6 Automata Theory Cheatsheet

- * **Alphabet** is a finite set of symbols, commonly denoted Σ .
- * Word $w \in \Sigma^*$ is a finite sequence of symbols from alphabet Σ For example, $w = abacaba \in \{a, b, c\}^*$.
- * **Length** of a word: |w| = n, where *n* is the number of symbols in word *w*. For example, |abacaba| = 7.
- * **Empty word** ε is a word of length 0.
- * Concatenation of words w_1 and w_2 is $w_1 \cdot w_2 = w_1 w_2$.
- * **Power** of a word *w* is $w^n = w \cdot w \cdot \ldots \cdot w$ (*n* times).
- * **Reverse** of a word w is w^R .
- * Language L over an alphabet Σ is a set of words $L \subseteq \Sigma^*$.
- * **Empty language** Ø is a language that contains no words.
- * Singleton language $\{w\}$ is a language that contains only one word w.
- * **Empty string language** $\{\varepsilon\}$ is a language that contains only one empty word ε .
- * **Operations** on languages:
 - ∘ **Union**: $L_1 \cup L_2 = \{ w \mid w \in L_1 \lor w \in L_2 \}$
 - ∘ **Intersection**: $L_1 \cap L_2 = \{w \mid w \in L_1 \land w \in L_2\}$
 - **Complement**: $\neg L = \{w \mid w \notin L\}$
 - Concatenation $\stackrel{\mathbf{C}}{:} L_1 \cdot L_2 = \{ab \mid a \in L_1, b \in L_2\}$
 - Kleene star (Kleene closure) $: L^* = \bigcup_{k=0}^{\infty} \Sigma^k$
- * **Equivalence**: $L_1 \equiv L_2 \leftrightarrow (L_1 \cap \overline{L_2}) \cup (\overline{L_1} \cap L_2) = \emptyset$
- * **Regular language** [™] is a language that can be defined by a regular expression. Regular languages are defined inductively (recursively):
 - $\circ~$ The empty language \varnothing is regular.
 - ∘ For any $a \in \Sigma$, the singleton language $\{a\}$ is regular.
 - $\circ~$ If A is a regular language, then A^* (Kleene star) is also regular.
 - ∘ If *A* and *B* are regular languages, then $A \cup B$ (union) is also regular.
 - If *A* and *B* are regular languages, then $A \cdot B$ (concatenation) is also regular.
 - \circ No other languages over Σ are regular.
- * **REG (set of regular languages)** is set over an alphabet Σ

$$REG = \bigcup_{k=0}^{\infty} Reg_k = Reg_{\infty}.$$

- $\circ \operatorname{Reg}_0 = \{\emptyset, \{\varepsilon\}\} \cup \{\{c\} \mid c \in \Sigma\}.$
- $\circ \operatorname{Reg}_{i+1} = \operatorname{Reg}_i \cup \{A \cdot B, A \cup B \mid A, B \in \operatorname{Reg}_i\} \cup \{A^* \mid A \in \operatorname{Reg}_i\}.$
- * REG is closed under union, concatenation, and Kleene star operations.
- * Regular expressions (regex) $^{\mbox{\sc c}}$ is a sequence of special characters that define a regular language or an operation over regular languages. The table below illustrates the correspondence between regular languages and regular expressions. Here, $c \in \Sigma$ denotes the symbol of a given alphabet, $A \subseteq \Sigma^*$ and $B \subseteq \Sigma^*$ are some regular languages, α and β are regular expressions. In regular expressions, concatenation is denoted by \cdot (can be omitted in regex), union by \mid , Kleene star by *, and the grouping is made by parentheses.

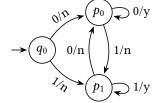
| Language | Regex |
|--------------------------|---------------------|
| Ø | Ø |
| $\{arepsilon\}$ | ε |
| $\{c\}$ | c |
| $A \cup B$ | $\alpha \beta$ |
| $A \cdot B$ | lphaeta pprox pprox |
| A^* | |
| $A \cdot A^*$ | α^+ |
| $A \cup \{\varepsilon\}$ | α ? |

- * **Deterministic Finite Automaton (DFA)** is a 5-tuple $\mathcal{A} = (\Sigma, Q, q_0, F, \delta)$, where:
 - \circ Σ is an alphabet;
 - $Q = \{q_1, \dots, q_n\}$ is a finite set of states;
 - ∘ $q_0 ∈ Q$ is an initial state;
 - $F \subseteq Q$ is a set of final (terminal, accepting) states;
 - ∘ δ : $Q \times \Sigma \rightarrow Q$ is a transition function.

