
Generalized Spectral Clustering via Gromov-Wasserstein Learning

Samir Chowdhury
Stanford University

Tom Needham
Florida State University

Abstract

We establish a bridge between spectral clustering and Gromov-Wasserstein Learning (GWL), a recent optimal transport-based approach to graph partitioning. This connection both explains and improves upon the state-of-the-art performance of GWL. The Gromov-Wasserstein framework provides probabilistic correspondences between nodes of source and target graphs via a quadratic programming relaxation of the node matching problem. Our results utilize and connect the observations that the GW geometric structure remains valid for any rank-2 tensor, in particular the adjacency, distance, and various kernel matrices on graphs, and that the heat kernel outperforms the adjacency matrix in producing stable and informative node correspondences. Using the heat kernel in the GWL framework provides new multiscale graph comparisons without compromising theoretical guarantees, while immediately yielding improved empirical results. A key insight of the GWL framework toward graph partitioning was to compute GW correspondences from a source graph to a template graph with isolated, self-connected nodes. We show that when comparing against a two-node template graph using the heat kernel at the infinite time limit, the resulting partition agrees with the partition produced by the Fiedler vector. This in turn yields a new insight into the k -cut graph partitioning problem through the lens of optimal transport. Our experiments on a range of real-world networks achieve comparable results to, and in many cases outperform, the state-of-the-art achieved by GWL.

1 INTRODUCTION

The Gromov-Wasserstein (GW) problem is a nonconvex quadratic program whose solution yields the *GW distance*, a variant of Wasserstein distance from classical optimal transport (OT) which is able to compare distributions defined on different metric spaces. This is accomplished by replacing classical Wasserstein loss with a loss function defined in terms of relational information coming from metric data. Because it is able to compare distributions defined on a priori incomparable spaces, GW distance is increasingly finding applications for learning problems on irregular domains such as graphs (Hendrikson, 2016; Tsitsulin et al., 2018; Vayer et al., 2019a; Xu et al., 2019b; Xu, 2020). In this context, a graph can be considered as a metric space by endowing it with geodesic distance. A soft matching between nodes of two different graphs is obtained by choosing distributions on each graph’s nodes (e.g., uniform distributions) and computing the GW optimal transport plan between them.

Applications of GW distance have been bolstered by the observation that the GW problem does not fundamentally require a *metric* to operate (Peyré et al., 2016); i.e., the definition of the GW loss function extends to other forms of relational data (Chowdhury and Mémoli, 2019). Xu et al. (2019a) used this observation to produce the state-of-the-art Scalable Gromov-Wasserstein Learning framework for graph matching and partitioning, which fundamentally uses the the adjacency matrix (as opposed to the shortest path distance matrix) of a graph. There are many ways to derive relational data from a graph beyond its distance and adjacency matrices, such as its various graph Laplacians and their corresponding heat kernels. A limitation of the current literature is a lack of tools for ascertaining if the adjacency matrix (or any other rank-2 tensor derived from a graph) is optimal in some sense beyond empirical benchmarks. Thus the potential flexibility of the GW framework for graph analysis remains largely unexplored.

Here we study the GW graph OT problem by representing graphs via heat kernels rather than adjacency matrices. This amounts to finding soft correspondences between the nodes of two graphs by comparing spec-

tral, rather than adjacency, data. We refer to this as the SpecGWL framework, reserving GWL for the adjacency-based framework of Xu et al. (2019a).

Numerical experiments¹ demonstrate that SpecGWL outperforms GWL in graph partitioning tasks. Moreover, a main goal of this paper is to introduce tools for studying the GW problem in a more rigorous manner. We use a Markov Chain sampling technique to explore the energy landscape of the GW loss function for adjacency and heat kernel graph representations, showing empirically that SpecGWL loss has fewer spurious local minima and a 10x acceleration in convergence of gradient descent over GWL loss. We also introduce a visualization technique which allows one to ascertain the quality of soft node matchings obtained by any GW method. Examples of this technique intuitively demonstrate the idea that heat kernel-based matchings more faithfully preserve global graph structure than adjacency-based matchings. Finally, we establish theoretical results on the sparsity of optimal couplings in the SpecGWL framework and on the precise relation of SpecGWL graph partitioning to classical spectral clustering. The latter result creates a novel connection between spectral clustering and optimal transport.

Related literature. Gromov-Wasserstein distance—as used in current ML settings—was introduced by Mémoli (2007) as a convex relaxation scheme for the Gromov-Hausdorff distance between different metric spaces. Further theoretical development was carried out by Mémoli (2011a); Sturm (2012), and a related formulation was introduced by Sturm (2006) to study the convergence of sequences of metric measure spaces. The idea of using heat kernels for GW matching goes back to the *Spectral Gromov-Wasserstein distance* introduced by Mémoli (2011b) in the context of Riemannian manifolds to further develop the notion of *Shape-DNA* introduced by Reuter et al. (2006). A related theoretical construction also appeared in Kasue and Kumura (1994). The Riemannian heat kernel has been celebrated for its *multiscale* and *informative* properties (Sun et al., 2009)—the former refers to the observation that the heat kernel defines a family of Gaussian filters that get progressively shorter and wider as $t \rightarrow \infty$, and the latter refers to the classical lemma of Varadhan showing that at the small time limit, the log-heat kernel approximates the geodesic distance on a Riemannian manifold. A surprising result due to Sun et al. (2009) in this direction is that under mild conditions, the collection of traces of the heat kernel forms an isometry invariant of a manifold despite giving up most of the information contained in the heat kernel. Heat kernel traces have recently been used for graph comparison

