Programming Paradigms

Syntax (Part 1)

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Motivation

- **Goal:**
  Specify a programming language
  - What code is part of the language?
  - What is the meaning of a piece of code?
- **Important for both developers and tools**
- **In contrast: Natural languages not formally specified**

Syntax vs. Semantics

Structure of code

Meaning of code

Example:

Grammar to define a language:

digit → 0 | 1 | ... | 9
non_zero_digit → 1 | ... | 9
number → non_zero_digit digit*

Could mean

- Natural numbers
- Days of a 10-day week
- Colors
- ...

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Focus of this and next lecture

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- Days of a 10-day week
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Syntax of Different PLs

Common: **Different syntax, same semantics**

Java:

```
if (foo > 100) {
  ...
}
```

Bash:

```
if [ $foo -gt 100 ]
then
  ...
fi
```

Syntax of Different PLs

Common: **Different syntax, same semantics**

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Sometimes: **Same syntax, different semantics**

Java:

JavaScript:

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if ("abc" != 5) {
  ...
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```

Syntax of Different PLs

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Sometimes: **Same syntax, different semantics**

Java:

Type error at compile time

JavaScript:

```
if ("abc" != 5) {
  ...
}
```

Branch is executed

4 concepts to specify syntax

concatenation

alternation / choice

repetition ("Kleene closure")

recursion

regular expression → recognized by **scanners**

context-free grammars (CFG) → recognized by **parsers**

Overview

- **Specifying syntax**
  - Regular expressions
  - Context-free grammars
- **Scanning**
- **Parsing**

Tokens

Basic building blocks of every PL

- Keywords, identifiers, constants, operators
- Think: ”Words” of the language

Example: C has more than 100 tokens

- Keywords, e.g., `double`, `if`, `return`, `struct`
- Identifiers, e.g., `my_var`, `printf`
- Literals, e.g., `6.022e23`, `'x'`
- Punctuators, e.g., `(`, `}`, `&&`

Regular Expressions

- **Used to specify tokens**
- **A regular expression is one of:**
  - A character
  - The empty string ϵ
  - The concatentation of two regular expressions
  - Two regular expressions separated by |
    - Means a string generated by one or the other
  - A reg. expression followed by the Kleene star *
    - Means zero or more repetitions

Regular Expressions

- **Used to specify tokens**
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No recursion!

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Example

Numeric constants accepted by a calculator

number → integer | real

integer → digit digit*

real → integer exponent | decimal (exponent | ε)

decimal → digit* (. digit | digit .) digit*

exponent → (e | E) (+ | - | ε) integer

digit → 0 | 1 | ... | 9

Quiz

Which of the following strings is accepted by the regular expression *number*?

- -23
- 000
- 7.003E-5
- 0.123.45
- 2e3
- 12+E

Quiz

Which of the following strings is accepted by the regular expression *number*?

- -23 ✗
- 000 ✓
- 7.003E-5 ✓
- 0.123.45 ✗
- 2e3 ✓
- 12+E ✗

More compact syntax for regular expressions

Language of tokens: { c, cac, cbc,
cacac, cbcbc,
cacbc, cbcac, ... }

$$\text{Token} \longrightarrow c \ \text{More}^*$$

$$\text{More} \longrightarrow \text{AorB} \ \ c$$

$$\text{AorB} \longrightarrow a \mid b$$

Shorter notation: Nest all into one

$$\underbrace{c\,(\underbrace{\underbrace{(a\mid b)}_{\text{AorB}}\ c}_{\text{More}})^*}_{\text{Token}}$$

Identifiers in Popular PLs

Different PLs allow different identifiers

- Case-sensitive vs. case-insensitive
  - E.g., `foo`, `Foo`, and `FOO` are the same in Ada and Common Lisp, but not in Perl and C
- Letters and digits: Almost always allowed
- Underscore: Allowed in most languages

In addition to syntax rules: Conventions

- E.g., Java: `ClassName`, `variableName`

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In addition to syntax rules: Conventions

- E.g., Java: `ClassName`, `variableName`

Know the rules of the language you use!

White space in Popular PLs

Free format vs. formatting as syntax

- Spaces and tabs sometimes matter
  - E.g., in Python
- Line breaks sometimes matter
  - E.g., to separate statements in JavaScript or Python

Demo

[demos/whitespace: show both stmts on one line; insert semi-colon; show not indenting print (after inverting condition)]

Overview

- **Specifying syntax**
  - Regular expressions
  - Context-free grammars ←
- **Scanning**
- **Parsing**

Are regular expression enough?

