Shuffling by semi-random transpositions

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Abstract

In the cyclic-to-random shuffle, we are given n cards arranged in a circle. At step k, we exchange the k'th card along the circle with a uniformly chosen random card. The problem of determining the mixing time of the cyclic-to-random shuffle was raised by Aldous and Diaconis in 1986. Recently, Mironov used this shuffle as a model for the cryptographic system known as "RC4" and proved an upper bound of $O(n \log n)$ for the mixing time. We prove a matching lower bound, thus establishing that the mixing time is indeed of order $\Theta(n \log n)$. We also prove an upper bound of $O(n \log n)$ for the mixing time of any "semi-random transposition shuffle", i.e., any shuffle in which a random card is exchanged with another card chosen according to an arbitrary (deterministic or random) rule. To prove our lower bound, we exhibit an explicit complex-valued test function which typically takes very different values for permutations arising from the cyclic-to-random-shuffle and for uniform random permutations; we expect that this test function may be useful in future analysis of RC4. Perhaps surprisingly, the proof hinges on the fact that the function $e^z - 1$ has nonzero fixed points in the complex plane. A key insight from our work is the importance of complex analysis tools for uncovering structure in nonreversible Markov chains.

1 Introduction

The *mixing time* of a Markov chain on a finite state space is the number of steps until it is close to its stationary distribution, starting from an arbitrary state. The mixing time is a key parameter in analyzing random sampling algorithms and is of intrinsic interest in probability and statistical physics as well. For many natural Markov chains, if some of the randomness is removed from the transition rule, resulting in a "more deterministic" process with the same stationary distribution, the chain becomes significantly harder to analyze. Indeed, some of the most challenging problems in the field concern the analysis of such "pseudo-random" variants of well understood chains. Some examples include the riffle shuffle [14, 19] compared to the thorp shuffle [20], the asymmetric exclusion process [8] compared with its systematic scan version [13] and the comparison between the standard and systematic versions of Glauber dynamics for Gaussian fields [15, 4, 5, 6].

Shuffling by random transpositions is one of the simplest random walks on the symmetric group: given n cards in a row, at each step two cards are picked uniformly at random and exchanged. This shuffle was precisely analyzed in 1981, see [12]. In the "cyclic-to-random" shuffle (invented by Thorp [21]), at step t a uniformly chosen random card is exchanged with the card at position $t \mod n$. It is easy to see that this semi-random shuffle still converges to the uniform distribution on permutations of n cards. In their landmark 1986 paper on card shuffling [3], Aldous and Diaconis posed as a challenge the analysis of the cyclic-to-random shuffle. More recently, Mironov [17] related this shuffle to the behavior of the RC4 encryption algorithm. Mironov showed that a strong uniform time argument, due

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to Broder, can be adapted to yield an upper bound of $O(n \log n)$ on the mixing time. He posed as an open problem whether this bound is tight.

In this paper we establish a lower bound of $\Omega(n \log n)$ for the mixing time of the cyclic-to-random shuffle, thus answering the questions posed by Aldous and Diaconis and by Mironov. We also prove a general upper bound of $O(n \log n)$ on the mixing time of *any* semi-random transposition shuffle, i.e., any shuffle in which a random card is exchanged with another card chosen according to an arbitrary (deterministic or random) rule that may vary at each step. Previously, the best available upper bound for such a general process was $O(n^2)$, proved by Pak [18].

To prove the lower bound for the cyclic-to-random transposition shuffle $\{\sigma_t\}$, we find an eigenfunction of the shuffle that mixes slowly. (This approach was used by Wilson [22, 23] to prove $\Omega(n^3 \log n)$ lower bounds for the shuffle generated by transpositions of adjacent cards and several variants.) First, we determine the eigenvalues of a nonreversible renewal Markov chain M on the n-cycle which describes the behavior of a single card. The asymptotics for the leading eigenvalues of M depend on the fact that the function $e^z - 1$ has nonzero fixed points in the complex plane. We then pick an eigenfunction f for M and use it to construct a test function F, defined on permutations, which is a weighted sum of f applied to the locations of all cards. To show that the distribution at time t of $F(\sigma_t)$ is far from the distribution of $F(\sigma)$ for a uniform random permutation σ, the key is to estimate the variance. The variance is a sum of correlations between pairs of cards; to bound these correlations, we couple the shuffle with a system of independent particles evolving according to M. This coupling approach has intuitive appeal, and could potentially be used for other chains on permutations. Alternatively, one could bound the variance of $F(\sigma_t)$ using the martingale decomposition method of Wilson [22, 23].

Our general upper bound for semi-random transpositions is proved via a strong uniform time argument, extending earlier arguments of Broder and Mironov.

We believe that some of our technical insights may be carried over to other situations where lower bounds for nonreversible or "pseudo-random" Markov chains are sought. These insights include:

- The analysis of a given Markov chain with a transition rule that varies in time can sometimes be reduced to the analysis of an equivalent time-homogeneous chain.
- Coupling arguments, which are often applied to obtain upper bounds for mixing times, can also be used to establish lower bounds.
- When seeking to understand a nonreversible Markov chain, results of classical complex analysis such as Rouché's theorem, can be powerful tools. Thus methods from complex analysis should be added to techniques from probability, combinatorics, functional analysis and representation theory in the toolkit of Markov chain analysis.

1.1 Statement of main results

Let $\{L_t\}_{t=1}^{\infty}$ be a sequence of random variables taking values in $[n] = \{0, 1, \ldots, n-1\}$ and let $\{R_t\}_{t=1}^{\infty}$ be a sequence of i.i.d. cards chosen uniformly from $[n]$. The **semi-random transposition shuffle** generated by $\{L_t\}$ is a stochastic process $\{\sigma_t^*\}_{t=0}^{\infty}$ on the symmetric group S_n, defined as follows. Fix the initial permutation σ_0^*. The permutation σ_t^* at time t is obtained from σ_{t-1}^* by transposing the cards at locations L_t and R_t.

