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Wasserstein Barycentric Coordinates: Histogram Regression Using Optimal Transport

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Abstract

This article defines a new way to perform intuitive and geometrically faithful regressions on histogram-valued data. It leverages the theory of optimal transport, and in particular the definition of Wasserstein barycenters, to introduce for the first time the notion of barycentric coordinates for histograms. These coordinates take into account the underlying geometry of the ground space on which the histograms are defined, and are thus particularly meaningful for applications in graphics to shapes, color or material modification. Beside this abstract construction, we propose a fast numerical optimization scheme to solve this backward problem (finding the barycentric coordinates of a given histogram) with a low computational overhead with respect to the forward problem (computing the barycenter). This scheme relies on a backward algorithmic differentiation of the Sinkhorn algorithm which is used to optimize the entropic regularization of Wasserstein barycenters. We showcase an illustrative set of applications of these Wasserstein coordinates to various problems in computer graphics: shape approximation, BRDF acquisition and color editing.

Keywords: optimal transport, fitting

Concepts: • Computing methodologies → Computer graphics; • Mathematics of computing → Automatic differentiation; • Applied computing → Transportation;

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1 Introduction

Probability histograms play an important role in graphics. From color histograms to reflectance distribution functions, or even digital 3D shapes, probability histograms are routinely used to encode complex physical properties into vectors. The space of features these distributions are supported on—here, color space, sphere and spatial grid—can be often endowed with a distance, which encodes important invariances among features.

Optimal transport theory [Villani 2008; Rubner et al. 2000] proposes a natural way to lift a distance between features to define a metric between probability histograms on features. Optimal transport theory sees probability histograms as heaps of sand, and quantifies the distance between two of them by considering the least costly way to move all sand particles from one histogram to reshape it into the other. In this way, two histograms only differing by a small displacement are very near in the optimal transport sense, while they could be, in sharp contrast, regarded as very dissimilar under the $\ell_2$ and $\ell_1$ metrics or the KL divergence, particularly so if these two histograms have little overlap.

Because the optimal transport metric emphasizes mass displace-
We propose the first numerical scheme to compute Wasserstein barycenters, which are particularly suited to applications in graphics, where such concepts of motions are often meaningful: the rotation of the color wheel, the motion of highlights in reflectance models, Hausdorff distances between shapes etc. From a practical perspective, these interpolations can only find applications in graphics if they are computationally cheap. Although direct approaches to compute such interpolations were first believed to be intractable and degenerated [Agueh and Carlier 2011, §4], recent work has shown that regularized formulations [Cuturi 2013; Benamou et al. 2015] can provide those cheap algorithms for graphics [Solomon et al. 2015].

We consider in this paper the inverse problem associated with histogram interpolation, which is that of forming, for a given histogram, a barycentric interpolation of reference histograms that approximates it best. The barycentric interpolation itself can be interpreted as a denoised version of the original input, with respect to the prior contained in those reference histograms. The usually much shorter vector of barycentric coordinates can serve as a handy representation to compress, visualize or carry out inference on the original histogram. The crucial novelty in this paper lies in the fact that the interpolation we consider here is in the optimal transport metric sense, which gives our barycentric coordinate system an intuitive and geometrically faithful flavor. We call this new notion of coordinates for histograms Wasserstein barycentric coordinates, and provide algorithms to compute them efficiently. We apply our algorithms on histograms frequently encountered in computer graphics, ranging from color histograms to reflectance distributions.

Contributions. We propose a method to project an input histogram $q$ onto the set of all Wasserstein barycenters formed by $S$ histograms $(p_1, \ldots, p_S)$ (see Fig. 3). This corresponds to approximating the input histogram $q$ by its closest (with respect to some loss) Wasserstein barycenter $P(\lambda)$ of $(p_1, \ldots, p_S)$, where $\lambda = (\lambda_1, \ldots, \lambda_S)$ is the optimal weight vector sought for. We call this weight vector $\lambda$ the Wasserstein barycentric coordinates of $q$.

We propose the first numerical scheme to compute Wasserstein barycentric coordinates. This scheme builds upon gradient descent, and requires thus the computation of the (usually high-dimensional) Jacobian of the barycenter operator $\lambda \mapsto P(\lambda)$. To be tractable, our solution relies on an approximation of $P(\lambda)$ that uses a fixed number of steps of a fixed-point iteration computation proposed by Benamou et al. [2015]. We can therefore use a recursive differentiation method to compute that Jacobian efficiently. This leads to an algorithm which is both fast and stable, allowing for the computation of optimal barycentric weights on large scale dense 3-D grids and other domains. We showcase a set of typical applications of our methods to color analysis (Fig. 7, fitting sparse reflectance measurements (Fig. 6) and reconstructing 3D shapes (Fig. 9).