Specifying arithmetic expressions

↳ E.g., $\boxed{5+7}$

$\boxed{(\boxed{5+7})+6}$

$\boxed{(\boxed{(\boxed{5+7})+6})-23}$

Each $\boxed{}$ is an arithmetic expression

→ Want: Nesting

→ Need recursion

Context-free Grammars

≈ Regular expressions + Recursion

Example: Arithmetic expressions

expr → `id` | `number` | **expr op expr** | **(expr)**

op → **+** | **−** | ***** | **/**

Context-free Grammars

≈ **Regular expressions + Recursion**

Example: Arithmetic expressions

expr → `id` | `number` | **expr op expr** | **(expr)**

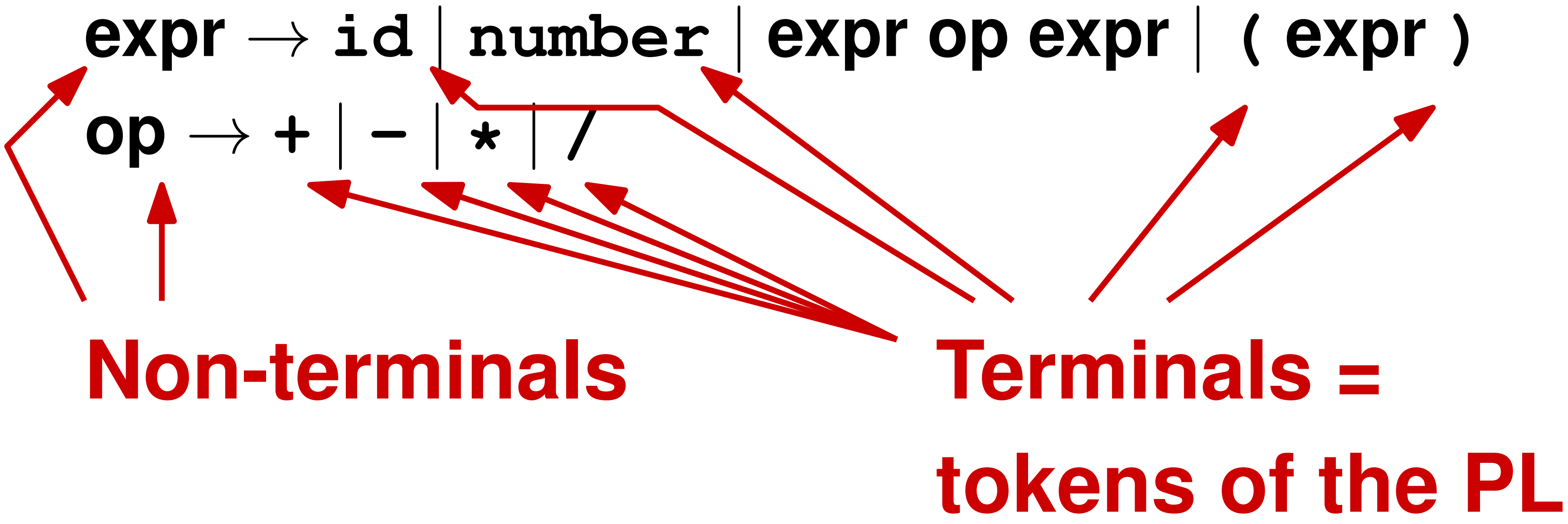
op → `+` | `-` | `*` | `/`

Non-terminals

Context-free Grammars

≈ Regular expressions + Recursion

Example: Arithmetic expressions



expr → `id` | `number` | **expr op expr** | (**expr**)

op → + | − | * | /

Non-terminals

Terminals = tokens of the PL

Context-free Grammars

≈ **Regular expressions + Recursion**

Example: Arithmetic expressions

expr → `id` | `number` | **expr op expr** | **(expr)**

op → **+** | **−** | ***** | **/**

Recursion allows for nesting expressions

Definition of CFG

$G = (N, T, R, s)$

N ... finite set of non-terminals

T ... finite set of terminals

= alphabet of the language

= (for PLs) tokens of the lang.