In the **cyclic-to-random shuffle**, the sequence L_t is given by $L_t = t \mod n$.

The stochastic process $\{\sigma_t^*\}$ is a time-inhomogeneous Markov chain on S_n, and converges to the uniform stationary distribution for any σ_0^* and any choice of $\{L_t\}$. It is a time-homogeneous Markov chain if the L_t are i.i.d. The special case where the L_t are i.i.d. uniform is the random transposition shuffle [2, 3, 12], the random walk on S_n generated by all transpositions; at the other extreme, if all the L_t are identically 0, we get the random walk generated by "star transpositions", where in each step a randomly chosen card is exchanged with the card in position 0.

Let μ_t^* be the distribution of σ_t^* at time t, and let $\|\mu_t^* - \mathcal{U}\|_{\mathrm{TV}}$ denote the total variation distance between μ_t^* and the uniform distribution $\mathcal{U}$. Define the *mixing time* by

$$\tau_{\mathrm{mix}} = \max_{\sigma_0} \min\{t : \|\mu_t^* - \mathcal{U}\|_{\mathrm{TV}} \le \frac{1}{2e}\}.$$

The choice of constant $\frac{1}{2e}$ ensures that, for any $\epsilon > 0$, we have $\|\mu_t^* - \mathcal{U}\|_{\mathrm{TV}} \le \epsilon$ if $t \ge \lceil \log \epsilon^{-1} \rceil \tau_{\mathrm{mix}}$ (see [2]).

Theorem 1.1 *The cyclic-to-random transposition shuffle has mixing time $\Omega(n \log n)$. More precisely, the mixing time is at least*

$$\frac{n \log n}{|\zeta + 1|(1 + o(1))},$$

where ζ is any nonzero complex root of the equation $\psi(z) = e^z - z - 1 = 0$.

Using Mathematica, we find the root $\zeta = 2.088... + 7.461... \times i$ of ψ. This gives $|1 + \zeta| = 8.075...$ and yields a lower bound of $(.123 + o(1))n \log n$ for the mixing time.

Theorem 1.2 *The semi-random transposition shuffle $\{\sigma_t^*\}$ generated by any sequence $\{L_t\}$, has mixing time at most $O(n \log n)$. More precisely, there is a constant C_0 such that for any $C_1 > C_0$ and any initial configuration σ_0^*, we have*

$$\|\mu_t^* - \mathcal{U}\|_{\mathrm{TV}} \le n^{-\beta} \text{ for all } t > C_1 n \log n\,,$$

for some $\beta = \beta(C_1) > 0$.

Remark. The proof shows that we can take $C_0 = 32\theta^{-3} + \theta^{-1}$ where $\theta = e^{-2}(1 - e^{-1})/2$. We do not know the minimal value of C_0; it cannot be strictly less than 1 because of the star transpositions shuffle, where the mixing time is $(1 + o(1))n \log n$, see [10].

2 A lower bound for the cyclic-to-random shuffle

2.1 The behavior of a single card via renewals

Fixing a specific card a, it is natural to study the renewal chain on the state space $[n] = \{0, \ldots, n-1\}$, where state $i \in [n]$ indicates that the location j of card a satisfies $j + i = t \mod n$. This chain is described by the transition matrix M, where for all $i \in [n]$, we have $M_{0,i} = 1/n$ and $M_{i,1} = 1/n$, while $M_{i,i+1} = 1 - 1/n$, for all $i \ge 1$. (For $i = n-1$, the last equation reads $M_{n-1,0} = 1 - 1/n$.) In other words,

$$M = \begin{pmatrix} \frac{1}{n} & \frac{1}{n} & \frac{1}{n} & \frac{1}{n} & \cdots & \frac{1}{n} & \frac{1}{n} \\ 0 & \frac{1}{n} & 1-\frac{1}{n} & 0 & 0 & \ldots & 0 \\ 0 & \vdots & 0 & \ddots & 0 & \ldots & 0 \\ 0 & \vdots & 0 & 0 & \ddots & \ldots & 0 \\ 0 & \vdots & 0 & \ldots & 0 & \ddots & 0 \\ 0 & \frac{1}{n} & 0 & \ldots & 0 & 0 & 1-\frac{1}{n} \\ 1-\frac{1}{n} & \frac{1}{n} & 0 & \ldots & 0 & 0 & 0 \end{pmatrix}.$$

We will now find the eigenfunctions of the chain, that is, the right eigenvectors of the matrix M. Let $f = (f_0, \ldots, f_{n-1})^T$ be such a (column) eigenvector. Then we obtain the following equations:

$$\frac{1}{n}\sum_{j=0}^{n-1} f_j = \lambda f_0, \tag{1}$$

and, for $1 \le i \le n-1$,

$$\frac{1}{n} f_1 + (1 - \frac{1}{n}) f_{i+1} = \lambda f_i \quad \text{(where we denote } f_n = f_0\text{)}. \tag{2}$$

It is easy to check that, up to scaling, $(1, \ldots, 1)^T$ is the unique eigenvector corresponding to the eigenvalue $\lambda = 1$, and that $(-1, n-1, -1, \ldots, -1)^T$ is the unique eigenvector corresponding to $\lambda = 0$.

We now assume that f is a right eigenvector corresponding to an eigenvalue $\lambda \notin \{0, 1\}$. Since M is doubly stochastic, (1) implies that $\sum_{i=0}^{n-1} f_i = 0$ and $f_0 = 0$; to verify this, sum (1) and the $n-1$ equations in (2).