2 Previous works

Optimal transport (OT) is a powerful way to define distances (also known as Wasserstein or earth mover’s distances) between probability distributions on general metric spaces, which takes into account the geometry of the underlying space. Initially formulated by Monge as an intractable non-convex optimization [Monge 1781], its modern linear programming formulation is due to Kantorovich [1942], and is presented in much details in Villani’s monograph [2003]. Its practical applications are more recent, starting with computer vision [Haker et al.; Rubner et al. 2000], image processing [Rabin and Papadakis 2015], machine learning [Cuturi 2013; Solomon et al. 2014b] and computer graphics [Bonneel et al. 2011].

Classical linear programming and combinatorial optimization approaches to OT [Burkard et al. 2009] scale roughly with cubic complexity, and are very costly. Alternative methods somehow alleviate this issue – e.g., the special case of $W_1$ transport [Solomon et al. 2014a], semi-discrete approach with Laguerre’s cells [Mérigot 2011] and a dynamical formulation [Benamou and Brenier 2000]. These approaches are however very restrictive in the sense that they only work for particular cost structures or discretizations (typically in low dimension) and are thus not usable for the applications this paper targets. Of particular relevance to this paper is the recent interest for entropy regularized approaches to solve OT [Cuturi 2013]. Instead of a linear program, entropic smoothing allows the use of Bregman optimization tools [Bregman 1967], in particular Sinkhorn’s algorithm [Sinkhorn 1964; Deming and Stephan 1940]. This approach provides two benefits: since the computation of regularized OT only involves matrix-vector products, that problem can be computed efficiently on parallel architectures; since the problem is regularized with a strongly convex term, the regularized distance becomes a smooth function of all its parameters.

Because OT was considered expensive, computing OT distances faster has been for many years a goal in and by itself. Only recently was it realized that—now that OT distances can be efficiently approximated—far more interesting problems involving OT distances can be considered, starting with the introduction of OT barycenters [Agueh and Carlier 2011]. Among all approaches proposed to compute them in practice [Rubin et al. 2012; Cuturi and Doucet 2014; Bonneel et al. 2015], that of Benamou et al. [2015] stands out for its simplicity. These barycenters have been independently considered in statistics [Bigot and Klein 2012; Sriavastava et al. 2015], image processing [Bonneel et al. 2015] and computer graphics [Solomon et al. 2015]. These developments have paved the way for even more complicated problems on the space of probability measures that incorporate OT in their formulation, such as Principal Component Analysis (PCA) [Seguy and Cuturi 2015; Bigot et al. 2015] or non-negative matrix factorization (NMF) [Sandler and Lindenbaum 2009; Rolet et al. 2016] which have been recently rephrased using OT loss functions. More precisely, the NMF problem (even when used in conjunction with a Wasserstein loss) corresponds to looking for a linear combination of base distributions that approximates a given input histogram. In contrast, our Wasserstein barycentric coordinate regression uses a non-linear combination of the base distributions, which uses the OT geometry by enabling interpolation through mass transportation (see Figures 2 and 3 for simple illustrations of this important distinction).

While we propose a generic approach, application specific solutions have been proposed. For instance, Matusik et al. [2003] has shown that measured reflectance data form a manifold of histograms which can be learned via charting [Brand and Brand 2003]. Their approach allows to locate a new measured reflectance within this manifold. Wills et al. [2009] locates reflectance functions in a manifold ob-
tograms. It then exoops our main contribution: the presentation and resolution of the barycentric coordinates inverse problem.

\section{3.1 Notations}

We consider the simplex $\Sigma_N \defeq \{ p \in \mathbb{R}_+^N : \sum_i p_i = 1 \}$ of $N$-dimensional normalized histograms, and consider a family of $S$ reference histograms $(p_1, \ldots, p_S)$ in $\Sigma_N$. To interpolate between these $S$ histograms, we consider barycentric weights $\lambda \in \Sigma_S$. For a matrix $T \in \mathbb{R}_+^{N \times N}$, we write $H(T) = \sum_{i,j} T_{i,j} \log(T_{i,j})$ its negative entropy, with the convention $0 \log 0 = 0$. For two matrices $A, B$ of the same size, we write $\langle A, B \rangle = \text{tr}(A^\top B)$ for their usual inner-product, where $A^\top$ is the transpose of $A$. We write $\mathbb{I}$ for the vector with unit coordinates and whose size depends on the context.