by Tsitsulin et al. (2018, 2020), who showed that the desirable properties of the heat kernel for Riemannian manifolds have natural and informative analogues in the setting of graphs. Heat kernels have been incorporated into GW-based graph matching in recent work of Barbe et al. (2020), where they are used to augment the matching process in the Fused GW framework of Vayer et al. (2018). Our work is distinguished from that of Barbe et al. (2020) in that we use heat kernels directly to define a GW loss function for graph matching, whereas Barbe et al. (2020) employs heat kernels to improve feature space matchings for attributed graphs. There is a deep literature on spectral graph comparison, and a few other references include works of Patro and Kingsford (2012); Bronstein and Glashoff (2013); Hu et al. (2014); Nassar et al. (2018); Dong and Sawin (2020).

Starting from its early applications in computer vision (Mémoli, 2007, 2011a; Schmitzer and Schnörr, 2013), GW distance has been applied to alignment of word embedding spaces (Alvarez-Melis and Jaakkola, 2018), learning of generative models across different domains (Bunne et al., 2019), graph factorization (Xu et al., 2019b), and learning autoencoders (Xu et al., 2020). Related theoretical directions include the *sliced GW* of Vayer et al. (2019b) and the *Gromov-Monge* problem studied by Mémoli and Needham (2018). Sturm (2012) studied the structure of geodesics and gradient flows in GW geometry, and recently these techniques were utilized by Chowdhury and Needham (2020) to create a Riemannian framework for performing averaging and tangent PCA across different graph-structured domains. Unbalanced formulations of the GW problem permitting input probability measures of different total sums have been studied by Chapel et al. (2020); De Ponti and Mondino (2020); Séjourné et al. (2020).

2 SPECTRAL GW DISTANCES

Gromov-Wasserstein Distance. The following can be stated for Borel probability measures on Polish spaces; however, we are interested in the finite setting where measure-theoretic complications do not arise, so we freely use matrix-vector notation. Given probability distributions p, q on finite sets X, Y , a coupling of p and q is a joint probability measure C on $X \times Y$ with marginals p and q ; i.e., $C = (C_{ij}) \in \mathbb{R}^{|X| \times |Y|}$ satisfies equality constraints $C1^{|Y| \times 1} = p$ and $C^T 1^{|X| \times 1} = q$ ($1^{m \times n}$ denoting the $m \times n$ matrix of all ones), and entrywise inequality constraints $0 \leq C \preceq 1$. The set of all couplings of p and q is denoted $\mathcal{C}(p, q)$ —this is a convex polytope in $\mathbb{R}^{|X| \times |Y|}$. Given functions $f^X : X \times X \rightarrow \mathbb{R}$, $f^Y : Y \times Y \rightarrow \mathbb{R}$, written as square matrices F^X, F^Y ,

¹<https://github.com/trneedham/Spectral-Gromov-Wasserstein>

the GW problem solves:

$$\min_{C \in \mathcal{C}(p,q)} \sum_{i,k} \sum_{j,l} (F_{ik}^X - F_{jl}^Y)^2 C_{ij} C_{kl}. \quad (1)$$

The GW problem is a nonconvex quadratic program over a convex domain for which approximate solutions may be obtained via projected gradient descent (Peyré et al., 2016) or Sinkhorn iterations with an entropy (Solomon et al., 2016) or KL divergence regularizer (Xu et al., 2019b). Computational implementations can be found in the Python Optimal Transport library of Flamary and Courty (2017).

Historically, the GW problem was defined by Mémoli (2007) in the setting of *metric measure (mm) spaces*, where its solution leads to a metric known as the Gromov-Wasserstein distance. A finite mm space (X, d, p) consists of a finite set of points X , a metric function d written as a matrix $d = (d_{ik}) \in \mathbb{R}^{|X| \times |X|}$, and a probability distribution p on X written as a vector $p = (p_i) \in [0, 1]^{|X| \times 1}$. Given mm spaces (X, d^X, p) , (Y, d^Y, q) , the Gromov-Wasserstein distance is defined as:

$$d_{\text{GW}}(X, Y)^2 := \min_{C \in \mathcal{C}(p,q)} \sum_{i,k} \sum_{j,l} (d_{ik}^X - d_{jl}^Y)^2 C_{ij} C_{kl}. \quad (2)$$

Peyré et al. (2016) observed that solving the GW problem (1) with input matrices that are not strictly distances—in particular kernel matrices—still leads to a discrepancy that is informative when comparing matrices of different sizes and arising in incompatible domains. This idea was pushed further by the theoretical work of Chowdhury and Mémoli (2019), which showed that *any* square matrix representation of a graph, including the adjacency matrix, can be used in the GW problem (1) to obtain a bona fide distance (actually a pseudometric). This observation was used by Xu et al. (2019b,a) to create a unified *Gromov-Wasserstein Learning* (GWL) framework for unsupervised learning tasks on graphs—e.g. finding node correspondences between unlabeled graphs and graph partitioning—with state-of-the-art performance. We now formulate the GWL framework precisely.