Writing $y_i = f_{i+1} - f_i$ for $1 \le i \le n-1$ (recall that $f_n = f_0$) the equation (2) for $i = 1$ gives:

$$y_1 = \frac{n(\lambda - 1)}{n-1} f_1$$

For $1 \le i \le n-2$, subtracting successive equations in (2) yields

$$(1 - \frac{1}{n}) y_{i+1} = \lambda y_i.$$

Thus if we set $\gamma = \frac{n\lambda}{n-1}$, then $y_1 = (\gamma - \frac{n}{n-1}) f_1$ and $y_j = \gamma^{j-1} y_1$ for $2 \le j \le n-1$. Without loss of generality we may assume that $f_1 = 1$. Therefore,

$$f_k = 1 + \sum_{j=1}^{k-1} y_j = 1 + y_1 \sum_{j=1}^{k-1} \gamma^{j-1} = 1 + \left(\gamma - \frac{n}{n-1}\right) \sum_{j=1}^{k-1} \gamma^{j-1} \tag{3}$$

for $1 \le k \le n$. Thus

$$(n-1)(1-\gamma) f_k = \Big(n - (n-1)\gamma\Big) \gamma^{k-1} - 1 \tag{4}$$

for $1 \le k \le n$. Since $\sum_{k=0}^{n-1} f_i = 0$ and $f_n = f_0$, we infer that

$$0 = (n-1)(1-\gamma)^2 \sum_{k=1}^{n} f_k = \Big(n - (n-1)\gamma\Big)(1 - \gamma^n) - n(1-\gamma) = \gamma - n\gamma^n + (n-1)\gamma^{n+1}\,.$$

Since $\gamma \ne 0$, it follows that

$$(n-1)\gamma^n - n\gamma^{n-1} + 1\,. \tag{5}$$

Note that this equation has a double root at $\gamma = 1$. We therefore conclude that the eigenvalues $\lambda \ne 0, 1$ correspond (via the relation $\gamma = \frac{n\lambda}{n-1}$) to the roots $\gamma \ne 1$ of (5). We investigate these roots next.

2.2 Properties of roots of equation (5).

Lemma 2.1 *All the solutions of (5) satisfy* $|\gamma| \le 1$.

Proof: If $|\gamma| > 1$, then

$$|(n-1)\gamma^{n-1}| > \Big|\sum_{i=0}^{n-2} \gamma^i\Big| = \Big|\frac{\gamma^{n-1} - 1}{\gamma - 1}\Big|,$$

and multiplying by $|\gamma - 1|$ gives

$$|(n-1)\gamma^n - (n-1)\gamma^{n-1}| > |\gamma^{n-1} - 1|,$$

so γ cannot be a solution to (5). ■

In the other direction, we need to show that (5) has solutions close to 1. We prove:

Lemma 2.2 *There exists a solution of the equation* $(n-1)\gamma^n - n\gamma^{n-1} + 1 = 0$ *which satisfies*

$$|1 - \gamma| \le \frac{|\zeta|}{n} + O(\frac{1}{n^2}), \tag{6}$$

and

$$|1 - \lambda| \le \frac{|\zeta + 1|}{n} + O(\frac{1}{n^2}), \tag{7}$$

where ζ *is any nonzero root of* $e^\zeta - \zeta - 1 = 0$, *and* $\lambda = (1 - 1/n)\gamma$.

Proof: By defining $\omega = \gamma^{-1}$, we obtain the equation $\omega^n - n\omega + n - 1 = 0$, or $\omega^n + n(1-\omega) - 1 = 0$. Now write $\omega = 1 + z/n$ to get the asymptotic equation $\psi(z) = e^z - z - 1 = 0$. By Hurwitz's theorem (see [1]), every solution ζ of the equation $\psi(\zeta) = 0$ is a limit of solutions z_n of the equations $(1 + z_n/n)^n - z_n - 1 = 0$. Since $\omega - 1 = z_n/n$, we obtain

$$\gamma = 1 - z_n/n + O(\frac{1}{n^2}). \tag{8}$$

Therefore

$$\lambda = (1 - 1/n)\gamma = 1 - \frac{1 + z_n}{n} + O(\frac{1}{n^2}). \tag{9}$$

To get more precise estimates, recall $\psi(z) = e^z - z - 1$ and let $\varphi_n(z) = (1 + z/n)^n - z - 1$. By Taylor expansion,

$$|n \log(1 + z/n) - z| = \frac{|z|^2}{2n} + O(\frac{1}{n^2}),$$

so in a bounded domain,

$$|\varphi_n(z) - \psi(z)| = |(1 + z/n)^n - e^z| = \frac{|z^2 e^z|}{2n} + O(\frac{1}{n^2}).$$

Below we will prove that the equation $e^z - z - 1 = 0$ has nonzero roots. Let ζ be such a root, then ζ is a simple root, since $\psi'(\zeta) = e^\zeta - 1 = \zeta$. Thus for z on the circle $\{|z - \zeta| = b/n\}$, we have

$$|\psi(z)| = |\psi'(\zeta)|\frac{b}{n} + O(\frac{1}{n^2}) = |\zeta|\frac{b}{n} + O(\frac{1}{n^2}).$$

On the other hand, for z on that circle,

$$|\varphi_n(z) - \psi(z)| = \frac{|\zeta^2 e^\zeta|}{2n} + O(n^{-2}).$$

By Rouché's Theorem (see [1]), it follows that if $b > |\zeta e^\zeta/2|$ and n is large enough, then φ_n has the same number of zeros as ψ in the disk $\{|z - \zeta| < b/n\}$, namely, exactly one zero. We thus obtain (6) by (8). Similarly, (7) follows from (9).

