsing:** Convert a list of tokens into an abstract syntax tree

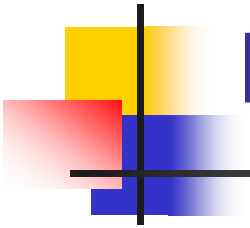


Lexing

- Different syntactic categories of “words”: tokens

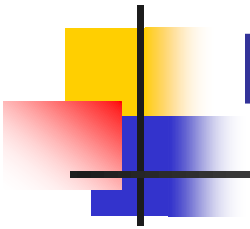
- Example: given token categories *String*, *Int*, and *Float*, "asd 123 jkl 3.14" will become:

[String "asd"; Int 123; String "jkl"; Float 3.14]



Lexing

- Each category described by regular expression (with extended syntax)
- Words recognized by (encoding of) corresponding finite state automaton
- Problem: we want to pull all words out of a string, not just recognize one word

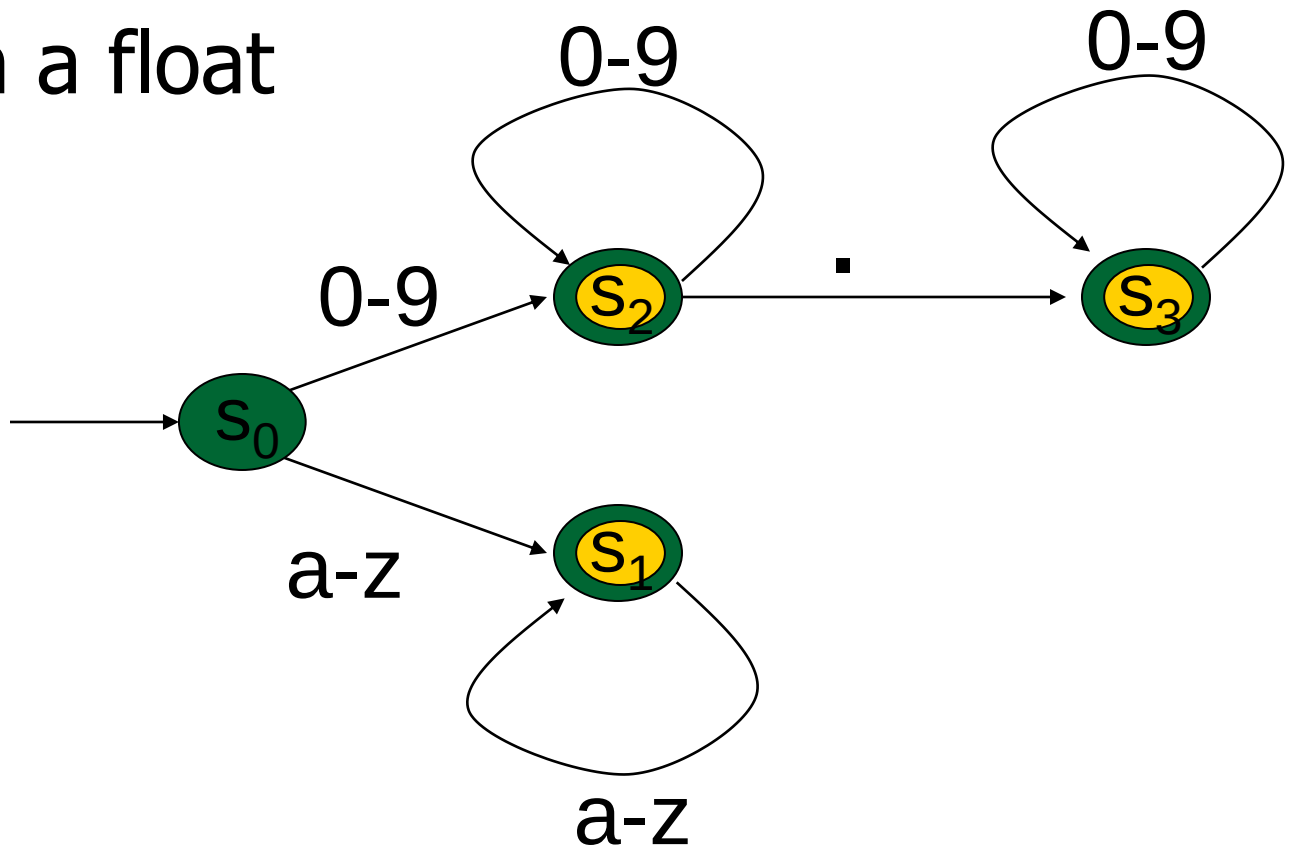


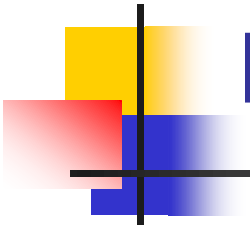
Lexing

- Modify behavior of DFA
- When we encounter a character in a state for which there is no transition
  - Stop processing the string
  - If in an accepting state, return the token that corresponds to the state, and the remainder of the string
  - If not, fail
- Add recursive layer to get sequence

