BILL AND NATHAN START RECORDING

Context Free Languages

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4) Which languages are **not** context free?

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2) Closure properties of CFLs.
3) CFL's are all in P (poly time).
4) Which languages are **not** context free?
5) Languages that are CFL but not Regular.

Examples of Context Free Grammars

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$S \to e$

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$S \rightarrow AT$

$T \rightarrow aTb$

$T \rightarrow e$

$A \rightarrow Aa$

$A \rightarrow a$

Context Free Grammars

Def A **Context Free Grammar** is a tuple $G = (N, \Sigma, R, S)$

- N is a finite set of **nonterminals**.
- Σ is a finite **alphabet**. Note $\Sigma \cap N = \emptyset$.
- $R \subseteq N \times (N \cup \Sigma)^*$ and are called **Rules**.
- $S \in N$, the **start symbol**.

L(G)

If A is non-terminal then the CFG gives us gives us rules like:

- $A \to AB$
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Then, if w is string of **non-terminals only**, we define $L(G)$ by:

$$L(G) = \{w \in \Sigma^* \mid S \Rightarrow w\}$$

Number of a's = Number of b's

Is

$$L = \{w \mid \#_a(w) = \#_b(w)\}$$

context free?

YES

Let G be the CFG

$S \rightarrow aSb$

$S \rightarrow bSa$

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YES

Let G be the CFG
$S \to aSb$
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(Exception: a course on foundations. I proved $x + y = y + x$.)

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Thm $L(G) \subseteq \{w \mid \#_a(w) = \#_b(w)\}$. We prove something stronger.

Let $L(G)' = \{\alpha \in \{S, a, b\}^* : S \Rightarrow \alpha\}$ (Note that we allow S in α.)

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Case 1 $S \Rightarrow \alpha' S \alpha'' \rightarrow \alpha' aSb\alpha$. By IH $\#_a(\alpha' S \alpha'') = \#_b(\alpha' S \alpha'')$.
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Case 2 Other cases for last step similar.

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Case 3 $w = aw'a$. This is first NON-OBVIOUS part!

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a: $\#_a(a) > \#_b(a)$

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For all $2 \le i \le n-1$, EITHER
$\#_a(a\sigma_2 \cdots \sigma_i) = \#_a(a\sigma_2 \cdots \sigma_{i-1}) + 1$.
OR
$\#_b(a\sigma_2 \cdots \sigma_i) = \#_b(a\sigma_2 \cdots \sigma_{i-1}) + 1$.
But NOT both.

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But NOT both.

$\#_a(a\sigma_2 \cdots \sigma_{n-1}) = \frac{n}{2} - 1$
$\#_b(a\sigma_2 \cdots \sigma_{n-1}) = \frac{n}{2}$

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But NOT both.

$\#_a(a\sigma_2 \cdots \sigma_{n-1}) = \frac{n}{2} - 1$
$\#_b(a\sigma_2 \cdots \sigma_{n-1}) = \frac{n}{2}$

Hence

$\{w \mid \#_a(w) = \#_b(w)\} \subseteq L(G)$

Let G be the CFG
$S \rightarrow aSb \mid bSa \mid SS \mid e$

Case 3 $w = aw'a$. Let $w = a\sigma_2 \cdots \sigma_{n-1}a$. Look at prefixes of w:
a: $\#_a(a) > \#_b(a)$

For all $2 \leq i \leq n-1$, EITHER
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So $w = w'w''$ where $w, w' \in L(G)$. Since $|w'| < |w|$ and $|w''| < |w|$, by IH
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So
$S \rightarrow SS \Rightarrow w'w'' = w$.

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We will not be proving Langs NOT CFL.

CLOSURE PROPERTIES AND REG$\subset$ CFL

Closure Properties: PROVE or DISPROVE

If L_1, L_2 are Context Free Languages then

1. IS $L_1 \cup L_2$ is a context free Lang?
2. IS $L_1 \cap L_2$ is a context free Lang?
3. IS $L_1 \cdot L_2$ is a context free Lang?
4. IS $\overline{L_1}$ is a context free Lang?
5. IS L_1^* is a context free Lang?

BREAKOUT ROOMS

L_1, L_2 CFL $\rightarrow L_1 \cup L_2$ CFL

L_1 is CFL via CFG (N_1, Σ, R_1, S_1).
L_2 is CFL via CFG (N_2, Σ, R_2, S_2).

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Note We assume $N_1 \cap N_2 = \emptyset$.

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This is true for 3 languages or 4 languages or 98 languages.

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No, because:

- $L_1 = \{ab\}$ is regular.
- $L_k = \{a^k b^k\}$ is regular.
- $L_1 \cup L_2 \cup \cdots = \{a^n b^n : n \in \mathrm{N}\}$ is not regular.

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What about for CFLs?

- $L_1 = \{abc\}$ is a CFL.
- $L_k = \{a^k b^k c^k\}$ is a CFL.
- We will see later that $\bigcup_{i=1}^{\infty} L_i = \{a^n b^n c^n : n \in \mathbb{N}\}$ is not CFL.

L_1, L_2 CFL $\rightarrow L_1 \cap L_2$ CFL

NOT TRUE: $a^n b^n c^* \cap a^* b^n c^n = a^n b^n c^n$.

L_1, L_2 CFL $\rightarrow L_1 \cdot L_2$ CFL

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L CFL $\rightarrow \overline{L}$ CFL

FALSE.
Let

$$L = \overline{\{a^n b^n c^n : n \in \mathbb{N}\}}$$

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$$L = \overline{\{a^n b^n c^n : n \in \mathsf{N}\}}$$

This is a CFL. This will be a HW.

