Asymptotic Behaviour of Max-Plus and Min-Plus Automata

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based on joint works with Thomas Colcombet (LIAFA)
and Florian Zuleger (TU Vienna)

What are min-plus and max-plus automata ?

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NDFA that compute
functions

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Results about the behaviour of these functions

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An algebraic definition with matrices

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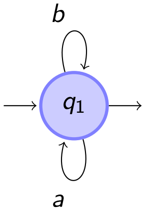
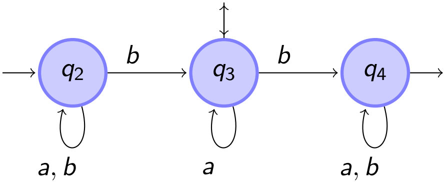
Results about the behaviour of these functions

Ideas of the proofs

Max-Plus and Min-plus Automata

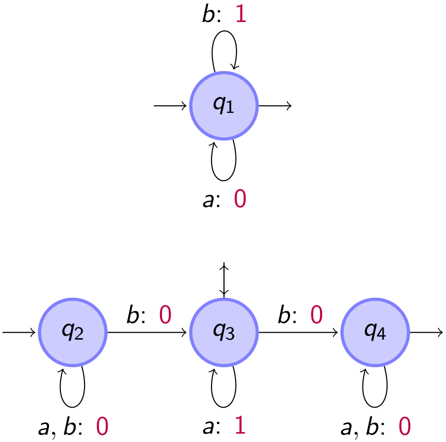
From NDFA to Min-Plus and Max-Plus Automata





Non deterministic finite automata : $A^* \to \{0, \infty\}$

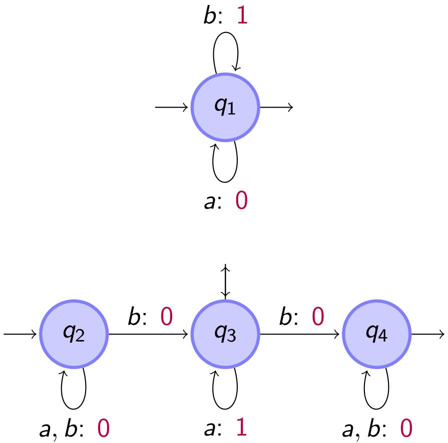
From NDFA to Min-Plus and Max-Plus Automata



Min-plus automata : $A^* \to \mathbb{N} \cup \{+\infty\}$

Max-plus automata : $A^* \to \mathbb{N} \cup \{-\infty\}$

Min-Plus and Max-Plus Automata



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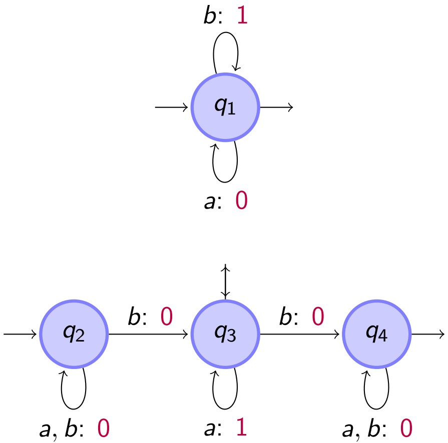

Weight of a run:
sum of the weights of the transitions

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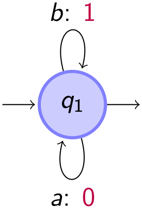

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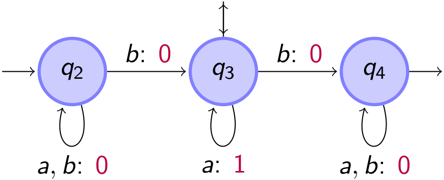

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$w \mapsto$ minimum of the weights of the accepting runs labelled by w

