Reg / DFA / NFA

	$\overline{\text{REG}}$	REG	CFL	DEC.	REC.	P	NP	NPC
$L_1 \cup L_2$	no	✓	✓	✓	✓	✓	✓	no
$L_1 \cap L_2$	no	✓	no	✓	✓	✓	✓	no
$\overline{L}$	✓	✓	no	✓	no	✓	?	?
$L_1 \cdot L_2$	no	✓	✓	✓	✓	✓	✓	no
L^*	no	✓	✓	✓	✓	✓	✓	no
$L^{\mathcal{R}}$	✓	✓	✓	✓	✓	✓		
$L_1 \setminus L_2$	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)** $(Q, \Sigma, \delta, q_0, q_a)$,
  $\delta : (Q \setminus \{q_a\}) \times (Q \setminus \{q_{\text{start}}\}) \longrightarrow \mathcal{R}$ (where
  $\mathcal{R} = \{\text{all regex over } \Sigma\}$)
  GNFA accepts $w \in \Sigma^*$ if $w = w_1 \cdots w_k$, where $w_i \in \Sigma^*$
  and there exists a sequence of states $q_0, q_1, \ldots, q_k$ s.t.
  $q_0 = q_{\text{start}}$, $q_k = q_a$ and for each i, we have $w_i \in L(R_i)$,
  where $R_i = \delta(q_{i-1}, q_i)$.
- **(DFA ⤳ GNFA)** $G = (Q', \Sigma, \delta', s, a)$,
  $Q' = Q \cup \{s, a\}$, $\quad \delta'(s, \varepsilon) = q_0$, $\quad$ For each $q \in F$,
  $\delta'(q, \varepsilon) = a$, $\quad$ ((TODO...))
- Every NFA can be converted to an equivalent one that
  has a single accept state.
- **(reg. grammar)** $G = (V, \Sigma, R, S)$. Rules: $A \to aB$,

- $A \to a$ or $S \to \varepsilon$. $(A, B, S \in V; a \in \Sigma)$.
- **(NFA ⤳ DFA)**
  - $N = (Q, \Sigma, \delta, q_0, F)$
  - $D = (Q', \Sigma, \delta', q_0' = E(\{q_0\}), F')$
  - $F' = \{q \in Q' \mid \exists p \in F : p \in q\}$
  - $E(\{q\}) := \{q\} \cup \{\text{states reachable from } q \text{ via } \varepsilon\text{-arrows}\}$
  - $\forall R \subseteq Q, \forall a \in \Sigma, \delta'(R, a) = E\left(\bigcup_{r \in R} \delta(r, a)\right)$
- $L(\varepsilon \cup 0\Sigma^*0 \cup 1\Sigma^*1) = \{w \mid \#_w(01) = \#_w(10)\}$,
- Regular Expressions Examples:
  - $L = \{a^n w b^n : w \in \Sigma^*\} \equiv a(a \cup b)^* b$
  - $L = \{w \in \Sigma^* : \#_w(0) \geq 2 \wedge \#_w(1) \leq 1\} \equiv$
    $((0 \cup 1)^*0(0 \cup 1)^*0(0 \cup 1)^*) \cup (0^*(\varepsilon \cup 1)0^*)$

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

- $\{w = a^{2^k}\}$; $\quad k = \lfloor \log_2 |w| \rfloor, s = a^{2^k} = xyz$.
  $2^k = |xyz| < |xy^2z| \leq |xyz| + |xy| \leq 2^k + p < 2^{k+1}$.

- $\{w = w^{\mathcal{R}}\}$; $\quad s = 0^p10^p = xyz$. then
  $xy^2z = 0^{p+|y|}10^p \notin L$.
- $\{a^nb^n\}$; $\quad s = a^pb^p = xyz$, where $|y| > 0$ and $|xy| \leq p$.

