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# Let's Get Movin': Frontiers of Optimal Transport

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## 1 Introduction and Background

### 1.1 The Optimal Transport Problem and Basic Properties

Let  $\mathbf{a} \in \mathbb{R}_{\geq 0}^n$  and  $\mathbf{b} \in \mathbb{R}_{\geq 0}^m$  be two vectors of non-negative real numbers such that  $\mathbf{a}^T \mathbf{1} = \mathbf{b}^T \mathbf{1} = 1$ , where  $a_i$  and  $b_j$  represents the amount of “mass” at different positions. We are interested in a matrix  $\mathbf{P} \in \mathbb{R}_{\geq 0}^{n \times m}$  where  $P_{ij}$  prescribes the amount of mass flowing from  $a_i$  to  $b_j$ . Naturally, we must have  $\sum_j P_{ij} = a_i$  and  $\sum_i P_{ij} = b_j$ , so that mass is preserved. Let  $\mathbf{C} \in \mathbb{R}^{n \times m}$  be a *cost matrix*, where  $C_{ij}$  represents the cost of transporting one unit of  $a_i$  to  $b_j$ . The *Kantorovich optimal transport problem* is the following linear program:

$$\min_{\mathbf{P} \in \mathbf{U}(\mathbf{a}, \mathbf{b})} \sum_{i,j} P_{ij} C_{ij} \quad (\text{Kantorovich})$$

where

$$\mathbf{U}(\mathbf{a}, \mathbf{b}) = \{\mathbf{P} \in \mathbb{R}_{\geq 0}^{n \times m} : \mathbf{P} \mathbf{1} = \mathbf{a}, \mathbf{P}^T \mathbf{1} = \mathbf{b}\}.$$

*Remark 1* (A probabilistic view). Let  $X, Y$  be discrete random variables with support  $\mathbf{x} \in \mathcal{X}^m$  and  $\mathbf{y} \in \mathcal{Y}^n$ , such that their marginal distributions are prescribed by  $P(X = x_i) = a_i$  and  $P(Y = y_j) = b_j$ . Let  $P_{ij} = P(X = x_i, Y = y_j)$ , making  $\mathbf{P} = (P_{ij})_{ij}$  a joint distribution. Let  $C : \mathcal{X} \times \mathcal{Y} \rightarrow \mathbb{R}$  be a cost function. Then the (Kantorovich) is equivalent to the following:

$$\min_{\mathbf{P}} \mathbb{E}_{(X,Y) \sim \mathbf{P}} [C(X, Y)],$$

where the expectation is taken over valid joint distributions of  $(X, Y)$  respecting the marginal distributions. Note that when  $\mathcal{X} = \mathcal{Y} = \mathbb{R}^d$  and  $C(x, y) = \|x - y\|^p$ , then the optimal value of the above problem for  $X, Y$  is the  $p$ -Wasserstein distance between the marginal distributions  $\mu_X, \mu_Y$  (up to a power of  $1/p$ ), for discrete,  $d$ -dimensional distributions with finite support.

**Duality** It can be shown that the dual problem of the above LP takes the following form:

$$\begin{aligned} & \max_{(\mathbf{f}, \mathbf{g}) \in \mathbb{R}^m \times \mathbb{R}^n} \sum_i a_i f_i + \sum_j b_j g_j \\ & \text{subjected to } f_i + g_j \leq C_{ij} \text{ for all } i, j. \end{aligned}$$

The dual problem has a neat economic intuition. Suppose Kevin needs to transport  $\mathbf{a}$  to  $\mathbf{b}$  but does not understand how. Francisco, his profit-maximizing colleague, offers him a deal, where Kevin will pay  $f_i$  for Francisco to pick up a unit of mass at  $a_i$  and pay  $g_j$  for Francisco to dropoff a unit of mass at  $b_j$ . At minimum, Kevin knows that if any  $f_i + g_j > C_{ij}$ , then Francisco is ripping him off, as

transporting one unit from  $a_i$  to  $b_j$  costs exactly  $C_{ij}$ . If, on the other hand,  $f_i + g_j \leq C_{ij}$  is satisfied, then given any  $\mathbf{P}$ , we have

$$\sum_{i,j} C_{ij} P_{ij} \geq \sum_{i,j} f_i P_{ij} + \sum_{i,j} g_j P_{ij} = \sum_i f_i a_i + \sum_j g_j b_j, \quad (\text{Weak duality})$$

which means that Kevin cannot lose by taking Francisco's deal. Strong duality, which indeed holds, here imply that Francisco's optimal profit is zero, and the trade is fair.

