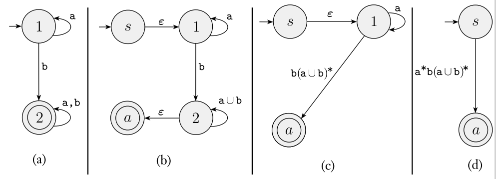
CHEAT SHEET: COMPUTATIONAL MODELS (20604)

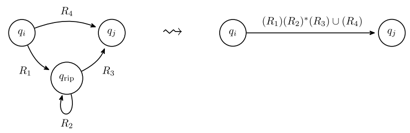
https://github.com/adielbm/20604

	$\overline{\text{REG}}$	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**) $M = (Q, \Sigma, \delta, q_0, F)$, $\delta : Q \times \Sigma \to Q$.
- (**NFA**) $M = (Q, \Sigma, \delta, q_0, F)$, $\delta : Q \times \Sigma_\varepsilon \to \mathcal{P}(Q)$.
- (**GNFA**) $(Q, \Sigma, \delta, q_0, q_a)$, $\delta : Q \setminus \{q_a\} \times Q \setminus \{q_0\} \to \text{Rex}_\Sigma$
- (DFAs D_1, D_2) $\exists$ DFA D s.t. $|Q| = |Q_1| \cdot |Q_2|$, $L(D) = L(D_1) \Delta L(D_2)$.
- (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.

- (**DFA** $\rightsquigarrow$ **GNFA** $\rightsquigarrow$ **Regex**)





- If $A = L(N_{\text{NFA}}), B = (L(M_{\text{DFA}}))^{\complement}$ then $A \cdot B \in \text{REG}$.

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

$NFA \to DFA$

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

Regular Expressions: Examples

- $\{a^n w b^n : w \in \Sigma^*\} \equiv a(a \cup b)^* b$
- $\{w : \#_w(0) \geq 2 \vee \#_w(1) \leq 1\} \equiv (\Sigma^* 0 \Sigma^* 0 \Sigma^*) \cup (0^*(\varepsilon \cup 1)0^*)$
- $\{w : |w| \bmod n = m\} \equiv (a \cup b)^m ((a \cup b)^n)^*$
- $\{w : \#_b(w) \bmod n = m\} \equiv (a^* b a^*)^m \cdot ((a^* b a^*)^n)^*$
- $\{w : |w| \text{ is odd}\} \equiv (a \cup b)^* ((a \cup b)(a \cup b)^*)^*$
- $\{w : \#_a(w) \text{ is odd}\} \equiv b^* a (a b^* a \cup b)^*$
- $\{w : \#_{ab}(w) = \#_{ba}(w)\} \equiv \varepsilon \cup a \cup b \cup a\Sigma^* a \cup b\Sigma^* b$
- $\{a^m b^n \mid m + n \text{ is odd}\} \equiv a(aa)^*(bb)^* \cup (aa)^* b(bb)^*$
- $\{aw : aba \not\subseteq w\} \equiv a(a \cup bb \cup bbb)^*(b \cup \varepsilon)$
- $\{w : bb \not\subseteq w\} \equiv (a \cup ba)^*(\varepsilon \cup b)$

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

the following are **non-reuglar but CFL**

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

the following are both **non-CFL and non-reuglar**

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

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

- (**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 $R \to uAvAw \mid uAvw \mid uvAw \mid uvw$. 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 $A \to u_1 u_2 \cdots u_k$ where $k \geq 3$ and $u_i \in (V \cup \Sigma)$, with the rules $A \to u_1 A_1$, $A_1 \to u_2 A_2$, ..., $A_{k-2} \to u_{k-1} u_k$, where A_i are new variables. Replace terminals u_i with $U_i \to u_i$.
- 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.
- $\forall L \in$ CFL, $\exists G \in$ 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.) $r_m \in F$.
- (**PDA transition**) "$a, b \to c$": **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 $c = \varepsilon$)
- $R \in \text{REG} \wedge C \in \text{CFL} \implies R \cap C \in \text{CFL}$. (*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)** $A \to BC$, $A \to a$, $S \to \varepsilon$, $(A, B, C \in V, a \in \Sigma, B, C \neq S)$.

