CHEAT SHEET: COMPUTATIONAL MODELS (20604)

https://github.com/adielbm/20604

	$\overline{\text{REG}}$	REG	CFL	DEC.	REC.	P	NP	NPC
$L1 \cup L2$	no	✓	✓	✓	✓	✓	✓	no
$L1 \cap L2$	no	✓	no	✓	✓	✓	✓	no
$\overline{L}$	✓	✓	no	✓	no	✓	?	?
$L1 \cdot L2$	no	✓	✓	✓	✓	✓	✓	no
L^*	no	✓	✓	✓	✓	✓	✓	no
$L^{\mathcal{R}}$	✓	✓	✓	✓	✓	✓		
$L1 \setminus L2$	no	✓	no	✓	no	✓	?	
$L \cap R$	no	✓	✓	✓	✓	✓		

- **DFA:** $D = (Q, \Sigma, \delta, q_0, F)$, $\delta : Q \times \Sigma \to Q$.
- **NFA:** $N = (Q, \Sigma, \delta, q_0, F)$, $\delta : Q \times \Sigma_\varepsilon \to \mathcal{P}(Q)$.
- **GNFA:** $(Q, \Sigma, \delta, q_0, q_{\text{a}})$, $\delta : Q \setminus \{q_{\text{a}}\} \times Q \setminus \{q_0\} \to \text{Reg}(\Sigma)$
- $\forall D_1, D_2, \exists D : |Q| = |Q_1| \cdot |Q_2|$, $L(D) = L(D_1) \Delta L(D_2)$.
- (DFA D) If $L(D) \neq \emptyset$ then $\exists\, s \in L(D)$ s.t. $|s| < |Q|$.

- $\forall$ NFA $\exists$ an equivalent NFA with 1 accept state.
- If $A = L(N_{\text{NFA}}), B = (L(M_{\text{DFA}}))^{\complement}$ then $A \cdot B \in \text{REG}$.

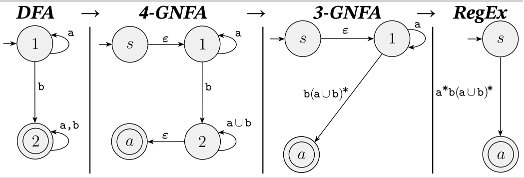
Regular Expressions: Examples

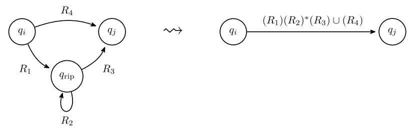
- $\{a^n w b^n : w \in \Sigma^*\} \equiv a(a \cup b)^* b$
- $\{w : \#_w(0) \geq 2 \vee \#_w(1) \leq 1\} \equiv (\Sigma^* 0 \Sigma^* 0 \Sigma^*) \cup (0^*(\varepsilon \cup 1)0^*)$
- $\{w : |w| \bmod n = m\} \equiv (a \cup b)^m((a \cup b)^n)^*$
- $\{w : \#_b(w) \bmod n = m\} \equiv (a^*ba^*)^m \cdot ((a^*ba^*)^n)^*$
- $\{w : |w| \text{ is odd}\} \equiv (a \cup b)^*((a \cup b)(a \cup b)^*)^*$
- $\{w : \#_a(w) \text{ is odd}\} \equiv b^*a(ab^*a \cup b)^*$
- $\{w : \#_{ab}(w) = \#_{ba}(w)\} \equiv \varepsilon \cup a \cup b \cup a\Sigma^*a \cup b\Sigma^*b$
- $\{a^m b^n \mid m + n \text{ is odd}\} \equiv a(aa)^*(bb)^* \cup (aa)^*b(bb)^*$
- $\{aw : aba \nsubseteq w\} \equiv a(a \cup bb \cup bbb)^*(b \cup \varepsilon)$
- $\{w : bb \nsubseteq w\} \equiv (a \cup ba)^*(\varepsilon \cup b)$
- $\{w : \#_w(a), \#_w(b) \text{ are even}\} \equiv (aa \cup\ bb \cup (ab \cup ba)^2)^*$
- $\{w : |w| \bmod n \neq m\} \equiv \bigcup_{r=0, r \neq m}^{n-1} (\Sigma^n)^* \Sigma^r$

N δ	a	b	ε
1	3	{}	2
A 2	1	{}	{}
3	2	2, 3	{}

$NFA \longrightarrow DFA$

D δ	a	b
1	3	{}
A 2	1, 2	{}
3	2	2,3
A 1,2	1,3,2	{}
1,3	2,3	2,3
A 2,3	1,2	2,3
A 1,2,3	1,2,3	2,3





Pumping lemma for regular languages: $A \in \text{REGULAR} \implies \exists p : \forall s \in A, |s| \geq p, s = xyz,$ **(i)** $\forall i \geq 0, xy^iz \in A$, **(ii)** $|y| > 0$ **and (iii)** $|xy| \leq p$.

non-regular but CFL: Examples

- $\{w = w^{\mathcal{R}}\}$; $s = 0^p10^p = xyz$. but $xy^2z = 0^{p+|y|}10^p \notin L$.
- $\{a^nb^n\}$; $s = a^pb^p = xyz$, $xy^2z = a^{p+|y|}b^p \notin L$.
- $\{w : \#_a(w) > \#_b(w)\}$; $s = a^pb^{p+1}$, $|s| = 2p + 1 \geq p$, $xy^2z = a^{p+|y|}b^{p+1} \notin L$.
- $\{w : \#_a(w) = \#_b(w)\}$; $s = a^pb^p = xyz$ but $xy^2z = a^{p+|y|}b^p \notin L$.
- $\{w : \#_w(a) \neq \#_w(b)\}$; (*pf.* by 'complement-closure', $\overline{L} = \{w : \#_w(a) = \#_w(b)\}$)
- $\{a^ib^jc^k : i < j \vee i > k\}$; $s = a^pb^{p+1}c^{2p} = xyz$, but $xy^2z = a^{p+|y|}b^{p+1}c^{2p}$, $p + |y| \geq p + 1$, $p + |y| \leq 2p$.

non-CFL and non-regular: Examples

- $\{w = a^{2^k}\}$; $\quad k = \lfloor \log_2 |w| \rfloor, s = a^{2^k} = xyz$. $2^k = |xyz| < |xy^2z| \leq |xyz| + |xy| \leq 2^k + p < 2^{k+1}$.
- $\{a^p : p \text{ is prime}\}$; $\quad s = a^t = xyz$ for prime $t \geq p$. $r := |y| > 0$
- $\{www : w \in \Sigma^*\}$; $s = a^pba^pba^p = xyz = a^{|x|+|y|+m}ba^pba^pb$, $m \geq 0$, but $xy^2z = a^{|x|+2|y|+m}ba^pba^pb \notin L$.
- $\{a^{2n}b^{3n}a^n\}$; $s = a^{2p}b^{3p}a^p = xyz = a^{|x|+|y|+m+p}b^{3p}a^p$, $m \geq 0$, but $xy^2z = a^{2p+|y|}b^{3p}a^p \notin L$.

