

Learning Graphs From Data

A signal representation perspective

The construction of a meaningful graph topology plays a crucial role in the effective representation, processing, analysis, and visualization of structured data. When a natural choice of the graph is not readily available from the data sets, it is thus desirable to infer or learn a graph topology from the data. In this article, we survey solutions to the problem of graph learning, including classical viewpoints from statistics and physics, and more recent approaches that adopt a graph signal processing (GSP) perspective. We further emphasize the conceptual similarities and differences between classical and GSP-based graph-inference methods and highlight the potential advantage of the latter in a number of theoretical and practical scenarios. We conclude with several open issues and challenges that are keys to the design of future signal processing and machine-learning algorithms for learning graphs from data.

Introduction

Modern data analysis and processing tasks typically involve large sets of structured data, where the structure carries critical information about the nature of the data. One can find numerous examples of such data sets in a wide diversity of application domains, including transportation networks, social networks, computer networks, and brain networks. Typically,

graphs are used as mathematical tools to describe the structure of such data. They provide a flexible way of representing the relationship between data entities. In the past decade, numerous signal processing and machine-learning algorithms have been introduced for analyzing structured data on a priori known graphs [1]–[3]. However, there are often settings where the graph is not readily available, and the structure of the data has to be estimated to permit the effective representation, processing, analysis, or visualization of the data. In this case, a crucial task is to infer a graph topology that describes the characteristics of the data observations, hence capturing the underlying relationship between these entities.

Consider an example in brain signal analysis: suppose we are given blood-oxygen-level-dependent (BOLD) signals, i.e., time series extracted from functional magnetic resonance imaging data that reflect the activities of different regions of the brain. An area of significant interest in neuroscience is the inference of functional connectivity, i.e., to capture the relationship between brain regions that correlate or synchronize given a certain condition of a patient, which may help reveal underpinnings of some neurodegenerative diseases (see Figure 1). This leads to the problem of inferring a graph structure, given the multivariate BOLD time series data.

Formally, the problem of graph learning is the following: given M observations on N variables or data entities represented in a data matrix $\mathbf{X} \in \mathbb{R}^{N \times M}$, and given some prior knowledge (e.g., distribution, data model, and so on) about

the data, we would like to build or infer the relationship between these variables that take the form of a graph \mathcal{G} . As a result, each column of the data matrix \mathbf{X} becomes a graph signal defined on the node set of the estimated graph, and the observations can be represented as $\mathbf{X} = \mathcal{F}(\mathcal{G})$, where \mathcal{F} represents a certain generative process or function on the graph.

The graph-learning problem is an important one because 1) a graph may capture the actual geometry of structured data, which is essential to efficient processing, analysis, and visualization; 2) learning the relationship between data entities benefits numerous application domains, such as understanding functional connectivity between brain regions or behavioral influence between a group of people; and 3) the inferred graph can help to predict future data evolution.

Generally speaking, inferring graph topologies from observations is an ill-posed problem, and there are many ways of associating a topology with the observed data samples. Some of the most straightforward methods include computing the sample correlation or using a similarity function, e.g., a Gaussian radius basis function kernel to quantify the similarity between data samples. These methods are based purely on observations without any explicit prior on or model of the data, hence they may be sensitive to noise and have difficulty in tuning the hyperparameters. A meaningful data model or accurate prior may, however, guide the graph-inference process and lead to a graph topology that better reveals the intrinsic relationship among the data entities. Therefore, a main challenge with this problem is to define such a model for the generative process or function \mathcal{F} , so that it captures the relationship between the observed data \mathbf{X} and the learned graph topology, \mathcal{G} . Typically, such models often correspond to specific criteria to describe or estimate structures between the data samples, e.g., models that put a smoothness assumption on the data, or that represent an information diffusion process on the graph.

Historically, there have been two general approaches for learning graphs from data: one based on statistical models and one based on physically motivated models. From the statistical perspective, $\mathcal{F}(\mathcal{G})$ is modeled as a function that draws realizations from a probability distribution over the variables, which is determined by the structure of \mathcal{G} . One prominent example is found in probabilistic graphical models [5], where the graph structure encodes the conditional independence relationship among random variables that are represented by the vertices. Therefore, learning the graph structure is equivalent to learning a factorization of a joint

probability distribution of these random variables. Typical application domains include inferring interactions between genes using gene expression profiles, and the relationship between politicians given their voting behaviors [6].