Given optimal solutions to the primal and dual,  $\mathbf{P}$ ,  $(\mathbf{f}, \mathbf{g})$ , respectively, *complementary slackness* implies that

$$P_{ij}(C_{ij} - f_i - g_j) = 0 \quad (\text{Complementary slackness})$$

holds, which means that  $\mathbf{P}_{ij} \neq 0 \implies C_{ij} = f_i - g_j$  and vice versa.

## 1.2 Applications

## 2 Exact Methods

### 2.1 Linear Programming

The **Kantorovich** Optimal Transport problem as formulated is an LP. This means that a natural first-step to benchmarking the problem difficulty is to use a generic LP solver. The only difficulty we face when doing this is that we must flatten our arguments from matrices to vectors in order to fit the API of a generic LP solver, such as `cvxopt.solvers.lp` which we employ. Recall that our problem inputs are  $\mathbf{a} \in \mathbb{R}_{\geq 0}^n$ ,  $\mathbf{b} \in \mathbb{R}_{\geq 0}^m$  with sum of entries equal to 1 and  $\mathbf{C} \in \mathbb{R}^{n,m}$ . We flatten  $\mathbf{C}$  into a vector  $\mathbf{c} \in \mathbb{R}^{nm}$  and define the matrix

$$\mathbf{A} := \begin{bmatrix} I_n \otimes \mathbf{1}_m \\ \mathbf{1}_n \otimes I_m \end{bmatrix}$$

which allows us to formulate our LP as,

$$\min \mathbf{c}^\top \mathbf{x} \text{ such that } \mathbf{x} \geq 0, \mathbf{A}\mathbf{x} = \begin{bmatrix} \mathbf{a} \\ \mathbf{b} \end{bmatrix}.$$

We may then benchmark the performance of this data by generating data. We generate random square  $n \times n$  cost matrices by making each entry i.i.d.  $\chi^2(1)$ , and perform optimal transport on  $\mathbf{a} = \mathbf{b} = \mathbf{1}_n/n$ . The runtimes for different values of  $n$  are documented in **Fig. 1**.

### 2.2 Hungarian Algorithm

## 3 Inexact Methods

### 3.1 Entropic Regularization and Sinkhorn's Algorithm

Let

$$H(\mathbf{P}) = - \sum_{i,j} P_{ij} (\log P_{ij} - 1)$$

be the *entropy* of the transport matrix  $\mathbf{P}$ . Observe that

$$\nabla_{\mathbf{P}}^2(-H(\mathbf{P})) - I \text{ is positive semidefinite,}$$

and so  $-H(\mathbf{P})$  is 1-strongly convex. We regularize the objective of (**Kantorovich**) by  $-\epsilon H(\mathbf{P})$ :

$$\min_{\mathbf{P} \in \mathbf{U}(\mathbf{a}, \mathbf{b})} \sum_{i,j} P_{ij} C_{ij} - \epsilon H(\mathbf{P}) \quad (\text{Entropic Regularization})$$