(PDA) $M = (Q, \Sigma, \Gamma, \delta, q_0 \in Q, F \subseteq Q)$. $\delta : Q \times \Sigma_\varepsilon \times \Gamma_\varepsilon \longrightarrow \mathcal{P}(Q \times \Gamma_\varepsilon)$. $\quad L \in$ **CFL** $\Leftrightarrow \exists G_{\text{CFG}} : L = L(G) \Leftrightarrow \exists P_{\text{PDA}} : L = L(P)$

- "$a, b \to c$": **reads** a from the input (or read nothing if $a = \varepsilon$). **pops** b from the stack (or pops nothing if $b = \varepsilon$). **pushes** c onto the stack (or pushes nothing if $c = \varepsilon$)
- If $G \in$ CNF, and $w \in L(G)$, then $|w| \leq 2^{|h|} - 1$, where h is the height of the parse tree for w.
- $\forall L \in \text{CFL}, \exists G \in \text{CNF} : L = L(G)$.
- **(derivation)** $S \Rightarrow u_1 \Rightarrow u_2 \Rightarrow \cdots \Rightarrow u_n = w$, where each u_i is in $(V \cup \Sigma)^*$. (in this case, G **generates** w (or S **derives** w), $S \overset{*}{\Rightarrow} w$)
- M **accepts** $w \in \Sigma^*$ if there is a seq. $r_0, r_1, \ldots, r_m \in Q$ and $s_0, , s_1, \ldots, s_m \in \Gamma^*$ s.t.: (1.) $r_0 = q_0$ and $s_0 = \varepsilon$; (2.) For $i = 0, 1, \ldots, m-1$, we have $(r_i, b) \in \delta(r_i, w_{i+1}, a)$, where $s_i = at$ and $s_{i+1} = bt$ for some $a, b \in \Gamma_\varepsilon$ and $t \in \Gamma^*$; (3.) $r_m \in F$.
- $R \in \text{REGULAR} \wedge C \in \text{CFL} \implies R \cap C \in \text{CFL}$. (*pf.* construct PDA $P' = P_C \times D_R$.)

(CFG) $G = (V, \Sigma, R, S)$, $A \to w$, $(A \in V, w \in (V \cup \Sigma)^*)$; **(CNF)** $A \to BC$, $A \to a$, $S \to \varepsilon$, $(A, B, C \in V, a \in \Sigma, B, C \neq S)$.

(**CFG** $\rightsquigarrow$ **CNF**) **(1.)** Add a new start variable S_0 and a rule $S_0 \to S$. **(2.)** Remove ε-rules of the form $A \to \varepsilon$ (except for $S_0 \to \varepsilon$). and remove A's occurrences on the RH of a rule (e.g. $R \to uAvAw$ becomes $R \to uAvAw|uAvw|uvAw|uvw$. where $u, v, w \in (V \cup \Sigma)^*$). **(3.)** Remove unit rules $A \to B$ then whenever $B \to u$ appears, add $A \to u$, unless this was a unit rule previously removed. ($u \in (V \cup \Sigma)^*$). **(4.)** Replace each rule $A \to u_1u_2 \cdots u_k$ where $k \geq 3$ and $u_i \in (V \cup \Sigma)$, with the rules $A \to u_1A_1$, $A_1 \to u_2A_2$, ..., $A_{k-2} \to u_{k-1}u_k$, where A_i are new variables. Replace terminals u_i with $U_i \to u_i$.

CFL but non-regular: Examples

- $\{w : w = w^{\mathcal{R}}\}$; $S \to aSa \mid bSb \mid a \mid b \mid \varepsilon$
- $\{w : w \neq w^{\mathcal{R}}\}$; $S \to aSa \mid bSb \mid aXb \mid bXa; X \to aX|bX|\varepsilon$
- $\{ww^{\mathcal{R}}\} = \{w : w = w^{\mathcal{R}} \wedge |w| \text{ is even}\}$; $S \to aSa \mid bSb \mid \varepsilon$
- $\overline{\{ww^{\mathcal{R}}\}}$; $S \to aSa \mid bSb \mid aXb \mid bXa \mid a \mid b$; $X \to aXa \mid bXb \mid bXa \mid aXb \mid a \mid b \mid \varepsilon$
- $\{wa^nw^{\mathcal{R}}\}$; $S \to aSa \mid bSb \mid M; M \to aM \mid \varepsilon$
- $\{w\#x : w^{\mathcal{R}} \subseteq x\}$; $S \to AX$; $A \to 0A0 \mid 1A1 \mid \#X$; $X \to 0X \mid 1X \mid \varepsilon$
- $\{w : \#_w(a) > \#_w(b)\}$; $S \to IaI; I \to II \mid aIb \mid bIa \mid a \mid \varepsilon$
- $\{w : \#_w(a) \geq \#_w(b)\}$; $S \to SS \mid aSb \mid bSa \mid a \mid \varepsilon$
- $\{w : \#_w(a) = \#_w(b)\}$; $S \to SS \mid aSb \mid bSa \mid \varepsilon$
- $\{w : \#_w(a) = 2 \cdot \#_w(b)\}$; $S \to SS|S_1bS_1|bSaa|aaSb|\varepsilon; S_1 \to aS|SS_1$
- $\{w : \#_w(a) \neq \#_w(b)\} = \{\#_w(a) > \#_w(b)\} \cup \{\#_w(a) < \#_w(b)\}$
- $\overline{\{a^nb^n\}}$; $S \to XbXaX \mid A \mid B$; $A \to aAb \mid Ab \mid b$; $B \to aBb \mid aB \mid a$; $X \to aX \mid bX \mid \varepsilon$.
- $\{a^nb^m \mid n \neq m\}$; $S \to aSb|A|B; A \to aA|a; B \to bB|b$
- $\{x \mid x \neq ww\}$; $S \to A \mid B \mid AB \mid BA$; $A \to CAC \mid 0$; $B \to CBC \mid 1; C \to 0 \mid 1$
- $\{a^nb^m \mid m \leq n \leq 3m\}$; $S \to aSb \mid aaSb \mid aaaSb \mid \varepsilon$;
- $\{a^nb^n\}$; $S \to aSb \mid \varepsilon$
- $\{a^nb^m \mid n > m\}$; $S \to aSb \mid aS \mid a$
- $\{a^nb^m \mid n \geq m \geq 0\}$; $S \to aSb \mid aS \mid a \mid \varepsilon$
- $\{a^ib^jc^k \mid i + j = k\}$; $S \to aSc \mid X; X \to bXc \mid \varepsilon$
- $\{a^ib^jc^k \mid i \leq j \vee j \leq k\}$; $S \to S_1C \mid AS_2; A \to Aa \mid \varepsilon$; $S_1 \to aS_1b \mid S_1b \mid \varepsilon; S_2 \to bS_2c \mid S_2c \mid \varepsilon; C \to Cc \mid \varepsilon$
- $\{a^ib^jc^k \mid i = j \vee j = k\}$; $S \to AX_1|X_2C; X_1 \to bX_1c|\varepsilon; X_2 \to aX_2b|\varepsilon; A \to aA|\varepsilon; C$
- $\{xy : |x| = |y|, x \neq y\}$; $S \to AB \mid BA$; $A \to a \mid aAa \mid aAb \mid bAa \mid bAb$; $B \to b \mid aBa \mid aBb \mid bBa \mid bBb$;
- $\{a^ib^j : i, j \geq 1,\ i \neq j,\ i < 2j\}$; $S \to aSb|X|aaYb; Y \to aaYb|ab; X \to bX|abb$