Gromov-Wasserstein Learning on Graphs. Let $G = (V, E)$ be a finite, unweighted, possibly directed graph. We refer to V as the set of nodes and E as the set of edges. Let $A : V \times V \rightarrow \{0, 1\}$ and $D : V \rightarrow \mathbb{Z}$ denote the *adjacency* and *degree* functions defined as $A(v, w) := 1$ if $(v, w) \in E$, 0 otherwise, and $D(v) := |\{w : (v, w) \in E\}|$. Given an ordering on V , these functions can be represented as matrices in $\mathbb{R}^{|V| \times |V|}$, and we will switch between both the function and matrix forms. In addition to the adjacency function, which fully encodes a graph, there are numerous *derived representations* which capture information

about a graph. An example is the geodesic distance function d which contains all the shortest path lengths in the graph. In particular, the graph geodesic distance representation was used by Hendrikson (2016) to solve graph matching problems via the original mm-space GW distance formulation (2) of Mémoli (2007).

One of the key ideas in the GWL framework is to use *adjacency matrices* in the GW problem. Specifically, let G and H be graphs with distributions p and q on their nodes and let A^G and A^H denote their adjacency matrices. The GWL framework considers the loss

$$\text{Adj} = \text{Adj}_{G,p,H,q} : \mathcal{C}(p, q) \rightarrow \mathbb{R}$$

defined by

$$\text{Adj}(C) = \sum_{i,k} \sum_{j,l} (A_{ik}^G - A_{jl}^H)^2 C_{ij} C_{kl}, \quad (3)$$

which we refer to as *adjacency loss*. The minimum of $\text{Adj}(C)^{1/2}$ defines a distance between the pairs (G, p) and (H, q) —we refer to such pairs as *measure graphs* and assume for convenience that distributions are fully supported. If p and q are themselves derived from adjacency data then the minimizer C of (3) provides a natural soft correspondence between the nodes of G and H . For example, Xu et al. (2019a) consider the family of node distributions $p = (p_1, \dots, p_n)^T$, where

$$p_j = \frac{\bar{p}_j}{\sum_{k=1}^n \bar{p}_k}, \quad \bar{p}_j = (\deg(v_j) + a)^b, \quad (4)$$

where $p_j = p(v_j)$ for v_j a vertex of G , $a \geq 0$ is used to enforce the full support condition and the exponent $b \in [0, 1]$ allows interpolation between the *uniform distribution* and the *degree distribution*.

Heat Kernels. Our contributions begin by studying the structure imposed on the GW problem (1) by *spectral losses* that we describe next. Given an undirected graph $G = (V, E)$, let $L^2(V)$ denote the linear space of functions $f : V \rightarrow \mathbb{R}$. The *Laplacian* of G is the operator $L : L^2(V) \rightarrow L^2(V)$ defined by

$$L(\phi)(v) := D(v)\phi(v) - \sum_{(v,w) \in E} \phi(w).$$

After fixing an ordering on V , we can use matrix-vector notation to write $\mathbb{R}^{|V| \times |V|} \ni L = D - A$ and $\phi \in \mathbb{R}^{|V| \times 1}$. The Laplacian is symmetric positive semidefinite, so the spectral theorem guarantees an eigendecomposition $L = \Phi \Lambda \Phi^T$ with real, nonnegative eigenvalues $\lambda_1 \leq \lambda_2 \leq \dots \leq \lambda_n$ arranged on the diagonal of Λ . The corresponding eigenvectors $\phi_1, \phi_2, \dots, \phi_n$ are arranged as the columns of Φ . There are several variants of the Laplacian with analogous properties, including the

normalized Laplacian given by $I - D^{-1/2}AD^{-1/2}$. This is the version that we will typically use for experiments.

For a (strongly connected) directed graph $G = (V, E)$, we use the normalized Laplacian defined by Chung (2005) via the language of random walks. Consider the transition probability matrix P defined by writing $P_{ij} = 1/D_i$ if $(i, j) \in E$, 0 otherwise. By Perron-Frobenius theory, there is a unique left eigenvector ψ with all entries positive such that $\psi^T P = \psi^T$. The directed graph Laplacian is defined as $L := I - (\Psi^{1/2} P \Psi^{-1/2} + \Psi^{-1/2} P^T \Psi^{1/2})/2$, where $\Psi = \text{diag}(\psi)$.

In what follows, we use L generically to refer to any of the Laplacians defined above. The *heat equation* on a graph G (either undirected or directed) is then given as $du/dt = -Lu$, where $u \in L^2(V \times \mathbb{R}_{>0})$. If u represents a time-dependent heat distribution on the nodes of G , the heat equation describes heat diffusion according to Newton’s Law. The *heat kernel* is the fundamental solution to this heat equation, given in closed form as $K^t = \exp(-tL) = \Phi \exp(-t\Lambda) \Phi^T$.