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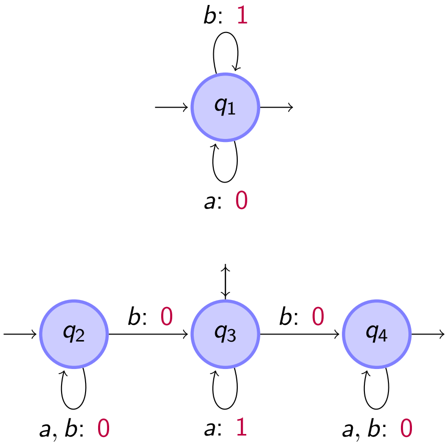

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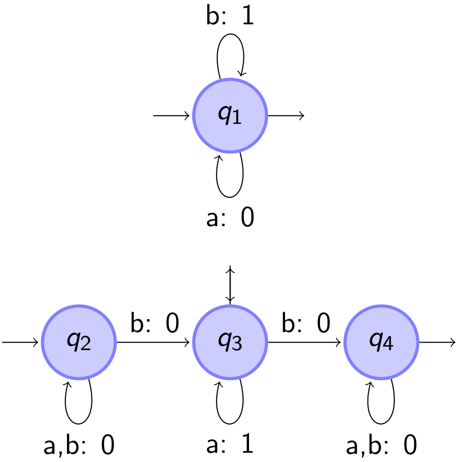
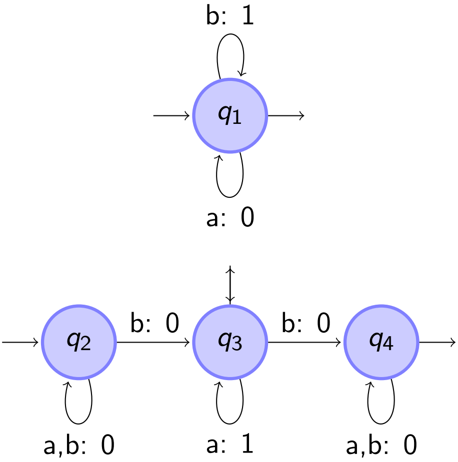
Min-plus automata: $A^* \to \mathbb{N} \cup \{+\infty\}$
$w \mapsto$ minimum of the weights of the accepting runs labelled by w
Max-plus automata: $A^* \to \mathbb{N} \cup \{-\infty\}$
$w \mapsto$ maximum of the weights of the accepting runs labelled by w

An example



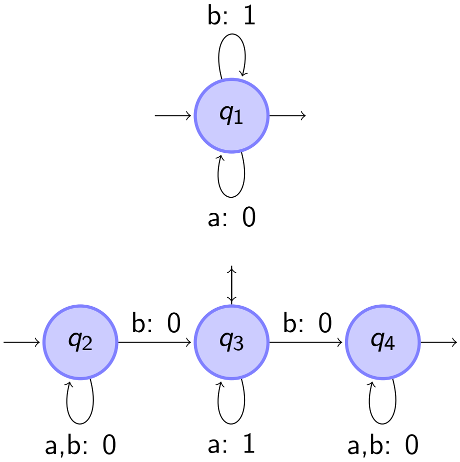
$$a^m b a^n b a^p \mapsto ?$$

An example



$$a^m b a^n b a^p \mapsto \min(2, m, n, p)$$

An example



$$a^m b a^n b a^p \mapsto \min(2, m, n, p)$$

$$a^m b a^n b a^p \mapsto \max(2, m, n, p)$$

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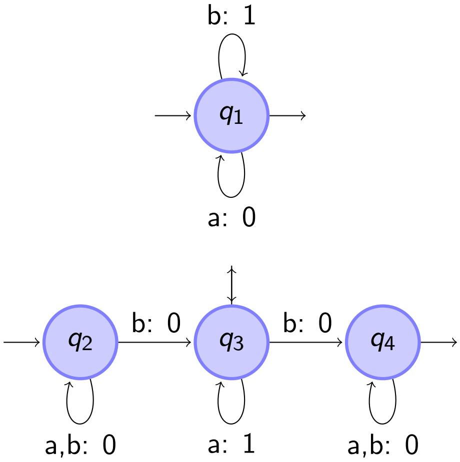

