

Parikh's Theorem for CFL's

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27 September 2013

Outline

- 1 Parikh map
- 2 Parikh's theorem
- 3 Proof

Parikh map of a string

- Let $A = \{a_1, \dots, a_n\}$ be a finite alphabet.
- The **Parikh map** of a string $w \in A^*$ is a vector in $\mathbb{N}^n$ given by:

$$\psi(w) = (\#_{a_1}(w), \#_{a_2}(w), \dots, \#_{a_n}(w)).$$

- For example if $A = \{a, b\}$, then $\psi(baabb) = (2, 3)$.
- Parikh map is also called the “letter-count” of a string.
- Extend the map to languages L over A :

$$\psi(L) = \{\psi(w) \mid w \in L\}.$$

- What is $\psi(\{a^n b^n \mid n \geq 0\})$?

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 - $\{(i, j) \mid i \leq j\}$.

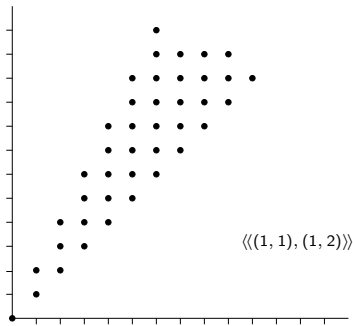
Semi-linear sets of vectors

- The set of vectors **generated** by a set of vectors $u_1, \dots, u_k$ in $\mathbb{N}^n$, denoted $\langle\langle u_1, \dots, u_k \rangle\rangle$, is the set

$$\{d_1 \cdot u_1 + d_2 \cdot u_2 + \dots + d_k \cdot u_k \mid d_i \in \mathbb{N}\}.$$

- A subset X of $\mathbb{N}^n$ is called **linear** if there exist vectors $u_0, u_1, \dots, u_k$ such that

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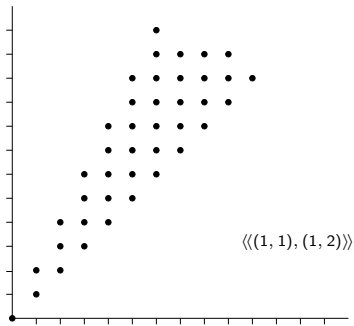
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- A set of vectors is called **semi-linear** if it is a finite union of linear sets.

Parikh's Theorem for CFL's

Theorem (Parikh)

The Parikh map of a CFL is a semi-linear set. That is, if L is a CFL then $\psi(L)$ is semi-linear.

Some corollaries:

- Every CFL is “letter-equivalent” to a regular language.
 - For example: $\psi(\{a^n b^n \mid n \geq 0\})$

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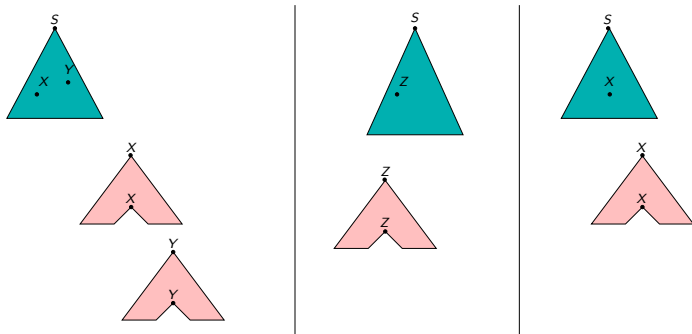
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Is Parikh's theorem a sufficient condition for context-freeness as well?

- No, since $\psi(\{a^n b^n c^n \mid n \geq 0\}) = \{(n, n, n) \mid n \geq 0\}$ is semi-linear.

Idea of proof

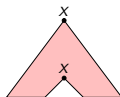
- Partition parse trees into finite number of blocks
- Each block is represented by a “minimal” parse trees and associated “basic pumps”.
- Argue that set of strings derived in each block is linear.



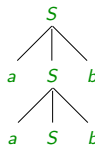
Proof: Pumps

Let us fix a CFG $G = (N, A, S, P)$ in CNF form.