R .. finite relation from N to $(N \cup T)^*$

= production rules

s .. start symbol

Extension of basic definition

- Kleene star
  - ↳ E.g., id_list → id (, id)* ← means zero or more
  - ↳ short-hand for id_list → id
    id_list → id_list , id

- Kleene plus
  - ↳ Same, but <u>one</u> or more

- Vertical bar
  - ↳ E.g., op → + | - | * | /
  - ↳ Short-hand for op → +
    op → −
    ⋮

Derivations

Create concrete strings from the grammar

- Begin with start symbol
- Repeat until no non-terminals remain:
  - Choose non-terminal and a production with this non-terminal on the left-hand side
  - Replace it with right-hand side of the production (choose one option if multiple options)

Example:

$$\begin{aligned} \text{expr} &\rightarrow \text{id} \mid \text{number} \mid (\ \text{expr}\ ) \mid \text{expr}\ \text{op}\ \text{expr} \\ \text{op} &\rightarrow + \mid - \mid * \mid / \end{aligned}$$

Derivation of foo * x + bar

"derive"

$$\begin{aligned} \text{expr} &\Rightarrow \text{expr}\ \text{op}\ \underline{\text{expr}} \\ &\Rightarrow \text{expr}\ \underline{\text{op}}\ \text{id} \\ &\Rightarrow \underline{\text{expr}}\ +\ \text{id} \\ &\Rightarrow \text{expr}\ \text{op}\ \underline{\text{expr}}\ +\ \text{id} \\ &\Rightarrow \text{expr}\ \underline{\text{op}}\ \text{id}\ +\ \text{id} \\ &\Rightarrow \underline{\text{expr}}\ *\ \text{id}\ +\ \text{id} \\ &\Rightarrow \text{id}\ *\ \text{id}\ +\ \text{id} \end{aligned}$$

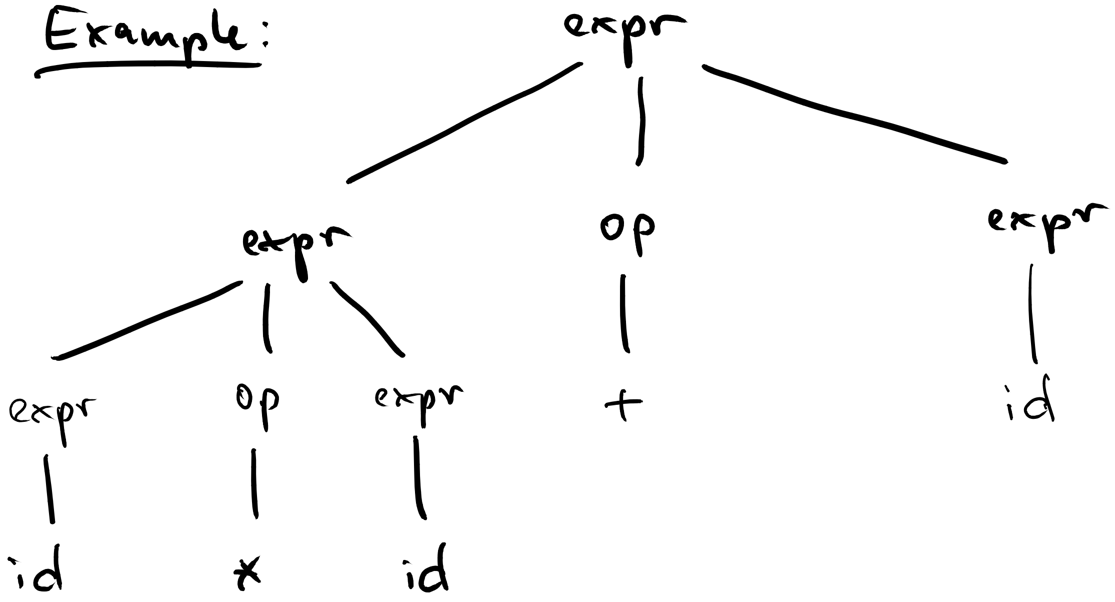
foo x bar

Parse Trees

Tree-structured representation of a derivation

- Root = Start symbol
- Leaf nodes = Tokens that result from derivation
- Intermediate nodes = Application of a production

Example:



Not All Grammars are Equal

Each language has infinitely many grammars

Some grammars are ambiguous

- A single string may have multiple derivations
- Unambiguous grammars facilitate parsing