$$a^{n_0} b a^{n_1} b \cdots b a^{n_k} \mapsto ?$$

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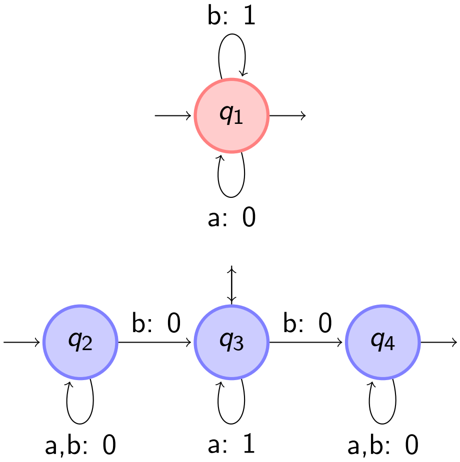

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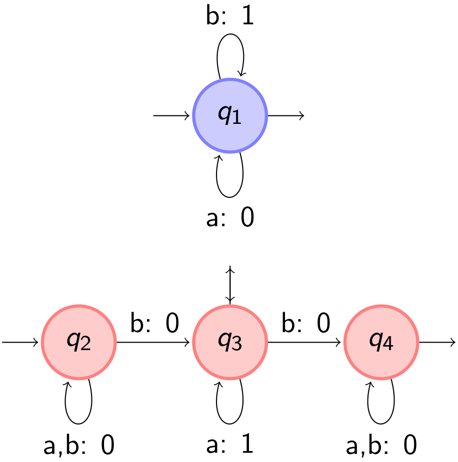

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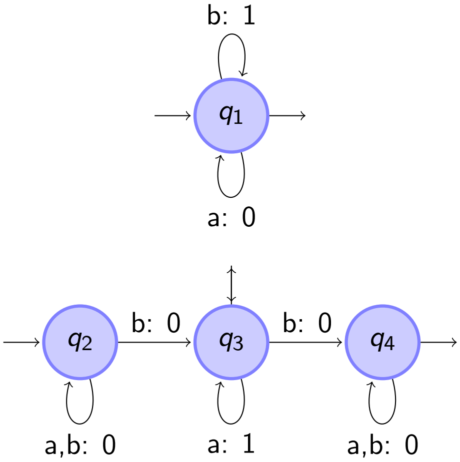

Min-plus: $a^{n_0}ba^{n_1}b\cdots ba^{n_k} \mapsto \min(n_0, n_1, \ldots, n_k, k)$

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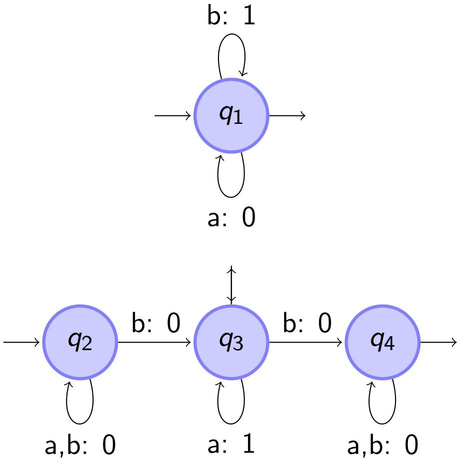

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Description of the behaviour of computed functions

Asymptotic behaviour

Undecidable: Given f, g computed by min-plus (resp. max-plus) automata, is $f(w) \leqslant g(w)$ for all words w ? [Krob, 92]

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$$h(n) = \sup_{|w| \leqslant n} f(w)$$

for all n, $h(n) \leqslant n$?

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Decidable: Given f computed by min-plus (resp. max-plus) automata, is f bounded ? [max: easy, min: Hashiguchi, 82]

Example

Min-Plus $a^{n_0} b a^{n_1} b \cdots b a^{n_k} \mapsto \min(n_0, n_1, \ldots, n_k, k)$

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What is the maximal weight for words of length at most n ?