- Then $xy^2z = a^{p+|y|}b^p \notin L$.
- $L = \{a^p : p \text{ is prime}\}$; $\quad s = a^t = xyz$ for prime $t \geq p$.
  $r := |y| > 0$

CFL / CFG / PDA

- **(CFG)** $G = (\underset{\text{n.t.}}{V}, \underset{\text{ter.}}{\Sigma}, R, S)$. Rules: $A \to w$. (where $A \in V$
  and $w \in (V \cup \Sigma)^*$).
- A derivation of w is a **leftmost derivation** if at every
  step the leftmost remaining variable is the one
  replaced.
- w is derived **ambiguously** in G if it has at least two
  different l.m. derivations. G is **ambiguous** if it
  generates at least one string ambiguously. A CFG is
  ambiguous iff it generates some string with two
  different parse trees. A CFL is **inherently ambiguous**
  if all CFGs that generate it are ambiguous.
- **(CNF)** $A \to BC$, $A \to a$, or $S \to \varepsilon$, (where $A, B, C \in V$,
  $a \in \Sigma$, and $B, C \neq S$).
- **(CFG ⤳ 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 $A \to u_1u_2\cdots u_k$ 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 $U_i \to u_i$.
- If $G \in \text{CNF}$, and $w \in L(G)$, then $|w| \leq 2^{|h|} - 1$, where h
  is the height of the parse tree for w.
- $L \in \textbf{CFL} \Leftrightarrow \exists \underset{\text{CFG}}{G} : L = L(G) \Leftrightarrow \exists \underset{\text{PDA}}{M} : L = L(M)$
- $\forall L \in \text{CFL}, \exists G \in \text{CNF} : L = L(G)$.
- **(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), $S \overset{*}{\Rightarrow} w$)
- **(PDA)** $M = (Q, \underset{\text{input}}{\Sigma}, \underset{\text{stack}}{\Gamma}, \delta, q_0 \in Q, \underset{\text{accepts}}{F} \subseteq Q)$. (where
  Q, Σ, Γ, F finite). $\delta : Q \times \Sigma_\varepsilon \times \Gamma_\varepsilon \longrightarrow \mathcal{P}(Q \times \Gamma_\varepsilon)$.

- 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.:
  - $r_0 = q_0$ and $s_0 = \varepsilon$
  - 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
    $t \in \Gamma^*$.
  - $r_m \in F$
- A PDA can be represented by a state diagram, where
  each transition is labeled by the notation "$a, b \to c$" to
  denote that the PDA: **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 $c = \varepsilon$)
- **(CSG)** $G = (V, \Sigma, R, S)$. Rules: $S \to \varepsilon$ or $\alpha A \beta \to \alpha \gamma \beta$
  where: $\alpha, \beta \in (V \cup \Sigma \setminus \{S\})^*$; $\gamma \in (V \cup \Sigma \setminus \{S\})^+$;
  $A \in V$.

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

- $\{w = a^nb^nc^n\}$; $\quad s = a^pb^pb^p = uvxyz$. vxy can't contain
  all of a, b, c thus uv^2xy^2z must pump one of them less
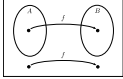
- than the others.
- $\{ww : w \in \{a, b\}^*\}$;

$$L \in \text{DECIDABLE} \iff (L \in \text{REC. and } L \in \text{co-REC.}) \iff \exists M_{\text{TM}} \text{ decides } L.$$

- **(TM)** $M = (Q, \underset{\text{input}}{\Sigma} \subseteq \Gamma, \underset{\text{tape}}{\Gamma}, \delta, q_0, q_{\text{accept}}, q_{\text{reject}})$, where
  $\sqcup \in \Gamma$ **(blank)**, $\sqcup \notin \Sigma$, $q_{\text{reject}} \neq q_{\text{accept}}$, and
  $\delta : Q \times \Gamma \longrightarrow Q \times \Gamma \times \{\text{L}, \text{R}\}$
- **(recognizable)** accepts if $w \in L$, rejects/loops if $w \notin L$.
  - $L \in \text{RECOGNIZABLE} \iff L \leq_{\text{m}} A_{\text{TM}}$.
  - A is **co-recognizable** if $\overline{A}$ is recognizable.