Spectral GW Distance. Given measure graphs (G, p) and (H, q) , we consider the *spectral loss*

$$\text{Spec}^t = \text{Spec}_{G,p,H,q}^t : \mathcal{C}(p, q) \rightarrow \mathbb{R}$$

defined by

$$\text{Spec}^t(C) = \sum_{i,k} \sum_{j,l} (K_{ik}^{G,t} - K_{jl}^{H,t})^2 C_{ij} C_{kl} \quad (5)$$

for each $t > 0$, where $K^{G,t}$ and $K^{H,t}$ are the heat kernels of G and H , written in matrix form. We then obtain a one parameter family of pseudometrics

$$d_{\text{GW}}^{\text{spec}}[t]((G, p), (H, q)) := \min_{C \in \mathcal{C}(p, q)} \text{Spec}^t(C)^{1/2} \quad (6)$$

on the space of measure graphs. As in the GWL framework, choosing node distributions p and q from the family (4) yields minimizing couplings C which give meaningful correspondences between the nodes of G and H . As t varies, one obtains multiscale couplings between nodes, with small t encoding local and large t encoding global structure (this is made precise in Section 3). Intuitively, the heat kernel replaces each node of a graph with a Gaussian filter with width controlled by t , progressively “smoothing” the graph. Different smoothing levels emphasize multiscale geometric and topological features that drive coupling optimization; Figure 6 in the Supplementary Materials shows clusters in coupling space corresponding to matchings at different scales. The “best” choice of t emphasizes the feature scale which is most important for a given task.

One can further define an overall pseudometric by, say, considering the function

$$f_{G,p,H,q}(t) = d_{\text{GW}}^{\text{spec}}[t]((G, p), (H, q))$$

and defining $d_{\text{GW}}^{\text{spec}} := \|\xi \cdot f_{G,p,H,q}\|$ for an appropriately chosen norm on functions $\mathbb{R} \rightarrow \mathbb{R}$ and normalizing function ξ preventing blow up of the norm; for example, taking $\xi(t) = \exp(-(t + t^{-1}))$ and the ℓ_∞ norm here is analogous to the spectral GW distance between Riemannian manifolds defined by Mémoli (2011b). This is an interesting direction of future research, but we found it most useful in our applications to instead treat t as a scale parameter that is tuned via cross-validation.

Properties of SpecGWL. For measure graphs (G, p) and (H, q) , fix $t > 0$ and write $J := K^{G,t}$, $K := K^{H,t}$. After expanding the square and invoking the marginalization constraints (Solomon et al. (2016) provide an explicit derivation), one sees that minimizing (5) is equivalent to maximizing $\langle JC, CK \rangle$ subject to $C \in \mathcal{C}(p, q)$, where $\langle \cdot, \cdot \rangle$ denotes the Frobenius inner product. Because the graph heat kernel is symmetric positive definite, we take Cholesky decompositions $J = U^T U$, $K = V^T V$ to write

$$\begin{aligned} \langle JC, CK \rangle &= \text{tr}((JC)^T CK) = \text{tr}(C^T U^T U C V^T V) \\ &= \text{tr}(V C^T U^T U C V^T) = \|UCV^T\|^2. \end{aligned}$$

The map $C \mapsto \|UCV^T\|^2$ is convex. We record this as the following lemma, which appeared previously as (Alvarez-Melis et al. (2019), Lemma 4.3).

Lemma 1. *For each $t > 0$, spectral loss (5) is minimized over the convex polytope $\mathcal{C}(p, q)$ by a maximizer of the convex function $C \mapsto \langle K^{G,t} C, C K^{H,t} \rangle$.*

Optimization problems of this type are not tractable to solve deterministically, but we demonstrate experimentally that approximation via gradient descent enjoys faster convergence and fewer spurious local minima than adjacency loss (3). It has been empirically observed by Xu et al. (2019b) that (local) minimizers of adjacency loss tend to become sparse, and this sparsity is crucial in the gradient descent-based algorithm of Chowdhury and Needham (2020) for computing averages of networks. A key advantage of our spectral setting (5) over (2) or (3) is that this empirical observation of sparsity admits a formal proof.

Theorem 2. *Let (G, p) and (H, q) be measure graphs on $\sim n$ nodes. Then for any $t > 0$, there is a minimizer of spectral loss with $o(n)$ nonzero entries.*

Complexity of SpecGWL. Assuming graphs of comparable size n , the eigendecomposition incurs a time complexity of $O(n^3)$ and memory complexity of $\Theta(n^2)$. Computing the GW loss using gradient descent involves computing $\nabla \langle JC, CK \rangle = J^T CK + JCK^T$, which incurs a time complexity of $O(n^3 \log(n))$ (Kolouri et al. (2017) and memory complexity of $O(n^2)$. Regularized methods with Sinkhorn iterations still require

paying a cost for matrix multiplication (Peyré et al., 2016). However, accelerations have already been proposed: Tsitsulin et al. (2018) suggest methods for approximating heat kernels in $O(n^2)$ operations and Xu et al. (2019a) propose a recursive divide-and-conquer approach to reduce the complexity of the GW comparison to $O(n^2 \log n)$. Note that because heat kernel matrices are dense, we lose the advantages of sparse matrix operations.

3 GRAPH PARTITIONING

Graph Partitioning Method. Graph partitioning is a crucial unsupervised learning task used for community detection in social and biological networks (Girvan and Newman, 2002). The goal is to partition the vertices of a graph into some number of clusters m in accordance with the *maximum modularity principle*—edges within clusters are dense, while edges between clusters are sparse. Xu et al. (2019a) proposed a GW-based approach to graph partitioning where an m -way partition of a measured graph (G, p) is obtained by minimizing the following variant of adjacency loss (3):

$$\mathcal{C}(p, q) \ni C \mapsto \sum_{i,k} \sum_{j,l} (A_{ik} - Q_{jl})^2 C_{ij} C_{kl}, \quad (7)$$

where A is the adjacency matrix of G , $Q = \text{diag}(q)$ and q is a distribution estimated by sorting the weights of p , sampling m values via linear interpolation and renormalizing. Intuitively, Q is the weighted adjacency matrix of a graph on m nodes with only self-loops—an *ideally clustered template* graph. The heuristic for choosing the distribution q in this manner is that if within-cluster nodes of the graph G have similar degrees then this method allows a node in Q to accept all of the mass from this cluster. A minimizer C of (7) defines an m -way partition of G : each node v_i of G is assigned a label in $\{1, \dots, m\}$ according to the column index of the maximum weight in row i of C .