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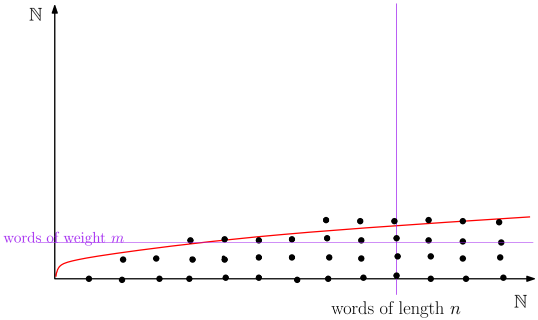
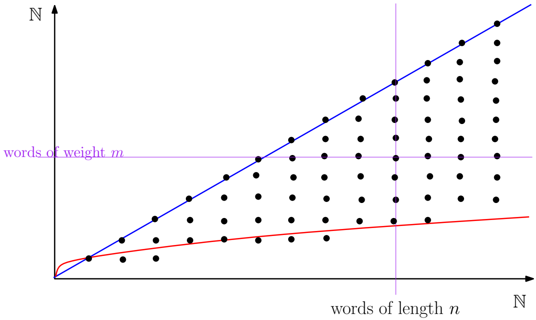


Example

Max-Plus $a^{n_0} b a^{n_1} b \cdots b a^{n_k} \mapsto \max(n_0, n_1, \ldots, n_k, k)$

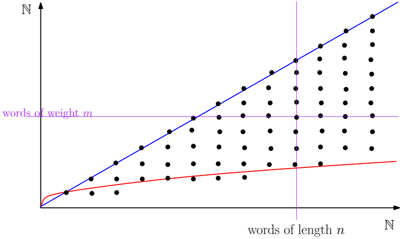
$$h(n) = \inf_{|w| \geqslant n} f(w)$$

What is the minimal weight for words of length at least n ?



Asymptotic equivalent

Max-Plus $h(n) = \inf_{|w| \geqslant n} f(w)$



Theorem: There exists effectively $\alpha \in (\mathbb{Q} \cap [0,1]) \cup \{-\infty\}$ such that:

$$h(n) = \Theta(n^{\alpha})$$

Asymptotic equivalent

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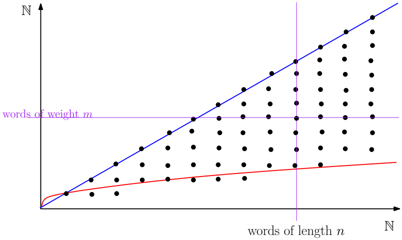

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Min-Plus $h(n) = \sup_{|w| \leqslant n} f(w)$

$h_1 \leqslant h \leqslant h_2$ with $h_1(n) = O(n^{\frac{1}{p+1}})$, $h_2 = O(n^{\frac{1}{p}})$ for some integer p [Simon, 90].

Ratio function-length

Min-Plus

$$h(n) = \sup_{|w| \leqslant n} f(w)$$

$$r = \sup_{n} \frac{h(n)}{n}$$

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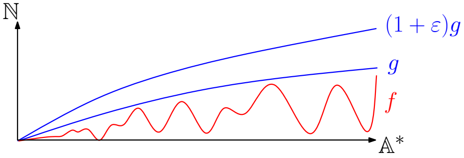
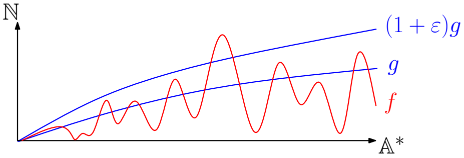
Theorem: There is an algorithm that, given a min-plus automaton (resp. a max-plus automaton), and $\varepsilon > 0$, computes r up to ε.

Approximate comparison

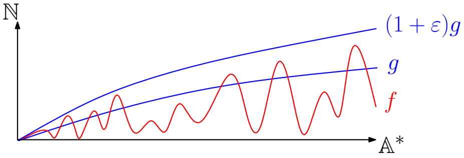
f,g computed by min-plus automata - Case $\varepsilon = 0$: undecidable result of Krob.