- Every inf. recognizable lang. has an inf. dec. subset.
- **(decidable)** accepts if $w \in L$, rejects if $w \notin L$.
- $L \in \text{DECIDABLE} \iff L \leq_{\text{m}} 0^*1^*$.
- $L \in \text{DECIDABLE} \iff L^{\mathcal{R}} \in \text{DECIDABLE}$.
- **(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.
- {all TMs} is countable; Σ^* is countable (for every finite Σ); {all languages} is uncountable;
  {all infinite binary sequences} is uncountable.
- DFA $\equiv$ NFA $\equiv$ GNFA $\equiv$ REG $\subset$ NPDA $\equiv$ CFG $\subset$ DTM $\equiv$ NTM

FINITE $\subset$ REGULAR $\subset$ CFL $\subset$ CSL $\subset$ DECIDABLE $\subset$ RECOGNIZABLE

- **(unrecognizable)** $\overline{A_{TM}}$, $\overline{EQ_{\text{TM}}}$, EQ_{CFG}, $\overline{HALT_{\text{TM}}}$,
  $\text{REGULAR}_{\text{TM}} = \{M \text{ is a TM and } L(M) \text{ is regular}\}$, E_{TM}
  , $EQ_{\text{TM}} = \{M_1, M_2 \text{ are TMs and } L(M_1) = L(M_2)\}$,
  ALL_{CFG}, EQ_{CFG}
- **(recognizable but undecidable)** A_{TM},
  $HALT_{\text{TM}} = \{\langle M, w \rangle \mid M \text{ is a TM halts on } w\}$,

- $D = \{p \mid p \text{ is an int. poly. with an int. root}\}$, $\overline{EQ_{\text{CFG}}}$,
  $\overline{E_{\text{TM}}}$,
- **(decidable)** A_{DFA}, A_{NFA}, A_{REX}, E_{DFA}, EQ_{DFA}, A_{CFG},
  E_{CFG}, A_{LBA}, $ALL_{\text{DFA}} = \{\langle M \rangle \mid M \text{ is a DFA}, L(A) = \Sigma^*\}$,
  $A\varepsilon_{\text{CFG}} = \{\langle G \rangle \mid G \text{ is a CFG that generates } \varepsilon\}$,
  $\text{INFINITE}_{\text{DFA}}$, $\text{INFINITE}_{\text{PDA}}$

- **(not CFL)** $\{a^i b^j c^k \mid 0 \leq i \leq j \leq k\}$, $\{a^n b^n c^n \mid n \in \mathbb{N}\}$,
  $\{ww \mid w \in \{a, b\}^*\}$, $\{a^{n^2} \mid n \geq 0\}$,
  $\{w \in \{\texttt{a}, \texttt{b}, \texttt{c}\}^* \mid \#_\texttt{a}(w) = \#_\texttt{b}(w) = \#_\texttt{c}(w)\}$,
  $\{a^p \mid p \text{ is prime}\}$, $L = \{ww^{\mathcal{R}}w : w \in \{a, b\}^*\}$
- **(CFL but not REGULAR)** $\{w \in \{a, b\}^* \mid w = w^{\mathcal{R}}\}$,
  $\{ww^{\mathcal{R}} \mid w \in \{a, b\}^*\}$,
  $\{a^n b^n \mid n \in \mathbb{N}\}$, $\{w \in \{\texttt{a}, \texttt{b}\}^* \mid \#_\texttt{a}(w) = \#_\texttt{b}(w)\}$,
  $L = \{a^n b^m : n \neq m\}$

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

- $f : \Sigma^* \to \Sigma^*$ is **computable** if there exists a TM M s.t. for every $w \in \Sigma^*$, M halts on w and outputs $f(w)$ on its tape.

- If $A \leq_{\text{m}} B$ and B is decidable, then A is dec.
- If $A \leq_{\text{m}} B$ and A is undecidable, then B is undec.
- If $A \leq_{\text{m}} B$ and B is recognizable, then A is rec.
- If $A \leq_{\text{m}} B$ and A is unrecognizable, then B is unrec.
- (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 $A \in \text{RECOGNIZABLE}$, then $A \in \text{DEC}$.

