Primitive Digraphs, Markov Chains and Synchronizing Automata

Mikhail Volkov

Ural Federal University, Ekaterinburg, Russia

JM, September 11, 2012

Definitions and Terminology

We consider complete deterministic finite automata (DFA) $\mathscr{A} = \langle Q, \Sigma, \delta \rangle$ where Q stands for the state set, Σ is the input alphabet, and $\delta : Q \times \Sigma \to Q$ is a (total) transition function.

To simplify notation we often write $q \,.\, w$ for $\delta(q, w)$ and $P \,.\, w$ for $\{\delta(q, w) \mid q \in P\}$.

$\mathscr{A}$ is called synchronizing if there is a word $w \in \Sigma^*$ whose action resets $\mathscr{A}$, that is, leaves $\mathscr{A}$ in one particular state no matter at which state in Q it started: $q \,.\, w = q' \,.\, w$ for all $q, q' \in Q$. In short, $|Q \,.\, w| = 1$.

Any w with this property is a reset word for $\mathscr{A}$.

Other names:

- for automata: directable, cofinal, collapsible, etc;
- for words: directing, recurrent, synchronizing, etc.

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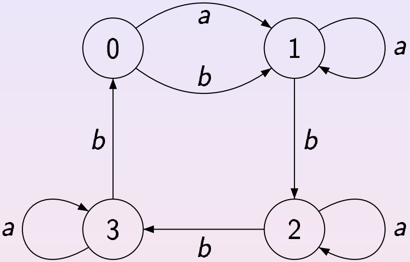

A reset word is *abbbabbba*: applying it at any state brings the automaton to the state 1.

In fact, this is the reset word of minimum length for the automaton whence the reset threshold of the automaton is 9.

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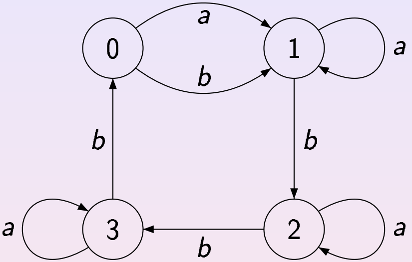

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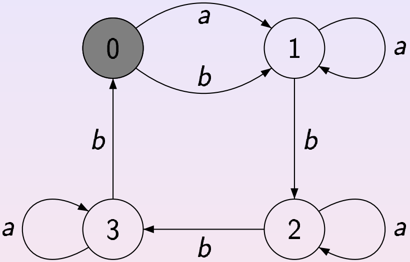

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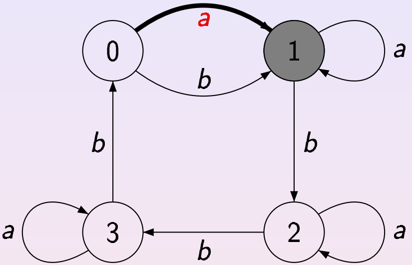

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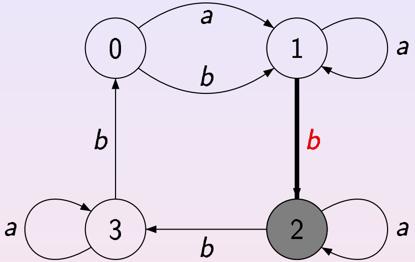

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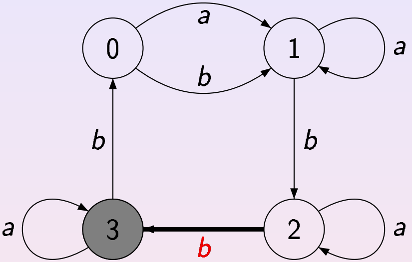

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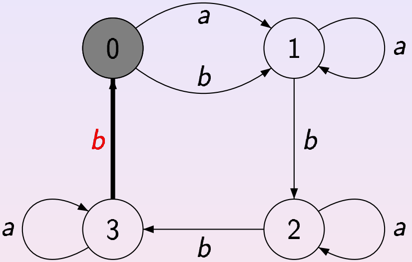

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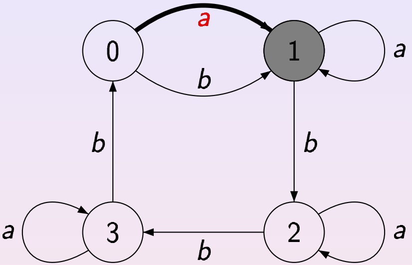

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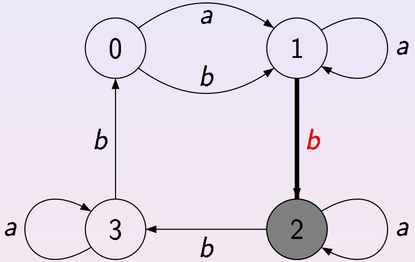

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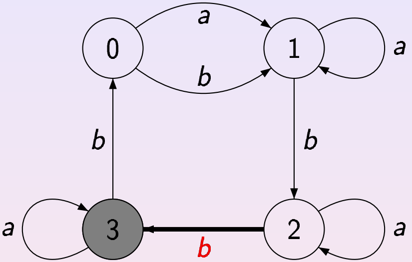

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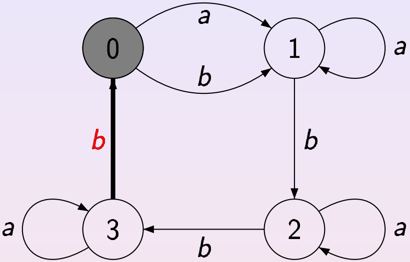

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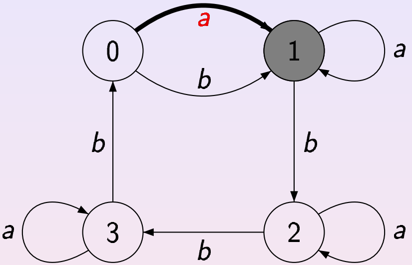

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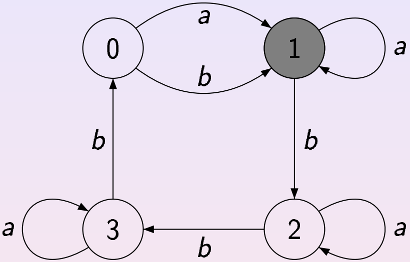