$\Longrightarrow$ YES



$\Longrightarrow$ NO

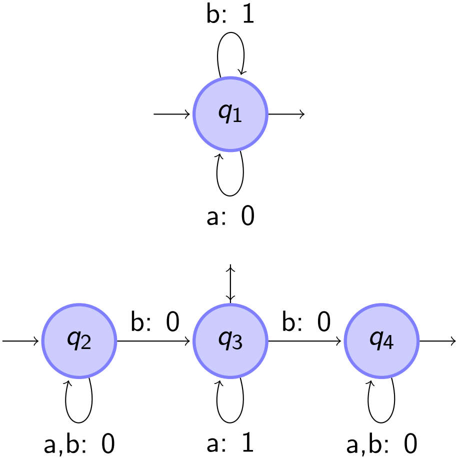


$\Longrightarrow$ YES or NO

Algebraic definition

Automata: an algebraic view

Min-Plus



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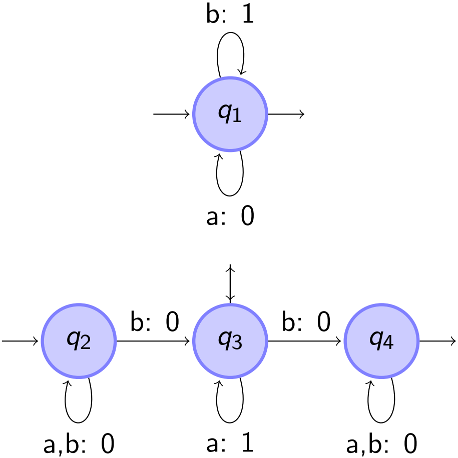

Semiring: $(\mathbb{N} \cup \{+\infty\}, \min, +)$

$$(M \otimes N)_{i,j} = \min_{1 \leqslant k \leqslant n} (M_{i,k} + N_{k,j})$$

Automata: an algebraic view

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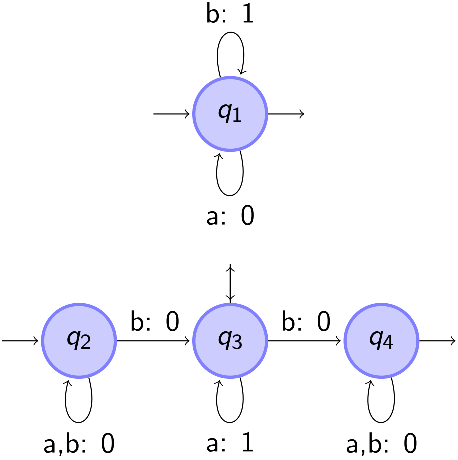

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$$\mu(a) = \begin{pmatrix} 0 & +\infty & +\infty & +\infty \\ +\infty & 0 & +\infty & +\infty \\ +\infty & +\infty & 1 & +\infty \\ +\infty & +\infty & +\infty & 0 \end{pmatrix}$$

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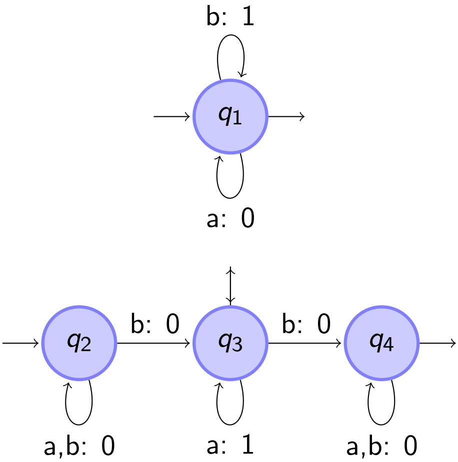

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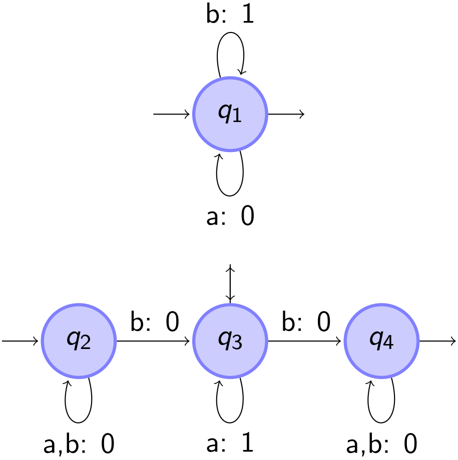