The $\ell_\alpha$ norm for $\alpha \geq 1$ is $\|p\|_\alpha \defeq \sum_i p_i^\alpha$. The Kullback-Leibler divergence between histograms is $\text{KL}(p,q) \defeq \sum_i p_i \log(p_i/q_i)$. In this paper, multiplication $\prod$ for products of many terms and $\odot$ for two terms) and division $\odot$ operators between vectors are applied entry-wise, as well as exponential exp and logarithmic log maps.

\section{3.2 Regularized Wasserstein Distance}

Following [Cuturi 2013] (see also §2), we define the entropy regularized OT distance between two histograms $(p,q) \in \Sigma_N^2$ as

$$W(p,q) \defeq \min_{T \in \mathbb{R}_+^{N \times N}} \left\{ \langle T, C \rangle + \gamma H(T) : T \mathbb{1} = p, T^\top \mathbb{1} = q \right\},$$

(1)

where the matrix $C = (C_{i,j})_{i,j}$ quantifies the cost of transporting mass between histogram bins. For instance, if bins are sampled at some locations $(x_i)$ in a Euclidean space, a common choice for $C$ would be $C_{i,j} = \|x_i - x_j\|_p^\alpha$ for some $\alpha > 0$. We assume that the regularization parameter $\gamma$ is positive, which ensures that the optimal solution of this program is unique and that the program itself is easier (faster, parallel computations) to solve.

\section{3.3 Regularized Wasserstein Barycenters}

Agueh and Carlier defined Wasserstein barycenters [2011] as Fréchet means in the space of probability measures endowed with the Wasserstein metric. They studied several of their properties, such as uniqueness; established links with the multi-marginal OT problem; described barycenters of Gaussian distributions. We consider in this work a simplified setting for this problem, in which measures are discrete and supported on the same set of $N$ points. Following Cuturi and Doucet [2014] (see also [Benamou et al. 2015; Solomon et al. 2015]), we propose to compute the Wasserstein barycenters of $S$ histograms $(p_s)_s$ in $\Sigma_N$ using the regularized Wasserstein distance defined in Eq. (1).

\textbf{Definition 1.} Given a family of $S$ input histograms $(p_s)_s$, the barycentric map $P : \Sigma_S \rightarrow \Sigma_N$ associates to a vector $\lambda \in \Sigma_S$ the barycenter of $(p_s)_s$ with weights $\lambda$, uniquely defined as

$$P : \lambda \mapsto P(\lambda) \defeq \arg\min_{p \in \Sigma_N} \sum_s \lambda_s W(p,p_s).$$

(2)

The uniqueness of $P(\lambda)$ comes from the strong convexity (as a function of $p$) of the energy defined on the right-hand side of Eq. (2), itself inherited from the regularization term in Eq. (1).

Wasserstein barycenters are very different from the usual linear averaging $\sum_s \lambda_s p_s$, which corresponds to barycenters in the $\ell_2$ sense. Indeed, the usual $\ell_2$ averaging is completely blind to the geometry of the domain, and is in some sense “non-physical” (induces transport of mass at infinite speed), as highlighted by Figure 2. Note that the same remark applies to barycenters induced by other separable divergences on $\Sigma_N$ such as Hellinger, Kullback-Leibler or $\ell_1$.

Although there is no closed-form expression for $P(\lambda)$, Benamou et al. [2015] have shown that the celebrated Sinkhorn fixed-point algorithm—which is used to solve problem (1)—can be extended to compute Wasserstein barycenters. This extension consists in an augmented fixed-point algorithm:
We now come to the core of our contributions. Given a histogram $\Sigma$ where, for the gradient of $P$.

Applying the transpose of the Jacobian

\[
\forall \gamma \in \mathbb{R}, \quad \nabla L = \left[ \frac{\partial L}{\partial \gamma} \right] \tag{5}
\]

where $K \triangleq e^{-C/\gamma}$ is the $N \times N$ kernel matrix corresponding to the cost $C$ and regularization term. Then $P^{(\ell)}(\lambda) \to P(\lambda)$.

As detailed in [Benamou et al. 2015], iterations (3) correspond to iterative projections for the KL divergence on a set of affine constraints. The main computational burden of these iterations is that of applying the kernel $K$ or $K^\top$ to $S$ vectors. In our settings, where the cost $C$ is translation invariant, these operations are cheap because they amount to carrying out $S$ convolutions in parallel.