Grammar should reflect the internal structure of the PL

- E.g., associativity and precedence of operators

Example: Revised Grammar

A better version of the grammar of arithmetic expressions:

expr → term | expr add_op term

term → factor | term mult_op factor

factor → `id` | `number` | – factor | (expr)

add_op → + | –

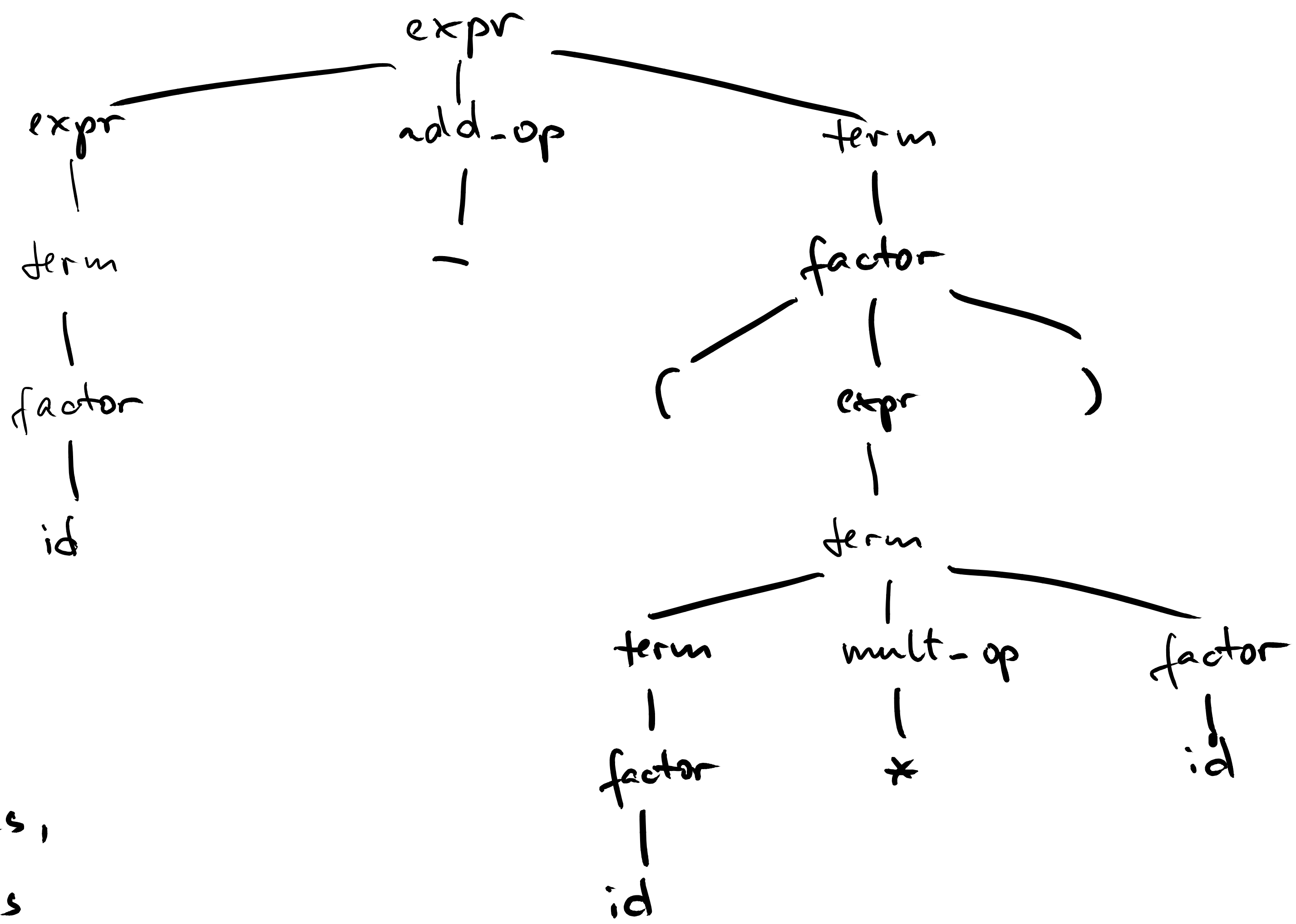
mult_op → `*` | `/`

Quiz: Context-free Grammars

Draw the parse tree of

`foo - (bar * bar)`

with the revised grammar. How many nodes and edges does the tree have?