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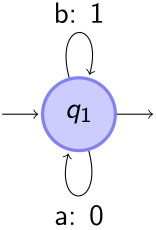

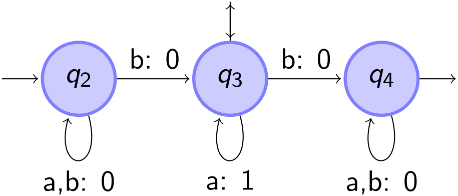

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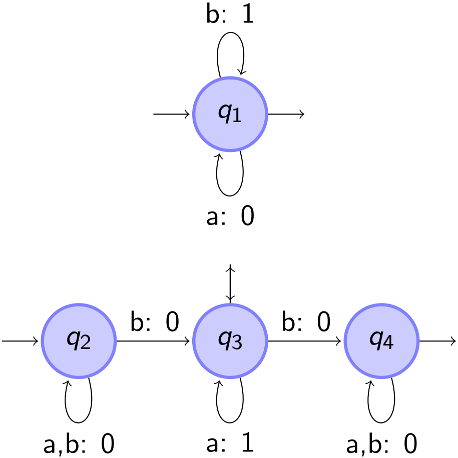
$\mu(w)_{i,j}$ is the minimal weight of runs going from i to j labelled by w.

Automata: an algebraic view

Max-Plus



Semiring: $(\mathbb{N} \cup \{-\infty\}, \max, +)$

$$(M \otimes N)_{i,j} = \max_{1 \leqslant k \leqslant n} (M_{i,k} + N_{k,j})$$

$$\mu(a) = \begin{pmatrix} 0 & -\infty & -\infty & -\infty \\ -\infty & 0 & -\infty & -\infty \\ -\infty & -\infty & 1 & -\infty \\ -\infty & -\infty & -\infty & 0 \end{pmatrix}$$

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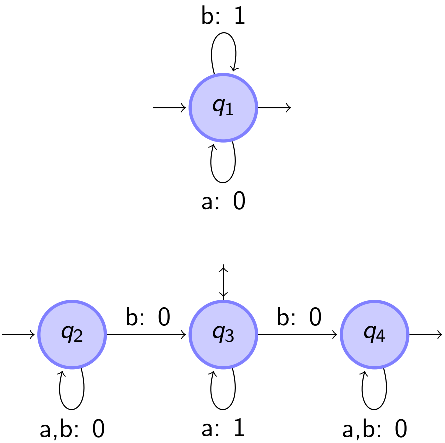
Automata: an algebraic view



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$$I = \begin{pmatrix} 0 & 0 & 0 & \infty \end{pmatrix} \qquad F = \begin{pmatrix} 0 \\ \infty \\ 0 \\ 0 \end{pmatrix}$$

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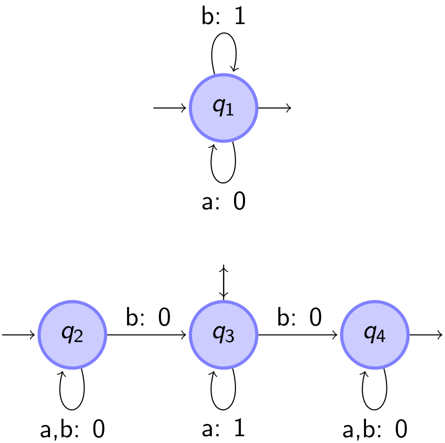

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$$f(w) = I \otimes \mu(w) \otimes F$$

Ideas of proofs

Weighted matrices

Compare $f(w)$ with $|w|$

Weighted matrices

Compare $\cancel{f(w)}$ $\mu(w)$ with $|w|$

Weighted matrices

Compare ~~$f(w)$~~ $\mu(w)$ with $|w|$ $\longrightarrow$ Describe $\{(\mu(w), |w|) \mid w \in A^*\}$