4 Barycentric Coordinate Regression

We now come to the core of our contributions. Given a histogram $q \in \Sigma_N$, our goal is to define and compute the barycentric coordinates of $q$ with respect to $p$ and $s$, namely to find the vector of probability weights $\lambda \in \Sigma_S$ such that $q \approx P(\lambda)$ with respect to a loss function $L : \Sigma_N \times \Sigma_N \to \mathbb{R}_+$.

Definition 2. Let $q, p_1, \ldots, p_s \in \Sigma_N$. The barycentric coordinates of $q$ with respect to $(p_s)$, are any optimal solution to the problem

\[
\arg\min_{\lambda \in \Sigma_S} E(\lambda), \quad \text{where } E(\lambda) \triangleq L(P(\lambda), q). \tag{4}
\]

In contrast to the convexity of problem (2), the energy of problem (4) is in general not convex. Our goal is thus to recover a stationary point of that energy through gradient descent. The gradient of $E$ with respect to $\lambda$ can be computed using the chain rule:

\[
\nabla E(\lambda) = \left[ \frac{\partial P(\lambda)}{\partial \lambda} \right]\nabla L(P(\lambda), q), \tag{5}
\]

where $\frac{\partial P(\lambda)}{\partial \lambda}$ is the Jacobian of $\lambda \mapsto P(\lambda)$, $\nabla L(p, q)$ is the gradient of the loss $p \mapsto L(p, q)$, and, with these notations, $\nabla L(P(\lambda), q)$ is that gradient evaluated at $P(\lambda)$.

Among the two quantities in Eq. (5), the gradient of the loss $\nabla L(P(\lambda), q)$ is the least problematic since it can be easily derived for several common losses as shown below, and evaluated at $P(\lambda)$. Applying the transpose of the Jacobian $\left[ \frac{\partial P(\lambda)}{\partial \lambda} \right]^\top$ to that gradient is more challenging, both in theory and practice: We show first in §4.2 that, although an exact expression for $\frac{\partial P(\lambda)}{\partial \lambda}$ can be obtained, computing it is impractical for large dimensions $N$. We present in §4.2.2 an efficient alternative, by replacing the true barycenter $P(\lambda)$ in the definition of the energy $E$ by the running estimate $P^{(L)}(\lambda)$ obtained after $L$ iterations of the map described in Eq. (3), where $L$ is a number of iterations fixed beforehand.

Gradient of the loss. The gradient with respect to $p$ of commonly used separable losses $L(p, q)$ is

\[
\nabla \frac{1}{2}||p - q||_2^2 = p - q, \quad \nabla ||p - q||_1 = \text{sign}(p - q), \tag{6}
\]

\[
\nabla KL(p||q) = \log(\frac{p}{q}), \quad \nabla W(p, q) = \gamma \log(a), \tag{7}
\]

where, for the gradient of $W(p, q)$, $a \in \mathbb{R}^N$ is the left scaling produced by Sinkhorn’s fixed-point algorithm, namely the unique vector with geometric mean 1 such that the matrix $\text{diag}(a)K\text{diag}(q/Ka)$ has row-sum $p$ and column-sum $q$ [Cuturi and Doucet 2014, §5]. Note that the notation $\nabla ||p - q||_1$ is not rigorous, since the $\ell_1$-norm is not differentiable everywhere and the sign vector is only a subgradient of that quantity. We side-step this issue in this paper, which is only problematic for the 1-norm, by using quasi-Newton solvers such as L-BFGS that work well even with non-smooth objectives [Lewis and Overton 2013].

4.1 Exact Computation of the Jacobian

We show in Proposition 2 below that $[\frac{\partial P(\lambda)}{\partial \lambda}]^\top$ can be computed, assuming that the barycenter $P(\lambda)$ can be computed exactly. To simplify this exposition, we introduce two bi-variate functions $(\Phi, \Psi)$ to rewrite the iterations of Proposition 1 as operating only on the second variables. The matrices corresponding to these differentials are spelled out in Appendix A.

Proposition 2. One has

\[
[\partial \lambda P(\lambda)]^\top = [\partial \lambda b(\lambda)]^\top + [\partial s \Psi(\lambda, b(\lambda)) ]^\top \quad \tag{10}
\]

\[
[\partial \lambda b(\lambda)]^\top = [\partial \lambda \Phi(\lambda, b(\lambda))]^\top \left( \text{Id} - [\partial s \Phi(\lambda, b(\lambda))] \right)^{-1}, \tag{11}
\]

where $\partial \lambda \Phi$ and $\partial \lambda s \Phi$ (resp. $\partial s \Psi$ and $\partial \lambda s \Psi$) correspond to the partial derivatives of $\Phi(\lambda, b)$ (resp. $\Psi(\lambda, b)$) with respect to its first and second variables. The matrices corresponding to these differentials are spelled out in Appendix A.