the following are **CFL but non-reuglar**:

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

the following are both **CFL and regular**:

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

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

- $\{w = a^n b^n c^n\}$; $s = a^p b^p b^p = uvxyz$. 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**) $\{a^i b^j c^k \mid 0 \leq i \leq j \leq k\}$, $\{a^n b^n c^n \mid n \in \mathbb{N}\}$, $\{ww \mid w \in \{a, b\}^*\}$, $\{a^{n^2} \mid n \geq 0\}$, $\{a^p \mid p \text{ is prime}\}$, $L = \{ww^{\mathcal{R}}w : w \in \{a, b\}^*\}$
- $\{w \mid \#_w(a) = \#_w(b) = \#_w(c)\}$: (*pf.* since Regular $\cap$ CFL $\in$ CFL, but $\{a^* b^* c^*\} \cap L = \{a^n b^n c^n\} \notin$ CFL)

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

- (**TM**) $M = (Q, \underbrace{\Sigma}_{\text{input}} \subseteq \Gamma, \underbrace{\Gamma}_{\text{tape}}, \delta, q_0, q_{Ⓐ}, q_{Ⓡ})$, where $\sqcup \in \Gamma$, $\sqcup \notin \Sigma$, $q_{Ⓡ} \neq q_{Ⓐ}$, $\delta : Q \times \Gamma \longrightarrow Q \times \Gamma \times \{\text{L}, \text{R}\}$
- (**Turing-Recognizable** (**TR**)) Ⓐ if $w \in L$, Ⓡ/loops if $w \notin L$; A is **co-recognizable** if $\overline{A}$ is recognizable.
- $L \in \text{TR} \iff L \leq_{\text{m}} A_{\text{TM}}$.
- Every inf. recognizable lang. has an inf. dec. subset.
- (**Turing-Decidable** (**TD**)) Ⓐ if $w \in L$, Ⓡ if $w \notin L$.
- $L \in \text{TD} \iff L^{\mathcal{R}} \in \text{TD}$.
- (**decider**) TM that halts on all inputs.
- (**Rice**) Let P be a lang. of TM descriptions, s.t. (**i**) P is nontrivial (not empty and not all TM desc.) and (**ii**) for each two TM M_1 and M_2, we have $L(M_1) = L(M_2) \implies (\langle M_1 \rangle \in P \iff \langle M_2 \rangle \in P)$. Then P is undecidable. (*e.g.* $INFINITE_{\text{TM}}$, ALL_{TM}, E_{TM}, $\{\langle M_{\text{TM}} \rangle : 1 \in L(M)\}$)
- $\{\text{all TMs}\}$ is count.; Σ^* is count. (finite Σ); $\{\text{all lang.}\}$ is uncount.; $\{\text{all infinite bin. seq.}\}$ is uncount.
- $f : \Sigma^* \to \Sigma^*$ is **computable** if $\exists M_{\text{TM}} : \forall w \in \Sigma^*$, M halts on w and outputs $f(w)$ on its tape.
- If $A \leq_{\text{m}} B$ and $B \in \text{TD}$, then $A \in \text{TD}$.
- If $A \leq_{\text{m}} B$ and $A \notin \text{TD}$, then $B \notin \text{TD}$.
- If $A \leq_{\text{m}} B$ and $B \in \text{TR}$, then $A \in \text{TR}$.
- If $A \leq_{\text{m}} B$ and $A \notin \text{TR}$, then $B \notin \text{TR}$.
- (transitivity) If $A \leq_{\text{m}} B$ and $B \leq_{\text{m}} C$, then $A \leq_{\text{m}} C$.
- $A \leq_{\text{m}} B \iff \overline{A} \leq_{\text{m}} \overline{B}$ (esp. $A \leq_{\text{m}} \overline{A} \iff \overline{A} \leq_{\text{m}} A$)
- If $A \leq_{\text{m}} \overline{A}$ and $A \in \text{TR}$, then $A \in \text{TD}$