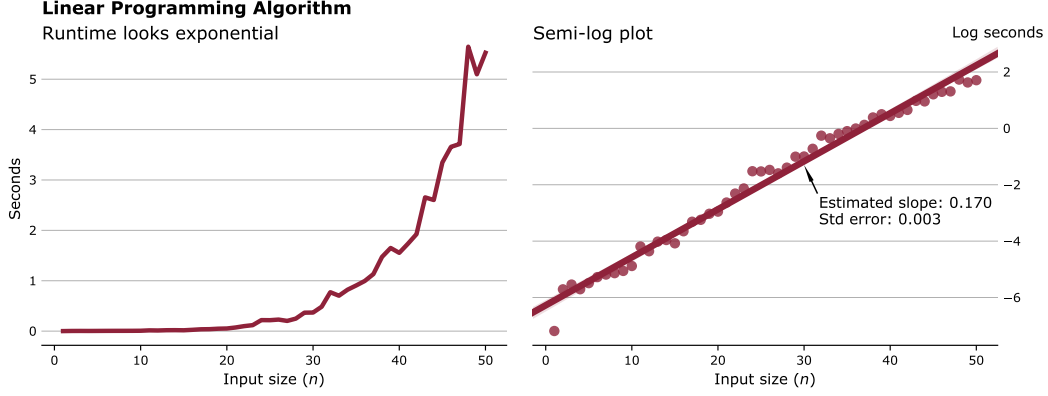


Figure 1: Runtime comparison

so as to make the objective  $\epsilon$ -strongly convex. *Entropic regularization* approximates (Kantorovich) by solving (Entropic Regularization), where

$$\arg \min_{\mathbf{P} \in \mathbf{U}(\mathbf{a}, \mathbf{b})} \sum_{i,j} P_{ij} C_{ij} - \epsilon H(\mathbf{P}) \xrightarrow{n \rightarrow \infty} \arg \min_{\mathbf{P} \in \mathbf{U}(\mathbf{a}, \mathbf{b})} \sum_{i,j} P_{ij} C_{ij},$$

where the convergence is towards the maximal-entropy solution of (Kantorovich). The convergence property makes (Entropic Regularization) an attractive alternative to solving optimal transport; other reasons why (Entropic Regularization) is useful is explored in a seminal article by [Cut13].

Leveraging duality theory, the Lagrangian of the regularized problem is

$$\begin{aligned} \mathcal{L}(\mathbf{P}, \mathbf{f}, \mathbf{g}) &= \sum_{i,j} P_{ij} C_{ij} + \epsilon \sum_{i,j} P_{ij} (\log P_{ij} - 1) \\ &\quad + \sum_i f_i \left( a_i - \sum_j P_{ij} \right) + \sum_j g_j \left( b_j - \sum_i P_{ij} \right), \end{aligned}$$

where the first-order condition on  $\mathbf{P}$  shows that the optimum  $\mathbf{P}^*$  satisfies

$$C_{ij} + \epsilon \log P_{ij}^* - f_i^* - g_j^* = 0 \implies \mathbf{P}^* = \text{diag}(\exp(\mathbf{f}^*/\epsilon)) \exp(-\mathbf{C}/\epsilon) \text{diag}(\exp(\mathbf{g}^*/\epsilon)) \quad (1)$$

for some  $\mathbf{f}^*, \mathbf{g}^*$ , where the exp is taken component-wise. Suppose  $\mathbf{f}^*, \mathbf{g}^*$  is such that  $\mathbf{P}^*$  defined by (1) is within the constraints  $\mathbf{U}(\mathbf{a}, \mathbf{b})$ , then the value of the Lagrangian  $\mathcal{L}(\mathbf{P}^*, \mathbf{f}^*, \mathbf{g}^*)$  equals the value of (Entropic Regularization), and since  $\mathbf{P}^*$  is chosen to maximize the strongly concave function  $\mathbf{P} \mapsto \mathcal{L}(\mathbf{P}, \mathbf{f}^*, \mathbf{g}^*)$ , we have that  $(\mathbf{P}^*, \mathbf{f}^*, \mathbf{g}^*)$  solves both programs.

Before proceeding, we define some notation that is a hybrid of [PC<sup>+</sup>17] and [AWR17]. Let  $\mathbf{A} = \exp(-\mathbf{C}/\epsilon)$ ,  $\mathbf{u} = \exp(\mathbf{f}/\epsilon)$ ,  $\mathbf{v} = \exp(\mathbf{g}/\epsilon)$ ,  $\mathbf{x} = \log \mathbf{u}$ ,  $\mathbf{y} = \log \mathbf{v}$ ,  $\mathbf{X} = \text{diag}(\mathbf{u})$ ,  $\mathbf{Y} = \text{diag}(\mathbf{v})$ , where exp, log are taken componentwise. Thus, we aim to find vectors  $\mathbf{u}, \mathbf{v}$ , such that

$$\mathbf{P}^* = \mathbf{XAY}.$$

satisfies the constraints  $\mathbf{U}(\mathbf{a}, \mathbf{b})$ . In terms of  $\mathbf{u}, \mathbf{v}$ , the constraints are

$$\mathbf{u} \odot (\mathbf{A}\mathbf{v}) = \mathbf{a} \quad \text{and} \quad \mathbf{v} \odot (\mathbf{A}^T \mathbf{u}) = \mathbf{b} \quad (2)$$