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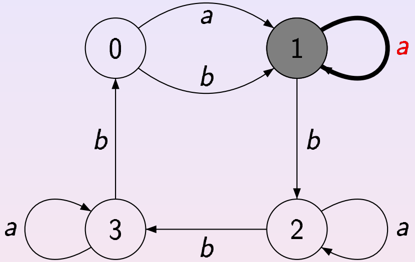

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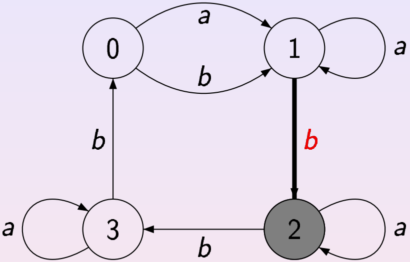

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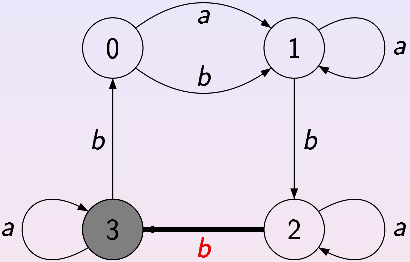

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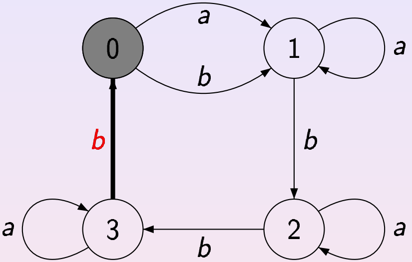

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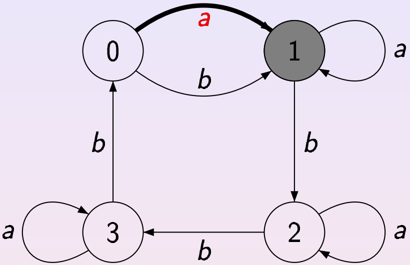

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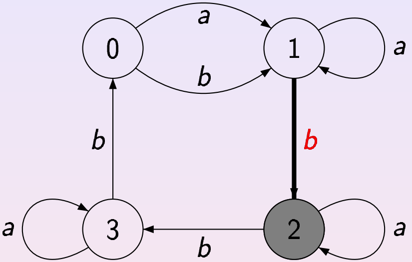

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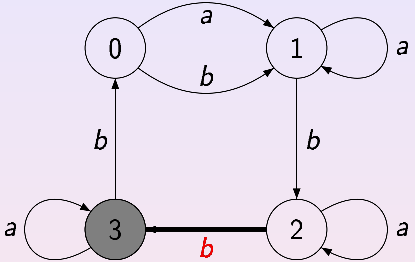

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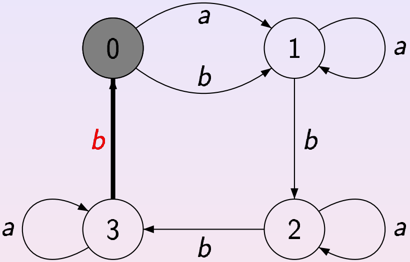

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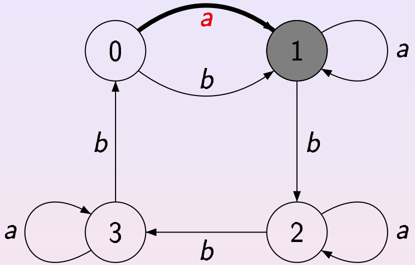

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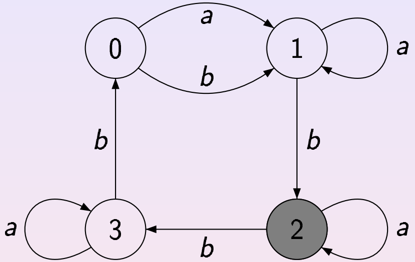

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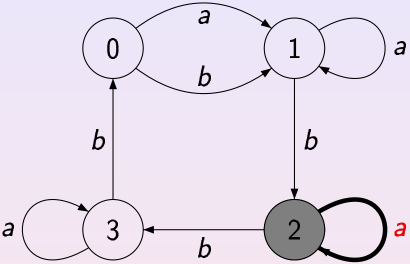

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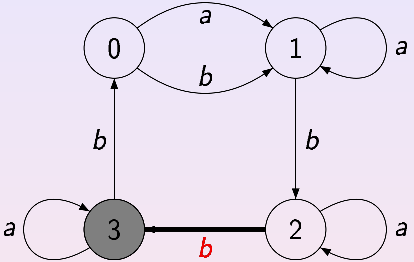

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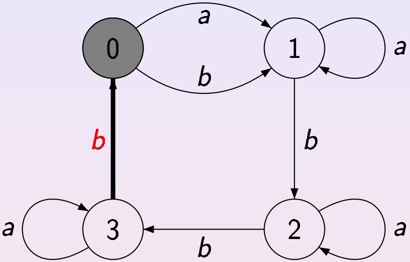

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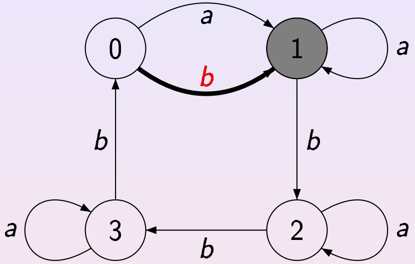

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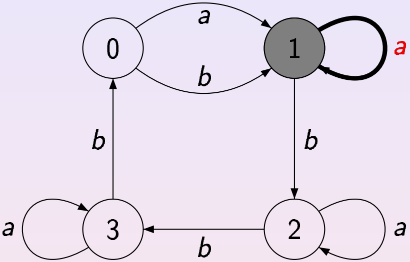

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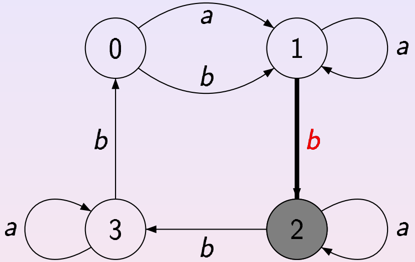