CFL and regular: Examples

- $\{w : \#_w(a) \geq 3\}$; $S \to XaXaXaX; X \to aX \mid bX \mid \varepsilon$
- $\{w : |w| \text{ is odd}\}$; $S \to aaS \mid abS \mid bbS \mid baS \mid a \mid b$
- $\{w : |w| \text{ is even}\}$; $S \to aaS \mid abS \mid bbS \mid baS \mid \varepsilon$
- $\emptyset$; $S \to S$

Pumping lemma for context-free languages: $L \in \text{CFL} \implies \exists p : \forall s \in L, |s| \geq p, s = uvxyz,$ **(i)** $\forall i \geq 0, uv^ixy^iz \in L$, **(ii)** $|vxy| \leq p$, **and (iii)** $|vy| > 0$.

- $\{w = a^nb^nc^n\}$; $s = a^pb^pb^p = uvxyz$. vxy can't contain all of a, b, c thus uv^2xy^2z must pump one of them less than the others.
- $\{ww : w \in \{a, b\}^*\}$;
- (**more example of not CFL**) $\{a^ib^jc^k \mid 0 \leq i \leq j \leq k\}$, $\{a^nb^nc^n \mid n \in \mathbb{N}\}$, $\{ww \mid w \in \{a, b\}^*\}$, $\{\mathtt{a}^{n^2} \mid n \geq 0\}$, $\{a^p \mid p \text{ is prime}\}$, $L = \{ww^{\mathcal{R}}w : w \in \{a, b\}^*\}$
- $\{w \mid \#_w(a) = \#_w(b) = \#_w(c)\}$; (*pf.* since Regular $\cap$ CFL $\in$ CFL, but $\{a^*b^*c^*\} \cap L = \{a^nb^nc^n\} \notin$ CFL)

Examples

- $A \leq_{\text{m}} B$, $B \in \text{REGULAR}$, $A \notin \text{REGULAR}$: $A = \{0^n1^n\}$, $B = \{1\}$, $f : A \to B$, $f(w) = 1$ if $w \in A$, 0 if $w \notin A$.
- $L \in \text{CFL}, \overline{L} \notin \text{CFL}$: $L = \{x \mid x \neq ww\}$, $\overline{L} = \{ww\}$.
- $L_1, L_2 \in \text{CFL}, L_1 \cap L_2 \notin \text{CFL}$: $L_1 = \{a^nb^nc^m\}$, $L_2 = \{a^mb^nc^n\}$, $L_1 \cap L_2 = \{a^nb^nc^n\}$.
- $L_1, L_2 \notin \text{CFL}$, $L_1 \cap L_2 \in \text{CFL}$: $L_1 = \{a^nb^nc^n\}$, $L_2 = \{c^nb^na^n\}$, $L_1 \cap L_2 = \{\varepsilon\}$
- $L_1 \in \text{CFL}$, $L_2, L_1 \cap L_2 \notin \text{CFL}$: $L_1 = \Sigma^*$, $L_2 = \{a^{i^2}\}$.
- $L_1 \in \text{REGULAR}$, $L_2 \notin \text{CFL}$, but $L_1 \cap L_2 \in \text{CFL}$: $L_1 = \{\varepsilon\}$, $L_2 = \{a^nb^nc^n \mid n \geq 0\}$.
- $L_1 \in \text{CFL}$, L_2 is infinite, $L_1 \setminus L_2 \notin \text{REGULAR}$: $L_1 = \Sigma^*$, $L_2 = \{a^nb^n\}$, $L_1 \setminus L_2 = \{a^mb^n \mid m \neq n\}$.
- $L_1, L_2 \in \text{REGULAR}$, $L_1 \not\subset L_2$, $L_2 \not\subset L_1$, but, $(L_1 \cup L_2)^* = L_1^* \cup L_2^*$: $L_1 = \{a, b, ab\}$, $L_2 = \{a, b, ba\}$.
- $L_1, L_1 \cup L_2 \in \text{REGULAR}$, $L_2, L_1 \cap L_2 \notin \text{REGULAR}$, $L_1 = L(\mathtt{a}^*\mathtt{b}^*)$, $L_2 = \{\mathtt{a}^n\mathtt{b}^n \mid n \geq 0\}$.
- $L_1, L_2, \dots \in \text{REGULAR}$, $\bigcup_{i=1}^{\infty} L_i \notin \text{REGULAR}$: $L_i = \{\mathtt{a}^i\mathtt{b}^i\}$, $\bigcup_{i=1}^{\infty} L_i = \{\mathtt{a}^n\mathtt{b}^n \mid n \geq 0\}$.
- $L_1 \cdot L_2 \in \text{REGULAR}$, $L_1 \notin \text{Reg.}$: $L_1 = \{a^nb^n\}$, $L_2 = \Sigma^*$
- $L_2 \in$ CFL, and $L_1 \subseteq L_2$, but $L_1 \notin$ CFL : $\quad \Sigma = \{a, b, c\}$, $L_1 = \{a^nb^nc^n \mid n \geq 0\}$, $L_2 = \Sigma^*$.
- $L_1, L_2 \in$ TD, and $L_1 \subseteq L \subseteq L_2$, but $L \notin$ TD : $\quad L_1 = \emptyset$, $L_2 = \Sigma^*$, L is some undecidable language over Σ.
- $L^* \in \text{REGULAR}$, but $L \notin \text{REGULAR}$: $L = \{a^p \mid p \text{ is prime}\}$, $L^* = \Sigma^* \setminus \{a\}$.
- $A \not\leq_m \overline{A}$: $A = A_{\text{TM}} \in \text{TR}$, $\overline{A} = \overline{A_{\text{TM}}} \notin \text{TR}$
- $A \notin \text{DEC.}$, $A \leq_m \overline{A}$: $f(0x) = 1x$, $f(1y) = 0y$, $A = \{w \mid \exists x \in A_{\text{TM}} : w = 0x \vee \exists y \in \overline{A_{\text{TM}}} : w = 1y\}$
- $L \in \text{CFL}, L \cap L^{\mathcal{R}} \notin \text{CFL} : L = \{a^nb^na^m\}$.
- $A \leq_m B, B \not\leq_m A : A = \{a\}, B = HALT_{\text{TM}}, f(w) = \langle M \rangle$, $M =$"On x, if $w \in A$, A; O/W, loop"