(2) shows that, given  $\mathbf{v}$ , we can only set  $\mathbf{u} = \frac{\mathbf{a}}{\mathbf{A}\mathbf{v}}$ , where division is componentwise. This motivates the Sinkhorn-Knopp algorithm [SK67], which iteratively updates  $\mathbf{u}, \mathbf{v}$  such that one of the constraints hold exactly in this fashion. In practical implementation, to prevent numerical underflow, the algorithm should work in log-space with  $\mathbf{x}, \mathbf{y}$ . Algorithm 1 presents a numerically stable implementation of Sinkhorn-Knopp that terminates when the  $\ell_1$  error on constraint violation gets sufficiently small.

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**Algorithm 1** Numerically stable Sinkhorn-Knopp algorithm as presented in [AWR17]

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function SINKHORN(A, a, b,  $\epsilon$ )
  Initialize  $k = 0$ 
   $\mathbf{P}^{(0)} \leftarrow \mathbf{A}, \mathbf{x}^0 \leftarrow 0, \mathbf{y}^0 \leftarrow 0$ 
  while  $\|\mathbf{P}^{(k)} \mathbf{1} - \mathbf{a}\|_1 + \|(\mathbf{P}^{(k)})^T \mathbf{1} - \mathbf{b}\|_1 > \epsilon$  do
     $k \leftarrow k + 1$ 
    if  $k$  is odd then
       $\Delta \mathbf{x} \leftarrow \log \frac{\mathbf{a}}{\mathbf{P}^{(k-1)} \mathbf{1}}$ 
       $\mathbf{x}^k \leftarrow \mathbf{x}^{k-1} + \Delta \mathbf{x}, \mathbf{y}^k \leftarrow \mathbf{y}^{k-1}$ 
    end if
    if  $k$  is even then
       $\Delta \mathbf{y} \leftarrow \log \frac{\mathbf{b}}{(\mathbf{P}^{(k-1)})^T \mathbf{1}}$ 
       $\mathbf{x}^k \leftarrow \mathbf{x}^{k-1}, \mathbf{y}^k \leftarrow \mathbf{y}^{k-1} + \Delta \mathbf{y}$ 
    end if
     $\mathbf{P}^{(k)} \leftarrow \mathbf{X}^k \mathbf{A} \mathbf{Y}^k$ 
  end while
  return  $\mathbf{P}^{(k)} / \|\mathbf{P}^{(k)}\|_1$ 
end function

```

$\triangleright \mathbf{P}^{(0)}$  is not normalized;  $\mathbf{P}^{(k)}, k > 0$  is normalized.

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At each step of [Algorithm 1](#), if  $k$  is odd, then  $\mathbf{P}^{(k)}$  matches row-wise with  $\mathbf{a}$ , and if  $k$  is even, then  $\mathbf{P}^{(k)}$  matches column-wise with  $\mathbf{b}$ .

Note that [Algorithm 1](#) does not output a matrix that satisfies the conditions  $\mathbf{U}(\mathbf{a}, \mathbf{b})$  exactly. However, [AWR17, Algorithm 2] analyzes a rounding scheme that forces the output to be inside  $\mathbf{U}(\mathbf{a}, \mathbf{b})$ . The rounding scheme introduces error on the order of  $\epsilon$  and thus does not pose any problems for solving the original program ([Entropic Regularization](#)). The rest of this section will be devoted to an analysis of [Algorithm 1](#).

### 3.1.1 Convergence

*A priori*, it is unclear that [Algorithm 1](#) converges, nor is the speed of convergence obvious. [AWR17] presents an extremely succinct analysis of [Algorithm 1](#), which we reproduce in this section. Let

$$f(\mathbf{x}, \mathbf{y}) = \sum_{i,j} A_{ij} e^{x_i + y_j} - \sum_i a_i x_i - \sum_j b_j y_j.$$