The equation $\psi(z) = e^z - z - 1 = 0$ has the solution $z = 0$. In order to show that it has a root $z \neq 0$, write $z = x + iy$ to get

$$e^x \cos y = 1 + x \text{ and } e^x \sin y = y.$$

Solve for x to get $x = y \cos y / \sin y - 1$. Inserting this value of x into the second equation we get

$$\frac{y}{\sin y} = \exp\left(\frac{y \cos y}{\sin y} - 1\right). \tag{10}$$

We will find a solution of the form $y = 2\pi m + a$, where $\pi/4 < a < \pi/2$. Note that if $y = 2\pi m + \pi/4$, then the left hand side of (10) is $\sqrt{2}y$, while the right hand side is $\exp(y - 1)$, which is strictly larger than $\sqrt{2}y$ for all $m \geq 1$. If, on the other hand, $y = 2\pi m + \pi/2$, then the left hand side is y while the right hand side is $\exp(-1)$, which is strictly smaller than y. We conclude that for all integers $m \geq 1$, there exists at least one solution $y = 2\pi m + a$, where $\pi/4 < a < \pi/2$. ■

2.3 The test function

In this subsection we fix an eigenvalue λ of M such that $|\lambda| \geq 1 - O(1/n)$, and let $f : [n] \to \mathbb{C}$ be a corresponding eigenfunction. We will denote the states of the n cards at time t by $\sigma_t(0), \ldots, \sigma_t(n-1)$, and assume that at time 0 we start with the identity permutation, so $\sigma_0(i) = i$ for all i. We emphasize that σ_t is obtained from σ_{t-1} by first transposing the card at state 0 with a uniform random card, and then moving all cards one state up (modulo n). Thus for each i, the sequence $\{\sigma_t(i)\}_{t \geq 0}$ is a Markov chain with transition matrix M. To relate this to the description of the cyclic-to-random shuffle $\{\sigma_t^*\}$ in the introduction, observe that σ_t^* is obtained from σ_t by a rotation of size $t \mod n$.

We will focus on the following test function $F : S_n \to \mathbb{C}$:

$$F(\sigma) = \frac{1}{n} \sum_{i=0}^{n-1} f(\sigma(i)) \overline{f(i)}. \tag{11}$$

Since f satisfies $\sum_{i=0}^{n-1} f(i) = 0$, under the uniform distribution $\mathcal{U}$ on S_n we have

$$\mathbf{E}_{\mathcal{U}}[F(\sigma)] = 0. \tag{12}$$

It is also easy to see that for the cyclic-to-random shuffle,

$$\mathbf{E}[F(\sigma_t)] = \frac{1}{n} \sum_{i=0}^{n-1} \mathbf{E}[f(\sigma_t(i))] \overline{f(i)} = \lambda^t F(\sigma_0) = \lambda^t \|f\|_2^2, \tag{13}$$

where $\| \cdot \|_2$ denotes the ℓ_2-norm w.r.t. the uniform distribution on $[n]$, i.e., $\|f\|_2^2 = \frac{1}{n} \sum_{i=0}^{n-1} |f(i)|^2$.

We now calculate the second moment of $F(\sigma)$ under the stationary distribution.

Lemma 2.3

$$\mathbf{E}_{\mathcal{U}}\Big(|F(\sigma)|^2\Big) = \frac{\|f\|_2^4}{n-1}\,.$$

Proof: We have

$$\mathbf{E}_{\mathcal{U}}\Big(|F(\sigma)|^2\Big) = \frac{1}{n^2} \sum_{i \neq j} \mathbf{E}_{\mathcal{U}}\Big(f(\sigma(i))\overline{f(\sigma(j))}\Big) f(j)\overline{f(i)} + \frac{1}{n^2} \sum_{i} \mathbf{E}_{\mathcal{U}}\Big(|f(\sigma(i))|^2\Big) |f(i)|^2. \tag{14}$$

The second term in (14) can be evaluated as

$$\frac{1}{n^2} \sum_{i} \mathbf{E}_{\mathcal{U}}\Big(|f(\sigma(i))|^2\Big) |f(i)|^2 = \frac{\|f\|_2^2}{n^2} \sum_{i} |f(i)|^2 = \frac{\|f\|_2^4}{n}. \tag{15}$$

Now let $i \neq j$ and let η be an independent copy of σ. Then

$$\mathbf{E}_{\mathcal{U}}[f(\sigma(i))\overline{f(\sigma(j))}] = \frac{n}{n-1} \left(\mathbf{E}_{\mathcal{U}}\Big(f(\sigma(i))\overline{f(\eta(j))}\Big) - \frac{1}{n} \mathbf{E}_{\mathcal{U}}\Big(|f(\sigma(i))|^2\Big) \right) = -\frac{\mathbf{E}_{\mathcal{U}}\Big(|f(\sigma(i))|^2\Big)}{n-1} = -\frac{\|f\|_2^2}{n-1}.$$

Similarly,

$$\sum_{i \neq j} f(j)\overline{f(i)} = \sum_{i} \sum_{j} f(j)\overline{f(i)} - \sum_{i} |f(i)|^2 = -n\|f\|_2^2.$$

Therefore the first term in (14) can be evaluated as

$$\frac{1}{n^2} \sum_{i \neq j} \mathbf{E}_{\mathcal{U}}[f(\sigma(i))\overline{f(\sigma(j))}] f(j)\overline{f(i)} = -\frac{\|f\|_2^2}{n^2(n-1)} \sum_{i \neq j} f(j)\overline{f(i)} = \frac{\|f\|_2^4}{n(n-1)}. \tag{16}$$

Combining (15) and (16), we obtain the result via (14). ■

For later use, we record here a simple variational bound on f:

Lemma 2.4 *There exists a universal constant c such that $\|f\|_\infty \leq c\|f\|_2$ for all n.*

Proof: Recall that $|\gamma - 1| \leq c/n$ for some $c > 1$ and that $|\gamma| \leq 1$. It follows from (3) that, for all $k \neq 0$,

$$|f(k)| \leq 1 + \frac{c}{n} \sum_{j=1}^{k-1} |\gamma^{j-1}| \leq 1 + c. \tag{17}$$

On the other hand, for $1 \le k \le n/2c$ we have

$$|f(k)| \ge 1 - \frac{c}{n} \sum_{j=1}^{k-1} |\gamma^{j-1}| \ge 1 - \frac{ck}{n} \ge \frac{1}{2}. \tag{18}$$