Weighted matrices

Compare ~~$f(w)$~~ $\mu(w)$ with $|w|$ ⟶ Describe $\{(\mu(w), |w|) \mid w \in A^*\}$

Weighted matrices:

$$(M, \ell)$$

M: matrix $\ell \in \mathbb{N} - \{0\}$

Weighted matrices

Compare ~~$f(w)$~~ $\mu(w)$ with $|w|$ $\longrightarrow$ Describe $\{(\mu(w), |w|) \mid w \in A^*\}$

Weighted matrices:

$$(M, \ell)$$

matrix $\qquad \in \mathbb{N} - \{0\}$

$$(M, \ell) \otimes (M', \ell') = (M \otimes M', \ell + \ell')$$

Weighted matrices

Compare ~~$f(w)$~~ $\mu(w)$ with $|w|$ ⟶ Describe $\{(\mu(w), |w|) \mid w \in A^*\}$

Weighted matrices:

(M, ℓ) — M: matrix, $\ell \in \mathbb{N} - \{0\}$

$$(M,\ell)\otimes(M',\ell') = (M\otimes M', \ell+\ell')$$

$$(\mu(w), |w|) \otimes (\mu(w'), |w'|)$$
$$= (\mu(ww'), |ww'|)$$

Weighted matrices

Compare ~~$f(w)$~~ $\mu(w)$ with $|w|$ ⟶ Describe $\{(\mu(w), |w|) \mid w \in A^*\}$

↓

Describe $\langle\{(\mu(a), 1) \mid a \in A\}\rangle$

Weighted matrices:

(M, ℓ): M → matrix, $\ell \in \mathbb{N} - \{0\}$

$$(M,\ell)\otimes(M',\ell') = (M\otimes M', \ell+\ell')$$

$$(\mu(w), |w|) \otimes (\mu(w'), |w'|) = (\mu(ww'), |ww'|)$$

Weighted matrices

Compare ~~$f(w)$~~ $\mu(w)$ with $|w|$ ⟶ Describe $\{(\mu(w), |w|) \mid w \in A^*\}$

↓

Describe $\langle\{(\mu(a), 1) \mid a \in A\}\rangle$

↙

Impossible to describe precisely

=

Approximation $\approx$

Weighted matrices:

$$(M, \ell)$$

matrix ↙ ↘ $\in \mathbb{N} - \{0\}$

$$(M,\ell)\otimes(M',\ell') = (M\otimes M', \ell+\ell')$$

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↘ With nice sets = Presentable sets

Weighted matrices:

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Given a finite set X of weighted matrices, one can compute a presentable set Y of weighted matrices such that $\langle X\rangle \approx Y$.

Approximation

Theorem: There is an algorithm that, given a min-plus automaton computing a function f, and $\varepsilon > 0$, approximates, up to ε, the value:

$$\sup_{w \in A^*} \frac{f(w)}{|w|}$$

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$$(M, \ell) \preccurlyeq_\varepsilon (N, k) \quad \text{if} \quad \begin{cases} M \leqslant N + \varepsilon\ell \\ \ell \geqslant k \\ \varphi(M) = \varphi(N) \end{cases}$$

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$X \preccurlyeq_\varepsilon Y$ if for all $(M, \ell) \in X$, there is $(N, k) \in Y$ such that $(M, \ell) \preccurlyeq_\varepsilon (N, k)$.

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$X \approx_\varepsilon Y$ if $X \preccurlyeq_\varepsilon Y$ and $Y \preccurlyeq_\varepsilon X$.

Presentable sets

Theorem: There is an algorithm that, given a min-plus automaton computing a function f, and $\varepsilon > 0$, approximates, up to ε, the value:

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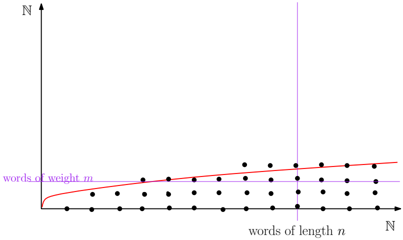
A set is finitely presented if it is a finite union of:

- singleton sets,
- sets of the form $\{(kM, k) : \; k \geqslant \ell\}$ for some ℓ.