The first order conditions for the optimality of  $f$  gives  $\mathbf{x}, \mathbf{y}$  that ensures (2). Sinkhorn-Knopp can be viewed as coordinate descent on  $f$ : To optimize  $x_i^k$ , the first order condition yields

$$x_i^k = \log \frac{a_i}{\sum_j A_{ij} e^{y_j^{k-1}}} = \log \frac{a_i}{e^{x_i^{k-1}} \sum_j A_{ij} e^{y_j^{k-1}}} + x_i^{k-1} = \log \frac{a_i}{\mathbf{P}^{(k-1)} \mathbf{1}} + x_i^{k-1},$$

which is exactly the update rule in [Algorithm 1](#).

*Remark 2.* We do not need to limit ourselves to using coordinate descent to minimize  $f$ . For instance [BCLW17] uses Newton's method, and achieves similar convergence performance as [Algorithm 1](#).

The proof of [AWR17] uses the follow strategy. First, we calculate the step gain in the Sinkhorn-Knopp algorithm for optimizing  $f$  in terms of Kullback-Leibler divergences. Next we bound the distance of  $f$ 's initial value from its optimal value. Lastly, using Pinsker's inequality, we show that if [Algorithm 1](#) does not terminate, then the step size must be larger than  $C\epsilon^2$ , which then gives a bound of convergence in  $\epsilon^{-2}$ .

For  $k > 1$ , we can calculate the gain of each step [AWR17, Lemma 2]:

$$\begin{aligned}
f(\mathbf{x}^{k-1}, \mathbf{y}^{k-1}) - f(\mathbf{x}^k, \mathbf{y}^k) &= \left( \sum_{i,j} A_{ij} e^{x_i^{k-1} + y_j^{k-1}} - \sum_{i,j} A_{ij} e^{x_i^k + y_j^k} \right) \\
&\quad + \langle \mathbf{a}, \mathbf{x}^k - \mathbf{x}^{k-1} \rangle + \langle \mathbf{b}, \mathbf{y}^k - \mathbf{y}^{k-1} \rangle \\
&= (1 - 1) + \text{KL}(\mathbf{a} \| \mathbf{P}^{(k)} \mathbb{1}) + \text{KL}(\mathbf{b} \| (\mathbf{P}^{(k)})^T \mathbb{1}) \\
&\quad \text{(Writing out the inner products)} \\
&= \text{KL}(\mathbf{a} \| \mathbf{P}^{(k)} \mathbb{1}) + \text{KL}(\mathbf{b} \| (\mathbf{P}^{(k)})^T \mathbb{1}). \tag{3}
\end{aligned}$$

(3) gives an elegant formulation of the gain each step exactly as a function of the Kullback-Leibler divergence between the target distribution and the current marginal distribution.

Next, we claim that the total distance in  $f$  that we are required to travel is bounded above [AWR17, Lemma 3]. Note that **Algorithm 1** behaves almost identically—producing the same  $\mathbf{P}^{(k)}$  at each iteration—if the input  $\mathbf{A}$  passed in is multiplied by a constant. Thus we may without loss of generality replace  $\mathbf{A}$  with  $\mathbf{A}_0 = \mathbf{A} / \|\mathbf{A}\|_1$ . Let  $f^k$  denote  $f(\mathbf{x}^k, \mathbf{y}^k)$  and  $f^*$  denote  $\min f$ . Then we have  $f(0, 0) - f^1 = \text{KL}(\mathbf{a} \| \mathbf{A}_0 \mathbb{1}) \geq 0$ . Thus

$$f^1 - f^* \leq f(0, 0) - f^* = \sum_i a_i x_i^* + \sum_j b_j y_j^* \leq \max_{i,j} (x_i^* + y_j^*).$$

Observe that  $A_{0,ij} e^{x_i^* + y_j^*} \leq \sum A_{0,ij} e^{x_i^* + y_j^*} = 1$ . Therefore  $x_i^* + y_j^* \leq -\log A_{0,ij} \leq \log \frac{\|\mathbf{A}\|_1}{\min_{i,j} A_{ij}}$ . Putting these together shows that