Example

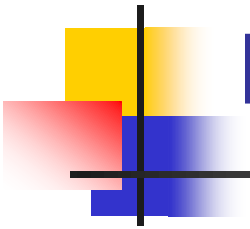
- s_1: return a string
- s_2: return an integer
- s_3: return a float





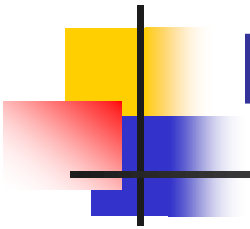
Lex, ocamllex

- Could write the regexp, then translate to DFA by hand
- Better: Write program to take regexp as input and automatically generate automata
- The most popular tool for this is Lex
- ocamllex is the OCaml version



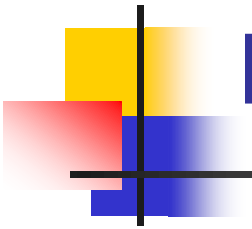
How to do it

- To use regular expressions to parse our input we need:
  - Some way to access the input string — call it a *lexing buffer*
  - Set of regular expressions
  - For each regexp, an action to take when matched



How to do it

- Lexer takes regular expressions and generates a state machine
- State machine takes lexing buffer and applies transitions
- When accepting state is reached, perform appropriate action



Mechanics

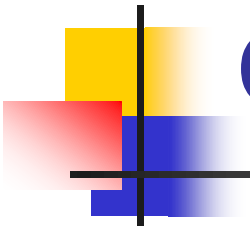
- Put table of regexp and corresponding actions (written in OCaml) into a file <*filename*>.mll
- Run ocamllex <*filename*>.mll
- Produces OCaml code for a lexical analyzer in <*filename*>.ml

Sample Input

```
rule main = parse
 ['0'-'9']+                    { print_string "Int\n"}
 | ['0'-'9']+'.'['0'-'9']+     { print_string "Float\n"}
 | ['a'-'z']+                  { print_string "String\n"}
 | _                           { main lexbuf }
 {
 let newlexbuf = (Lexing.from_channel stdin) in
 print_string "Ready to lex.\n";
 main newlexbuf
}
```

General Input

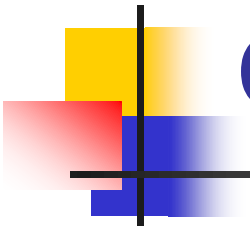
{ *header* }
let *ident* = *regexp* ...
rule *entrypoint* [*arg1*... *argn*] = parse
    regexp { *action* }
  | ...
  | *regexp* { *action* }
and *entrypoint* [*arg1*... *argn*] = parse ...
and ...
{ *trailer* }



Ocamllex Input

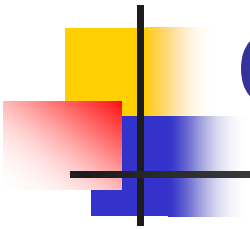
- *header* and *trailer* contain arbitrary OCaml code put at top and bottom of *<filename>*.ml

- let *ident* = *regexp* ... defines abbreviations for regexps to use in rules



Ocamllex Input

- *<filename>*.ml contains one lexing function per *entrypoint*
  - Name of function is name given for *entrypoint*
  - Each entry point becomes an Ocaml function that takes *n*+1 arguments, the extra implicit last argument being of type Lexing.lexbuf
- *arg1*... a*rgn* are for use in *action*



Ocamllex Regular Expressions

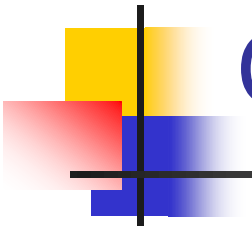
- Single quoted characters for letters: 'a'
- _ (underscore): matches any letter
- Eof: special “end_of_file” marker
- Concatenation same as usual
- "*string*": concatenation of sequence of characters
- e_1 / e_2: choice (as $e_1 \vee e_2$)

Ocamllex Regular Expression

- [c_1 - c_2]: choice of any character between first and second inclusive, as determined by character codes
- [^c_1 - c_2]: choice of any character NOT in set
- e*: same as before (repetition)
- e+: same as $e\ e$*
- e?: option (as $e_1 \vee \varepsilon$)