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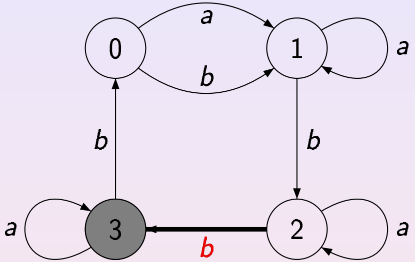

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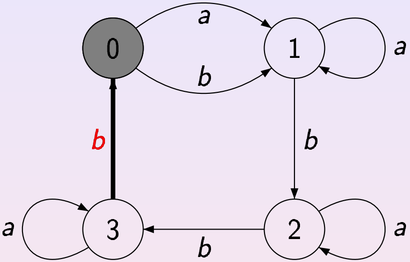

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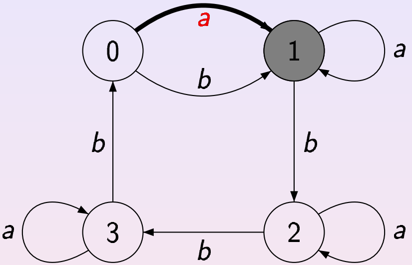

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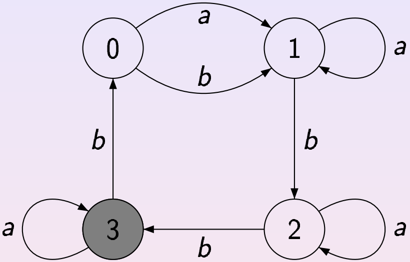

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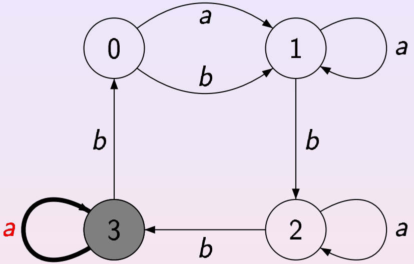

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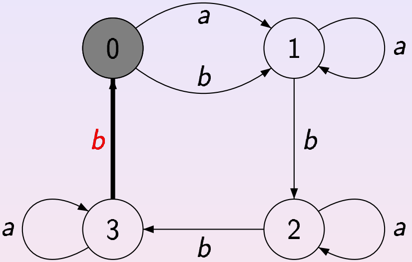

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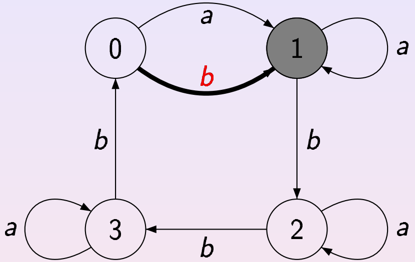

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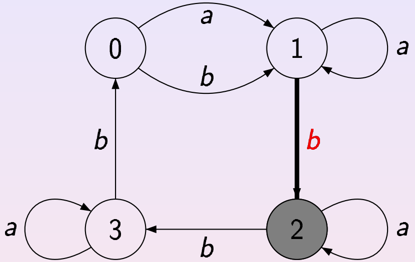

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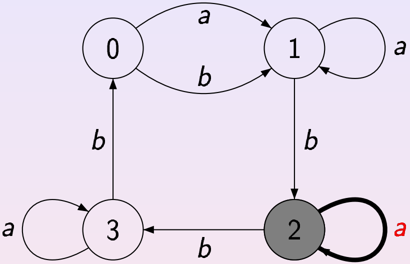

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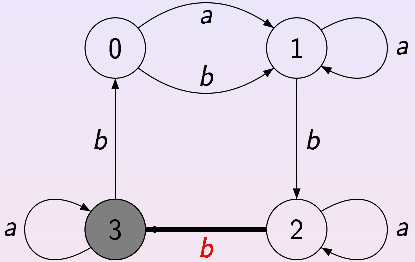

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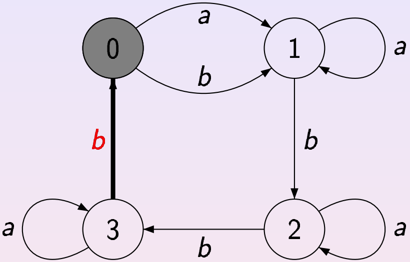

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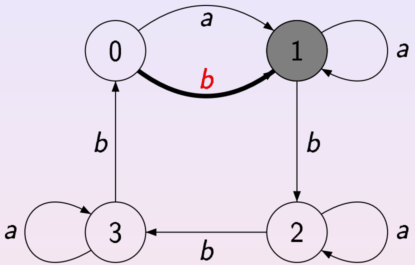

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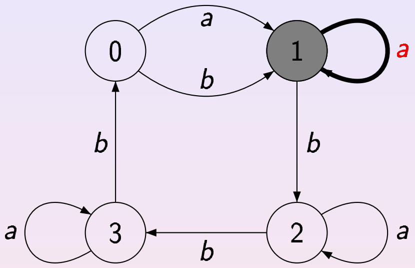

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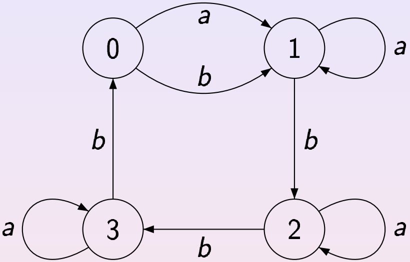

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The validity of the conjecture is main open problem of the area and arguably one of the most long-standing open problems in combinatorial theory of finite automata.

Define the *Černý function* $C(n)$ as the maximum reset threshold for synchronizing automata with n states. In terms of this function, our current knowledge can be summarized in one line:

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Advantage of Being Old

Thus, the pattern is:

$(n-1)^2$ the first gap the "island" the second gap

The second gap first appears at 9 states and grows rather regularly with the number of states. The size of the island depends only on the parity of the number of states.

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A non-negative matrix A is said to be primitive if some power A^k is positive. The minimum k with this property is called the exponent of A, denoted $\exp A$.

Helmut Wielandt proved in 1950 that for any primitive $n \times n$-matrix A, one has $\exp A \leq n^2 - 2n + 2 = (n-1)^2 + 1$, and this bound is tight. Possible exponents of $n \times n$-matrices were intensively studied in the 1960s, and it was discovered that two extreme values are each attained by a unique matrix, then there is a gap followed by an island followed by another gap. The sizes of the gaps and of the island perfectly match the sizes of the gaps and of the islands in possible reset thresholds of synchronizing automata with n states — basically one has the same picture shifted by 1. Clearly, this cannot be a mere coincidence.