Soft-matching nodes of the target graph to an ideally clustered template is intuitively appealing and it was shown by Xu et al. (2019b) that this method achieves state-of-the-art performance. We propose a variant of the algorithm: letting K^t denote the heat kernel for G at some $t > 0$, we minimize

$$\mathcal{C}(p, q) \ni C \mapsto \sum_{i,k} \sum_{j,l} (K_{ik}^t - Q_{jl})^2 C_{ij} C_{kl}, \quad (8)$$

with Q defined as above. For each $t > 0$, we obtain an optimal coupling which is used to partition G as described above. Experimental results in Section 4 show that this change to the algorithm gives a significant performance boost over the adjacency-based version.

Connection to Spectral Clustering. Let G be an undirected, connected graph with graph Laplacian L . The connectivity of G implies that L has exactly one zero eigenvalue with constant eigenvector. Assume for simplicity that the multiplicity of the smallest positive eigenvalue of L is one. A fundamental concept in spectral graph theory is that the corresponding eigenvector—the *Fiedler vector* of G —gives a 2-way partitioning of G with good theoretical properties: nodes of G are partitioned according to the sign of their entry in the Fiedler vector (Fiedler, 1973). We refer to this as the *Fiedler partition* of G , and find that it arises as a special case of spectral GW partitioning:

Theorem 3. *Let G be a connected graph whose first positive eigenvalue has multiplicity one, endowed with the uniform node probability distribution p . For sufficiently large t , the 2-way partition of G derived from a minimizer of (8) agrees with the Fiedler partitioning.*

The theorem demonstrates a novel connection between optimal transport and classical spectral clustering and shows that partitioning graphs via spectral GW matching (8) is a generalization of these classical methods. For the small- t regime, note that the heat kernel of G has Taylor expansion $K^t = I_n + tL + O(t^2)$, where I_n is the $n \times n$ identity matrix. Thus for low values of t , spectral GW partitioning is driven by matchings of graph Laplacians, which contain local adjacency information.

4 EXPERIMENTS

We present several numerical experiments demonstrating the boost in performance obtained by using heat kernels in the GW problem rather than adjacency matrices. In experiments with undirected graphs, we used the normalized graph Laplacian to construct heat kernels—results were qualitatively similar using heat kernels of the standard Laplacian, but we found some boost in quantitative performance in graph partitioning when using the normalized version. Experiments with directed graphs use Chung’s normalized Laplacian.

Energy Landscapes and Convergence Rates.

Adjacency loss (3) is highly nonconvex, while Lemma 1 shows that minimizing spectral loss (5) is equivalent to maximizing a convex function over a convex polytope. While the latter optimization problem is still intractable, we now demonstrate that its approximation via gradient descent is well-behaved. In each trial, two random graphs from the **IMDB-Binary** (Yanardag and Vishwanathan, 2015) actor collaboration graph dataset (1000 graphs with 19.77 nodes and 96.53 edges on average) are selected. The nodes of the graphs are endowed with uniform distributions p and q (results obtained when using other distributions from

Table 1: Results of Energy Landscape Experiment.

| Loss | Time (s) | Err. (%) | Prod. Err. (%) |
|--------------------|----------|----------|----------------|
| Adj | .0230 | 24.21 | 4.81 |
| Spec ⁵ | .0014 | 22.35 | 6.00 |
| Spec ¹⁰ | .0013 | 3.86 | 1.34 |
| Spec ²⁰ | .0010 | 0.05 | .02 |

the family (4) are similar). An ensemble of couplings between these measures is generated by running a custom Markov Chain Monte Carlo (MCMC) hit-and-run sampler (Smith, 1984) on the coupling polytope $\mathcal{C}(p, q)$ (details in Supplementary Materials). We sampled 100 points in the polytope by running 100,000 MCMC steps and subsampling uniformly. Using each coupling in the ensemble as an initialization, we run projected gradient descent on adjacency loss (3) and spectral loss (5) with $t = 5, 10$ and 20 and record the loss at the local minimum from each initialization. This process is repeated 100 times (100 choices of pairs of graphs).

Statistics for the experiment are reported in Table 1. For each method, we report the mean time for convergence of each gradient descent. For each trial, we obtain a distribution of losses from the 100 initializations in the ensemble, with the minimum loss treated as the putative global minimum. The “Worst Error” for each trial is $(\max \text{loss} - \min \text{loss}) / \min \text{loss}$. We report the mean Worst Error over 100 trials. In available packages, gradient descent for GW matching is by default initialized with the product coupling $C = pq^T$, so we also report the “Product Error” $(\text{product loss} - \min \text{loss}) / \min \text{loss}$, averaged over all trials. We note that the absolute losses of the adjacency and heat kernel methods are not directly comparable, which is why we report these relative errors. The heat kernel representations provide an order of magnitude speed up of convergence, with decreasing error as the t parameter increases; e.g., for $t = 20$, all initializations converge to a coupling with less than 0.1% error. More details are provided in the Supplementary Materials.