By (17), we have $\|f\|_\infty \le 1 + c$. From (18), it follows that

$$\|f\|_2 \ge \left(\frac{1}{2c} \left(\frac{1}{2} \right)^2 \right)^{1/2} \ge \frac{1}{2} \frac{1}{(2c)^{1/2}}$$

This completes the proof. ■

2.4 The second moment of $F(\sigma_t)$.

We begin with an estimate of the contribution to the second moment from a specific pair of cards. Fix two distinct cards, i and j. Denote by $A_i(s) = \{\sigma_s(i) = 0\}$ the event that at step s card i is in state 0 (so it will be transposed with a uniform random card in the next step). Let

$$N_{ij}(t) = \sum_{s=0}^{t-1} (\mathbf{P}[A_i(s)] + \mathbf{P}[A_j(s)])$$

denote the expected number of times $s < t$ where one of cards i, j was at state 0. Since at each step there is exactly one card at position 0, we have $\sum_{i=0}^{n-1} \sum_{s=0}^{t-1} \mathbf{P}[A_i(s)] = t$ and therefore

$$\sum_{i \ne j} N_{ij}(t) \le 2nt\,. \tag{19}$$

Next, we will couple $\{\sigma_t\}$ with a process $\{(\eta_t, \widetilde{\eta}_t)\}$, where η and $\widetilde{\eta}$ are two *independent* copies of the cyclic-to-random shuffle starting from the identity permutation. We will observe the motions of cards i, j in $\eta, \widetilde{\eta}$ respectively; note that, unlike in σ, these two motions are independent. We use the coupling to bound the dependence between the cards in σ.

Lemma 2.5 *For any two cards $i \ne j$ and all t we have*

$$\left| \mathbf{E}\left[f(\sigma_t(i)) \overline{f(\sigma_t(j))} \right] - \mathbf{E}\left[f(\eta_t(i)) \overline{f(\widetilde{\eta}_t(j))} \right] \right| \le \frac{4t + 4nN_{ij}(t)}{n^2} \|f\|_\infty^2. \tag{20}$$

Proof: We define inductively a coupling of the process $\{\sigma_t\}$ and the pair process $\{(\eta_t, \widetilde{\eta}_t)\}$. If $(\sigma_s(i), \sigma_s(j)) \ne (\eta_s(i), \widetilde{\eta}_s(j))$ then the updates for the σ and $(\eta, \widetilde{\eta})$ are performed independently. Otherwise, we have

$$(\sigma_s(i), \sigma_s(j)) = (\eta_s(i), \widetilde{\eta}_s(j))\,, \tag{21}$$

and there are three cases to consider in the definition of the coupling at step $s + 1$:

Case 1. Card i is at position 0 at time s.

Case 2. Card j is at position 0 at time s.

Case 3. Both of the cards i, j are not in position 0 at time s.

In Case 1, we take

$$(\sigma_{s+1}(i), \sigma_{s+1}(j)) = \begin{cases} (\ell, \sigma_s(j) + 1) & \mod n \quad \text{w.p. } \frac{1}{n} \text{ for all } \ell \ne \sigma_s(j) + 1, \\ (\sigma_s(j) + 1, 1) & \mod n \quad \text{w.p. } \frac{1}{n}, \end{cases}$$

and

$$(\eta_{s+1}(i),\widetilde{\eta}_{s+1}(j)) = \begin{cases} (\ell,\widetilde{\eta}_s(j)+1) & \bmod n \quad \text{w.p. } \frac{n-1}{n^2} \text{ for all } \ell \neq \widetilde{\eta}_s(j)+1 \\ (\widetilde{\eta}_s(j)+1,1) & \bmod n \quad \text{w.p. } \frac{1}{n^2}, \\ (\widetilde{\eta}_s(j)+1,\widetilde{\eta}_s(j)+1) & \bmod n \quad \text{w.p. } \frac{n-1}{n^2}, \\ (\ell,1) & \bmod n \quad \text{w.p. } \frac{1}{n^2}, \end{cases}$$

Thus, given that the processes satisfy (21) at time s and that at that time card i is at location 0, we may couple the processes to satisfy (21) at time $s+1$ with conditional probability at least $\frac{(n-1)^2}{n^2} > 1-\frac{2}{n}$. Similarly, in Case 2, if the coupling satisfies (21) at time s then (21) can be satisfied at time $s+1$ with conditional probability at least $1-\frac{2}{n}$.

In Case 3, the transition probabilities for the process σ are given by

$$(\sigma_{s+1}(i),\sigma_{s+1}(j)) = \begin{cases} (\sigma_s(i)+1,\sigma_s(j)+1) & \bmod n \quad \text{w.p. } 1-\frac{2}{n}, \\ (\sigma_s(i)+1,1) & \bmod n \quad \text{w.p. } \frac{1}{n}, \\ (1,\sigma_s(j)+1) & \bmod n \quad \text{w.p. } \frac{1}{n}. \end{cases}$$

and the transition probabilities for the process $(\eta,\widetilde{\eta})$ are given by

$$(\eta_{s+1}(i),\widetilde{\eta}_{s+1}(j)) = \begin{cases} (\eta_s(i)+1,\widetilde{\eta}_s(j)+1) & \bmod n \quad \text{w.p. } 1-\frac{2}{n}+\frac{1}{n^2}, \\ (\eta_t(i)+1,1) & \bmod n \quad \text{w.p. } \frac{1}{n}-\frac{1}{n^2}, \\ (1,\widetilde{\eta}_s(j)+1) & \bmod n \quad \text{w.p. } \frac{1}{n}-\frac{1}{n^2}, \\ (1,1) & \bmod n \quad \text{w.p. } \frac{1}{n^2}. \end{cases}$$

It therefore follows that in Case 3, if the processes satisfy (21) at time s, they may be coupled to satisfy it at time $s+1$ with conditional probability $1-\frac{4}{n^2}$.

