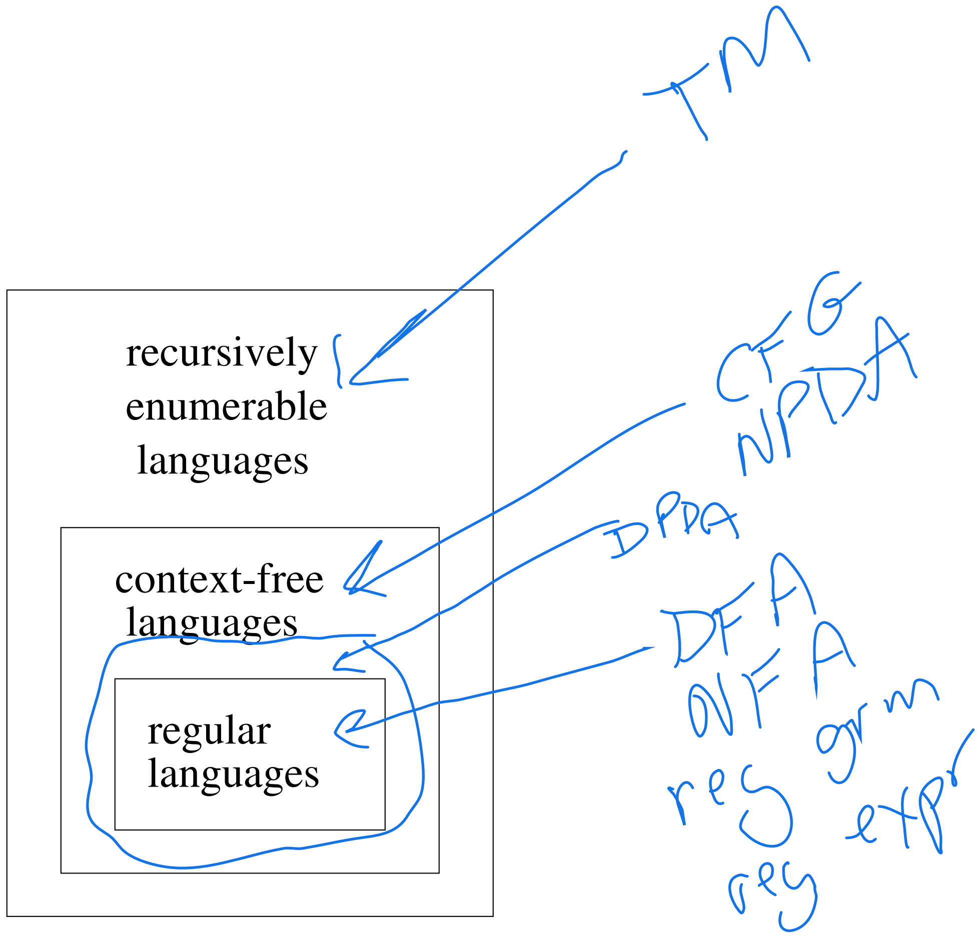
CompSci 334 Spring 2024 11/19/24

Section: Recursively Enumerable Languages

Definition: A language L is *recursively enumerable* **if there exists a TM M such that L=L(M).**



Definition: A language L is *recursive* **if there exists a TM M such that L=L(M) and M halts on every w$\in \Sigma^+$.**

To enumerate all w$\in \Sigma^+$ in a recursive language L:

- **Let M be a TM that recognizes L, L = L(M).**
- **Construct 2-tape TM M'**

  Tape 1 will enumerate the strings in Σ^+

  Tape 2 will enumerate the strings in L.

  - **On tape 1 generate the next string v in Σ^+**
  - **simulate M on v**

    if M accepts v, then write v on tape 2.

To enumerate all w$\in \Sigma^+$ in a recursively enumerable language L:

Repeat forever

- **Generate next string (Suppose k strings have been generated: $w_1, w_2, ..., w_k$)**
- **Run M for one step on w_k**

  Run M for two steps on w_{k-1}.

  ...

  Run M for k steps on w_1.

  If any of the strings are accepted then write them to tape 2.

$w_1 - 1$

$w_1 - 2$

$w_2 - 1$

$w_1 - 3 \rightarrow$ halt

$w_2 - 2$

$w_3 - 1$

STOPPED

Theorem Let S be an infinite countable set. Its powerset 2^S is not countable.

Proof - Diagonalization

- **S is countable, so it's elements can be enumerated.**
  S $= \{s_1, s_2, s_3, s_4, s_5, s_6 \ldots\}$
  Example, $\{s_2, s_3, s_5\}$ **represented by**

  Example, set containing every other element from S, starting with s_1 **is** $\{s_1, s_3, s_5, s_7, \ldots\}$ **represented by**

Suppose 2^S countable. Then we can emunerate all its elements: t_1, t_2, ...

	s_1	s_2	s_3	s_4	s_5	s_6	s_7		...	
t_1	**0**	**1**	**0**	**1**	**0**	**0**		**1**		...
t_2	**1**	**1**	**0**	**0**	**1**	**1**		**0**		...
t_3	**0**	**0**	**0**	**0**	**1**	**0**		**0**		...
t_4	**1**	**0**	**1**	**0**	**1**	**1**		**0**		...
t_5	**1**	**1**	**1**	**1**	**1**	**1**		**1**		...
t_6	**1**	**0**	**0**	**1**	**0**	**0**		**1**		...
t_7	**0**	**1**	**0**	**1**	**0**	**0**		**0**		...
...										

Theorem For any nonempty Σ, there exist languages that are not recursively enumerable.

Proof:

- **A language is a subset of Σ^*.**
  The set of all languages over Σ is

Theorem There exists a recursively enumerable language L such that $\bar{L}$ is not recursively enumerable.

Proof:

- **Let $\Sigma = \{a\}$**
  Enumerate all TM's over Σ:

	a	aa	aaa	aaaa	aaaaa	...
$\mathbf{L}(M_1)$	0	1	1	0	1	...
$\mathbf{L}(M_2)$	1	0	1	0	1	...
$\mathbf{L}(M_3)$	0	0	1	1	0	...
$\mathbf{L}(M_4)$	1	1	0	1	1	...
$\mathbf{L}(M_5)$	0	0	0	1	0	...
...						

Theorem If languages L and $\bar{L}$ are both RE, then L is recursive.

Proof:

- **$\exists$ M_1 s.t. M_1 can enumerate all elements in L.**

  $\exists$ M_2 s.t. M_2 can enumerate all elements in $\bar{L}$.

  To determine if a string w is in L or not in L

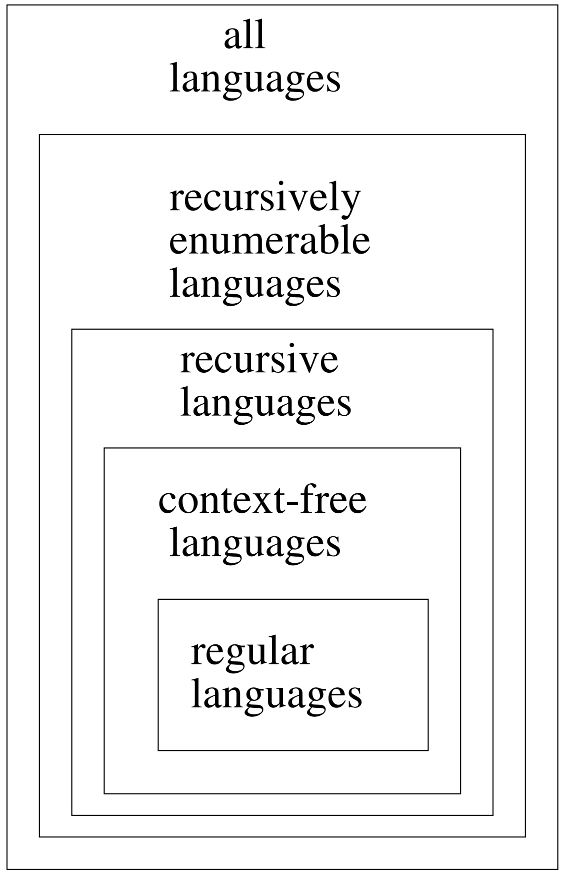
Theorem: If L is recursive, then $\bar{L}$ is recursive.

Proof:

- **L is recursive, then there exists a TM M such that M can determine if w is in L or w is not in L.**

  Construct TM M' that does the following. M' first simulates TM M.

Hierarchy of Languages:



Definition A grammar G=(V,T,S,P) is *unrestricted* **if all productions are of the form**

$$u \rightarrow v$$

where $u \in$**(V**$\cup$**T)**$^+$ **and** $v \in$**(V**$\cup$**T)***

Example:

Let G=(\{S,A,X\},\{a,b\},S,P), P=

$$\begin{aligned}
&\mathbf{S} \rightarrow \mathbf{bAaaX}\\
&\mathbf{bAa} \rightarrow \mathbf{abA}\\
&\mathbf{AX} \rightarrow \lambda
\end{aligned}$$

Example Find an unrestricted grammar G s.t. L(G)=$\{a^nb^nc^n|n>0\}$

G=(V,T,S,P)

V=$\{$**S,A,B,D,E,X**$\}$

T=$\{$**a,b,c**$\}$

P=

1) **S** $\rightarrow$ **AX**
2) **A** $\rightarrow$ **aAbc**
3) **A** $\rightarrow$ **aBbc**
4) **Bb** $\rightarrow$ **bB**
5) **Bc** $\rightarrow$ **D**
6) **Dc** $\rightarrow$ **cD**
7) **Db** $\rightarrow$ **bD**
8) **DX** $\rightarrow$ **EXc**

$$\mathbf{S} \Rightarrow \mathbf{AX} \Rightarrow \mathbf{aAbcX} \Rightarrow \mathbf{aaAbcbcX} \Rightarrow \mathbf{aaaBbcbcbcX}$$

Theorem If G is an unrestricted grammar, then L(G) is recursively enumerable.

Proof:

- List all strings that can be derived in one step.

  List all strings that can be derived in two steps.

Theorem If L is recursively enumerable, then there exists an unrestricted grammar G such that L=L(G).

Proof:

- **L is recursively enumerable.**

  $\Rightarrow$ **there exists a TM M such that L(M)=L.**

  M $= (Q, \Sigma, \Gamma, \delta, q_0, B, F)$

  $q_0 w \overset{*}{\vdash} x_1 q_f x_2$ **for some** $q_f \in$**F,**

  $x_1, x_2 \in \Gamma^*$

  Construct an unrestricted grammar G s.t. L(G)=L(M).

  $S \overset{*}{\Rightarrow} w$

  Three steps

  1. $S \overset{*}{\Rightarrow} B \ldots B \# x q_f y B \ldots B$

  2. $B \ldots B \# x q_f y B \ldots B \overset{*}{\Rightarrow}$
  $B \ldots B \# q_0 w B \ldots B$

  3. $B \ldots B \# q_0 w B \ldots B \overset{*}{\Rightarrow} w$

Definition A grammar G is *context-sensitive* **if all productions are of the form**

$$x \to y$$

where $x, y \in (V \cup T)^+$ **and** $|x| \le |y|$

Definition L is context-sensitive (CSL) if there exists a context-sensitive grammar G such that L=L(G) or L=L(G) $\cup \{\lambda\}$**.**

Theorem For every CSL L not including λ, $\exists$ an LBA M s.t. L=L(M).

Theorem If L is accepted by an LBA M, then $\exists$ CSG G s.t. L(M)=L(G).

Theorem Every context-sensitive language L is recursive.

Theorem There exists a recursive language that is not CSL.