FINITE $\subset$ REGULAR $\subset$ CFL $\subset$ CSL $\subset$ Turing-Decidable $\subset$ Turing-Recognizable

- (**unrecognizable**) $\overline{A_{\mathsf{TM}}}$, $\overline{EQ_{\mathsf{TM}}}$, EQ_{CFG}, $\overline{HALT_{\mathsf{TM}}}$, REG_{TM}, E_{TM}, EQ_{TM}, ALL_{CFG}, EQ_{CFG}
- (**recognizable but undecidable**) A_{TM}, $HALT_{\mathsf{TM}}$, $\overline{EQ_{\mathsf{CFG}}}$, $\overline{E_{\mathsf{TM}}}$, $\{\langle M,k\rangle \mid \exists x\ (M(x) \text{ halts in } \geq k \text{ steps})\}$
- (**decidable**) A_{DFA}, A_{NFA}, A_{REX}, E_{DFA}, EQ_{DFA}, A_{CFG}, E_{CFG}, A_{LBA}, ALL_{DFA}, $A\varepsilon_{\mathsf{CFG}} = \{\langle G\rangle \mid \varepsilon \in L(G)\}$

Examples of Recognizers:

- $\overline{EQ_{\mathsf{CFG}}}$: "On $\langle G_1, G_2\rangle$: for each $w \in \Sigma^*$ (lexico.): Test (by A_{CFG}) whether $w \in L(G_1)$ and $w \notin L(G_2)$ (vice versa), if so A; O/W, continue"

Examples of Deciders:

- $\mathrm{INFINITE}_{\mathsf{DFA}}$: "On n-state DFA $\langle A\rangle$: const. DFA B s.t. $L(B) = \Sigma^{\geq n}$; const. DFA C s.t. $L(C) = L(A) \cap L(B)$; if $L(C) \neq \emptyset$ (by E_{DFA}) A; O/W, $\boxed{\text{R}}$"
- $\{\langle D\rangle \mid \nexists w \in L(D) : \#_1(w) \text{ is odd}\}$: "On $\langle D\rangle$: const. DFA A s.t. $L(A) = \{w \mid \#_1(w) \text{ is odd}\}$; const. DFA B s.t. $L(B) = L(D) \cap L(A)$; if $L(B) = \emptyset$ (E_{DFA}) A; O/W $\boxed{\text{R}}$"
- $\{\langle R, S\rangle \mid R, S \text{ are regex}, L(R) \subseteq L(S)\}$: "On $\langle R, S\rangle$: const. DFA D s.t. $L(D) = L(R) \cap \overline{L(S)}$; if $L(D) = \emptyset$ (by E_{DFA}), A; O/W, $\boxed{\text{R}}$"
- $\{\langle D_{\mathsf{DFA}}, R_{\mathsf{REX}}\rangle \mid L(D) = L(R)\}$: "On $\langle D, R\rangle$: convert R to DFA D_R; if $L(D) = L(D_R)$ (by EQ_{DFA}), A; O/W, $\boxed{\text{R}}$"
- $\{\langle D_{\mathsf{DFA}}\rangle \mid L(D) = (L(D))^{\mathcal{R}}\}$: "On $\langle D\rangle$: const. DFA $D^{\mathcal{R}}$ s.t. $L(D^{\mathcal{R}}) = (L(D))^{\mathcal{R}}$; if $L(D) = L(D^{\mathcal{R}})$ (by EQ_{DFA}), A; O/W, $\boxed{\text{R}}$"
- $\{\langle M, k\rangle \mid \exists x\ (M(x) \text{ runs for} \geq k \text{ steps})\}$: "On $\langle M, k\rangle$: (foreach $w \in \Sigma^{\leq k+1}$: if $M(w)$ not halt within k steps, A); O/W, $\boxed{\text{R}}$"
- $\{\langle M, k\rangle \mid \exists x\ (M(x) \text{ halts in} \leq k \text{ steps})\}$: "On $\langle M, k\rangle$: (foreach $w \in \Sigma^{\leq k+1}$: run $M(w)$ for $\leq k$ steps, if halts, A); O/W, $\boxed{\text{R}}$"
- $\{\langle M_{\mathsf{DFA}}\rangle \mid L(M) = \Sigma^*\}$: "On $\langle M\rangle$: const. DFA $M^{\complement} = (L(M))^{\complement}$; if $L(M^{\complement}) = \emptyset$ (by E_{DFA}), A; O/W $\boxed{\text{R}}$."
- $\{\langle R_{\mathsf{REX}}\rangle \mid \exists s, t \in \Sigma^* : w = s111t \in L(R)\}$: "On $\langle R\rangle$: const. DFA D s.t. $L(D) = \Sigma^* 111 \Sigma^*$; const. DFA C s.t. $L(C) = L(R) \cap L(D)$; if $L(C) \neq \emptyset$ (E_{DFA}) A; O/W $\boxed{\text{R}}$"