It now follows that the probability that the processes "unglue" by time t (i.e., (21) fails for some $s \leq t$) is at most

$$\frac{2}{n}N_{ij}(t) + \frac{2t}{n^2}\,. \tag{22}$$

We now estimate the difference of expected values in (20). On the event where the processes satisfy (21) at time t we get a 0 contribution. On the complementary event we get a contribution bounded by $2\|f\|_\infty^2$. We thus obtain (20) by (22). ■

Since the processes η and $\widetilde{\eta}$ are independent, it follows from (13) that

$$\mathbf{E}\left[f(\eta_t(i))\overline{f(\widetilde{\eta}_t(j))}\right] = \mathbf{E}[f(\eta_t(i))]\mathbf{E}[\overline{f(\widetilde{\eta}_t(j))}] = \lambda^t f(i)\overline{\lambda^t f(j)} = |\lambda|^{2t} f(i)\overline{f(j)}.$$

Therefore, by Lemma 2.5 we obtain

Corollary 2.6 *For any two cards $i \neq j$ we have*

$$\left|\mathbf{E}\Big(f(\sigma_t(i))\overline{f(\sigma_t(j))}\Big)\right| \leq \left(|\lambda|^{2t} + \frac{4t+4nN_{ij}(t)}{n^2}\right)\|f\|_\infty^2. \tag{23}$$

We can now bound the second moment of F.

Lemma 2.7 $\mathbf{E}\left[|F(\sigma_t)|^2\right] \leq \left(|\lambda|^{2t} + \dfrac{12t+n}{n^2}\right)\|f\|_\infty^4.$

Proof: We have

$$\mathbf{E}\left[|F(\sigma_t)|^2\right] = \frac{1}{n^2}\sum_{i\neq j}\mathbf{E}\left[f(\sigma_t(i))\overline{f(\sigma_t(j))}\right]f(j)\overline{f(i)} + \frac{1}{n^2}\sum_i \mathbf{E}\left[|f(\sigma_t(i))|^2\right]|f(i)|^2. \tag{24}$$

Note that

$$\frac{1}{n^2}\sum_i \mathbf{E}\left[|f(\sigma_t(i))|^2\right]|f(i)|^2 \leq \frac{\|f\|_\infty^4}{n}. \tag{25}$$

By Corollary 2.6, for any $i \neq j$,

$$\left|\mathbf{E}\left[f(\sigma_t(i))\overline{f(\sigma_t(j))}\right] f(j)\overline{f(i)}\right| \leq \left(|\lambda|^{2t} + \frac{4t+4nN_{ij}(t)}{n^2}\right)\|f\|_\infty^4. \tag{26}$$

Inserting (25) and (26) into (24) we obtain

$$\mathbf{E}\left[|F(\sigma_t)|^2\right] \leq \frac{\|f\|_\infty^4}{n^2}\left(n+n^2|\lambda|^{2t}+4t+\frac{4n}{n^2}\sum_{i\neq j} N_{ij}(t)\right) \leq \frac{\|f\|_\infty^4}{n^2}\left(n+n^2|\lambda|^{2t}+12t\right),$$

using (19). This completes the proof. ■

2.5 The mixing time

Given the bound on the second moment of our test function from the previous section, and the bound on the eigenvalue from section 2.2, it is straightforward to derive a lower bound on the mixing time.

Proof of Theorem 1.1 Recall from Lemma 2.2 that the equation $e^z - z - 1 = 0$ has nonzero roots and let ζ be such a root. By Lemma 2.2 it follows that for large n there exists a solution γ of the equation $(n-1)\gamma^n - n\gamma^{n-1} + 1 = 0$ satisfying (6) and (7). Fix γ and let f be the corresponding eigen-function of M. Let F be the test function (11). Write $\rho = n|1-\lambda|$ and note that $\rho = |\zeta+1| + O(\frac{1}{n})$ by (7).

We use the test function F. Let μ_t be the distribution of σ_t in the cyclic-to-random shuffle where σ_0 is the identity permutation and recall that $\mathcal{U}$ denotes the (uniform) stationary measure on S_n. Let g^2 be the density of μ_t with respect to $\nu = (\mu_t + \mathcal{U})/2$. Let h^2 be the density of $\mathcal{U}$ with respect to ν.

By (12) and (13) we have that

$$|\lambda|^t\|f\|_2^2 = |\mathbf{E}_{\mu_t}[F] - \mathbf{E}_{\mathcal{U}}[F]| = \left|\int Fg^2\,d\nu - \int Fh^2\,d\nu\right|.$$

On the other hand, by Cauchy-Schwartz,

$$\left|\int Fg^2\,d\nu - \int Fh^2\,d\nu\right|^2 = \left|\int F(g+h)(g-h)\,d\nu\right|^2 \leq \int |F|^2(g+h)^2\,d\nu \cdot \int (g-h)^2\,d\nu\,.$$

By Lemma 2.3 and Lemma 2.7,

$$\begin{aligned}\int |F|^2(g+h)^2\,d\nu &\leq 2\int |F|^2g^2\,d\nu + 2\int |F|^2h^2\,d\nu = 2\mathbf{E}_{\mu_t}\left(|F|^2\right) + 2\mathbf{E}_{\mathcal{U}}\left(|F|^2\right)\\ &\leq \frac{2\|f\|_2^4}{n-1} + 2\left(|\lambda|^{2t} + \frac{12t+n}{n^2}\right)\|f\|_\infty^4 \leq 2\left(|\lambda|^{2t} + \frac{12t+3n}{n^2}\right)\|f\|_\infty^4.\end{aligned}$$

Moreover,

$$\int (g-h)^2\,d\nu \leq \int |g^2-h^2|\,d\nu = 2\|\mu_t - \mathcal{U}\|_{\mathrm{TV}}.$$

Recalling Lemma 2.4, we conclude that

$$\|\mu_t - \mathcal{U}\|_{\mathrm{TV}} \geq \frac{|\lambda|^{2t}\|f\|_2^4}{4\|f\|_\infty^4\left(|\lambda|^{2t} + \frac{12t+3n}{n^2}\right)} = \Omega\left(\frac{|\lambda|^{2t}}{\left(|\lambda|^{2t} + \frac{12t+3n}{n^2}\right)}\right).$$