EXAMPLES

- $A_{TM} \leq_{\text{m}} S_{TM} = \{\langle M \rangle \mid w \in L(M) \iff w^{\mathcal{R}} \in L(M)\}$,
  $f(\langle M, w \rangle) = \langle M' \rangle$, where $M' =$"On x, if $x \notin \{01, 10\}$, reject; if $x = 01$, return $M(x)$; if $x = 10$, accept;"
- $A_{TM} \leq_{\text{m}} L = \{\langle \underset{\text{TM}}{M}, \underset{\text{DFA}}{D} \rangle \mid L(M) = L(D)\}$,
  $f(\langle M, w \rangle) = \langle M', D \rangle$, where $M' =$"On x: if $x = w$ return $M(x)$; otherwise, reject;" and D is DFA s.t. $L(D) = \{w\}$.
- $A \leq_{\text{m}} HALT_{\text{TM}}$, $f(w) = \langle M, \varepsilon \rangle$, where $M =$"On x: if $w \in A$, halt; if $w \notin A$, loop forever;"
- $A_{TM} \leq_{\text{m}} CF_{\text{TM}} = \{\langle M \rangle \mid L(M) \text{ is CFL}\}$,
  $f(\langle M, w \rangle) = \langle N \rangle$, where $N =$"On x: if $x = a^n b^n c^n$, accept; otherwise, return $M(w)$;"
- $A \leq_{\text{m}} B = \{0w : w \in A\} \cup \{1w : w \notin A\}$, $f(w) = 0w$.

- $E_{\text{TM}} \leq_{\text{m}} \text{USELESS}_{\text{TM}}$; $f(\langle M \rangle) = \langle M, q_{\text{accept}} \rangle$
- $A_{TM} \leq_{\text{m}} EQ_{\text{TM}}$; $f(\langle M, w \rangle) = \langle M_1, M_2 \rangle$, where $M_1 =$ "Accept everything"; $M_2 =$"On x: return $M(w)$;"
- $A_{TM} \leq_{\text{m}} \overline{EQ_{\text{TM}}}$; $f(\langle M, w \rangle) = \langle M_1, M_2 \rangle$, where $M_1 =$ "Reject everything"; $M_2 =$"On x: return $M(w)$;"
- $ALL_{\text{CFG}} \leq_{\text{m}} EQ_{\text{CFG}}$; $f(\langle G \rangle) = \langle G, H \rangle$, where $L(H) = \Sigma^*$.
- $HALT_{\text{TM}} \leq_{\text{m}} \{\langle M_{TM} \rangle \mid \exists x : M(x) \text{ halts in more than } |\langle M \rangle|$
  $f(\langle M, w \rangle) = \langle M' \rangle$, where $M' =$"On x: if $M(w)$ halts, make $|\langle M \rangle| + 1$ steps and then halt; otherwise, loop"

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

- **((Running time)** decider M is a $f(n)$-time TM.)
  $f : \mathbb{N} \to \mathbb{N}$, where $f(n)$ is the max. num. of steps that DTM (or NTM) M takes on any n-length input (and any branch of any n-length input. resp.).
- $\text{TIME}(t(n)) = \{L \mid L \text{ is dec. by } O(t(n)) \text{ DTM}\}$.
- $\text{NTIME}(t(n)) = \{L \mid L \text{ is dec. by } O(t(n)) \text{ NTM}\}$.
- $\mathbf{P} = \bigcup_{k \in \mathbb{N}} \text{TIME}(n^k)$
- **(verifier** for L) TM V s.t.
  $L = \{w \mid \exists c : V(\langle w, c \rangle) = \text{accept}\}$.
  - **(certificate** for $w \in L$) str. c s.t. $V(\langle w, c \rangle) = \text{accept}$.
- $\mathbf{NP} = \bigcup_{k \in \mathbb{N}} \text{NTIME}(n^k)$
- $\mathbf{NP} = \{L \mid L \text{ is decidable by a PT verifier}\}$.
- $\text{P} \subseteq \text{NP}$.
- $f : \Sigma^* \to \Sigma^*$ is **PT computable** if there exists a PT TM M s.t. for every $w \in \Sigma^*$, M halts with $f(w)$ on its tape.
- If $A \leq_{\text{P}} B$ and $B \in \text{P}$, then $A \in \text{P}$.
- If $A \leq_{\text{P}} B$ and $B \leq_{\text{P}} A$, then A and B are **PT equivalent**, denoted $A \equiv_P B$. $\equiv_P$ is an equivalence