$L \in$ **Turing-Decidable** $\iff$ ($L \in$ **Turing-Recognizable and** $\overline{L} \in$ **Turing-Recognizable**) $\iff \exists M_{\text{TM}}$ **decides** L**.**

- (**TM**) $M = (Q, \underset{\text{input}}{\Sigma} \subseteq \Gamma, \underset{\text{tape}}{\Gamma}, \delta, q_0, q_{Ⓐ}, q_{\boxed{R}})$, where $\sqcup \in \Gamma$, $\sqcup \notin \Sigma$, $q_{\boxed{R}} \neq q_{Ⓐ}$, $\delta : Q \times \Gamma \longrightarrow Q \times \Gamma \times \{\mathrm{L}, \mathrm{R}\}$
- (**Turing-Recognizable** ($\mathbf{TR}$)) Ⓐ if $w \in L$, $\boxed{R}$/loops if $w \notin L$; A is **co-recognizable** if $\overline{A}$ is recognizable.
- (**Turing-Decidable** ($\mathbf{TD}$)) Ⓐ if $w \in L$, $\boxed{R}$ if $w \notin L$.
- $L \in \mathrm{TR} \iff L \leq_{\mathrm{m}} A_{\mathsf{TM}}$.
- $(A \in \mathrm{TR} \wedge |A| = \infty) \Rightarrow \exists B \in \mathrm{TD} : (B \subseteq L \wedge |B| = \infty)$
- $L \in \mathrm{TD} \iff L^{\mathcal{R}} \in \mathrm{TD}$.
- (**decider**) TM that halts on all inputs.
- (**Rice**) If $P = \{\langle M \rangle : L(M)$ has property $\mathcal{P}\}$ s.t. (**1**) $\forall M_1, M_2 : L(M_1) = L(M_2) \Rightarrow (\langle M_1 \rangle \in P \Leftrightarrow \langle M_2 \rangle \in P)$. (**2**) P is nontrivial. Then $P \notin \mathrm{TD}$. (*e.g.* $\mathit{INFINITE}_{\mathsf{TM}}$, $\mathit{ALL}_{\mathsf{TM}}$, E_{TM}, $\{\langle M_{\mathsf{TM}} \rangle : 1 \in L(M)\}$)
- $\{$all TMs$\}$ is count.; Σ^* is count. (finite Σ); $\{$all lang.$\}$ is uncount.; $\{$all infinite bin. seq.$\}$ is uncount.
- If $A \leq_{\mathrm{m}} B$ and $B \in \mathrm{TD}$, then $A \in \mathrm{TD}$.
- If $A \leq_{\mathrm{m}} B$ and $A \notin \mathrm{TD}$, then $B \notin \mathrm{TD}$.
- If $A \leq_{\mathrm{m}} B$ and $B \in \mathrm{TR}$, then $A \in \mathrm{TR}$.
- If $A \leq_{\mathrm{m}} B$ and $A \notin \mathrm{TR}$, then $B \notin \mathrm{TR}$.
- (transitivity) If $A \leq_{\mathrm{m}} B$ and $B \leq_{\mathrm{m}} C$, then $A \leq_{\mathrm{m}} C$.
- $A \leq_{\mathrm{m}} B \iff \overline{A} \leq_{\mathrm{m}} \overline{B}$ (esp. $A \leq_{\mathrm{m}} \overline{A} \iff \overline{A} \leq_{\mathrm{m}} A$)

- If $A \leq_{\mathrm{m}} \overline{A}$ and $A \in \mathrm{TR}$, then $A \in \mathrm{TD}$

- $\mathrm{REGULAR} \subset \mathrm{CFL} \subset \mathbf{T}$uring-$\mathbf{D}$ecidable $\subset \mathbf{T}$uring-$\mathbf{R}$ecognizable
- (**not TR**) $\overline{A_{\mathsf{TM}}}$, $\overline{EQ_{\mathsf{TM}}}$, EQ_{CFG}, $\overline{HALT_{\mathsf{TM}}}$, REG_{TM}, E_{TM}, EQ_{TM}, ALL_{CFG}, EQ_{CFG}
- (**TR, but not TD**) A_{TM}, $HALT_{\mathsf{TM}}$, $\overline{EQ_{\mathsf{CFG}}}$, $\overline{E_{\mathsf{TM}}}$, $\{\langle M, k \rangle \mid \exists x\ (M(x)$ halts in $\geq k$ steps$)\}$
- (**TD**) A_{DFA}, A_{NFA}, A_{REX}, E_{DFA}, EQ_{DFA}, A_{CFG}, E_{CFG}, A_{LBA}

Deciders: Examples

- $\mathit{INFINITE}_{\mathsf{DFA}}$: "On $\langle D \rangle$: $n := |Q_D|$; const. D_1 s.t. $L(D_1) = \Sigma^{\geq n}$; const. D_2 s.t. $L(D_2) = L(D) \cap L(D_1)$; if $\langle D_2 \rangle \notin E_{\mathsf{DFA}}$, Ⓐ; O/W, $\boxed{R}$"
- $\mathit{ALL}_{\mathsf{DFA}}$: "On $\langle D \rangle$: const. $D^{\complement}$ s.t. $L(D^{\complement}) = L(D)^{\complement}$ (swap accept and non-accept); if $D^{\complement} \in E_{\mathsf{DFA}}$, Ⓐ; O/W $\boxed{R}$"
- $\{\langle D \rangle \mid \nexists w \in L(D) : \#_1(w)$ is odd$\}$: "On $\langle D \rangle$: const. D_1 s.t. $L(D_1) = \{w \mid \#_1(w)$ is odd$\}$; const. D_2 s.t. $L(D_2) = L(D) \cap L(D_1)$; if $\langle D_2 \rangle \in E_{\mathsf{DFA}}$ Ⓐ; O/W $\boxed{R}$"
- $\{\langle r, s \rangle \mid r, s \in \mathrm{Reg}(\Sigma), L(r) \subseteq L(s)\}$: "On $\langle r, s \rangle$: const. D s.t. $L(D) = L(r) \cap \overline{L(s)}$; if $\langle D \rangle \in E_{\mathsf{DFA}}$, Ⓐ; O/W, $\boxed{R}$"
- $\{\langle D, r \rangle \mid L(D) = L(r)\}$: "On $\langle D, r \rangle$: convert r to DFA D_r; if $\langle D, D_r \rangle \in EQ_{\mathsf{DFA}}$, Ⓐ; O/W, $\boxed{R}$"
- $\{\langle D_{\mathsf{DFA}} \rangle \mid L(D) = (L(D))^{\mathcal{R}}\}$: "On $\langle D \rangle$: const. $D^{\mathcal{R}}$ s.t. $L(D^{\mathcal{R}}) = (L(D))^{\mathcal{R}}$; if $\langle D, D^{\mathcal{R}} \rangle \in EQ_{\mathsf{DFA}}$), Ⓐ; O/W, $\boxed{R}$"

- $\{\langle r \rangle \mid \exists x, y \in \Sigma^* : w = x111y \in L(r)\}$: "On $\langle r \rangle$: const. D s.t. $L(D) \equiv \Sigma^* 111 \Sigma^*$; const. D_1 s.t. $L(D_1) = L(r) \cap L(D)$; if $L(D_1) \notin E_{\mathsf{DFA}}$, Ⓐ; O/W $\boxed{R}$"
- $\{\langle G, k \rangle : |L(G)| = k \in \mathbb{N} \cup \{\infty\}\}$: "On $\langle G, k \rangle$: run ; if $\langle G \rangle \in \mathit{INFINITE}_{\mathsf{CFG}}$: (if $k = \infty$, Ⓐ; O/W, $\boxed{R}$). if $\langle G \rangle \notin \mathit{INFINITE}_{\mathsf{CFG}}$: (if $k = \infty$, $\boxed{R}$; O/W, m counts each $w \in \Sigma^{\leq p}$ s.t. $w \in L(G)$, where p is the pump. len.; if $m = k$, Ⓐ, O/W, $\boxed{R}$)
- $A\varepsilon_{\mathsf{CFG}}$: "On $\langle G \rangle$: If $\langle G, \varepsilon \rangle \in A_{\mathsf{CFG}}$, Ⓐ; O/W, $\boxed{R}$"
- $\mathit{INFINITE}_{\mathsf{PDA}}$: "On $\langle P \rangle$: conv. P to G; $p :=$ p.l. of G; set $G' \equiv L(G') = L(G) \cap \Sigma^{>p}$; If $\langle G' \rangle \notin E_{\mathsf{CFG}}$, Ⓐ; O/W $\boxed{R}$"
- $\{\langle G \rangle : 1^* \cap L(G) \neq \emptyset\}$; "On $\langle G \rangle$: const. G' s.t. $L(G') = 1^* \cap L(G)$. (since $\mathrm{REGULAR} \cap \mathrm{CFL} \subseteq \mathrm{CFL}$); If $\langle G' \rangle \notin E_{\mathsf{CFG}}$, Ⓐ; O/W, $\boxed{R}$"
- $\{\langle M, k \rangle \mid \exists x\ (M(x)$ runs for $\geq k$ steps$)\}$: "On $\langle M, k \rangle$: $(\forall w \in \Sigma^{\leq k+1}$: if $M(w)$ not halt within k steps, Ⓐ); $\boxed{R}$"
- $\{\langle M, k \rangle \mid \exists x\ (M(x)$ halts in $\leq k$ steps$)\}$: "On $\langle M, k \rangle$: $(\forall w \in \Sigma^{\leq k+1}$: run $M(w)$ for $\leq k$ steps, if halts, Ⓐ); $\boxed{R}$"

Recognizers: Examples

- $\overline{EQ_{\mathsf{CFG}}}$: "On $\langle G_1, G_2 \rangle$: (for each $w \in \Sigma^*$ (lexico.): If $\langle G_1, w \rangle \in A_{\mathsf{CFG}}$ and $\langle G_2, w \rangle \notin A_{\mathsf{CFG}}$ (vice versa), Ⓐ);"
- $\overline{E_{\mathsf{TM}}}$: "On $\langle M \rangle$: $\Sigma^* = \{s_1, s_2, \ldots\}$; $\forall i \in \mathbb{N}$: $\forall j \leq i$: Run $M(s_j)$ for i steps, if accepts, Ⓐ;"

Mapping Reduction (from A to B): $A \leq_{\mathrm{m}} B$ if $\exists f : \Sigma^* \to \Sigma^* : \forall w \in \Sigma^*$, $w \in A \iff f(w) \in B$ and f is computable.