$$f^1 - f^* \leq \log \frac{\|\mathbf{A}\|_1}{\min_{i,j} A_{ij}}. \tag{4}$$

Lastly, Pinsker’s inequality [AWR17, Lemma 4], a well-known result in information theory, states that for any probability measures  $p, q$ ,

$$\|p - q\|_1^2 \leq 2 \text{KL}(p \| q).$$

Applying Pinsker’s inequality shows that every step in **Algorithm 1** before termination has

$$\epsilon < \left\| \mathbf{P}^{(k)} \mathbb{1} - \mathbf{a} \right\|_1 + \left\| (\mathbf{P}^{(k)})^T \mathbb{1} - \mathbf{b} \right\|_1 \leq \left[ 4 \left( \text{KL}(\mathbf{a} \| \mathbf{P}^{(k)} \mathbb{1}) + \text{KL}(\mathbf{b} \| (\mathbf{P}^{(k)})^T \mathbb{1}) \right) \right]^{1/2}.$$

Therefore we improve  $f$  by more than  $\frac{1}{4}\epsilon^2$  every step before termination. Since the total improvement is bounded by (4), we arrive at the main result of [AWR17]:

**Theorem 1** ([AWR17]). *Algorithm 1 terminates in at most  $4\epsilon^{-2} \log \frac{\|\mathbf{A}\|_1}{\min_{i,j} A_{ij}}$  steps.*

### 3.1.2 Numerical Experiments

We implement **Algorithm 1** and compute the  $\ell_1$  distance  $\left\| \mathbf{P}^{(k)} \mathbb{1} - \mathbf{a} \right\|_1 + \left\| (\mathbf{P}^{(k)})^T \mathbb{1} - \mathbf{b} \right\|_1$  as a function of  $k$ . We generate random marginal distribution targets  $\mathbf{a}, \mathbf{b}$  by sampling from a uniform distribution on the unit interval and normalizing by the sum. We generate random cost matrices by sampling each component from a uniform distribution. We plot the log-log plot in Fig. 2. Note that if the results of **Theorem 1** is tight for these random matrices and constraints, then the log-log plot should look linear with slope  $-2$ . This is not what we observe in Fig. 2, suggesting that the average case—if not worst case—of **Algorithm 1** may be better than  $O(\epsilon^{-2})$ . In fact, if we plot the log of error against  $k$ , we find that the relationship is linear, suggesting that, for these random matrices and distributions, the behavior of **Algorithm 1** is  $O(\log(1/\epsilon))$ .

### 3.1.3 Towards a Tightness Analysis of **Theorem 1**

Section 3.1.2 suggests that the bound of  $\epsilon^{-2}$  may be far too generous. In this section we sketch a potential direction in analyzing the worst-case performance of **Algorithm 1**. [Sas15] gives a reverse

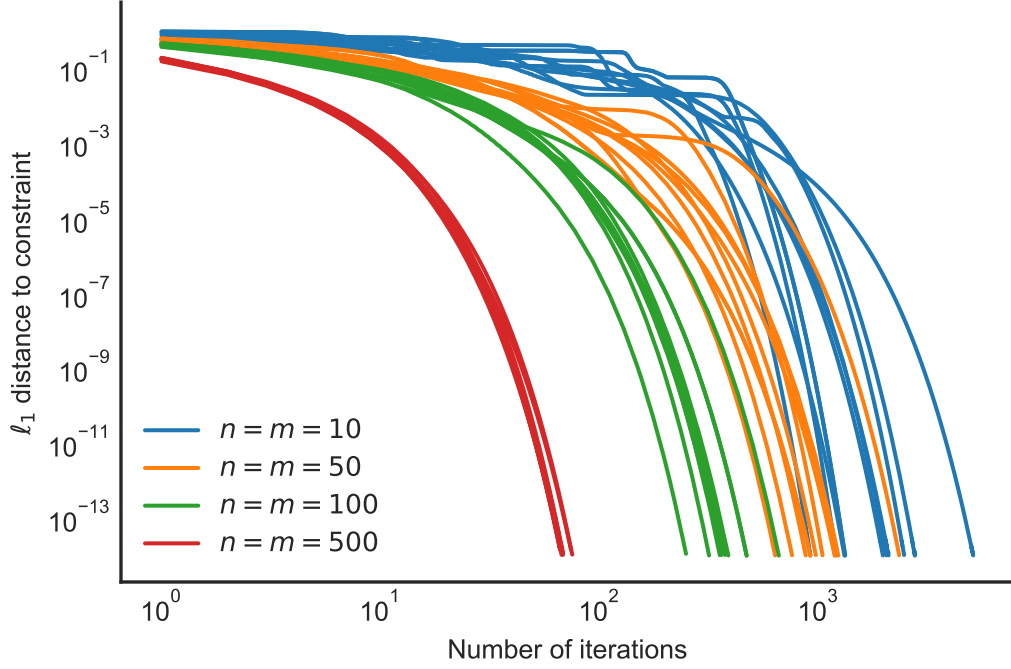


Figure 2: Numerical experiments on the speed of  $\ell_1$  convergence for [Algorithm 1](#)

Pinsker's inequality: For discrete probability measures on finite support  $p, q$ ,

$$\text{KL}(p||q) \leq \log \left( 1 + \frac{1}{q_{\min}} \|p - q\|_1^2 \right) \leq \frac{1}{q_{\min}} \|p - q\|_1^2,$$

where  $q_{\min}$  is the minimum of  $q$  on its support. The inequality suggests that before termination and after the  $\ell_1$  error reaches some  $\delta$ , every step of [Algorithm 1](#) improves  $f$  by at most

$$\text{KL}(\mathbf{a}||\mathbf{P}^{(k)}\mathbb{1}) + \text{KL}(\mathbf{b}||(\mathbf{P}^{(k)})^T\mathbb{1}) \leq \frac{C}{\min(\mathbf{P}^{(k)}\mathbb{1}, (\mathbf{P}^{(k)})^T\mathbb{1})} \delta^2,$$