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Digraphs and Matrices

A directed graph (digraph) is a pair $D = \langle V, E \rangle$.

- V set of vertices
- $E \subseteq V \times V$ set of edges

This definition allows loops but excludes multiple edges.

The matrix of a digraph $D = \langle V, E \rangle$ is just the incidence matrix of the edge relation, that is, a $V \times V$-matrix whose entry in the row v and the column v' is 1 if $(v, v') \in E$ and 0 otherwise.

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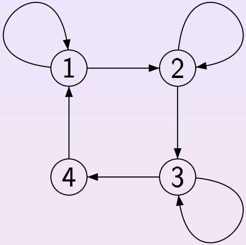

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Conversely, given an $n \times n$-matrix $P = (p_{ij})$ with non-negative real entries, we assign to it a digraph $D(P)$ on the set $\{1, 2, \ldots, n\}$ as follows: (i, j) is an edge of $D(P)$ if and only if $p_{ij} > 0$.

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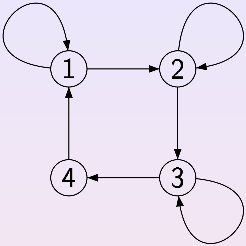

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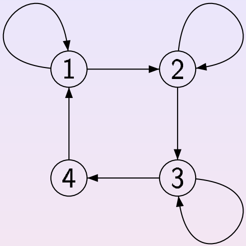

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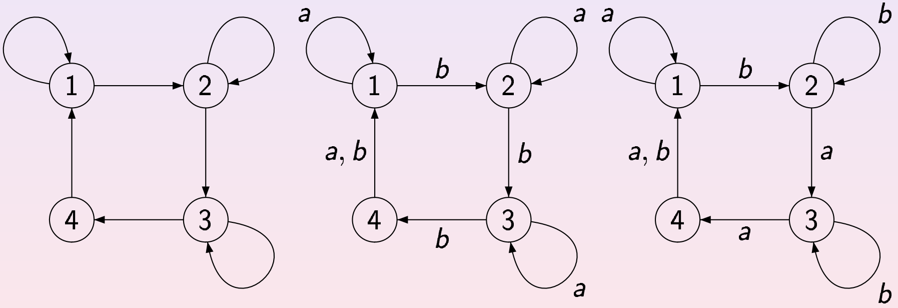

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Primitive Digraphs

A digraph D is primitive if D is strongly connected and the greatest common divisor of the lengths of all cycles in D is equal to 1.

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Exponents

A digraph D is primitive iff there exists t such that for each pair of vertices there exists a path between them of length exactly t. (This is equivalent to saying that the t-th power of the matrix of D is positive.) The least t with this property is called the exponent of the digraph D and is denoted by $\gamma(D)$.

1950, Wielandt: The exponent of every primitive digraph on n vertices is not greater than $(n-1)^2+1$ and this bound is tight.

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JM, September 11, 2012

Exponents

A digraph D is primitive iff there exists t such that for each pair of vertices there exists a path between them of length exactly t. (This is equivalent to saying that the t-th power of the matrix of D is positive.) The least t with this property is called the exponent of the digraph D and is denoted by $\gamma(D)$.

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Exponents of primitive digraphs with 9 vertices vs reset thresholds of 2-letter strongly connected synchronizing automata with 9 states

N	65	64	63	62	61	60	59	58	57	56	55	54	53	52	51
# of primitive digraphs with exponent N	1	1	0	0	0	0	0	1	1	2	0	0	0	0	3
# of 2-letter synchronizing automata with reset threshold N	0	1	0	0	0	0	0	1	2	3	0	0	0	4	4

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The Wielandt automaton $\mathscr{W}_n$ is a (unique) coloring of the Wielandt digraph W_n with $\gamma(W_n) = (n-1)^2 + 1$. Wielandt digraph has n vertices $1, 2, \ldots, n$, say, and the following $n+1$ edges: $(i, i+1)$ for $i = 1, \ldots, n-1$, $(n, 1)$, and $(n, 2)$.

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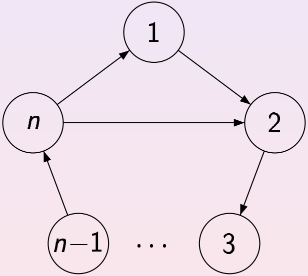

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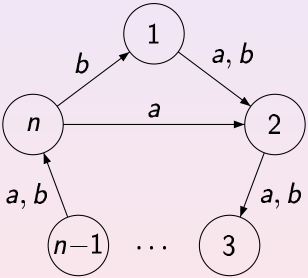

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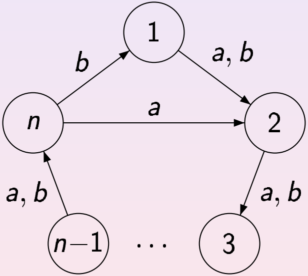

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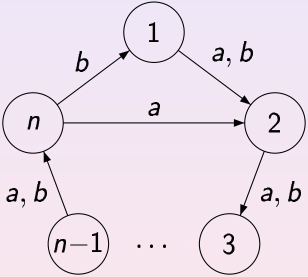

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In a similar way, each digraph with large exponent generates slowly synchronizing automata.