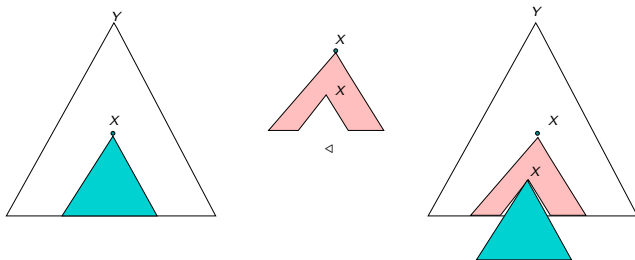
- A **pump** is a derivation tree s which has at least two nodes, and $yield(s) = x \cdot root(s) \cdot y$, for some terminal strings x, y .



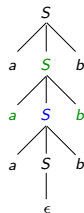
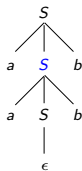
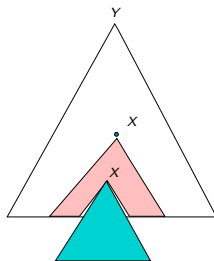
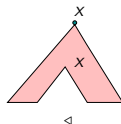
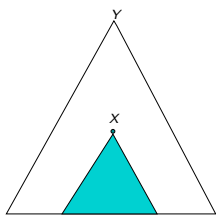
- Example pumps for grammar $S \rightarrow aSb \mid SS \mid \epsilon$:



Growing and shrinking with pumps

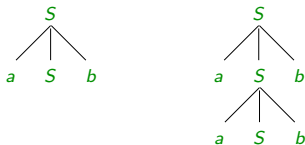


Growing and shrinking with pumps



Basic Pumps

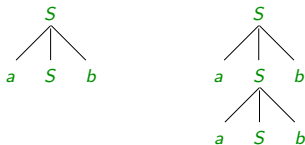
A pump is **basic** if it is $\Leftarrow$ -minimal. Thus a pump s is a basic pump if it cannot be shrunk by some pump and still remain a pump.



- First pump is basic but second is not.
- How many pumps are there?

Basic Pumps

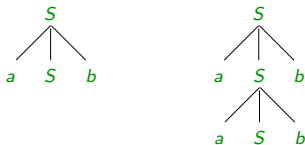
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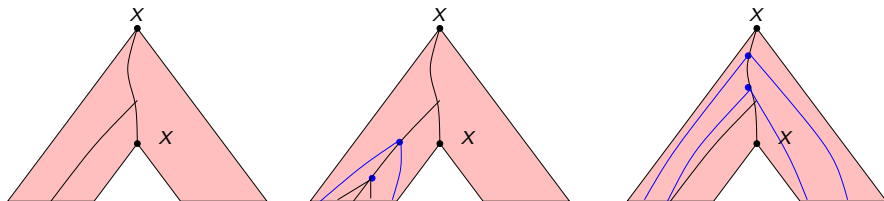
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- First pump is basic but second is not.
- How many pumps are there? Infinitely many.
- How many basic pumps are there? Finitely many since their height is bounded by $2|N|$.

Basic pumps height bounded by $2N$

Consider longest path from root to leaf in a pump.
The number of nodes on it is bounded by $2N$.



$\leq$ relation on parse trees

- Let s and t be derivation trees of terminal strings starting from start symbol S .
- Then we say $s \leq t$ iff t can be grown from s by basic pumps whose non-terminals are contained in those of s (thus the pumps do not introduce any new non-terminals, and s and t have the same set of non-terminal nodes).
- A parse tree s is thus $\leq$ -minimal if it does not contain a basic pump that can be cut out **without** reducing the set of non-terminals that occur in s .
- $\leq$ -minimal trees can be seen to be finite in number (height bounded by $(p + 1)(n + 1)$).

Overall strategy of Proof

- Begin with the $\leq$ -minimal derivation trees, say $s_1, \dots, s_k$.
- Associate with each s_i the set of basic pumps whose non-terminals are contained in that of s_i .
- Argue that the set of derivation trees obtained by starting with s_i and growing using the associated basic pumps, gives rise to a set of strings whose Parikh map is linear.