for some constant  $C$ , where the minimum is taken element-wise. We can remove the dependence on  $k$  of the right-hand side by the following consideration. Let  $k'$  be the first time that the  $\ell_1$ -error is below  $\frac{1}{2} \min(\mathbf{a}, \mathbf{b})$ . Then for every  $k > k'$ ,  $\min(\mathbf{P}^{(k)}\mathbb{1}, (\mathbf{P}^{(k)})^T\mathbb{1}) \geq \frac{1}{2} \min(\mathbf{a}, \mathbf{b})$ , and so the bound becomes

$$\text{KL}(\mathbf{a}||\mathbf{P}^{(k)}\mathbb{1}) + \text{KL}(\mathbf{b}||(\mathbf{P}^{(k)})^T\mathbb{1}) \leq \frac{C'}{\min(\mathbf{a}, \mathbf{b})} \delta^2, \quad (5)$$

for  $k > k'$ . Let  $k_\epsilon$  be the step immediately before termination. Let  $k_\delta$  be the first iteration such that  $k_\delta > k'$  and that  $k_\delta$  reaches  $\ell_1$ -error of  $\delta$ . If we can show that there is some inputs  $\mathbf{A}, \mathbf{a}, \mathbf{b}, \epsilon$  for which we can bound the total improvement  $f^{k_\epsilon} - f^{k_\delta}$  below by some quantity  $M(\mathbf{A}, \mathbf{a}, \mathbf{b}, \epsilon, \delta)$ , then for the inputs  $\mathbf{A}, \mathbf{a}, \mathbf{b}, \epsilon$ , [Algorithm 1](#) has a lower bound of  $\Omega(M(\mathbf{A}, \mathbf{a}, \mathbf{b}, \epsilon, \delta)\delta^{-2} \min(\mathbf{a}, \mathbf{b}))$ . Here,  $\delta$  should be implicitly a function of  $\epsilon$ , e.g.  $\delta = \sqrt{\epsilon}$ , so that the bound is a function of  $\epsilon$ . Choosing  $\delta(\epsilon)$  such that the bound  $M(\mathbf{A}, \mathbf{a}, \mathbf{b}, \epsilon, \delta)$  is tractable is a major difficulty, which we leave to future work.

### 3.2 Genetic Algorithm

Recent advances in machine learning points towards the versatility of genetic algorithms, even as a competitive alternative to deep learning based on gradient methods [[SMC<sup>+</sup>17](#)]. Inspired by these advances, we consider the following genetic algorithm

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**Algorithm 2** A toy genetic algorithm for optimal transport

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```
function GENETICOT( $\phi, \gamma, k, \mathbf{a}, \mathbf{b}, T$ )  
  initial  $\leftarrow \mathbf{a}\mathbf{b}^T$   
  family  $\leftarrow \text{Array}[\phi]$ , initialized to initial  
  children  $\leftarrow \text{Array}[\phi\gamma]$ , initialized to empty  
  for generation in  $1 : T$  do  
    for person in family do  
      for person' in SUBSET(family,  $\gamma$ ) do ▷ SUBSET chooses a subset of size  $\gamma$   
        child  $\leftarrow \text{MARRY}(\text{person}, \text{person}')$   
        child  $\leftarrow \text{PERTURB}(\text{child}, k)$   
        Add child to children  
      end for  
    end for  
    Choose the  $\phi$  elements in children with minimal cost for (Kantorovich) and set to family  
  end for  
  return element in family that achieves minimal cost  
end function
```