4.2 Algorithmic Differentiation of the Jacobian

Because the exact computation of $P(\lambda)$ outlined above in §4.1 is impractical, we propose in this section to minimize a loss on the approximate barycenter $P^{(L)}(\lambda)$ computed after a finite number of iterations $L \geq 1$, to solve instead:

\[
\arg\min_{\lambda \in \Sigma_S} E_L(\lambda) \triangleq L(P^{(L)}(\lambda), q). \tag{12}
\]

The gradient formula (5) thus needs to be replaced by

\[
\nabla E_L(\lambda) = [\partial P^{(L)}(\lambda)]^\top (u^{(L)}), \quad u^{(L)} \triangleq \nabla L(P^{(L)}(\lambda), q). \tag{13}
\]

Because $P^{(L)}(\lambda)$ is obtained by recursively applying the same map $L$ times, the application of the transposed Jacobian $[\partial P^{(L)}(\lambda)]^\top$ to
Algorithm 1: Given a database of histograms $p_s$, the input distribution $q$, weights $\lambda$, this function computes $\nabla E_\lambda(p) \in \mathbb{R}^S$. The barycenter $P^{(L)}(\lambda)$ is obtained as a by-product.

\begin{align*}
\text{function} \quad \text{SINKHORN-DIFFERENTIATE}((p_s)_{s=1}^S, q, \lambda) \\
\forall s, b^{(0)}_s &\leftarrow \mathbf{1} \\
(w, r) &\leftarrow ((0^S, 0^{S \times N}) \\
\text{for} \quad \ell = 1, 2, \ldots, L \quad \text{// Sinkhorn loop} \\
\forall s, \varphi^{(\ell)}_s &\leftarrow K^T \frac{p_s}{Kb^{(\ell-1)}=\mathbf{1}} \\
p &\leftarrow \prod_s \left( \varphi^{(\ell)}_s \right)^{\lambda_s} \\
\forall s, b^{(\ell)}_s &\leftarrow \frac{p}{\varphi^{(\ell)}_s} \\
g &\leftarrow \nabla \mathcal{L}(p, q) \odot p \\
\text{for} \quad \ell = L, L-1, \ldots, 1 \quad \text{// Reverse loop} \\
\forall s, w_s &\leftarrow w_s + \log \varphi^{(\ell)}_s, g \\
\forall s, r_s &\leftarrow -K^T \left( K \left( \frac{\varphi^{(\ell)}_s}{\lambda_s} - r_s \right) \odot \frac{p_s}{(Kb^{(\ell-1)}=\mathbf{1})^T} \right) \odot b^{(\ell-1)}_s \\
g &\leftarrow \sum_s r_s \\
\text{return} \quad P^{(L)}(\lambda) \leftarrow p, \nabla E_\lambda(p) \leftarrow w
\end{align*}

The overall numerical scheme to compute $\nabla E_\lambda(p)$ is detailed in Algorithm 1, which can be obtained by plugging the expression for the differential of $(\Phi, \Psi)$—used to prove Proposition 2 and detailed in Appendix A—into the formulas of Proposition 3. The algorithm first performs a forward loop to compute the barycenter $P^{(L)}(\lambda)$ and then an inverse loop to implement (15) and accumulate the sum appearing in (14). This efficient implementation computes both the gradient and barycenter in twice as many Gibbs kernel $K$ and $K^T$ applications as required to compute the barycenter alone, making it a competitive approach, even against naive approximate numerical differentiation, which would run $(S+1)/2$ times slower.

4.3 Barycentric Coordinates using Quasi-Newton

With the function SINKHORN-DIFFERENTIATE at hand, which is able to compute both the current barycenter estimate $P^{(L)}(\lambda)$ and the gradient $\nabla E_\lambda(p)$, one can now efficiently compute barycentric coordinates $\lambda$ as a local minimizer of (12) through a descent method. Quasi-Newton methods proved very efficient in our experiments. We tested two methods, which turned out to be equally effective: The PQN constrained quasi-Newton [Schmidt et al. 2009], which can optimize smooth functions such as $E_\lambda$ over the simplex $\Sigma_S$; a standard quasi-Newton (L-BFGS) over a logarithmic domain using the change of variables $\lambda = \sum_{s} e^{\gamma s} \in \Sigma_S$ and carrying out the optimization over $\alpha \in \mathbb{R}^S$.