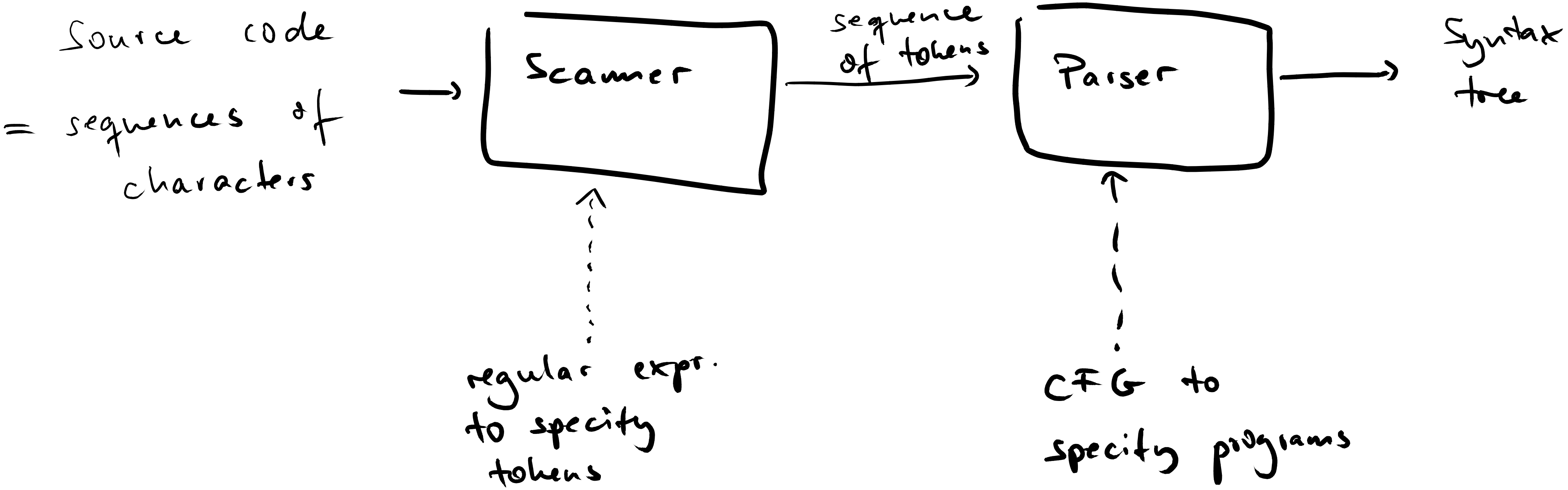


→ 20 nodes,
19 edges

Overview

- **Specifying syntax**
  - Regular expressions
  - Context-free grammars
- **Scanning** ←
- **Parsing**
  - Top-down parsing
  - Bottom-up parsing

Big Picture


Source code
= sequences of characters
Scanner
sequence of tokens
Parser
Syntax tree
regular expr. to specify tokens
CFG to specify programs

Implementing a Scanner

General idea

- Read one character at a time
- Whenever a full token is recognized, return it
- When no token can be recognized, report an error
- Sometimes, need to look multiple characters ahead to determine next token

Option 1: Ad-hoc Scanners

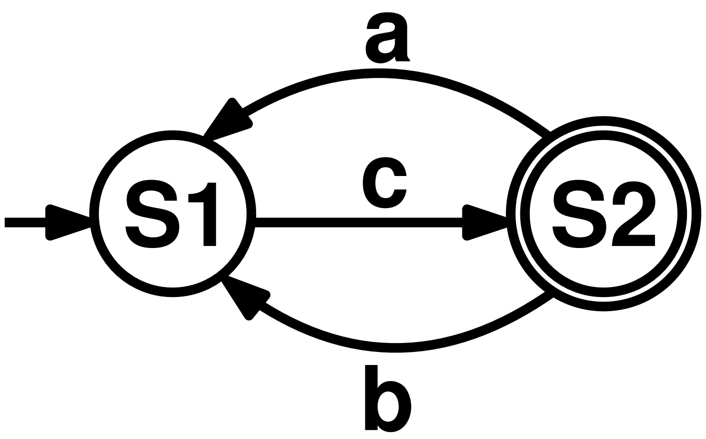
- **Manually implemented**
- **Handle common tokens first**
- **Used in many production compilers**
    - Compact code
    - Efficient scanning

Option 2: Finite Automata

- Each token specified by a regular expression
- Finite automata = Recognizers of regular expressions

Example:

c ((a | b) c)*



Definition: DFA

Deterministic finite automaton (DFA):

$(Q, \Sigma, \delta, q_0, F)$

- Finite set Q of states
- Finite set Σ of input symbols
- Transition function $\delta : Q \times \Sigma \to Q$
- Start state q_0
- Set of accept states $F \subseteq Q$

DFA versus NFA

- **Deterministic finite automaton (DFA)**
  - At most one outgoing transition for each input symbol
  - No ϵ transitions (empty word)
- **Non-deterministic finite automaton (NFA)**
  - Multiple outgoing transitions for same character
  - May have ϵ transitions

From Reg. Expr. to DFA

- **Regular expression to NFA**
- **NFA to DFA**
  - To avoid exploring multiple possible next states during scanning
- **DFA to minimal DFA**
  - Simplifies a DFA-based scanner
  - Remove unreachable and non-distinguishable states

See course on theoretical computer science or Chapter 2 of "Programming Language Pragmatics" for details