- $A_{\mathsf{TM}} \leq_{\mathrm{m}} \{\langle M_{\mathsf{TM}} \rangle \mid L(M) = (L(M))^{\mathcal{R}}\}$; $f(\langle M, w \rangle) = \langle M' \rangle$, where $M' =$"On x, if $x \notin \{01, 10\}$, $\boxed{R}$; if $x = 01$, return $M(x)$; if $x = 10$, Ⓐ;"
- $A_{\mathsf{TM}} \leq_{\mathrm{m}} \{\langle M_{\mathsf{TM}} \rangle \mid \varepsilon \in L(M)\}$; $f(\langle M, w \rangle) = \langle M' \rangle$ where $M' =$"On x, if $x \neq \varepsilon$, Ⓐ; O/W return $M(w)$"
- $A_{\mathsf{TM}} \leq_{\mathrm{m}} L = \{\langle \underset{\mathsf{TM}}{M}, \underset{\mathsf{DFA}}{D} \rangle \mid L(M) = L(D)\}$; $f(\langle M, w \rangle) = \langle M', D \rangle$, where $M' =$"On x: if $x = w$ return $M(x)$; O/W, $\boxed{R}$;" D is DFA s.t. $L(D) = \{w\}$.
- $A \leq_{\mathrm{m}} HALT_{\mathsf{TM}}$; $f(w) = \langle M, \varepsilon \rangle$, where $M =$"On x: if $w \in A$, halt; if $w \notin A$, loop;"
- $A_{\mathsf{TM}} \leq_{\mathrm{m}} \{\langle M \rangle \mid L(M)$ is CFL$\}$; $f(\langle M, w \rangle) = \langle N \rangle$, where $N =$"On x: if $x = a^n b^n c^n$, Ⓐ; O/W, return $M(w)$;"
- $A \leq_{\mathrm{m}} B = \{0w : w \in A\} \cup \{1w : w \notin A\}$; $f(w) = 0w$.
- $A_{\mathsf{TM}} \leq_{\mathrm{m}} HALT_{\mathsf{TM}}$; $f(\langle M, w \rangle) = \langle M', w \rangle$, where $M' =$ "On x: if $M(x)$ accepts, Ⓐ. If rejects, loop"
- $HALT_{\mathsf{TM}} \leq_{\mathrm{m}} A_{\mathsf{TM}}$; $f(\langle M, w \rangle) = \langle M', \langle M, w \rangle \rangle$, where $M' =$"On $\langle X, x \rangle$: if $X(x)$ halts, Ⓐ;"

- $E_{\mathsf{TM}} \leq_{\mathrm{m}} \mathit{USELESS}_{\mathsf{TM}}$; $f(\langle M \rangle) = \langle M, q_{Ⓐ} \rangle$
- $E_{\mathsf{TM}} \leq_{\mathrm{m}} EQ_{\mathsf{TM}}$; $f(\langle M \rangle) = \langle M, M' \rangle$, $M' =$"On x: $\boxed{R}$"
- $A_{\mathsf{TM}} \leq_{\mathrm{m}} \mathit{REGULAR}_{\mathsf{TM}}$; $f(\langle M, w \rangle) = \langle M' \rangle$, $M' =$"On $x \in \{0,1\}^*$: if $x = 0^n 1^n$, Ⓐ; O/W, return $M(w)$;"
- $A_{\mathsf{TM}} \leq_{\mathrm{m}} EQ_{\mathsf{TM}}$; $\quad f(\langle M, w \rangle) = \langle M_1, M_2 \rangle$, where $M_1 =$ "Ⓐ all"; $M_2 =$"On x: return $M(w)$;"
- $A_{\mathsf{TM}} \leq_{\mathrm{m}} \overline{EQ_{\mathsf{TM}}}$; $\quad f(\langle M, w \rangle) = \langle M_1, M_2 \rangle$, where $M_1 =$ "$\boxed{R}$ all"; $M_2 =$"On x: return $M(w)$;"
- $A_{\mathsf{TM}} \leq_{\mathrm{m}} \{\langle M \rangle : M$ halts on $\langle M \rangle\}$; $f(\langle M, w \rangle) = \langle M' \rangle$, where $M' =$"On x: if $M(w)$ accepts, Ⓐ; if rejects, loop;"
- $\mathit{ALL}_{\mathsf{CFG}} \leq_{\mathrm{m}} EQ_{\mathsf{CFG}}$; $f(\langle G \rangle) = \langle G, H \rangle$, s.t. $L(H) = \Sigma^*$.
- $A_{\mathsf{TM}} \leq_{\mathrm{m}} \{\langle M_{\mathsf{TM}} \rangle : |L(M)| = 1\}$; $f(\langle M, w \rangle) = \langle M' \rangle$, where $M' =$"On x: if $x = x_0$, return $M(w)$; O/W, $\boxed{R}$;" (where $x_0 \in \Sigma^*$ is fixed).
- $\overline{A_{\mathsf{TM}}} \leq_{\mathrm{m}} E_{\mathsf{TM}}$; $f(\langle M, w \rangle) = \langle M' \rangle$, where $M' =$"On x: if $x \neq w$, $\boxed{R}$; O/W, return $M(w)$;"