Graph Matching and Averaging. Let (G, p) and (H, q) be measure graphs. Minimizers of the loss functions (3) and (5) are couplings C giving soft node correspondences between G and H . To assess the intuitive meaning of such a coupling, it is useful to visualize this node correspondence at the graph level. We produce such visualizations using ideas from Chowdhury and Needham (2020), as shown in Figure 1. The figure shows six separate examples. For any particular example, we display an interpolation between graph G (on the left) and graph H (on the right). The optimal coupling C is used to interpolate node positions

Table 2: Node Correctness, Mean \pm St. Dev. (Time).

| Dataset | Adj | Spec ¹⁰ |
|----------|----------------------------|------------------------------|
| Proteins | .68 \pm .22 (31.9) | .78 \pm .22 (5.1) |
| Enzymes | .70 \pm .18 (8.9) | .79 \pm .17 (1.4) |
| Reddit | .29 \pm .21 (3941.7) | .50 \pm .11 (206.1) |
| Collab | .50 \pm .27 (4.3) | .50 \pm .27 (5.6) |

from G to H , with new edges phasing in during the interpolation—see Supplementary Materials for the details of the visualization algorithm as well as another experiment illustrating improved stability of the graph averaging algorithm of Peyré et al. (2016) when using spectral loss. We observe that in all cases, the matching produced via spectral loss preserves large scale qualitative features of the graphs more faithfully than adjacency-based matchings.

We also assess the quality of node correspondences quantitatively. In this experiment, we consider two biological graph databases **Proteins** (Borgwardt et al., 2005) (1113 graphs with 39.06 nodes and 72.82 edges on average) and **Enzymes** (Dobson and Doig, 2003; Schomburg et al., 2004) (600 graphs with 32.63 nodes and 62.14 edges on average), and two social graph databases **Reddit** (subset of 500 graphs with 375.9 nodes and 449.3 edges on average) and **Collab** (subset of 1000 graphs with 63.5 nodes and 855.6 edges on average), both from Yanardag and Vishwanathan (2015). All datasets were downloaded from Kersting et al. (2016). For each graph $G = (V, E)$, we assign a node distribution p from (4) (parameters tuned for the best performance in each method). A “new” measure graph (H, q) is created by randomly permuting node labels of G . There is a ground truth node correspondence between G and H and the goal is to measure the ability of GWL and SpecGWL to recover it. Given a coupling C of (G, p) and (H, q) , we measure its performance by the *node correctness score* $|S \cap S_{GT}| / |S|$, where $S = \{(i, j) \mid C_{ij} > \epsilon\}$, for $\epsilon > 0$ a small threshold parameter, is the set of node correspondences from C and S_{GT} comprises ground truth node correspondences. Xu et al. (2019a) showed that the adjacency-based GWL framework achieves state-of-the-art graph matching performance with respect to this metric.

For each graph G and permuted version H , we compute couplings minimizing adjacency loss (3) and spectral loss (5) with $t = 10$ and compute their node correctness scores. Mean scores for each dataset are provided in Table 2, where we see that spectral loss outperforms adjacency, except on the dense **Collab** graph where results agree. Minimizers of spectral loss in SpecGWL were computed via standard gradient descent. Minimizers of adjacency loss in GWL were computed via

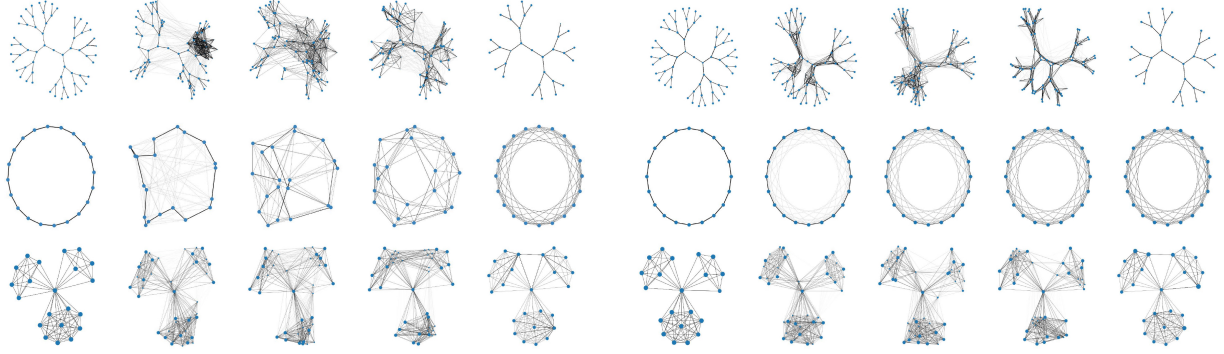


Figure 1: Visualizations of GW graph matchings via adjacency loss (3) (left column) and spectral loss (5) with $t = 20$ (right column). For each loss, we illustrate matchings between binary trees (Top), circular graphs (Middle) and IMDB graphs (Bottom). In each case, the interpolation is generated from node matchings inferred from the optimal GW coupling. Uniform node distributions are used in all examples.