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$S' \rightarrow S'S$

REG contained in CFL

Thm If L is regular then L is CFL.
BREAKOUT ROOMS

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Case 1 $\alpha = \beta_1 \cup \beta_2$. By IH $L(\beta_1)$ and $L(\beta_2)$ are CFL's. By closure under $\cup$, $L(\alpha)$ is CFL.

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Case 3 $\alpha = \beta^*$. By IH $L(\beta)$ is CFL. By closure under $*$, $L(\alpha)$ is CFL.

Examples of CFL's and Size of CFG's

Size of CFGs

How big is a CFL for the language $\{aaaaaaaa\}$ (there are 8 a's).

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Next slide has a standard form for CFL's that make size make sense.

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Def CFG G is in **Chomsky Normal Form** if the rules are all of the following form:

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Chomsky Normal Form

Def CFG G is in **Chomsky Normal Form** if the rules are all of the following form:
1) $A \to BC$ where $A, B, C \in N$ (nonterminals).
2) $A \to \sigma$ (where $A \in N$ and $\sigma \in \Sigma$).
3) $S \to e$ (where S is the start state).

Example of Chomsky Normal Form

Recall the CFG:

$$S \to aaaaaaaa$$

Example of Chomsky Normal Form

Recall the CFG:

$$S \rightarrow aaaaaaaa$$

BREAKOUT ROOM TO FIND A CHOMSKY NORMAL FORM CFG FOR $\{aaaaaaaa\}$.

Example of Chomsky Normal Form

Recall the CFG:
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Example of Chomsky Normal Form

Recall the CFG:

$S \to aaaaaaaa$

Chomsky Normal form CFG that generates same lang:

$S \to AA$

Example of Chomsky Normal Form

Recall the CFG:

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Chomsky Normal form CFG that generates same lang:

$S \rightarrow AA$

$A \rightarrow BB$

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Recall the CFG:
$S \to aaaaaaaa$

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$A \to BB$
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We measure the size of a Chomsky Normal Form CFG by the number of rules.

Example of Chomsky Normal Form

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Chomsky Normal form CFG that generates same lang:

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$C \rightarrow a$

We measure the size of a Chomsky Normal Form CFG by the number of rules.

So $\{aaaaaaaa\}$ has a Chomsky Normal Form CFG of size 4.

Chomsky Normal Form CFG for $\{a^n\}$

We say that $\{a^8\}$ has a CNF CFG of size 4.

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What about $\{a^{16}\}$? Vote
1) Size 8
2) Size 5
The answer is 5. Next slide.

Chomsky Normal Form CFG for $\{a^{16}\}$

$S \to AA$

Chomsky Normal Form CFG for $\{a^{16}\}$

$S \to AA$

$A \to BB$

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$$A \to BB$$
$$B \to CC$$

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$$B \to CC$$
$$C \to DD$$

Chomsky Normal Form CFG for $\{a^{16}\}$

$$S \rightarrow AA$$
$$A \rightarrow BB$$
$$B \rightarrow CC$$
$$C \rightarrow DD$$
$$D \rightarrow a$$

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$$A \rightarrow BB$$
$$B \rightarrow CC$$
$$C \rightarrow DD$$
$$D \rightarrow a$$

What to do if n is not a power of 2. HW.

$L = \{a\}^n$

Upshot

For $L_n = \{a^n\}$:

- Any DFA or NFA that recognizes L_n has $n + \Omega(1)$ states.
- There is a CFG that generates L_n with $O(\log n)$ rules.

Our Old Friend $L = \{a, b\}^* a \{a, b\}^n$

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1) We showed that L requires a 2^{n+1} size DFA.

2) We have an NFA of size $n+2$. There is no NFA of size n since then there would be a DFA of size $2^n < 2^{n+1}$.

3) BREAKOUT ROOMS for getting a CFG of size $\ll n$.

DFA, NFA, CFG

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$L = L_1 \cdot L_2$ where

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$L_1 = \{a, b\}^* a$. Has 5-rule Chomsky Normal Form CFG:
$S \rightarrow AS \mid BS \mid a$
$A \rightarrow a$
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$S \rightarrow AS \mid BS \mid a$
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$L_2 = \{a, b\}^n$. A $\lg(n) + 3$ rule Chomsky Normal Form CFG.
$S \rightarrow S_1 S_1$
$S_1 \rightarrow S_2 S_2$
$\vdots$
$S_{\lg(n)+1} \rightarrow S_{\lg(n)} S_{\lg(n)}$
$S_{\lg(n)} \rightarrow a \mid b$
Note We are assuming n is a power of 2.

DFA, NFA, CFG Size Diff

$$L = \{a, b\}^* a \{a, b\}^n$$

DFA, NFA, CFG Size Diff

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1) DFA of size $\Theta(2^n)$.

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1) DFA of size $\Theta(2^n)$.
2) NFA of size $n + \Theta(1)$.

DFA, NFA, CFG Size Diff

$$L = \{a, b\}^* a \{a, b\}^n$$

1) DFA of size $\Theta(2^n)$.
2) NFA of size $n + \Theta(1)$.
3) CFG of size $\Theta(\lg(n))$.

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Recall the CFG for $\{a^m b^n : m > n\}$. We put it into Chomsky Normal Form.

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Repeat the process with the other rules.

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Deterministic CFG's are **defined** by DPDA's where are DFAs with a stack.
The proof that PDA-recognizers and CFG-generators are equivalent is messy so we won't be doing it. We won't deal with PDA's in this course at all.