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Observation

Let a strongly connected synchronizing automaton with n states and reset threshold t be a coloring of a digraph D. Then

$$\gamma(D) \leq t + n - 1.$$

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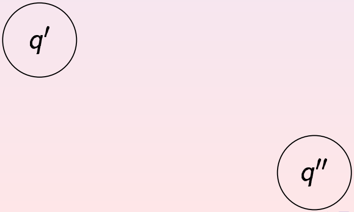

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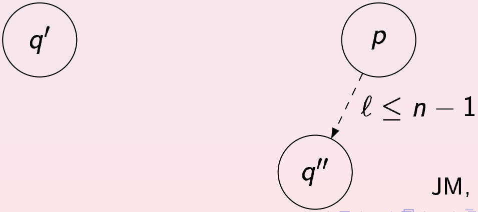

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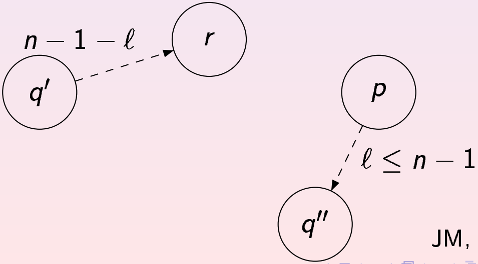

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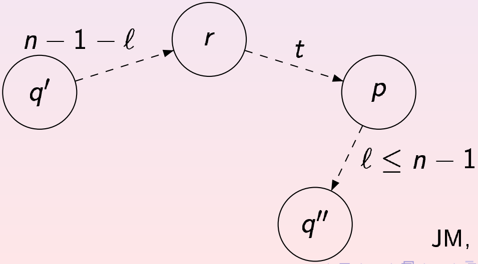

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$$\gamma(D) \leq t + n - 1.$$

For instance, the reset threshold t of the Wielandt automaton $\mathscr{W}_n$ must satisfy

$$t \geq \gamma(W_n) - n + 1 = (n-1)^2 + 1 - n + 1 = n^2 - 3n + 3,$$

and it is easy to find a reset word of length $n^2 - 3n + 3$.

The Černý Automaton

There are slowly synchronizing automata that cannot be obtained as colorings of a digraph with large exponent. For instance, the Černý automaton $\mathscr{C}_n$ has reset threshold $(n-1)^2$ while its underlying digraph has exponent $n-1$.

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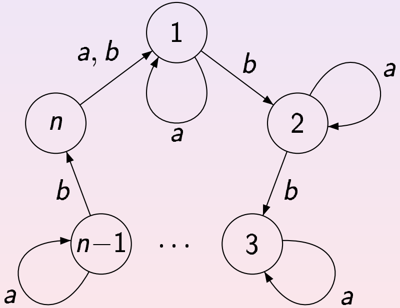

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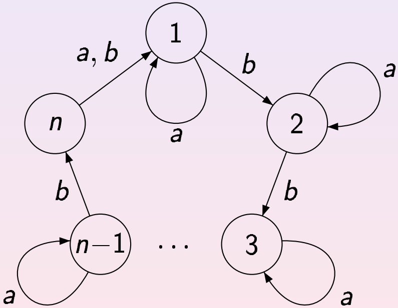

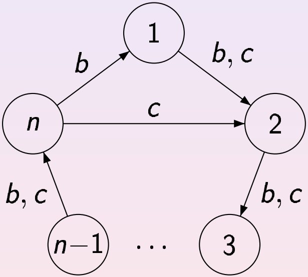

However, $\mathscr{C}_n$ becomes $\mathscr{W}_n$ under the action of b and $c = ab$.

The Černý Automaton

Let w be a shortest reset word for $\mathscr{C}_n$. It must end with a and every other occurrence of a in w is followed by an occurrence of b. Thus, $w = w'a$ where w' can be rewritten into a word v over the alphabet $\{b, c\}$. Since w' and v act in the same way, the word vc is a reset word for $\mathscr{W}_n$. Hence $|v| \geq n^2 - 3n + 2$.

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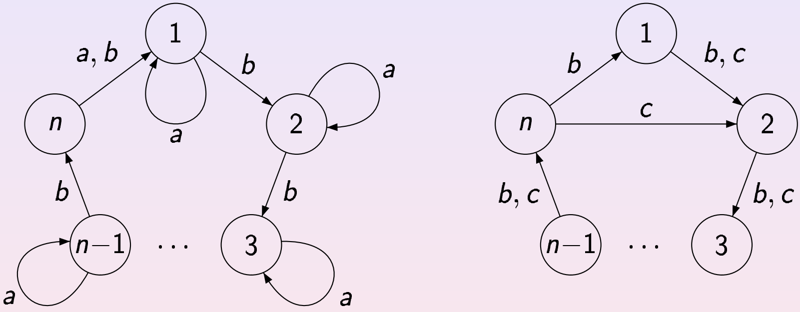

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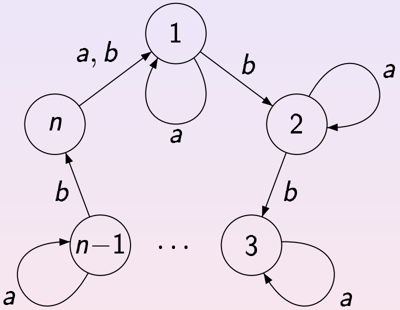

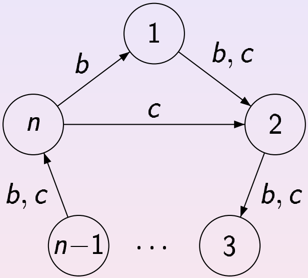

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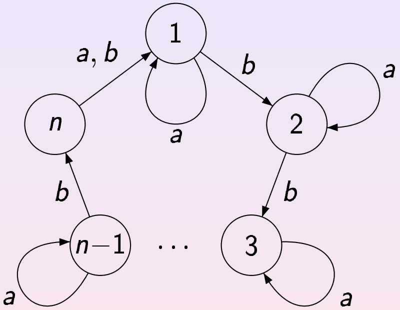

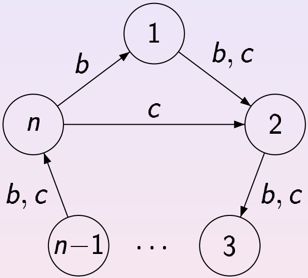

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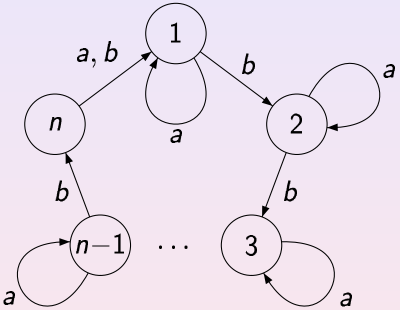

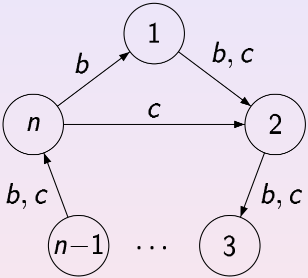

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Thus, it is the Wielandt digraph that stays behind the Černý automaton!