relation on NP. $\text{P} \setminus \{\emptyset, \Sigma^*\}$ is an equivalence class of $\equiv_P$.
- **NP-complete** $= \{B \mid B \in \text{NP}, \forall A \in \text{NP}, A \leq_{\text{P}} B\}$.
- CLIQUE, SUBSET-SUM, SAT, 3SAT, VERTEX-COVER, HAMPATH, UHAMATH, $3COLOR \in \text{NP-complete}$.
- $\emptyset, \Sigma^* \notin \text{NP-complete}$.
- If $B \in \text{NP-complete}$ and $B \in \text{P}$, then $\text{P} = \text{NP}$.
- If $B \in \text{NP-complete}$ and $C \in \text{NP}$ s.t. $B \leq_{\text{P}} C$, then $C \in \text{NP-complete}$.
- If $\text{P} = \text{NP}$, then $\forall A \in \text{P} \setminus \{\emptyset, \Sigma^*\}$, $A \in \text{NP-complete}$.

EXAMPLES

- SAT $\leq_{\text{P}}$ DOUBLE-SAT; $f(\phi) = \phi \land (x \lor \neg x)$
- SUBSET-SUM $\leq_{\text{P}}$ SET-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.
- $3COLOR \leq_{\text{P}} 3COLOR_{almost}$; $f(\langle G \rangle) = \langle G' \rangle$, where $G' = G \cup K_4$
- VERTEX-COVER $\leq_{\text{P}}$ WVC; $f(\langle G, k \rangle) = (G, w, k)$, $\forall v \in V(G), w(v) = 1$

- HAM-PATH $\leq_{\text{P}}$ 2HAM-PATH;
  $f(\langle G, s, t \rangle) = \langle G', s', t' \rangle$, where
  $V' = V \cup \{s', t', a, b, c, d\}$,
  $E' = E \cup \{(s', a), (a, b), (b, s)\} \cup \{(s', b), (b, a), (a, s)\}$
  $\cup \{(t, c), (c, d), (d, t')\} \cup \{(t, d), (d, c), (c, t')\}$.
- $\underset{\text{undir. } G \text{ has } k\text{-clique}}{\text{CLIQUE}} \leq_{\text{P}} \underset{\text{undir. } G \text{ has } |V|/2\text{-clique}}{\text{HALF-CLIQUE}}$;
  $f(\langle G = (V, E), k \rangle) = \langle G' = (V', E') \rangle$, 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
  $E' = E \cup \{\text{edges for new nodes}\}$
- UHAMPATH $\leq_{\text{P}}$ PATH$_{\geq k}$;
  $f(\langle G, a, b \rangle) = \langle G, a, b, k = |V(G)| - 1 \rangle$
- VERTEX-COVER $\leq_{\text{P}}$ CLIQUE;
  $f(\langle G, k \rangle) = \langle G^{\complement} = (V, E^{\complement}), |V| - k \rangle$
- CLIQUE$_k$ $\leq_{\text{P}}$ $\{\langle G, t \rangle : G \text{ has a } 2t\text{-clique}\}$;
  $f(\langle G, k \rangle) = \langle G', t = k/2 \rangle$
- CLIQUE $\leq_{\text{P}}$ INDEPENDENT-SET
- SET-COVER $\leq_{\text{P}}$ VERTEX-COVER
- 3SAT $\leq_{\text{P}}$ SET-SPLITTING
- INDEPENDENT-SET $\leq_{\text{P}}$ VERTEX-COVER