4.4 Evaluation

Problem (12) is non-convex, and optimization techniques may converge to local minima. In Figure 4, we illustrate the energy landscape of $E_\lambda(p)$ for various loss functions on simple 2D shapes. The resulting landscapes show that the energy seems nearly convex. In practice, we observed repeatedly that the algorithm converged to the same minimum for all initializations $\lambda_0$ within $\Sigma_S$. In our experiments, we hence set $\lambda_0 = \mathbf{1}/S$. With this setting, quasi-newton approaches typically converge within 10 iterations. Figure 5 evaluates the gradient relative accuracy $||\nabla E_\lambda(p) - \nabla E_\lambda(q)||/||\nabla E_\lambda(q)||$ when varying the number of iterations $L$ for various lags $\gamma = 2\sigma^2$. As the exact Jacobian (Section 4.2) cannot be reliably evaluated, we approximate $\nabla E_\lambda(p)$ using numerical finite differen-

tiation with 5000 iterations. This shows a small number of iterations often suffices.
We fit a measured anisotropic BRDF \(\tilde{\phi}_\lambda\) to a set of photographs, our algorithm projects a photograph \(\tilde{q}_0\) (a). We obtain an approximation \(\tilde{P}(\lambda)\) (c) that remains robust when decimating measurements prior to the fitting (d,e,f). Reported \(\lambda\) are normalized so that \(\sum \lambda = 100\), and PSNR values computed on BRDFs.

5 Applications

This section illustrates our histogram barycentric coordinates for various computer graphics applications.

5.1 Optimal Image Color Palettes

Color grading refers to the task of changing the color palette of a given image to improve its visual aspect. This task is often carried out manually by professional colorists [Pitie et al. 2007; Bonneel et al. 2013]. In this section, we build upon the automatic color grading approach pioneered by Reinhard et al. [2001] (see for instance [Bonneel et al. 2015] and references therein). This approach has shown that the visual style of images is contained to a large extent in the distribution of their colors, and that this visual aspect can be changed by adjusting the color palette of a given image to make it match that of another target image. In most automatic color grading approaches, that target palette is defined beforehand by choosing a single image’s palette. We propose in this section a novel approach to define such target palettes adaptively using multiple images.

Given an input photograph \(f\) and a small database of relevant color palettes, we compute first, among all barycenters of these palettes, the one that is the closest to the color palette of \(f\). We then modify the distribution of colors in \(f\) to make it match that of this closest palette. Color transfer towards a single predefined palette often results in artefacts, especially when the target palette is very far from the original one [Rabin et al. 2010]. Our approach sidesteps this problem, and considers automatically an infinite family of target palettes that retain the characteristics of the database.

We discretize RGB histograms with \(N = 128^3\) values on a uniform grid \((x_i)_{i=1}^{N}\) of the RGB cube. This defines the histograms \((p_i)_{i=1}^{N}\) of the input database \((f_i)_{i=1}^{N}\), and the histogram \(q\) of the image \(f\) to process. Our algorithm computes the optimal barycenter \(P(\lambda)\) using the ground cost \(C_{i,j} = \|x_i - x_j\|^2\) and the quadratic loss function...
\[ \mathcal{L}(p, p') = |p - p'|^2 \]

The image \( f \) is modified into an image \( \tilde{f} \), so that the histogram of \( \tilde{f} \) is equal, up to a small approximation error, to \( P(\lambda) \). This is achieved using the barycentric projection method detailed in [Solomon et al. 2015]. More precisely, if we denote \( p \) the histogram of the input image \( f \), we use the Sinkhorn algorithm [Cuturi 2013] to determine a transport plan \( T \) between \( p \) and \( P(\lambda) \), so that \( T \) solves (1) when setting \( q = P(\lambda) \). The transport map in the RGB color space is then approximated by the barycentric projection map \( x_i \in \mathbb{R}^3 \mapsto \frac{1}{N} \sum_j T_{i,j} x_j \in \mathbb{R}^3 \). This map is applied to each pixel of \( f \) using linear interpolation (since these pixel values do not necessary fall on the discretization grid \( (x_i)_i \)) to obtain the modified image \( \tilde{f} \). Note that this barycentric projection step is not related to the barycentric coordinate and the associated Wasserstein projection \( P(\lambda) \) defined in Section 4. Figure 7 illustrates our method using a database of professional photographs. Figure 8 shows an application in the context of text-based user interfaces. We use the top 10 results of the Flickr image search engine (www.flickr.com) for the query \texttt{autumn} to stylize an input summer photograph with a more autumnal aspect. Among various loss functions, the quadratic loss offered the best quality/speed tradeoff for this application.