For physically motivated models, $\mathcal{F}(\mathcal{G})$ is defined based on the assumption of an underlying physical phenomenon or process on the graph. One popular process is network diffusion or cascades [7]–[10], where $\mathcal{F}(\mathcal{G})$ dictates the diffusion behavior on \mathcal{G} , which leads to the observations \mathbf{X} , possibly at different time steps. In this case, the problem is equivalent to learning a graph structure on which the generative process of the observed signals may be explained. Practical applications include understanding information flowing over a network of online media sources [7] or observing epidemics spreading over a network of human interactions [11], given the state of exposure or infection at certain time steps.

The fast-growing field of GSP [3], [12] offers a new perspective on the problem of graph learning. In this setting, the columns of the observation matrix \mathbf{X} are explicitly considered as signals that are defined on the vertex set of a weighted graph, \mathcal{G} . The learning problem can then be cast as one of learning a graph \mathcal{G} , such that $\mathcal{F}(\mathcal{G})$ permits certain properties or characteristics of the observations \mathbf{X} to be explicit, e.g., smoothness with respect to \mathcal{G} or sparsity in a basis related to \mathcal{G} . This signal representation perspective is particularly interesting because it puts a strong and explicit emphasis on the relationship

between the signal representation and the graph topology, where $\mathcal{F}(\mathcal{G})$ often comes with an interpretation of frequency-domain analysis or filtering operation of signals on the graph. For example, it is common to adopt the eigenvectors of the graph Laplacian matrix associated with \mathcal{G} as a surrogate for the Fourier basis for signals supported on \mathcal{G} [3], [13]; we go deeper into the details of this view in the “Graph Learning: A Signal Representation Perspective” section.

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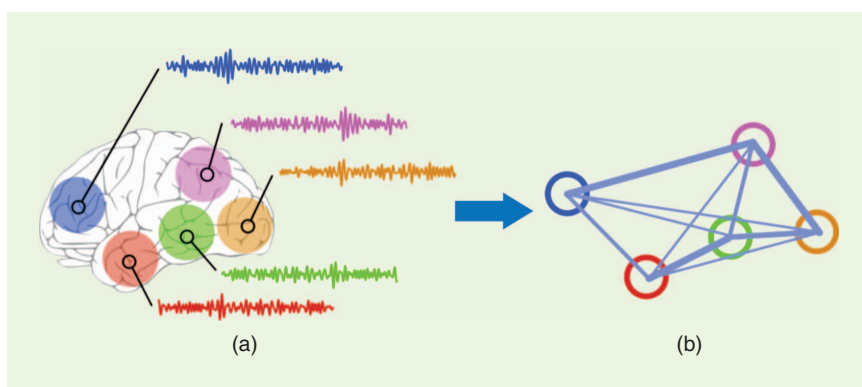


FIGURE 1. Inferring functional connectivity between different regions of the brain. (a) BOLD time series data recorded in different regions of the brain and (b) a functional connectivity graph where the vertices represent the brain regions and the edges (with thicker lines indicating heavier weights) represent the strength of functional connections between these regions. (This figure was adapted from [4, Fig. 1].)

One common representation of interest is a smooth representation in which \mathbf{X} has a slow variation on \mathcal{G} , which can be interpreted as \mathbf{X} mainly consisting of low-frequency components in the graph spectral domain. Such Fourier-like analysis on the graph leads to novel graph-inference methods compared to approaches rooted in statistics or physics. More importantly, it offers the opportunity to represent \mathbf{X} in terms of its behavior in the graph spectral domain, which makes it possible to capture complex and nontypical behavior of graph signals that cannot be explicitly handled by classical tools, e.g., bandlimited signals on graphs. Therefore, given potentially more accurate assumptions underlying the GSP models, the inference of \mathcal{G} , given a specifically designed \mathcal{F} , may better reveal the intrinsic relationship between the data entities and benefit subsequent data processing applications. Conceptually, as illustrated in Figure 2, GSP-based graph-learning approaches can thus be considered as a new family of methods that have close connections with classical methods while also offering certain unique advantages in graph inference.

In this article, we first review well-established solutions to the problem of graph learning, which adopt a statistics or a physics perspective. Next, we survey a series of recent GSP-based approaches and show how signal processing tools and concepts can be utilized to provide novel solutions to the graph-learning problem. Finally, we showcase applications of GSP-based methods in a number of domains and conclude with open questions and challenges that are central to the design of future signal processing and machine-learning algorithms for learning graphs from data.