Table 3: GRP model results; averaged AMI (time).

| p_{out} | Infomap | GWL | SpecGWL |
|-----------|------------|-------------|-------------------|
| .08 | .676 (.34) | .611 (1.44) | .845 (.62) |
| .10 | — | .624 (1.56) | .820 (.70) |
| .12 | — | .615 (1.64) | .820 (.75) |
| .15 | — | .611 (1.82) | .788 (.87) |

both gradient descent and the regularized proximal gradient descent method of Xu et al. (2019a), with the best results we obtained reported in Table 2 (proximal for the biological graphs, standard for the social graphs). We have empirically found that $t = 10$ gives good matching performance for graphs with tens or hundreds of nodes, and moreover that performance is generally quite robust to this parameter choice (cf. illustration in Supplementary Materials).

Optimizing the Scale Parameter. SpecGWL requires determining an appropriate scale parameter t , and here we propose two methods to this end in the context of graph partitioning. We first propose a supervised method for tuning t via **cross-validation**. We generate a dataset (illustration in Supplementary Materials) of $n = 10$ stochastic block model networks with blocks of uniformly random sizes in the range $[20, 50]$, within-block edge density 0.5, and uniformly random across-block edge densities in the range $[0, 0.35]$. Following a leave-one-out cross-validation scheme, we take n subsets of the data and run n trials. In trial j we use subset j as a training set to optimize the scale parameter t via a grid search. Specifically, the optimal t was the one that maximized the sum of the *adjusted mutual information* (AMI) scores computed between the ground truth clusterings and the cluster-

ings recovered by SpecGWL across the training set. We then evaluate the performance of SpecGWL on the test set according to the AMI score. Additionally we evaluate the following baselines: **Fluid** (Parés et al. 2017), **FastGreedy** (Clauset et al. 2004), **Louvain** (Blondel et al. 2008), **Infomap** (Rosvall and Bergstrom 2008), and the adjacency-based GWL (Xu et al. 2019a). Average AMI scores were: (Fluid, 0.59), (FastGreedy, 0.48), (Louvain, **0.65**), (Infomap, 0.0), (GWL, 0.62), (SpecGWL, **0.65**), where the results for Fluid and Louvain were tuned via gridsearch over their parameters (number of communities and *resolution*, respectively). Additionally, SpecGWL outperformed all other baselines in 5 out of 10 trials, with Louvain winning 4 and GWL winning the remaining trial. Moreover, SpecGWL outperformed GWL in 7 out of 10 trials.

We also propose a fully unsupervised method to tune the scale parameter via **modularity maximization**: here we use the *Newman modularity Q-score* as a proxy for AMI—Figure 2 illustrates how the peaks of AMI and modularity occur together across the scale parameter axis using synthetic data generated from a stochastic block model. In our unsupervised tuning method, the number of clusters k is selected by maximizing the modularity (which requires no ground truth partition) of a SpecGWL partitioning with respect to a fixed t -value (we use $t = 10$ at this stage, which we generally found to be stable to parameter perturbation for graphs on the order of 100s to 1000s of nodes) over a range of k -values. Once a k has been selected, the scale parameter t is also selected by maximizing modularity over a range of t values. To illustrate this method with an unsupervised task, we test partitioning performance on Gaussian Random Partition model networks. This is a parametric model for random graphs, where the parameters are number of nodes (we use 1000), mean number of nodes per cluster (we use 150), a probability

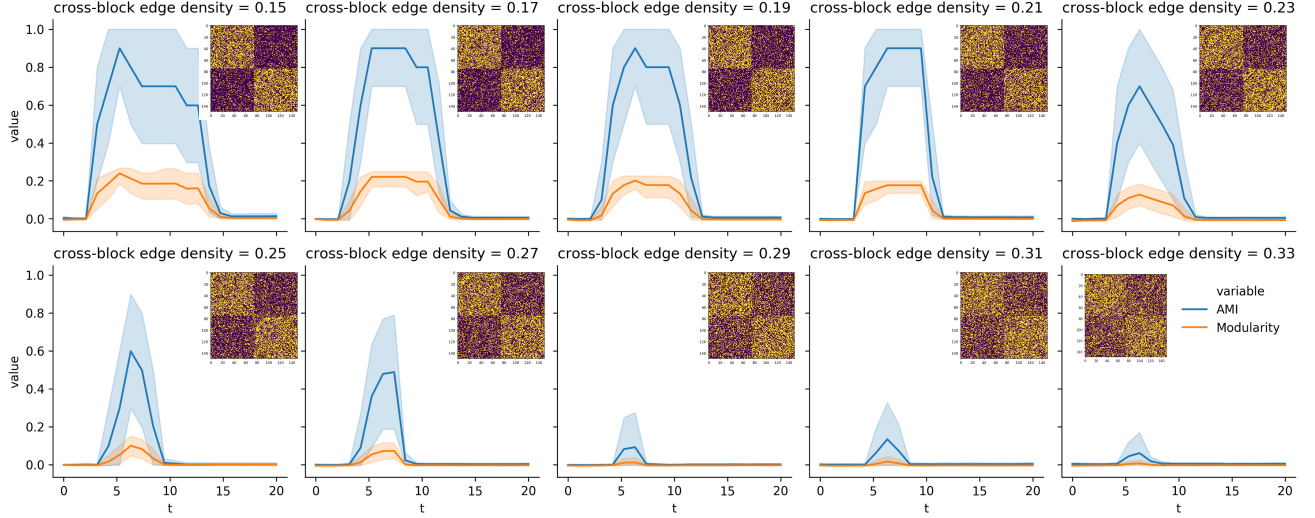


Figure 2: Plots of AMI and modularity for stochastic block model graphs across t parameters with clearly correlated peaks. **Inset:** Sample adjacency matrices for SBMs with increasing cross-block densities.

of within cluster edges (we use 0.5) and a probability of out-of-cluster edges $p_{out} \in \{.08, .10, .12, .15\}$. For each value of p_{out} , we construct a random graph on which SpecGWL is trained to determine number of clusters and optimal t -value. We then create 10 random graphs, partition them and compute AMI against ground truth clusters. Since this is a directed model, the only algorithms that apply are Infomap, GWL and SpecGWL. Average AMI scores and compute times for each p_{out} are reported in Table 3.