### 5.2 Sparse Reflectance Inference

Acquiring reflectance data can be cumbersome. Our method makes it possible to infer reflectance values from sparse data given a database of densely measured reflectances. A Bidirectional Reflectance Distribution Function (BRDF) \( \tilde{p} \) is a function \( \bar{p}(\omega, \xi) \) describing the probability for a photon hitting a surface with a direction \( \omega \) to be reflected off that surface with a direction \( \xi \), or to be absorbed by that surface. These functions are sampled on discretized hemispheres \( (\omega, \xi) \in \Omega^2 \) of \( N = 288 \) points. Since \( \tilde{p} \) describes distributions of energy, we consider \( (\bar{p}(\omega, \cdot))_{\omega \in \Omega} \) as a set of un-normalized histograms on the hemisphere. We thus first normalize the BRDF and define \( p(\omega, \xi) = \bar{p}(\omega, \xi) / \sum_{\xi'} \bar{p}(\omega, \xi') \), so that \( (p(\omega, \cdot))_{\omega \in \Omega} \) is a collection of normalized histograms.

Given a database \( \{ p_s \}_{s=1}^S \) of such normalized BRDF \( p_s(\omega, \xi) \), we extend (2) to define barycenters by jointly optimizing over all incoming direction \( \omega \)

\[
P(\lambda) = \arg \min_{(p(\omega, \cdot))_{\omega \in \Omega}} \sum_{\omega \in \Omega} \lambda_s W(p(\omega, \cdot), p_s(\omega, \cdot)).
\] (16)

We use the cost matrix \( C_{i,j} = d(x_i, x_j)^2 \) where \( d \) is the geodesic distance on the hemisphere. Using this extended notion of barycenters, we use (12) to define barycentric coordinates of a normalized BRDF \( q \) computed from some BRDF \( \tilde{q} \), where the loss \( \mathcal{L} \) is the Wasserstein loss, extended to collections of histograms. The gradient of \( \mathcal{L} \) is now obtained by summing the gradient contribution of all incident directions \( \omega \), so that we can use Algorithm 1 for the computation of the optimal \( \lambda \). One finally recovers the interpolated BRDF \( P(\lambda) \) from \( P(\lambda) \) by re-introducing the initial scaling factor of \( \tilde{q} \), i.e., \( P(\lambda)(\omega, \xi) \equiv \bar{p}(\omega, \xi) \sum_{\omega'} \tilde{q}(\omega, \xi') \)

Fig. 6 shows typical results for isotropic and anisotropic BRDFs from the UTIA database [Filip and Vávra 2014]. To simulate a sparse acquisition setup, we progressively decimate (which corresponds to replacing some histogram values by 0) an input BRDF \( \tilde{q}_0 \) by up to 95% to obtain the input BRDF \( q \), prior to computing barycentric coordinates \( \lambda \). We observe relatively good reconstruction quality even for highly degraded BRDFs. This suggests our approach could alleviate the BRDF capture process when reasonably similar materials have already been captured at higher resolution.

### 5.3 Inferring missing geometry

Capturing geometries can be difficult due to partial occlusions, measurement noise, or unreachable camera angles. Given a database of input 3-D models, our tool can be used to infer missing geometry in an input mesh. We voxelize all shapes on a \( N = 192^3 \)-uniform 3-D grid \( \{x_i\}_{i=1}^N \) and we use a ground cost \( C_{i,j} = \|x_i - x_j\|^2 \) and \( \mathcal{L} = \text{KL} \) as loss function. Each shape is represented as a normalized histogram representing the uniform distribution inside this shape, and a uniform mass of \( \varepsilon = 10^{-4} \) outside for compatibility with KL loss. We account for the mass missing in the input geometry by roughly estimating the amount of missing mass, and normalizing the input histogram accordingly. Specifically, if \( \alpha \) percent of the input shape is missing, we use a loss of the form \( \text{KL}(P(\lambda), (1 - \alpha)\sum_{\xi'} \tilde{q}(\omega, \xi')) \).

Figure 9 illustrates our results, and Figure 10 compares the Wasserstein and Euclidean projections.