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 $x \notin \{01, 10\}$, $\boxed{\text{R}}$; if $x = 01$, return $M(x)$; if $x = 10$, A;"
- $A_{\mathsf{TM}} \leq_{\mathrm{m}} L = \{\langle \underset{\mathsf{TM}}{M}, \underset{\mathsf{DFA}}{D}\rangle \mid L(M) = L(D)\}$; $f(\langle M, w\rangle) = \langle M', D\rangle$, where M' ="On x: if $x = w$ return $M(x)$; O/W, $\boxed{\text{R}}$;" 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;"
- $A_{\mathsf{TM}} \leq_{\mathrm{m}} CFL_{\mathsf{TM}} = \{\langle M\rangle \mid L(M) \text{ is CFL}\}$; $f(\langle M, w\rangle) = \langle N\rangle$, where N ="On x: if $x = a^n b^n c^n$, A; 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, A. 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, A;"
- $E_{\mathsf{TM}} \leq_{\mathrm{m}} USELESS_{\mathsf{TM}}$; $f(\langle M\rangle) = \langle M, q_{\mathrm{A}}\rangle$
- $E_{\mathsf{TM}} \leq_{\mathrm{m}} EQ_{\mathsf{TM}}$; $f(\langle M\rangle) = \langle M, M'\rangle$, M' ="On x: $\boxed{\text{R}}$"
- $A_{\mathsf{TM}} \leq_{\mathrm{m}} REGULAR_{\mathsf{TM}}$; $f(\langle M, w\rangle) = \langle M'\rangle$, M' ="On $x \in \{0,1\}^*$: if $x = 0^n 1^n$, A; O/W, return $M(w)$;"
- $A_{\mathsf{TM}} \leq_{\mathrm{m}} EQ_{\mathsf{TM}}$; $f(\langle M, w\rangle) = \langle M_1, M_2\rangle$, where M_1 = "A all"; M_2 ="On x: return $M(w)$;"
- $A_{\mathsf{TM}} \leq_{\mathrm{m}} \overline{EQ_{\mathsf{TM}}}$; $f(\langle M, w\rangle) = \langle M_1, M_2\rangle$, where M_1 = "$\boxed{\text{R}}$ all"; M_2 ="On x: return $M(w)$;"
- $ALL_{\mathsf{CFG}} \leq_{\mathrm{m}} EQ_{\mathsf{CFG}}$; $f(\langle G\rangle) = \langle G, H\rangle$, 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, $\boxed{\text{R}}$;" (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 $x \neq w$, $\boxed{\text{R}}$; 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: A 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: A if $M(w)$ halts"
- $\overline{HALT_{\mathsf{TM}}} \leq_{\mathrm{m}} \{\langle M_{\mathsf{TM}}\rangle : M \text{ A all even num.}\}$; $f(\langle M, w\rangle) = \langle M'\rangle$, where M' ="On x: $\boxed{\text{R}}$ if $M(w)$ halts within $|x|$. O/W, A"
- $\overline{HALT_{\mathsf{TM}}} \leq_{\mathrm{m}} \{\langle M_{\mathsf{TM}}\rangle : L(M) \text{ is finite}\}$; $f(\langle M, w\rangle) = \langle M'\rangle$, where M' ="On x: A if $M(w)$ halts"
- $\overline{HALT_{\mathsf{TM}}} \leq_{\mathrm{m}} \{\langle M_{\mathsf{TM}}\rangle : L(M) \text{ is infinite}\}$; $f(\langle M, w\rangle) = \langle M'\rangle$, where M' ="On x: $\boxed{\text{R}}$ if $M(w)$ halts within $|x|$ steps. O/W, A"
- $HALT_{\mathsf{TM}} \leq_{\mathrm{m}} \{\langle M_1, M_2\rangle : \varepsilon \in L(M_1) \cup L(M_2)\}$; $f(\langle M, w\rangle) = \langle M', M'\rangle$, M' ="On x: A 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 $x \neq w$ $\boxed{\text{R}}$; else, A if $M(w)$ halts"
- $HALT_{\mathsf{TM}} \leq_{\mathrm{m}} \{\langle M_{\mathsf{TM}}\rangle \mid \exists x : M(x) \text{ halts in } > |\langle M\rangle| \text{ steps}$ $f(\langle M, w\rangle) = \langle M'\rangle$, where M' ="On x: if $M(w)$ halts, make $|\langle M\rangle| + 1$ steps and then halt; O/W, loop"