Graph Partitioning on Real Data. We compare the performance of SpecGWL on a graph partitioning task against the baseline methods described earlier for four real-world datasets. The first is a directed **Wikipedia** hyperlink network (Leskovec and Krevl, 2014) that we preprocessed by choosing 15 webpage categories and extracting their induced subgraphs. The resulting digraph had 1998 nodes and 2700 edges. The second was obtained from an **Amazon** product network (Leskovec and Krevl, 2014) by taking the subgraph induced by the top 12 product categories. The resulting graph had 1501 nodes and 4626 edges. The third dataset was a digraph of email interactions between 42 departments of a European research institute (**EU-email**), and it comprised 1005 nodes and 25571 edges. The final dataset was a real-world network of interactions (8423 edges) among 1991 residents of 12 Indian villages (Banerjee et al., 2013), which we refer to as the **Village** dataset. We created noisy versions of each graph by adding up to 10% additional edges, and also created symmetrized versions of the Wikipedia and EU-email graphs by adding reciprocal edges.

The quality of each graph partition was measured by computing the AMI score against the ground-truth partition. The scores reported in Table 4 are obtained using parameters selected through the unsupervised procedure described in the previous section. Reported results use standard gradient descent to compute GWL and SpecGWL scores. Despite issues with numerical instability, we also computed scores via the regularized proximal gradient method of Xu et al. (2019a) where possible. Slight score improvements are possible in some cases, but overall score rankings between methods are unchanged—more experimental details are provided in the Supplementary Materials. We find that SpecGWL is the most consistent leader across all methods; in particular, it consistently produces improved results compared to GWL, the only other comprehensive method which is also applicable to graph matching and averaging. The performance of SpecGWL on directed graphs is especially relevant, considering that its closest competitor Infomap is a state-of-the-art method for digraph partitioning.

5 DISCUSSION

We have introduced a spectral notion of GW distance for graph comparison problems based on comparing heat kernels rather than adjacency matrices. This spectral variant is shown qualitatively and quantitatively to improve performance in graph matching and partitioning tasks. The techniques introduced here should be useful for studying further variants of GW distances. For example, work of Peyré et al. (2016) suggests that replacing the L^2 -type spectral loss (5) with a loss based

Table 4: Comparison of adjusted mutual information scores across a variety of datasets.

| | Dataset | Fluid | FastGreedy | Louvain | Infomap | GWL | SpecGWL |
|-----------|-------------|-------|--------------|--------------|--------------|--------------|---------------|
| Wikipedia | sym, raw | — | 0.382 | 0.377 | 0.332 | 0.312 | 0.442* |
| | sym, noisy | — | 0.341 | 0.329 | 0.329 | 0.285 | 0.395 |
| | asym, raw | — | — | — | 0.332 | 0.178 | 0.376 |
| | asym, noisy | — | — | — | 0.329 | 0.170 | 0.307 |
| EU-email | sym, raw | — | 0.312 | 0.447 | 0.374 | 0.451 | 0.487 |
| | sym, noisy | — | 0.251 | 0.382 | 0.379 | 0.404 | 0.425 |
| | asym, raw | — | — | — | 0.443 | 0.420 | 0.437 |
| | asym, noisy | — | — | — | 0.356 | 0.422 | 0.377 |
| Amazon | raw | — | 0.637 | 0.622 | 0.940 | 0.443* | 0.692 |
| | noisy | 0.347 | 0.573 | 0.584 | 0.463 | 0.352 | 0.441 |
| Village | raw | — | 0.881 | 0.881 | 0.881 | 0.606* | 0.801* |
| | noisy | — | 0.778 | 0.827 | 0.190 | 0.560 | 0.758 |

*Slight improvements possible with proximal gradient, but overall performance rankings are preserved.

on KL divergence could have benefits when performing statistical analysis on graph datasets. We also remark that, while spectral GW is faster than its adjacency counterpart on smaller graphs, it may not enjoy the same scalability properties due to the lack of sparse matrix operations. A significant direction of future work will be to construct multiscale approaches to analyze large scale graphs through both adjacency and spectral methods: the divide-and-conquer techniques of Xu et al. (2019a) can break graphs into manageable chunks, and then SpecGWL can finish the computation with improved runtime and accuracy. On the theoretical front, Theorems 2 and 3 suggest that it is tractable to study spectral GW rigorously, and developing Theorem 3 into a larger theory should illuminate further connections between optimal transport and spectral graph theory. It will also be interesting to explore more fully the dependence of our algorithms on the scale parameter t and to incorporate multiple t -values into computations.

Acknowledgments We would like to thank the reviewers on this work for their numerous helpful comments. We wish to also thank Facundo Mémoli for suggesting references related to the original work on Spectral GW.

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