It follows that $\|\mu_t - \mathcal{U}\|_{\mathrm{TV}} = \Omega(1)$ when $\frac{12t+3n}{|\lambda|^{2t}n^2} = O(1)$. Note that if $t \geq n$, then $\frac{12t+3n}{|\lambda|^{2t}n^2} = O(\frac{t}{n^2|\lambda|^{2t}})$ and that if

$$t = \frac{1}{\rho}n\left(\log n - \log\log n - b\right) = \frac{1+O(1/n)}{|\zeta+1|}n\left(\log n - \log\log n - b\right),$$

then

$$\frac{t}{n^2|\lambda|^{2t}} = (1+O(1/n))\frac{n\log n}{\rho n\log ne^b} = \frac{1+O(1/n)}{\rho e^b}.$$

The proof of the theorem follows. ■

3 An upper bound for general semi-random transpositions

In this final section we prove Theorem 1.2.

Proof: By the triangle inequality it suffices to prove the theorem assuming that the L_t are deterministic. We thus restrict to that case.

We define a *strong uniform time* for the shuffle, i.e., a stopping time T with the property that, given $T = t$, the random permutation σ_t^* has the uniform distribution over S_n. It is well known (see, e.g., [3]) that, if T is a strong uniform time, then the distribution μ_t^* of σ_t^* satisfies

$$\|\mu_t^* - \mathcal{U}\|_{\mathrm{TV}} \le \mathbf{P}[T > t] \quad \forall t.$$

Following Broder (as described in [11]) and Mironov [17], we define the stopping time in terms of a card marking process as follows. Initially all cards are unmarked. First, the card initially at L_1 is marked. Later, at time t, we mark the card at L_t if it is unmarked and the card at R_t is already marked, and also if $R_t = L_t$ and this location has an unmarked card. Once a card is marked it remains so at all future times. Set T to be the first time t at which all cards are marked. Clearly T is a stopping time. The theorem follows immediately from the following two claims:

Claim 1: T is a strong uniform time.

Claim 2: There exists $C_0 < \infty$ such that for any $C_1 > C_0$ we have

$$\mathbf{P}\Big(T > C_1 n \log n\Big) \le n^{-\beta},$$

for some $\beta = \beta(C_1) > 0$. Specifically, this holds for $C_0 = 32\theta^{-3} + \theta^{-1}$, where $\theta = e^{-2}(1 - e^{-1})/2$.

Proof of Claim 1: By induction, it is easy to check the following. At any time t, given that k cards have been marked, conditional on the set of marked cards and their locations, the mapping between these two sets (assigning to every marked card its location) is uniformly distributed among the $k!$ possibilities. See [17] or [11] for details.

Proof of Claim 2: Divide time into successive *epochs* of length $2n$, starting after the card at L_1 is marked. Denote by u_k the fraction of unmarked cards before epoch k, so $u_1 = 1 - 1/n$. Let $m_k = 1 - u_k$. Let $\mathcal{H}_k$ denote the history of the process prior to epoch k, and note that u_k is a function of $\mathcal{H}_k$.

Claim 3: $\mathbf{E}(u_{k+1}|\mathcal{H}_k) \le u_k[1 - 2\theta m_k]$ for all k, where $\theta = e^{-2}(1 - e^{-1})/2$.

Proof: Consider a card x, unmarked before epoch k. Of the $2n$ prescribed locations $\{L_t\}$ in the epoch, at most n are their last occurrence in the epoch. Thus for $1 \le j \le n$ we can find $t(j) < s(j)$ in the epoch such that $L_{t(j)} = L_{s(j)}$. For each $j \le n$, we have $R_{t(j)} = x$ with probability $1/n$. Therefore, the event A_x that there exists a $j \le n$ satisfying $R_{t(j)} = x$, has probability

$$\mathbf{P}(A_x|\mathcal{H}_k) \ge 1 - (1 - 1/n)^n \ge 1 - e^{-1}.$$

On A_x, we fix j to be minimal such that $R_{t(j)} = x$. Given A_x and $\mathcal{H}_k$, with probability at least $(1 - 1/n)^{2n-2} > e^{-2}$, we have $R_t \ne L_{t(j)}$ for all t such that $t(j) < t < s(j)$. In that case, x is untouched by the random choices between times $t(j)$ and $s(j)$, and then with probability at least m_k the card at $R_{s(j)}$ is one of the nm_k cards marked prior to epoch k. Thus x gets marked with probability at least $2\theta m_k$. The assertion of Claim 3 follows. ■

Proof of Claim 2 continued: Using Claim 3, we first quantify the time to mark at least half the cards (i.e., to achieve $m_k \ge 1/2$), and then the time to mark the remaining cards (i.e., to achieve $u_k < 1/n$). Denote by D_k the number of cards that get marked during epoch k as a result of being transposed with a card that was marked prior to epoch k. Clearly $m_{k+1} \ge m_k + D_k/n$. The proof of Claim 3 implies that

(i) if $m_k < 1/2$, then $\mathbf{E}(D_k|\mathcal{H}_k) \ge \theta n m_k$;

(ii) if $m_k \ge 1/2$, then $\mathbf{E}(u_{k+1}|\mathcal{H}_k) \le (1 - \theta)u_k$.