Digraphs vs Automata

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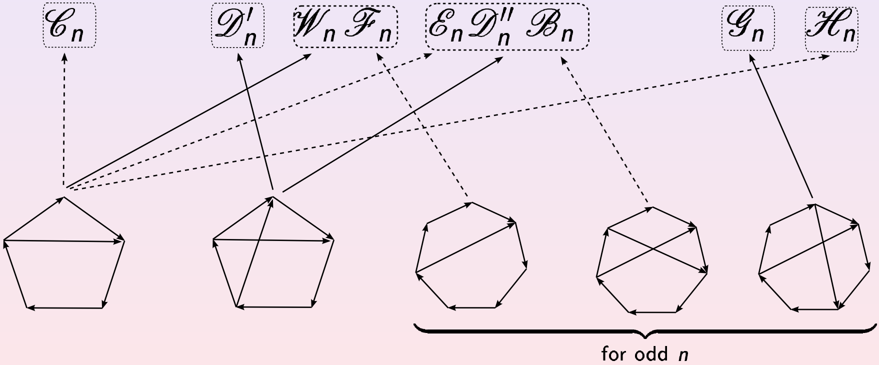

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How to get upper bounds for reset threshold?

For $\mathscr{A} = \langle Q, \Sigma, \delta \rangle$, a subset $P \subset Q$ is extensible if $P = R \,.\, w$ for some $w \in \Sigma^*$ of length at most $n = |Q|$ and some $R \subseteq Q$ with $|R| > |P|$. It was conjectured for some time that in synchronizing automata every proper non-singleton subset is extensible. Observe that this would imply the Černý conjecture.

Indeed, some letter a should sent two states q, q' to the same state p. Let $P_0 = \{q, q'\}$ and, for $i > 0$, let P_i be such that $|P_i| > |P_{i-1}|$ and $P_{i-1} = P_i \,.\, w_i$ for some word w_i of length $\leq n$. Then in at most $n - 2$ steps the sequence $P_0, P_1, P_2, \dots$ reaches Q and

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For $\mathscr{A} = \langle Q, \Sigma, \delta \rangle$, a subset $P \subset Q$ is extensible if $P = R \,.\, w$ for some $w \in \Sigma^*$ of length at most $n = |Q|$ and some $R \subseteq Q$ with $|R| > |P|$. It was conjectured for some time that in synchronizing automata every proper non-singleton subset is extensible. Observe that this would imply the Černý conjecture.

Indeed, some letter a should sent two states q, q' to the same state p. Let $P_0 = \{q, q'\}$ and, for $i > 0$, let P_i be such that $|P_i| > |P_{i-1}|$ and $P_{i-1} = P_i \,.\, w_i$ for some word w_i of length $\leq n$. Then in at most $n - 2$ steps the sequence $P_0, P_1, P_2, \dots$ reaches Q and

$$Q \,.\, w_{n-2} w_{n-3} \cdots w_1 a = \{p\},$$

that is, $w_{n-2} w_{n-3} \cdots w_1 a$ is a reset word. The length of this reset word is at most $n(n-2) + 1 = (n-1)^2$.

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Example

For an illustration, consider the subset automaton of the Černý automaton $\mathscr{C}_4$.

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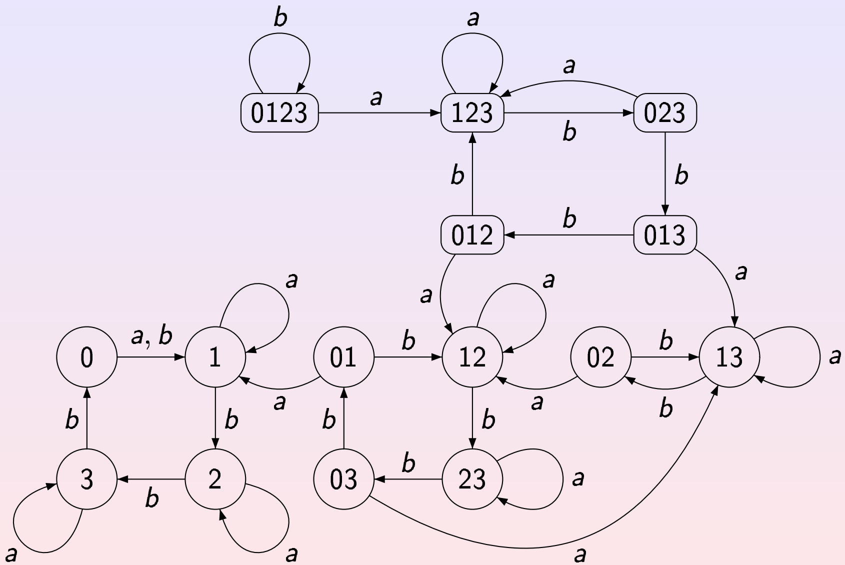
Example



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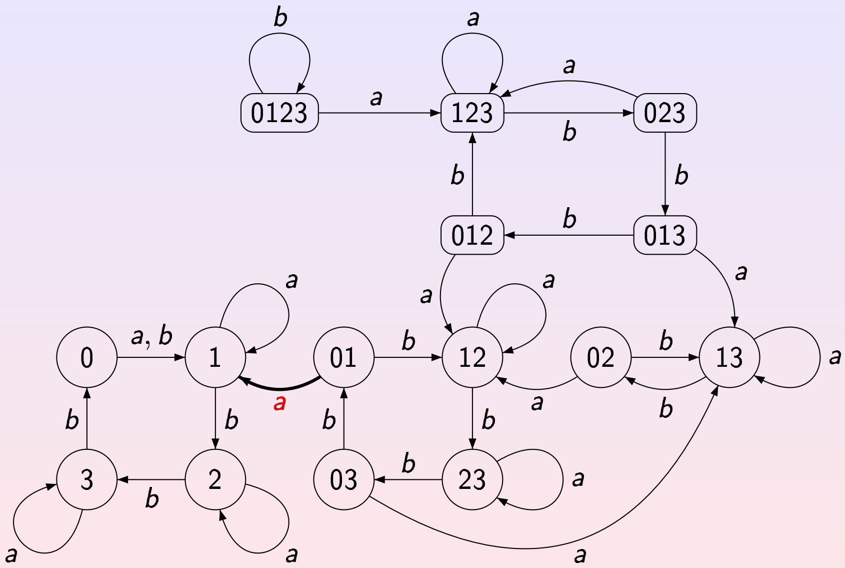