Conclusion and further questions

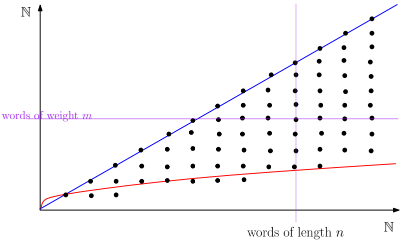
Min-plus

$$h(n) = \sup_{|w| \leqslant n} f(w)$$



Max-plus

$$h(n) = \inf_{|w| \geqslant n} f(w)$$



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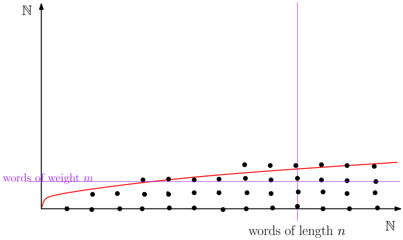

Approximation of $\sup_n \frac{h(n)}{n}$

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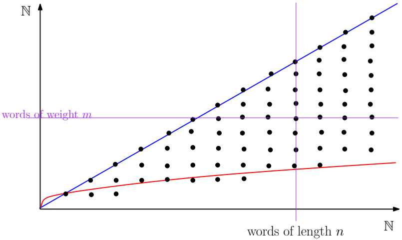

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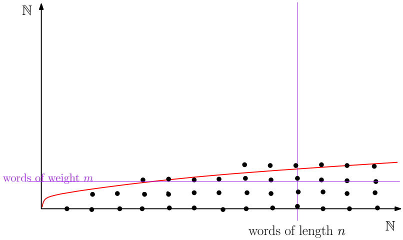

Approximation of $\sup_n \frac{h(n)}{n}$

Approximate comparison

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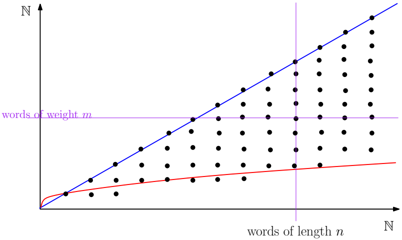

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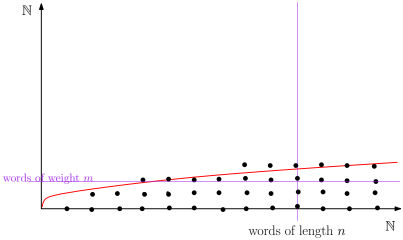

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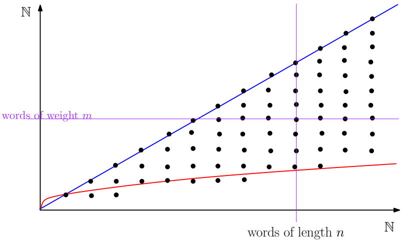

Approximation of $\inf_n \frac{h(n)}{n}$

??

$$h(n) = \Theta(n^{\alpha})$$

Conclusion and further questions

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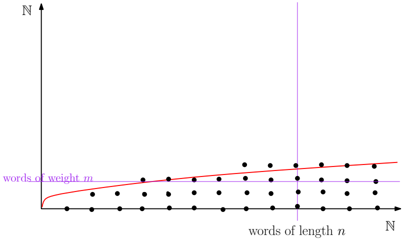

Approximation of $\sup_n \frac{h(n)}{n}$

Approximate comparison

??

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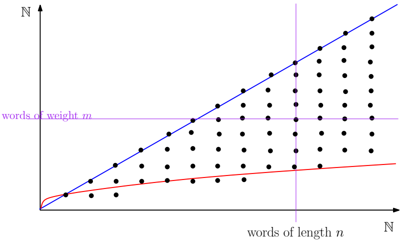

Approximation of $\inf_n \frac{h(n)}{n}$

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$$h(n) = \Theta(n^\alpha)$$

Describe h as cn^α with α rational and c up to ε