- * Language **accepted** by an automaton \mathcal{A} is the set $L(\mathcal{A}) = \{ w \mid \delta(q_0, w) \in F \}$.
- * Nondeterministic Finite Automaton (NFA)^{L'} is 5-tuple $\mathcal{A} = (\Sigma, Q, q_0, F, \delta)$, where:
 - \circ Σ is an alphabet;
 - $Q = \{q_1, \dots, q_n\}$ is a finite set of states;
 - ∘ $q_0 ∈ Q$ is an initial state;
 - ∘ $F \subseteq Q$ is a set of final (terminal, accepting) states;
 - ∘ δ : $Q \times \Sigma \rightarrow 2^Q$ is a transition function.
- * NFA to DFA conversion algorithm:
 - 1. Set initial state of NFA to initial state of DFA.
 - 2. Take the states in the DFA, and compute in the NFA what the union δ of those states for each letter in the alphabet and add them as new states in the DFA.
 - 3. Set every DFA state as accepting if it contains an accepting state from the NFA
- * **Epsilon-NFA** (ε -**NFA**) is a NFA that allows ε -moves, that is, the automaton can change state without consuming input.
 - $\circ \ \delta \colon Q \times (\Sigma \cup \{\varepsilon\}) \to 2^Q.$
- * ε-NFA to NFA:
 - 1. Find transitive-closure of ε .
 - 2. Back-propagate accepting states over ε -transitions.
 - 3. Perform symbol-transition back-closure over ε -transitions.
 - 4. Remove ε -transitions.
- * **Pumping lemma** states that if *L* is a regular language, then there exists an integer n > 1 depending only on *L*, such that $\forall w \in L$, |w| > n can be written as w = xyz, such that:
 - 1. |y| > 0, i.e. $y \neq \varepsilon$
 - 2. $|xy| \le n$
 - 3. $\forall k \ge 0$, word $xy^k z$ is also in language L
- * **Mealy**¹ **machine**^{L'} is a finite-state machine whose output is determined both by the current state and the current input.

Formally, $\mathcal{M}_{\text{Mealy}} = \{\Sigma, \Omega, Q, q_0, \delta, \lambda_{\text{Mealy}}\}$, where:

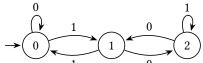
- $\circ \Sigma$ is an input alphabet;
- $\circ \Omega$ is an output alphabet;
- $Q = \{q_1, \dots, q_n\}$ is finite set of states;
- ∘ $q_0 ∈ Q$ is an initial state;
- ∘ δ : $Q \times \Sigma \rightarrow Q$ is a transition function;
- ∘ λ_{Mealy} : $Q \times \Sigma \to \Omega$ is an output function.



This Mealy machine's output is "y" whenever the last two symbols in the input are the same, and "n" otherwise.

* **Moore**² **machine**^{\mathbb{Z}} is a finite-state machine whose output is determined only by the current state. Formally, $\mathcal{M}_{\text{Moore}} = (\Sigma, \Omega, Q, q_0, \delta, \lambda_{\text{Moore}})$, where:

- $\circ \Sigma$ is an input alphabet;
- $\circ \Omega$ is an output alphabet;
- $Q = \{q_1, \dots, q_n\}$ is a finite set of states;
- ∘ $q_0 ∈ Q$ is an initial state;
- ∘ δ : $Q \times \Sigma \rightarrow Q$ is a transition function;
- $\lambda_{\text{Moore}}: Q \to \Omega$ is an output function.



This Moore machine's output is modulo 3 of a binary number.

- * **Emptiness**. Language L(M) is not empty $(L \neq \emptyset)$ if M accepts a word w such that $|w| \le n$.
- * **Infiniteness**. Language L(M) is infinite $(|L| = \infty)$ if M accepts a word w such that $n \le |w| < 2n$.
- * Myhill-Nerode theorem states that the following three statement are equivalent:
 - 1. $L \subseteq \Sigma^*$ is accepted by some finite automaton (*L* is regular).
 - 2. L is the union of some equivalence classes of right invariant equivalence relation of finite index.
 - 3. Let R_L be a relation over words: $x R_L y$ iff $\forall z \in \Sigma : xz \in L \equiv yz \in L$. Then the quotient Σ^*/R_L is finite.

¹ Mealy, George H. (1955). A Method for Synthesizing Sequential Circuits. The Bell System Technical Journal, 34(5), 1045–79.

² MOORE, EDWARD F. (1956). Gedanken-Experiments on Sequential Machines. Automata Studies, Annals of Mathematical Studies (34), 129–153.

- * **Formal grammar** is 4-tuple $\mathcal{G} = (V, T, S, \mathcal{P})$, where:
 - \circ $\mathcal V$ is a vocabulary, a set of variables or non-terminal symbols.
 - \circ *T* is a set of terminal symbols disjoint from \mathcal{V} .
 - \circ *S* is a start symbol, also called sentence symbol.
 - $\circ \mathcal{P}$ is a set of production rules, each rule of the form: $\mathcal{V}^*S\mathcal{V}^* \to \mathcal{V}^*$.
- * Binary relation \Rightarrow over an grammar \mathcal{G} is defined by:

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x \Rightarrow y \Longleftrightarrow \exists u, v, p, q \in \mathcal{V} : (x = upv) \land (p \rightarrow q \in \mathcal{P}) \land (y = uqv).
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Pronounce as "y is directly derivable from x".

- * Binary relation \Rightarrow * over a grammar \mathcal{G} is defined as reflexive transitive closure of \Rightarrow . Pronounced as "y is derivable from x".
- * Backus-Naur Form (BNF)² is notation to describe the syntax of formal language. A BNF specification is a set of derivation rules, written as follows:

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\langle symbol \rangle ::= \langle expression \rangle
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where:

- (*symbol*) is a non-terminal symbol that is enclosed in angle brackets.
- ⟨*expression*⟩ consists of one or more sequences of either terminal or non-terminal symbols where each sequence is separated by a vertical bar indicating a choice.
- ::= is a symbol that separates the production rule for a non-terminal symbol.