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Here MARRY picks two probability matrices and averages them elementwise, and PERTURB chooses random indices  $i_1, i_2, j_1, j_2$  and moves mass in the probability matrix in such a way that preserves the marginal distributions and respects the constraint that  $0 \leq p \leq 1$  for all components  $p$ . Such perturbations are repeated  $k$  times.  $\phi$  is a parameter that controls the size of families, and  $\gamma$  is a parameter that decides the number of offsprings. At each generation, we take the top  $\phi$  matrices that achieve the lowest cost. We hoped that the population drifts towards the optimal transport matrix as the number of generation increases.

The empirical results we obtain are less than encouraging, however. We plot the optimal cost each generation with  $n = m = 4, \phi = 100, \gamma = 5$  for various values of  $k$  in Fig. 3. Curiously, the improvement in the first generation is always large, with a magnitude of improvement increasing in  $k$ , but the algorithm seems to achieve some non-optimal steady state as generation goes on. Of course, Algorithm 2 can potentially be improved by thinking about the design of MARRY and PERTURB more carefully, perhaps leveraging some information about  $\mathbf{C}$ .

## 4 Applications and Experiments

## 5 Conclusion

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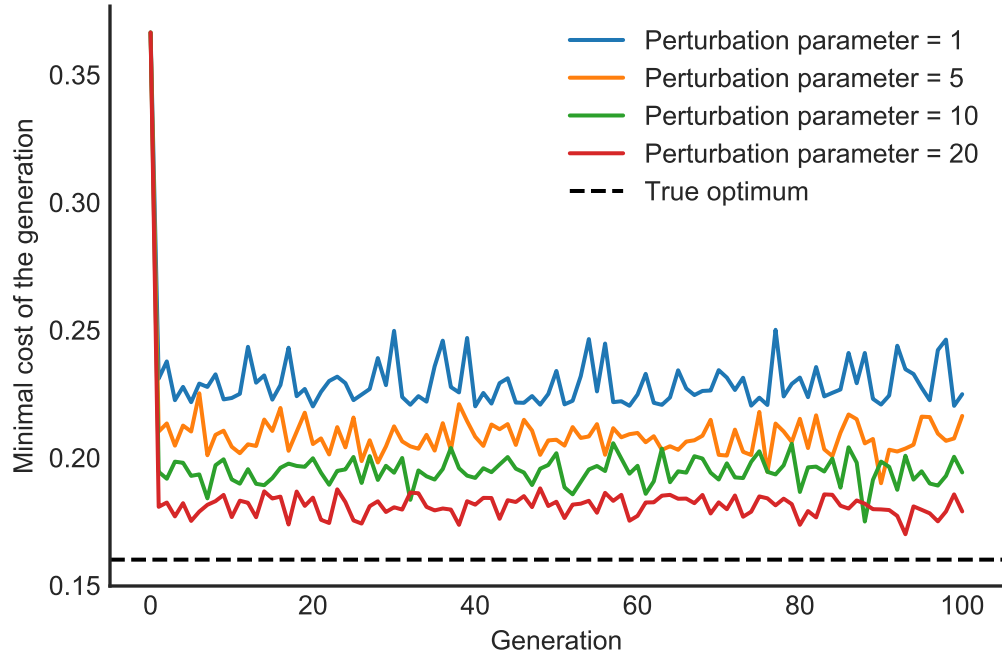


Figure 3: Non-convergence of Algorithm 2

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