Counterexamples

- $A \leq_{\text{m}} B$ and $B \in \text{REG}$, but, $A \notin \text{REG}$:
  $A = \{0^n 1^n \mid n \geq 0\}$, $B = \{1\}$, $f : A \to B$,
  $f(w) = \begin{cases} 1 & \text{if } w \in A \\ 0 & \text{if } w \notin A \end{cases}$
- $L \in \text{CFL}$ but $\overline{L} \notin \text{CFL}$: $L = \{x \mid \forall w \in \Sigma^*, x \neq ww\}$,
  $\overline{L} = \{ww \mid w \in \Sigma^*\}$.
- $L_1, L_2 \in \text{CFL}$ but $L_1 \cap L_2 \notin \text{CFL}$: $L_1 = \{a^n b^n c^m\}$,
  $L_2 = \{a^m b^n c^n\}$, $L_1 \cap L_2 = \{a^n b^n c^n\}$.
- $L_1 \in \text{CFL}$, L_2 is infinite, but $L_1 \setminus L_2 \notin \text{REG}$: $L_1 = \Sigma^*$
  , $L_2 = \{a^n b^n \mid n \geq 0\}$, $L_1 \setminus L_2 = \{a^m b^n \mid m \neq n\}$.

- $L_1, L_2 \in \text{REG}$, $L_1 \not\subset L_2$, $L_2 \not\subset L_1$, but,
  $(L_1 \cup L_2)^* \neq L_1^* \cup L_2^*$: $L_1 = \{\texttt{a}, \texttt{b}, \texttt{ab}\}$, $L_2 = \{\texttt{a}, \texttt{b}, \texttt{ba}\}$
  .
- $L_1 \in \text{REG}$, $L_2 \notin \text{REG}$, but, $L_1 \cap L_2 \in \text{REG}$, and
  $L_1 \cup L_2 \in \text{REG}$: $L_1 = L(\texttt{a}^*\texttt{b}^*)$, $L_2 = \{\texttt{a}^n\texttt{b}^n \mid n \geq 0\}$.
- $L_1, L_2, L_3, \cdots \in \text{REG}$, but, $\bigcup_{i=1}^{\infty} L_i \notin \text{REG}$:
  $L_i = \{\texttt{a}^i\texttt{b}^i\}$, $\bigcup_{i=1}^{\infty} L_i = \{\texttt{a}^n\texttt{b}^n \mid n \geq 0\}$.
- $L_1 \cdot L_2 \in \text{REG}$, but $L_1 \notin \text{REG}$: $L_1 = \{\texttt{a}^n\texttt{b}^n \mid n \geq 0\}$,
  $L_2 = \Sigma^*$.
- $L_2 \in \text{CFL}$, and $L_1 \subseteq L_2$, but $L_1 \notin \text{CFL}$: $\Sigma = \{a, b, c\}$,
  $L_1 = \{a^n b^n c^n \mid n \geq 0\}$, $L_2 = \Sigma^*$.

- $L_1, L_2 \in \text{DECIDABLE}$, and $L_1 \subseteq L \subseteq L_2$, but
  $L \in \text{UNDECIDABLE}$: $L_1 = \emptyset$, $L_2 = \Sigma^*$, L is some
  undecidable language over Σ.
- $L_1 \in \text{REG}$, $L_2 \notin \text{CFL}$, but $L_1 \cap L_2 \in \text{CFL}$: $L_1 = \{\varepsilon\}$,
  $L_2 = \{a^n b^n c^n \mid n \geq 0\}$.
- $L^* \in \text{REG}$, but $L \notin \text{REG}$: $L = \{a^p \mid p \text{ is prime}\}$,
  $L^* = \Sigma^* \setminus \{a\}$.
- $A \not\leq_{\text{m}} \overline{A}$: $A = A_{TM} \in \text{RECOGNIZABLE}$,
  $\overline{A} = \overline{A_{TM}} \notin \text{RECOG}$.
- $A \notin \text{DEC}$., $A \leq_{\text{m}} \overline{A}$: