CPS 140 - Mathematical Foundations of CS
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Section: Properties of Context-Free Languages (handout)

Which of the following languages are CFL?

- L=$\{a^n b^n c^j \mid 0 < n \leq j\}$
- L=$\{a^n b^j a^n b^j \mid n > 0, j > 0\}$
- L=$\{a^n b^j a^k b^p \mid n + j \leq k + p, n > 0, j > 0, k > 0, p > 0\}$

Pumping Lemma for Regular Language's: Let L be a regular language, Then there is a constant m such that $w \in L$, $|w| \geq m$, $w = xyz$ such that

- $|xy| \leq m$
- $|y| \geq 1$
- for all $i \geq 0$, $xy^i z \in L$

Pumping Lemma for CFL's Let L be any infinite CFL. Then there is a constant m depending only on L, such that for every string w in L, with $|w| \geq m$, we may partition $w = uvxyz$ such that:

$|vxy| \leq m$, (limit on size of substring)
$|vy| \geq 1$, (v and y not both empty)
For all $i \geq 0$, $uv^i xy^i z \in$L

- **Proof:** (sketch) There is a CFG G s.t. L=L(G).

  Consider the parse tree of a long string in L.

  For any long string, some nonterminal N must appear twice in the path.

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Example: Consider $L = \{a^n b^n c^n : n \geq 1\}$. Show L is not a CFL.

- **Proof:** (by contradiction)

  Assume L is a CFL and apply the pumping lemma.

  Let m be the constant in the pumping lemma and consider $w = a^m b^m c^m$. Note $|w| \geq m$.

  Show there is no division of w into $uvxyz$ such that $|vy| \geq 1$, $|vxy| \leq m$, and $uv^i xy^i z \in$L for $i = 0, 1, 2, \ldots$.

  Case 1: Neither v nor y can contain 2 or more distinct symbols. If v contains a's and b's, then $uv^2xy^2z \notin$L since there will be b's before a's.

  Thus, v and y can be only a's, b's, or c's (not mixed).

  Case 2: $v = a^{t_1}$, then $y = a^{t_2}$ or b^{t_3} ($|vxy| \leq m$)

  If $y = a^{t_2}$, then $uv^2xy^2z = a^{m+t_1+t_2}b^m c^m \notin L$ since $t_1 + t_2 > 0$, n(a)>n(b)'s (number of a's is greater than number of b's)

  If $y = b^{t_3}$, then $uv^2xy^2z = a^{m+t_1}b^{m+t_3}c^m \notin L$ since $t_1 + t_3 > 0$, either n(a)>n(c)'s or n(b)>n(c)'s.

  Case 3: $v = b^{t_1}$, then $y = b^{t_2}$ or c^{t_3}

  If $y = b^{t_2}$, then $uv^2xy^2z = a^m b^{m+t_1+t_2}c^m \notin L$ since $t_1 + t_2 > 0$, n(b)>n(a)'s.

  If $y = c^{t_3}$, then $uv^2xy^2z = a^m b^{m+t_1}c^{m+t_3} \notin L$ since $t_1 + t_3 > 0$, either n(b)>n(a)'s or n(c)>n(a)'s.

  Case 4: $v = c^{t_1}$, then $y = c^{t_2}$

  then, $uv^2xy^2z = a^m b^m c^{m+t_1+t_2} \notin L$ since $t_1 + t_2 > 0$, n(c)>n(a)'s.

  Thus, there is no breakdown of w into $uvxyz$ such that $|vy| \geq 1$, $|vxy| \leq m$ and for all $i \geq 0$, uv^ixy^iz is in L. Contradiction, thus, L is not a CFL. Q.E.D.

Example Why would we want to recognize a language of the type $\{a^n b^n c^n : n \geq 1\}$?

Example: Consider $L = \{a^n b^n c^p : p > n > 0\}$. Show L is not a CFL.

- **Proof:** Assume L is a CFL and apply the pumping lemma. Let m be the constant in the pumping lemma and consider $w =$ ____________ Note $|w| \geq m$.

  Show there is no division of w into $uvxyz$ such that $|vy| \geq 1$, $|vxy| \leq m$, and $uv^i xy^i z \in$L for $i = 0, 1, 2, \ldots$.

  Thus, there is no breakdown of w into $uvxyz$ such that $|vy| \geq 1$, $|vxy| \leq m$ and for all $i \geq 0$, $uv^i xy^i z$ is in L. Contradiction, thus, L is not a CFL. Q.E.D.

Example: Consider $L = \{a^j b^k : k = j^2\}$. Show L is not a CFL.

- **Proof:** Assume L is a CFL and apply the pumping lemma. Let m be the constant in the pumping lemma and consider $w =$ ____________

  Show there is no division of w into $uvxyz$ such that $|vy| \geq 1$, $|vxy| \leq m$, and $uv^ixy^iz \in$L for $i = 0, 1, 2, \ldots$.

  Case 1: Neither v nor y can contain 2 or more distinct symbols. If v contains a's and b's, then $uv^2xy^2z \notin$L since there will be b's before a's.

  Thus, v and y can be only a's, and b's (not mixed).

  Thus, there is no breakdown of w into $uvxyz$ such that $|vy| \geq 1$, $|vxy| \leq m$ and for all $i \geq 0$, uv^ixy^iz is in L. Contradiction, thus, L is not a CFL. Q.E.D.

Exercise: Prove the following is not a CFL by applying the pumping lemma. (answer is at the end of this handout).

Consider $L = \{a^{2n} b^{2p} c^n d^p : n, p \geq 0\}$. Show L is not a CFL.

Example: Consider $L = \{w\bar{w}w : w \in \Sigma^*\}$, $\Sigma = \{a, b\}$, where $\bar{w}$ is the string w with each occurence of a replaced by b and each occurence of b replaced by a. For example, $w = baaa$, $\bar{w} = abbb$, $w\bar{w} = baaaabbb$. Show L is not a CFL.

- **Proof:** Assume L is a CFL and apply the pumping lemma. Let m be the constant in the pumping lemma and consider $w =$ _____________

  Show there is no division of w into $uvxyz$ such that $|vy| \geq 1$, $|vxy| \leq m$, and $uv^ixy^iz \in$L for $i = 0, 1, 2, \ldots$.

  Thus, there is no breakdown of w into $uvxyz$ such that $|vy| \geq 1$, $|vxy| \leq m$ and for all $i \geq 0$, uv^ixy^iz is in L. Contradiction, thus, L is not a CFL. Q.E.D.

Example: Consider $L = \{a^n b^p b^p a^n\}$. L is a CFL. The pumping lemma should apply!

Let $m \geq 4$ be the constant in the pumping lemma. Consider $w = a^m b^m b^m a^m$.

We can break w into $uvxyz$, with:

If you apply the pumping lemma to a CFL, then you should find a partition of w that works!

Chap 8.2 Closure Properties of CFL's

Theorem CFL's are closed under union, concatenation, and star-closure.

- **Proof:**
  Given 2 CFG $G_1 = (V_1, T_1, S_1, P_1)$ and $G_2 = (V_2, T_2, S_2, P_2)$
  - Union:
    Construct G_3 s.t. L(G_3) = L(G_1) $\cup$ L(G_2).
    $G_3 = (V_3, T_3, S_3, P_3)$
  - Concatenation:
    Construct G_3 s.t. L(G_3) = L(G_1)$\circ$L(G_2).
    $G_3 = (V_3, T_3, S_3, P_3)$

- Star-Closure
  Construct G_3 s.t. $\mathrm{L}(G_3) = \mathrm{L}(G_1)^*$
  $G_3 = (V_3, T_3, S_3, P_3)$

QED.

Theorem CFL's are NOT closed under intersection and complementation.

- **Proof:**
  - Intersection:
  - Complementation:

Theorem: CFL's are closed under *regular* intersection. If L_1 is CFL and L_2 is regular, then $L_1 \cap L_2$ is CFL.

- **Proof:** (sketch) This proof is similar to the construction proof in which we showed regular languages are closed under intersection. We take a NPDA for L_1 and a DFA for L_2 and construct a NPDA for $L_1 \cap L_2$.

  $M_1 = (Q_1, \Sigma, \Gamma, \delta_1, q_0, z, F_1)$ is an NPDA such that $\mathrm{L}(M_1) = L_1$.

  $M_2 = (Q_2, \Sigma, \delta_2, q_0^{'}, F_2)$ is a DFA such that $\mathrm{L}(M_2) = L_2$.

  Example of replacing arcs (NOT a Proof!):

Note this is not a proof, but sketches how we will combine the DFA and NPDA. We must formally define δ_3. If

then

Must show

if and only if

Must show:
$w \in \mathrm{L}(M_3)$ iff $w \in \mathrm{L}(M_1)$ and $w \in \mathrm{L}(M_2)$.
QED.

Questions about CFL:

1. Decide if CFL is empty?

2. Decide if CFL is infinite?

Example: Consider $L = \{a^{2n}b^{2m}c^n d^m : n, m \geq 0\}$. Show L is not a CFL.

- **Proof:** Assume L is a CFL and apply the pumping lemma. Let m be the constant in the pumping lemma and consider $w = a^{2m}b^{2m}c^m d^m$.

  Show there is no division of w into $uvxyz$ such that $|vy| \geq 1$, $|vxy| \leq m$, and $uv^ixy^iz \in$L for $i = 0, 1, 2, \ldots$.

  Case 1: Neither v nor y can contain 2 or more distinct symbols. If v contains a's and b's, then $uv^2xy^2z \notin$L since there will be b's before a's.

  Thus, v and y can be only a's, b's, c's, or d's (not mixed).

  Case 2: $v = a^{t_1}$, then $y = a^{t_2}$ or b^{t_3} ($|vxy| \leq m$)

  If $y = a^{t_2}$, then $uv^2xy^2z = a^{2m+t_1+t_2}b^{2m}c^m d^m \notin L$ since $t_1 + t_2 > 0$, the number of a's is not twice the number of c's.

  If $y = b^{t_3}$, then $uv^2xy^2z = a^{2m+t_1}b^{2m+t_3}c^m d^m \notin L$ since $t_1 + t_3 > 0$, either the number of a's (denoted n(a)) is not twice n(c) or n(b) is not twice n(d).

  Case 3: $v = b^{t_1}$, then $y = b^{t_2}$ or c^{t_3}

  If $y = b^{t_2}$, then $uv^2xy^2z = a^{2m}b^{2m+t_1+t_2}c^m d^m \notin L$ since $t_1 + t_2 > 0$, n(b)> 2∗n(d).

  If $y = c^{t_3}$, then $uv^2xy^2z = a^{2m}b^{2m+t_1}c^{m+t_3}d^m \notin L$ since $t_1 + t_3 > 0$, either n(b)> 2∗n(d) or 2∗n(c)>n(a).

  Case 4: $v = c^{t_1}$, then $y = c^{t_2}$ or d^{t_3}

  If $y = c^{t_2}$, then $uv^2xy^2z = a^{2m}b^{2m}c^{m+t_1+t_2}d^m \notin L$ since $t_1 + t_2 > 0$, 2∗n(c)>n(a).

  If $y = d^{t_3}$, then $uv^2xy^2z = a^{2m}b^{2m}c^{m+t_1}d^{m+t_3} \notin L$ since $t_1 + t_3 > 0$, either 2∗n(c)>n(a) or 2∗n(d)>n(b).

  Case 5: $v = d^{t_1}$, then $y = d^{t_2}$

  then $uv^2xy^2z = a^{2m}b^{2m}c^m d^{m+t_1+t_2} \notin L$ since $t_1 + t_2 > 0$, 2∗n(d)>n(c).

  Thus, there is no breakdown of w into $uvxyz$ such that $|vy| \geq 1$, $|vxy| \leq m$ and for all $i \geq 0$, uv^ixy^iz is in L. Contradiction, thus, L is not a CFL. Q.E.D.