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

- (**verifier** for L) TM V s.t. $L = \{w \mid \exists c : V(\langle w, c\rangle) = \text{A}\}$; (**certificate** for $w \in L$) str. c s.t. $V(\langle w, c\rangle) = \text{A}$.
- 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. $\mathrm{P} \setminus \{\emptyset, \Sigma^*\}$ is an equiv. class of $\equiv_P$.
- ALL_{DFA}, $\mathit{CONNECTED}$, $\underset{\text{3-clique}}{\mathit{TRIANGLE}}$, $L(G_{\mathsf{CFG}})$, $\overset{\text{directed}}{\underset{s \to t}{\mathit{PATH}}} \in \mathrm{P}$
- $CNF_2 \in \mathrm{P}$: (**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, $\boxed{\text{R}}$. (**6**) If $\phi = \varepsilon$, A;)
- CLIQUE, $\mathit{SUBSET\text{-}SUM}$, SAT, $\mathit{3SAT}$, $\overset{\mathit{VERTEX}}{\mathit{COVER}}$, $\mathit{HAMPATH}$, $\mathit{UHAMATH}$, $\mathit{3COLOR} \in$ NP-complete. $\emptyset, \Sigma^* \notin$ NP-complete.
- If $B \in$ NP-complete and $B \in \mathrm{P}$, then $\mathrm{P} = \mathrm{NP}$.
- If $B \in$ NPC and $C \in$ NP s.t. $B \leq_{\mathrm{P}} C$, then $C \in$ NPC.
- If $\mathrm{P} = \mathrm{NP}$, then $\forall A \in \mathrm{P} \setminus \{\emptyset, \Sigma^*\}$, $A \in$ NP-complete.