- $\overline{HALT_{\mathsf{TM}}} \leq_{\mathrm{m}} \{\langle M_{\mathsf{TM}} \rangle : |L(M)| \leq 3\}$; $f(\langle M, w \rangle) = \langle M' \rangle$, where $M' =$"On x: Ⓐ if $M(w)$ halts"
- $HALT_{\mathsf{TM}} \leq_{\mathrm{m}} \{\langle M_{\mathsf{TM}} \rangle : |L(M)| \geq 3\}$; $f(\langle M, w \rangle) = \langle M' \rangle$, where $M' =$"On x: Ⓐ if $M(w)$ halts"
- $\overline{HALT_{\mathsf{TM}}} \leq_{\mathrm{m}} \{\langle M \rangle : M$ Ⓐ even num.$\}$; $f(\langle M, w \rangle) = \langle M' \rangle$, $M' =$"On x: $\boxed{R}$ if $M(w)$ halts within $|x|$. O/W, Ⓐ"
- $\overline{HALT_{\mathsf{TM}}} \leq_{\mathrm{m}} \{\langle M_{\mathsf{TM}} \rangle : L(M)$ is finite$\}$; $f(\langle M, w \rangle) = \langle M' \rangle$, where $M' =$"On x: Ⓐ if $M(w)$ halts"
- $\overline{HALT_{\mathsf{TM}}} \leq_{\mathrm{m}} \{\langle M_{\mathsf{TM}} \rangle : L(M)$ is infinite$\}$; $f(\langle M, w \rangle) = \langle M' \rangle$, where $M' =$"On x: $\boxed{R}$ if $M(w)$ halts within $|x|$ steps. O/W, Ⓐ"
- $HALT_{\mathsf{TM}} \leq_{\mathrm{m}} \{\langle M_1, M_2 \rangle : \varepsilon \in L(M_1) \cup L(M_2)\}$; $f(\langle M, w \rangle) = \langle M', M' \rangle$, $M' =$"On x: Ⓐ if $M(w)$ halts"
- $HALT_{\mathsf{TM}} \leq_{\mathrm{m}} \overline{E_{\mathsf{TM}}}$; $f(\langle M, w \rangle) = \langle M' \rangle$, where $M' =$"On x: if $x \neq w$ $\boxed{R}$; else, Ⓐ if $M(w)$ halts"
- $HALT_{\mathsf{TM}} \leq_{\mathrm{m}} \{\langle M_{\mathsf{TM}} \rangle \mid \exists x : M(x)$ halts in $> |\langle M \rangle|$ steps $f(\langle M, w \rangle) = \langle M' \rangle$, where $M' =$"On x: if $M(w)$ halts, make $|\langle M \rangle| + 1$ steps and then halt; O/W, loop"

$\mathbf{P} = \bigcup_{k \in \mathbb{N}} \mathsf{TIME}(n^k) \subseteq \mathbf{NP} = \bigcup_{k \in \mathbb{N}} \mathsf{NTIME}(n^k) = \{L \mid L$ is decidable by a PT verifier$\} \supseteq \mathbf{NP\text{-}complete} = \{B \mid B \in \mathrm{NP}, \forall A \in \mathrm{NP}, A \leq_{\mathrm{P}} B\}$.

- If $A \leq_{\mathrm{P}} B$ and $B \in \mathrm{P}$, then $A \in \mathrm{P}$.
- $A \equiv_P B$ if $A \leq_{\mathrm{P}} B$ and $B \leq_{\mathrm{P}} A$. $\equiv_P$ is an equiv. relation on NP. $\quad \mathrm{P} \setminus \{\emptyset, \Sigma^*\}$ is an equiv. class of $\equiv_P$.
- $\mathit{ALL}_{\mathsf{DFA}}$, $\mathit{CONNECTED}$, $\underset{\text{3-clique}}{\mathit{TRIANGLE}}$, $L(G_{\mathsf{CFG}})$, $\underset{s \to t}{\overset{\text{directed}}{\mathit{PATH}}} \in \mathrm{P}$

- $\mathit{CNF}_2 \in \mathrm{P}$: (**algo.** $\forall x \in \phi$: (**1**) If x occurs 1-2 times in same clause $\to$ remove cl.; (**2**) If x is twice in 2 cl. $\to$ remove both cl.; (**3**) Similar to (2) for $\overline{x}$; (**4**) Replace any $(x \vee y)$, $(\neg x \vee z)$ with $(y \vee z)$; (y, z may be ε); (**5**) If $(x) \wedge (\neg x)$ found, $\boxed{R}$. (**6**) If $\phi = \varepsilon$, Ⓐ;)

- CLIQUE, $\mathit{SUBSET\text{-}SUM}$, SAT, $\mathit{3SAT}$, $\overset{\mathit{VERTEX}}{\mathit{COVER}}$, $\mathit{HAMPATH}$, $\mathit{UHAMATH}$, $\mathit{3COLOR} \in \mathrm{NP\text{-}complete}$. $\emptyset, \Sigma^* \notin \mathrm{NP\text{-}complete}$.
- If $B \in \mathrm{NP\text{-}complete}$ and $B \in \mathrm{P}$, then $\mathrm{P} = \mathrm{NP}$.
- If $B \in \mathrm{NPC}$ and $C \in \mathrm{NP}$ s.t. $B \leq_{\mathrm{P}} C$, then $C \in \mathrm{NPC}$.
- If $\mathrm{P} = \mathrm{NP}$, then $\forall A \in \mathrm{P} \setminus \{\emptyset, \Sigma^*\}$, $A \in \mathrm{NP\text{-}complete}$.

Polytime Reduction (from A to B): $A \leq_{\mathrm{P}} B$ if $\exists f : \Sigma^* \to \Sigma^* : \forall w \in \Sigma^*$, $w \in A \iff f(w) \in B$ and f is polytime computable.