Ocamllex Regular Expression

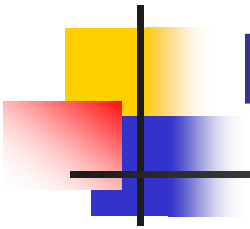
- e_1 # e_2: set of characters in e_1 but not in e_2; e_1 and e_2 must describe sets of characters
- *ident*: abbreviated regexp, previously defined by let *ident* = *regexp*
- e_1 as *id*: binds the result of e_1 to *id* to be used in the associated *action*



Ocamllex Manual

- More details can be found at

http://caml.inria.fr/pub/docs/manual-ocaml/manual026.html

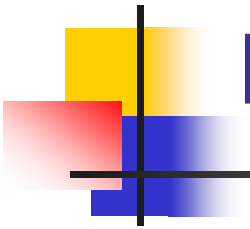


Example : test.mll

```
{ type result = Int of int | Float of float |
   String of string }
let digit = ['0'-'9']
let digits = digit +
let lower_case = ['a'-'z']
let upper_case = ['A'-'Z']
let letter = upper_case | lower_case
let letters = letter +
```

Example : test.mll

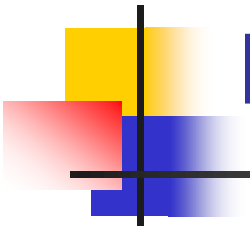
```
rule main = parse
   (digits)'.'digits as f  { Float (float_of_string f) }
 | digits as n             { Int (int_of_string n) }
 | letters as s            { String s}
 | _ { main lexbuf }
 { let newlexbuf = (Lexing.from_channel stdin) in
 print_string "Ready to lex.";
 print_newline ();
 main newlexbuf  }
```



Example

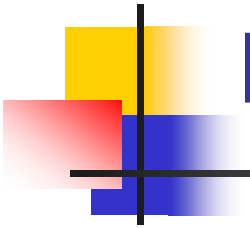
```
# #use "test.ml";;
...
val main : Lexing.lexbuf -> result = <fun>
val __ocaml_lex_main_rec : Lexing.lexbuf -> int ->
   result = <fun>
Ready to lex.
hi there 234 5.2
- : result = String "hi"
```

What happened to the rest?



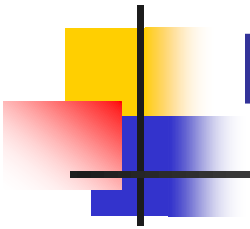
Example

```
# let b = Lexing.from_channel stdin;;
# main b;;
hi 673 there
- : result = String "hi"
# main b;;
- : result = Int 673
# main b;;
- : result = String "there"
```



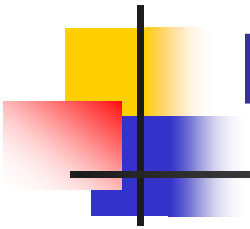
Problem

- How to get lexer to look at more than the first token at one time?
- Answer: *action* has to tell it to – with a recursive call
- Side benefit: can add "state" into lexing
- Note: already used this with the _ case



Example

```
rule main = parse
   (digits) '.' digits as f { Float
   (float_of_string f) :: main lexbuf}
 | digits as n              { Int (int_of_string n) ::
   main lexbuf }
 | letters as s             { String s :: main
   lexbuf}
 | eof                       { [] }
 | _                         { main lexbuf }
```



Example Results

Ready to lex.

hi there 234 5.2

- : result list = [String "hi"; String "there"; Int 234; Float 5.2]

#

Used Ctrl-d to send the end-of-file signal

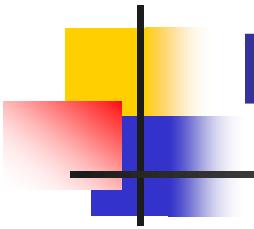
Dealing with comments

First Attempt

```
let open_comment = "(*"
let close_comment = "*)"
rule main = parse
    (digits) '.' digits as f { Float (float_of_string
   f) :: main lexbuf}
 | digits as n              { Int (int_of_string n) ::
   main lexbuf }
 | letters as s             { String s :: main lexbuf}
```

Dealing with comments

```
 | open_comment          { comment lexbuf }
 | eof                   { [] }
 | _ { main lexbuf }
and comment = parse
   close_comment         { main lexbuf }
 | _                     { comment lexbuf }
```



Dealing with nested comments

```
rule main = parse …
 | open_comment          { comment 1 lexbuf}
 | eof                   { [] }
 | _ { main lexbuf }
and comment depth = parse
   open_comment      { comment (depth+1) lexbuf }

 | close_comment     { if depth = 1 then main lexbuf
                       else comment (depth - 1) lexbuf }

 | _                       { comment depth lexbuf }
```