### 5.4 MRI Data

We consider processed data from the Human Connectome Project Q1 data set. The processing includes skull stripping, brain segmentation and cortical reconstruction of the cerebrum and the cerebellum at the native resolution of 0.7mm, as provided by the NITRC website. We selected \( S = 14 \) original MRIs represented as volumetric histograms of dimension \( 208 \times 276 \times 225 \), and considered an additional test one that we project on both the Euclidean simplex and...
The Euclidean barycentric coordinates consist in 8 non-zero values, whereas Wasserstein projection results in well-defined contours. Although the Euclidean barycenter looks sharper, close inspection reveals overlapping boundaries and edges (see insets) while our projections share 7 of these coefficients, with comparable weights. This sparsity might be attributed to Wasserstein barycentric coordinates and total computation time using $128^3$ voxel RGB color histograms, $L = 60$ and our CPU implementation. (Second row) We use the color matching of Pitie et al. [2007] to transfer colors from the most contributing photographs (numbered 0, 2, 4, 6 and 8). As existing techniques use a single target histogram, this can lead to large color distortion.

The Euclidean simplex of the 14 original MRIs, as illustrated in Figure 11. The test MRI is projected on both simplexes using a $\ell_2$ loss. The coefficients selected by these two procedures have a sparse support, with 9 and 8 non-zero weights respectively. These two projections share 7 of these coefficients, with comparable weights. Although the Euclidean barycenter looks sharper, close inspection reveals overlapping boundaries and edges (see insets) while our Wasserstein projection results in well-defined contours.

6 Discussion

This paper introduces the concept of Wasserstein barycentric coordinates. We illustrate this tool with applications to color manipulation, reflectance approximation, and shape inference.
to the minimization being carried out over the set, in $\Sigma_N$, of all Wasserstein barycentric combinations of the histograms $(p_i)$. If the reference histograms are close to each other (meaning that the volume of that set is small) and the input histogram is far apart, the projection onto that set is likely to lie in one of the faces of that set, i.e., on barycentric combinations that have sparse weights. This poses an interesting theoretical problem, which would likely benefit from a better understanding of the energy landscape of $E_L(\lambda)$. We believe that our method can find other practical applications in graphics, and find applications in vision and machine learning—notably if we consider extensions in which the basis $(p_i)$ is learned from data.

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A Differentials of $\Phi$ and $\Psi$

Proposition 4. One has

$$[\partial \varphi_s(b_s)]^\top = -K_s \text{diag} \left( \frac{\partial \varphi_s}{\partial \varphi_s} \right) K_s$$

(17)

$$[\partial \varphi_s(b_s)]^\top = \text{diag} \left( \frac{\partial \varphi_s(b_s)}{\partial \varphi_s} \right)$$

(18)

$$[\partial \varphi_{\Psi}(b, \lambda)]^\top = \text{diag} \left( \frac{\partial \varphi_{\Psi}(b, \lambda)}{\partial \varphi_{\Psi}(b, \lambda)} \right)$$

(19)

$$[\partial \varphi_{\Psi}(b, \lambda)]^\top = \text{diag} \left( \frac{\partial \varphi_{\Psi}(b, \lambda)}{\partial \varphi_{\Psi}} \right) I_{N,S} \text{diag} \left( \frac{\partial \varphi_{\Psi}(b, \lambda)}{\partial \varphi_{\Psi}} \right)$$

(20)

$$[\partial \varphi_{\Psi}(b, \lambda)]^\top = \text{diag} \left( \frac{\partial \varphi_{\Psi}(b, \lambda)}{\partial \varphi_{\Psi}} \right)$$

(21)

$$[\partial \varphi_{\Psi}(b, \lambda)]^\top = \text{diag} \left( \frac{\partial \varphi_{\Psi}(b, \lambda)}{\partial \varphi_{\Psi}} \right)$$

(22)

where we denoted

$$I_{N,S} \equiv (I_{N}, \ldots, I_{N}) \in \mathbb{R}^{N \times NS},$$

(23)

$$\forall a \in \mathbb{R}^N, J_a(\lambda) \equiv (\lambda_1a_1, \ldots, \lambda_S a_S) \in \mathbb{R}^{N \times NS},$$

(24)

$$\forall b \in \mathbb{R}^{NS}, P_a(b) \equiv (\lambda_1 b_1 - a_1, \ldots, \lambda_S b_S - a_S) \in \mathbb{R}^{NS},$$

(25)

$$\log(\varphi(b)) \equiv (\log(\varphi(a_1)) \ldots | \log(\varphi(b_S))) \in \mathbb{R}^{N \times S}.$$