- $\mathit{SAT} \leq_{\mathrm{P}} \mathit{DOUBLE\text{-}SAT}$; $\quad f(\phi) = \phi \wedge (x \vee \neg x)$
- $\mathit{3SAT} \leq_{\mathrm{P}} \mathit{4SAT}$; $\quad f(\phi) = \phi'$, where ϕ' is obtained from the 3cnf ϕ by adding a new var. x to each clause, and adding a new clause $(\neg x \vee \neg x \vee \neg x \vee \neg x)$.
- $\mathit{3SAT} \leq_{\mathrm{P}} \mathit{CNF}_3$; $f(\langle \phi \rangle) = \phi'$. If $\#_\phi(x) = k > 3$, replace x with $x_1, \ldots x_k$, and add $(\overline{x_1} \vee x_2) \wedge \cdots \wedge (\overline{x_k} \vee x_1)$.
- $\mathit{3SAT} \leq_{\mathrm{P}} \mathit{CLIQUE}$; $f(\phi) = \langle G, k \rangle$. where ϕ is 3cnf with k clauses. Nodes represent literals. Edges connect all pairs except those 'from the same clause' or 'contradictory literals'.
- $\mathit{SUBSET\text{-}SUM} \leq_{\mathrm{P}} \mathit{SET\text{-}PARTITION}$; $f(\langle x_1, \ldots, x_m, t \rangle) = \langle x_1, \ldots, x_m, S - 2t \rangle$, where S sum of $x_1, \ldots, x_m$, and t is the target subset-sum.
- $\mathit{3SAT} \leq_{\mathrm{P}} \overset{\text{almost}}{\mathit{3SAT}}$; $f(\phi) = \phi' = \phi \wedge (x \vee x \vee x) \wedge (\overline{x} \vee \overline{x} \vee \overline{x})$
- $\mathit{3COLOR} \leq_{\mathrm{P}} \overset{\text{almost}}{\mathit{3COLOR}}$; $f(\langle G \rangle) = \langle G' \rangle$, $G' = G \cup K_4$
- $\overset{\mathit{VERTEX}}{\mathit{COVER}}_k \leq_{\mathrm{P}} \mathit{WVC}$; $f(\langle G, k \rangle) = (G, w, k), \forall v \in V, w(v) = 1$
- (dir.) $\mathit{HAM\text{-}PATH} \leq_{\mathrm{P}} \mathit{2HAM\text{-}PATH}$; $f(\langle G, s, t \rangle) = \langle G', s', t' \rangle$, $V' = V \cup \{s', t', a, b, c, d\}$, $E' = E \cup \{(s', a), (a, b), (b, s)\} \cup \{(s', b), (b, a), (a, s)\} \cup \{(t, c), (c, d), (d, t')\} \cup \{(t, d), (d, c), (c, t')\}$.
- (undir.) $\mathit{CLIQUE}_k \leq_{\mathrm{P}} \underset{|V|/2\text{-clique}}{\mathit{HALF\text{-}CLIQUE}}$; $f(\langle G = (V, E), k \rangle) = \langle G' = (V', E') \rangle$, if $k = \frac{|V|}{2}$, $E = E'$, $V' = V$. if $k > \frac{|V|}{2}$, $V' = V \cup \{j = 2k - |V|$ new nodes$\}$. if $k < \frac{|V|}{2}$, $V' = V \cup \{j = |V| - 2k$ new nodes$\}$ and $E' = E \cup \{$edges for new nodes$\}$
- $\underset{s \rightsquigarrow t}{\mathit{HAM\text{-}PATH}} \leq_{\mathrm{P}} \mathit{HAM\text{-}CYCLE}$; $f(\langle G, s, t \rangle) = \langle G', s, t \rangle$, $V' = V \cup \{x\}$, $E' = E \cup \{(t, x), (x, s)\}$
- $\mathit{HAM\text{-}CYCLE} \leq_{\mathrm{P}} \mathit{UHAMCYCLE}$; $f(\langle G \rangle) = \langle G' \rangle$. For each $u, v \in V$: u is replaced by $u_{\mathsf{in}}, u_{\mathsf{mid}}, u_{\mathsf{out}}$; (v, u) replaced by $\{v_{\mathsf{out}}, u_{\mathsf{in}}\}, \{u_{\mathsf{in}}, u_{\mathsf{mid}}\}$; and (u, v) by $\{u_{\mathsf{out}}, v_{\mathsf{in}}\}, \{u_{\mathsf{mid}}, u_{\mathsf{out}}\}$.
- $\mathit{UHAMPATH} \leq_{\mathrm{P}} \mathit{PATH}_{\geq k}$; $f(\langle G, a, b \rangle) = \langle G, a, b, k = |V| - 1 \rangle$
- $\overset{\mathit{VERTEX}}{\mathit{COVER}} \leq_{\mathrm{P}} \mathit{CLIQUE}$; $f(\langle G, k \rangle) = \langle G^{\complement} = (V, E^{\complement}), |V| - k \rangle$
- $\mathit{CLIQUE}_k \leq_{\mathrm{P}} \{\langle G, t \rangle : G$ has $2t$-clique$\}$; $f(\langle G, k \rangle) = \langle G', t = \lceil k/2 \rceil \rangle$, $G' = G$ if k is even; $G' = G \cup \{v\}$ (v connected to all G nodes) if k is odd.

- $\mathit{CLIQUE}_k \leq_{\mathrm{P}} \overset{\text{almost}}{\mathit{CLIQUE}_k}$; $f(\langle G, k \rangle) = \langle G', k + 2 \rangle$, $G' = G \cup \{v_{n+1}, v_{n+2}\}$; v_{n+1}, v_{n+2} are con. to all V
- $\overset{\mathit{VERTEX}}{\mathit{COVER}}_k \leq_{\mathrm{P}} \mathit{DOMINATING\text{-}SET}_k$; $f(\langle G, k \rangle) = \langle G', k \rangle$, where $V' = \{$non-isolated nodes in $V\} \cup \{v_e : e \in E\}$, $E' = E \cup \{(v_e, u), (v_e, w) : e = (u, w) \in E\}$.
- $\mathit{CLIQUE} \leq_{\mathrm{P}} \mathit{INDEP\text{-}SET}$; $f(\langle G, k \rangle) = \langle G^{\complement}, k \rangle$
- $\overset{\mathit{VERTEX}}{\mathit{COVER}} \leq_{\mathrm{P}} \underset{\langle \mathcal{U}, \mathcal{S}, k \rangle}{\overset{\mathit{SET}}{\mathit{COVER}}} = \{\exists \mathcal{C} \subseteq \mathcal{S}, |\mathcal{C}| \leq k, \bigcup_{A \in \mathcal{C}} A = \mathcal{U}\}$; $f(\langle G, k \rangle) = \langle \mathcal{U} = E, \mathcal{S} = \{S_1, \ldots, S_n\}, k \rangle$, where $n = |V|$, $S_u = \{$edges incident to $u \in V\}$.
- $\mathit{INDEP\text{-}SET} \leq_{\mathrm{P}} \overset{\mathit{VERTEX}}{\mathit{COVER}}$; $f(\langle G, k \rangle) = \langle G, |V| - k \rangle$
- $\overset{\mathit{VERTEX}}{\mathit{COVER}} \leq_{\mathrm{P}} \mathit{INDEP\text{-}SET}$; $f(\langle G, k \rangle) = \langle G, |V| - k \rangle$
- $\mathit{HAM\text{-}CYCLE} \leq_{\mathrm{P}} \{\langle G, w, k \rangle : \exists$ hamcycle of weight $\leq k\}$; $f(\langle G \rangle) = \langle G', w, 0 \rangle$, where $G' = (V, E')$, $E' = \{(u, v) \in E : u \neq v\}$, $w(u, v) = 1$ if $(u, v) \in E$, $w(u, v) = 0$ if $(u, v) \notin E$.
- $\mathit{3COLOR} \leq_{\mathrm{P}} \mathit{SCHEDULE}$; $f(\langle G \rangle) = \langle F = V, S = E, h = 3 \rangle$