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

- $\mathit{SAT} \leq_{\mathrm{P}} \mathit{DOUBLE\text{-}SAT}$; $f(\phi) = \phi \wedge (x \vee \neg x)$
- $\mathit{3SAT} \leq_{\mathrm{P}} \mathit{4SAT}$; $f(\phi) = \phi'$, where ϕ' is obtained from the 3cnf ϕ by adding a new var. x to each clause, and adding a new clause $(\neg x \vee \neg x \vee \neg x \vee \neg x)$.
- $\mathit{3SAT} \leq_{\mathrm{P}} CNF_3$; $f(\langle\phi\rangle) = \phi'$. 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.
- $\mathit{3COLOR} \leq_{\mathrm{P}} \overset{\text{almost}}{\mathit{3COLOR}}$; $f(\langle G\rangle) = \langle G'\rangle$, $G' = G \cup K_4$
- $\overset{\mathit{VERTEX}}{\mathit{COVER}_k} \leq_{\mathrm{P}} \mathit{WVC}$; $f(\langle G, k\rangle) = (G, w, k), \forall v \in V, w(v) = 1$
- (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 $k > \frac{|V|}{2}$, $V' = V \cup \{j = 2k - |V| \text{ new nodes}\}$. if $k < \frac{|V|}{2}$, $V' = V \cup \{j = |V| - 2k \text{ new nodes}\}$ and $E' = E \cup \{\text{edges for new nodes}\}$
- $\underset{s \rightsquigarrow t}{\mathit{HAM\text{-}PATH}} \leq_{\mathrm{P}} \mathit{HAM\text{-}CYCLE}$; $f(\langle G, s, t\rangle) = \langle G', s, t\rangle$, $V' = V \cup \{x\}$, $E' = E \cup \{(t, x), (x, s)\}$
- $\mathit{HAM\text{-}CYCLE} \leq_{\mathrm{P}} \mathit{UHAMCYCLE}$; $f(\langle G\rangle) = \langle G'\rangle$. 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 $\{u_{\mathsf{out}}, v_{\mathsf{in}}\}, \{u_{\mathsf{mid}}, u_{\mathsf{out}}\}$.
- $\mathit{UHAMPATH} \leq_{\mathrm{P}} \mathit{PATH}_{\geq k}$; $f(\langle G, a, b\rangle) = \langle G, a, b, k = |V| - 1\rangle$
- $\overset{\mathit{VERTEX}}{\mathit{COVER}} \leq_{\mathrm{P}} \mathit{CLIQUE}$; $f(\langle G, k\rangle) = \langle G^{\complement} = (V, E^{\complement}), |V| - k\rangle$
- $\mathit{CLIQUE}_k \leq_{\mathrm{P}} \{\langle G, t\rangle : G \text{ has } 2t\text{-clique}\}$; $f(\langle G, k\rangle) = \langle G', t = \lceil k/2 \rceil\rangle$, $G' = G$ 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 $V' = \{\text{non-isolated nodes in } V\} \cup \{v_e : e \in E\}$, $E' = E \cup \{(v_e, u), (v_e, w) : e = (u, w) \in E\}$.
- $\mathit{CLIQUE} \leq_{\mathrm{P}} \mathit{INDEP\text{-}SET}$; $f(\langle G, k\rangle) = \langle G^{\complement}, k\rangle$
- $\overset{\mathit{VERTEX}}{\mathit{COVER}} \leq_{\mathrm{P}} \underset{\langle \mathcal{U}, \mathcal{S}, k\rangle}{\overset{\mathit{SET}}{\mathit{COVER}}} = \{\exists \mathcal{C} \subseteq \mathcal{S}, |\mathcal{C}| \leq k, \bigcup_{A \in \mathcal{C}} A = \mathcal{U}\}$; $f(\langle G, k\rangle) = \langle \mathcal{U} = E, \mathcal{S} = \{S_1, \ldots, S_n\}, k\rangle$, where $n = |V|$, $S_u = \{\text{edges incident to } u \in V\}$.
- $\mathit{INDEP\text{-}SET} \leq_{\mathrm{P}} \overset{\mathit{VERTEX}}{\mathit{COVER}}$; $f(\langle G, k\rangle) = \langle G, |V| - k\rangle$
- $\overset{\mathit{VERTEX}}{\mathit{COVER}} \leq_{\mathrm{P}} \mathit{INDEP\text{-}SET}$; $f(\langle G, k\rangle) = \langle G, |V| - k\rangle$

Examples

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