To bound the number of epochs where $m_k < 1/2$, we need a stochastic lower bound for D_k:

Claim 4: If $m_k < 1/2$, then

$$\mathbf{P}\Big(D_k \ge \frac{\theta n m_k}{2} \,\Big|\, \mathcal{H}_k\Big) \ge \frac{\theta^2}{8}.$$

Proof: Using the notation in the proof of Claim 3, Denote by $\widetilde{D}_k$ the number of $j \le n$ such that $R_{s(j)}$ is one of the nm_k cards marked prior to epoch k. Clearly $D_k \le \widetilde{D}_k$. The distribution of $\widetilde{D}_k$ is Binomial(n, m_k), and this also holds given $\mathcal{H}_k$. Therefore,

$$\mathbf{E}(D_k^2|\mathcal{H}_k) \le \mathbf{E}(\widetilde{D}_k^2|\mathcal{H}_k) \le (nm_k)^2 + nm_k \le 2(nm_k)^2.$$

In conjunction with (i) above, this yields

$$\mathbf{E}(D_k^2|\mathcal{H}_k) \le C_2\mathbf{E}(D_k|\mathcal{H}_k)^2 \,,$$

where $C_2 = 2\theta^{-2}$. A standard second moment bound (see, e.g., [16, p. 8]) now yields Claim 4. ∎

Proof of Claim 2 concluded: Call epoch k a "growth epoch" if $m_{k+1} \ge (1+\theta/2)m_k$. Call epoch k a "good epoch" if it is a growth epoch or it satisfies $m_k \ge 1/2$. Claim 4 implies that the conditional probability that epoch k is a good epoch, given $\mathcal{H}_k$, is at least $\theta^2/8$. Thus the number of good epochs among the first $k_3 = C_3 \log n$ epochs stochastically dominates a Binomial$(k_3, \theta^2/8)$ random variable. Fix $C_3 > 32\theta^{-3}$, and denote by Ω_3 the event that there are at least $(4\log n)/\theta$ good epochs among the first k_3 epochs. Recall that the probability that a binomial random variable differs from its mean by a constant multiple of the mean decays exponentially in the number of trials $k_3 = C_3 \log n$. We infer that $\mathbf{P}(\Omega_3^c) < n^{-\beta}/2$ for some $\beta > 0$. Since $(1+\theta/2)^{4/\theta} > e$ and $m_1 = 1/n$, the number of growth epochs must be smaller than $(4\log n)/\theta$. Thus on Ω_3 we have $m_{k_3} \ge 1/2$.

Turning now to the second portion, once $m_k \ge 1/2$ we have from (ii) above that $\mathbf{E}(u_{k+1}|u_k) \le (1-\theta)u_k$. Therefore for all $k > 0$, we have

$$\mathbf{E}(u_{k_3+k} \,|\, \Omega_3, u_{k_3}) \le (1-\theta)^k u_{k_3} \le \frac{e^{-\theta k}}{2} \,.$$

Thus if $k = (1+\beta)\theta^{-1}\log n$, then

$$\mathbf{P}(u_{k_3+k} \ge 1/n \,|\, \Omega_3) \le \mathbf{E}(nu_{k_3+k} \,|\, \Omega_3) \le n \cdot \frac{n^{-1-\beta}}{2} = \frac{n^{-\beta}}{2} \,.$$

In conjunction with the bound for $\mathbf{P}(\Omega_3^c)$, this implies that $\mathbf{P}(u_{k_3+k} \ge 1/n) \le n^{-\beta}$ for this value of k. In other words, if $C_1 > C_0 = 32\theta^{-3} + \theta^{-1}$ and $k_1 = C_1 \log n$, then there exists $\beta = \beta(C_1) > 0$ such that $\mathbf{P}(u_{k_1} \ge 1/n) \le n^{-\beta}$. This completes the proofs of Claim 2 and of the theorem. ∎

4 Concluding remarks and further problems

1. We have shown that the cyclic-to-random transposition shuffle on n cards has mixing time of order $\Theta(n \log n)$. However, the constant in our general upper bound, and that in the specific cyclic-to-random upper bound of Mironov [17], are significantly larger than the constant in our lower bound. We believe that the lower bound is closer to the truth, and moreover, that this shuffle exhibits the "cutoff phenomenon", i.e., there is a constant C_* such that for $t < (1-\epsilon)C_* n \log n$ the distribution after t steps, μ_t^*, satisfies $\|\mu_t^* - \mathcal{U}\|_{\mathrm{TV}} = 1 - o(1)$ as $n \to \infty$, while for $t > (1+\epsilon)C_* n \log n$ we have $\|\mu_t^* - \mathcal{U}\|_{\mathrm{TV}} = o(1)$ as $n \to \infty$. Proving this, and determining C_*, remain a challenge.

2. Does the cyclic-to-random shuffle capture the key features of the RC4 cryptographic system, as suggested by Mironov [17]?
   If the answer is positive, then we expect that the test function F defined in (11) may play a role in future analysis of RC4.

3. For which sequence $\{L_t\}$ does the resulting semi-random transposition shuffle on n cards have the largest mixing time?
   We suspect that the slowest shuffle in this class is the "star transpositions" shuffle, for which $L_t = 0$ for all t, and the mixing time is $(1+o(1))n \log n$ by [10].

4. Is there a universal constant $c > 0$ such that, for any semi-random transposition shuffle on n cards, the mixing time is at least $cn \log n$?
For this lower bound question there is no obvious reduction to the case where the sequence $\{L_t\}$ is deterministic, so conceivably the question could have different answers for deterministic $\{L_t\}$ and random $\{L_t\}$. Two specific cases of interest are:

   - For each $k \geq 0$, let $\{L_{kn+r}\}_{r=1}^{n}$ be a uniform random permutation of $\{0, \ldots, n-1\}$, where these permutations are independent.
   - Let $\{L_t\}$ be a Markov chain with memory 2, where $L_1 = 0, L_2 = 1$ and for each $t \geq 3$ we have $L_{t+1} = 2L_t - L_{t-1} \mod n$ with probability $1 - 1/n$ and $L_{t+1} = L_{t-1}$ with probability $1/n$. This choice of $\{L_t\}$ was suggested to us by Igor Pak (personal communication), motivated by [9].

   Each of these examples has a "quenched" version, where the sequence $\{L_t\}$ is picked in advance and then used as a deterministic sequence, and an "annealed" version, where the $\{L_t\}$ are random variables with the specified distribution.

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