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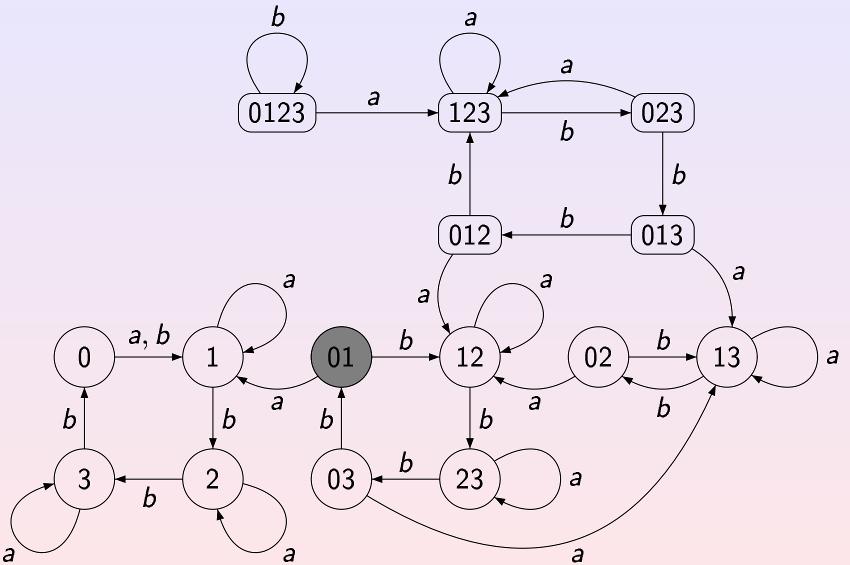

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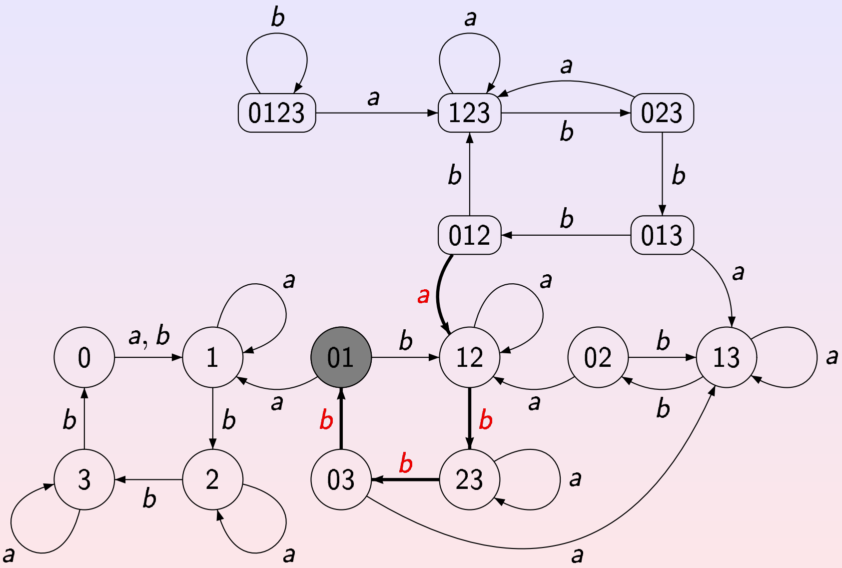

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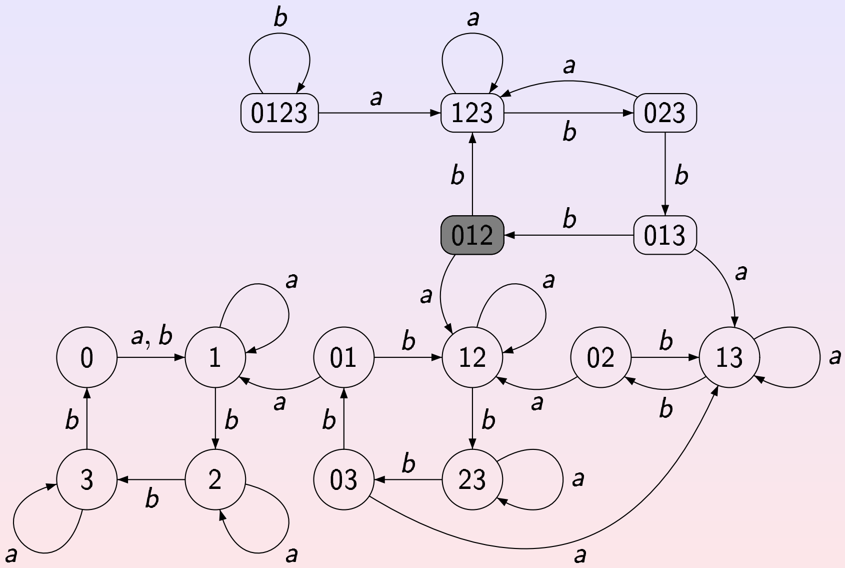

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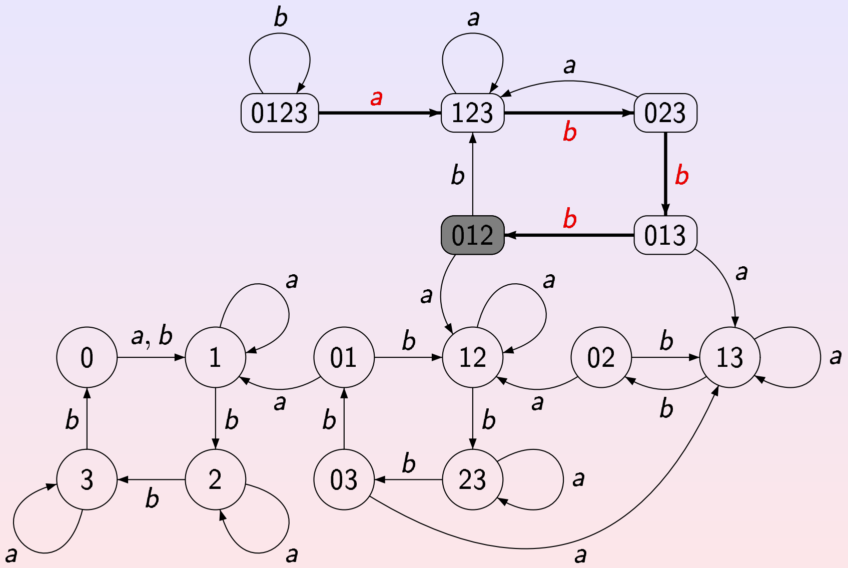

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Applications of Extensibility

Several important results confirming the Černý conjecture for various partial cases have been proved by verifying the extensibility conjecture for the corresponding automata. This includes:

• Louis Dubuc's result for automata in which a letter acts on the state set Q as a cyclic permutation of order $|Q|$ (Sur le automates circulaires et la conjecture de Černý, RAIRO Inform. Theor. Appl., 32 (1998) 21–34 [in French]).

• Jarkko Kari's result for automata with Eulerian digraphs (Synchronizing finite automata on Eulerian digraphs, Theoret. Comput. Sci., 295 (2003) 223–232).

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Limits of Extensibility

In general, the extensibility conjecture fails. The first (implicit) example was a 6-state automaton found by Jarkko Kari in 2001, and Mikhail Berlinkov has constructed for every $\alpha < 2$ an infinite series of synchronizing automata $\mathscr{B}_\alpha = \langle Q, \Sigma, \delta \rangle$ such that there is a proper non-singleton subset $P \subset Q$ that cannot be extended by any word of length $< \alpha|Q|$ (On a conjecture by Carpi and D'Alessandro, Int. J. Found. Comput. Sci. 22 (2011) 1565–1576).

It is not excluded that in every synchronizing automaton each proper non-singleton subset can be extended by a word of length $2 \times \#$ of states. On the other hand, we don't know even a quadratic (in the number of states) upper bound for the length of extending words.

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Linearization

We associate a natural linear structure with each automaton $\mathscr{A} = \langle Q, \Sigma, \delta \rangle$. Assume that $Q = \{1, 2, \ldots, n\}$ and assign to each subset $K \subseteq Q$ its characteristic vector $[K] \in \mathbb{R}^n$ (the space of n-dimensional column vectors): the i-th entry of $[K]$ is 1 if $i \in K$, otherwise the entry is 0.

For each word $w \in \Sigma^*$, its action on Q gives rise to a linear transformation of $\mathbb{R}^n$; we denote by $[w]$ the matrix of this transformation in the standard basis $[1], \ldots, [n]$ of $\mathbb{R}^n$. Clearly, the matrix $[w]$ has exactly one non-zero entry in each column and this entry is equal to 1.

For $K \subseteq Q$ and $v \in \Sigma^*$, let $K \,.\, v^{-1} = \{q \mid q.v \in K\}$. Then $[K \,.\, v^{-1}] = [v]^T[K]$, where $[v]^T$ stands for the usual transpose of the matrix $[v]$. A word w is a reset word for $\mathscr{A}$ iff $q \,.\, w^{-1} = Q$ for some state q. Now we can rewrite this as $[w]^T[q] = [Q]$.

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For vectors $g_1, g_2 \in \mathbb{R}^n$, we denote their usual inner product by (g_1, g_2). Then for any $K, L \subset Q$, we have $([K],[L]) = |K \cap L|$. Denote by $\mathbf{1}_n$ the uniform stochastic vector in $\mathbb{R}^n$, that is, the vector with all entries equal to $\frac{1}{n}$. Then the fact that a word w extends a subset $K \subset Q$ (that is, the inequality $|K| < |K\,.\,w^{-1}|$) can be rewritten as $([K], \mathbf{1}_n) < ([w]^T[K], \mathbf{1}_n)$.
Thus, the extension method amounts to finding a state q, a letter a, and a sequence of words $w_1, w_2, \ldots, w_d$ such that

$$\frac{1}{n} = ([q], \mathbf{1}_n) < ([a]^T[q], \mathbf{1}_n) < ([w_1 a]^T[q], \mathbf{1}_n) < \ldots$$
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Jungers's Dualization

Raphaël Jungers (The synchronizing probability function of an automaton, SIAM J. Discrete Math. 26 (2011) 177–192) has suggested an interesting idea that in our notation can be described as follows: one should substitute the uniform stochastic vector $\mathbf{1}_n$ by an adaptive positive stochastic vector p which can depend on both the automaton $\mathscr{A}$ and the given proper subset $K \subset Q$ but has the property that there exists a word v of length at most $|Q|$ such that $([v]^T[K], p) > ([K], p)$. Jungers has explored this idea using techniques from linear programming and has proved that such a positive stochastic vector indeed exists for every synchronizing automaton and every proper subset. We encounter a dual problem here since it is not clear how to find a linear upper bound for the number of extension steps.

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Markov Chains

Assume that $\Sigma = \{a_1, a_2, \ldots, a_k\}$. Each positive stochastic vector $\pi \in \mathbb{R}^k_+$ defines a probability distribution on Σ. Consider a process in which an agent randomly walks on the underlying graph of $\mathscr{A}$, choosing for each move an edge labeled a_i with probability $p(a_i)$. This is a Markov chain with the transition matrix

$$S = S(\mathscr{A}, \pi) = \sum_{i=1}^{k} p(a_i)[a_i].$$

By basic properties of Markov chains, there exists the stationary distribution $\alpha \in \mathbb{R}^n_+$ of this Markov chain, that is, a unique positive stochastic vector satisfying $S\alpha = \alpha$.

JM, September 11, 2012

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Berlinkov's Result

Theorem (Berlinkov, 2012)

Let $\mathscr{A}$ be a synchronizing automaton with n states and k letters, $\pi \in \mathbb{R}^k_+$ a positive stochastic vector, and α the stationary distribution of the Markov chain with the transition matrix $S(\mathscr{A}, \pi)$. Then there exist a state q, a letter a, and a sequence of words $w_1, w_2, \ldots, w_d$ of length at most n such that

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An immediate application: a new proof of the Černý conjecture for automata with Eulerian digraphs. In this case the matrix $S(\mathscr{A}, \pi)$ is doubly stochastic whence the uniform vector $\mathbf{1}_n$ is its stationary distribution and $d \leq n - 2$.

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