Literature review

The recent availability of large amounts of data collected in a variety of application domains leads to increased interest in estimating the structure (often encoded in a network or graph) that underlies the data. Two general approaches have been proposed in the literature, one based on statistical models and the other based on physically motivated models. We

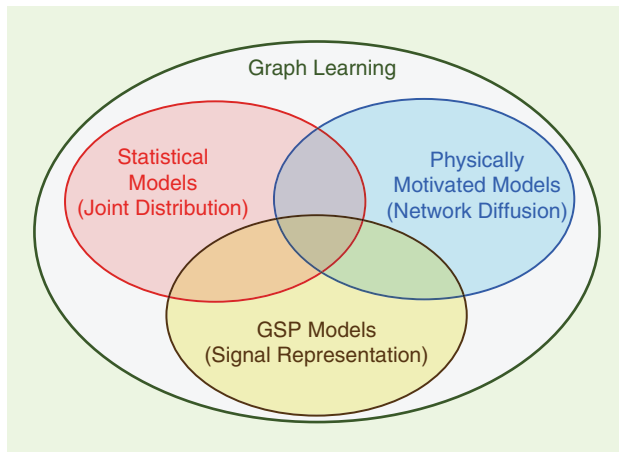


FIGURE 2. A broad categorization of different approaches to the problem of graph learning.

provide a detailed review of these two approaches in the following sections.

Statistical models

The general philosophy behind the statistical view is that there exists a graph \mathcal{G} , whose structure determines the joint probability distribution of the observations on the data entities, i.e., columns of the data matrix \mathbf{X} . In this case, the function $\mathcal{F}(\mathcal{G})$ in our problem formulation is one that draws a collection of realizations, i.e., the columns of \mathbf{X} , from the distribution governed by \mathcal{G} . Such models are known as *probabilistic graphical models* [5], [6], [14]–[16], where the edges (or lack thereof) in the graph encode conditional independence relationship among the random variables represented by the vertices.

There are two main types of graphical models: 1) undirected graphical models, also known as *Markov random fields* (MRFs), in which local neighborhoods of the graph capture the independence structure of the variables, and 2) directed graphical models, also known as *Bayesian networks* or *belief networks* (BNs), which have a more complicated notion of independence by taking into account the direction of edges. Both MRFs and BNs have their respective advantages and disadvantages. In this section, we focus primarily on the approaches for learning MRFs, which admit a simpler representation of conditional independence and also have connections to GSP-based methods. Those who are interested in the comparison between MRFs and BNs as well as approaches for learning BNs are referred to [5] and [17].

An MRF with respect to a graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$, where \mathcal{V} and \mathcal{E} denote the vertex and edge set, respectively, is a set of random variables $\mathbf{x} = \{x_i : v_i \in \mathcal{V}\}$ that satisfy a Markov property. We are particularly interested in the pairwise Markov property

$$(v_i, v_j) \notin \mathcal{E} \Leftrightarrow p(x_i | x_j, \mathbf{x} \setminus \{x_i, x_j\}) = p(x_i | \mathbf{x} \setminus \{x_i, x_j\}). \quad (1)$$

Equation (1) states that two variables, x_i and x_j , are conditionally independent given the rest if there is no edge between the corresponding vertices v_i and v_j in the graph. Suppose we have N random variables, then this condition holds for the exponential family of distributions with a parameter matrix $\Theta \in \mathbb{R}^{N \times N}$

$$p(\mathbf{x} | \Theta) = \frac{1}{Z(\Theta)} \exp \left(\sum_{v_i \in \mathcal{V}} \theta_{ii} x_i^2 + \sum_{(v_i, v_j) \in \mathcal{E}} \theta_{ij} x_i x_j \right), \quad (2)$$

where θ_{ij} represents the ij th entry of Θ , and $Z(\Theta)$ is a normalization constant.

Pairwise MRFs consist of two main classes: 1) Gaussian graphical models, i.e., Gaussian MRFs (GMRFs), in which the variables are continuous, and 2) discrete MRFs, in which the variables are discrete. In the case of a (zero-mean) GMRF, the joint probability can be written as

$$p(\mathbf{x} | \Theta) = \frac{|\Theta|^{1/2}}{(2\pi)^{N/2}} \exp \left(-\frac{1}{2} \mathbf{x}^T \Theta \mathbf{x} \right), \quad (3)$$

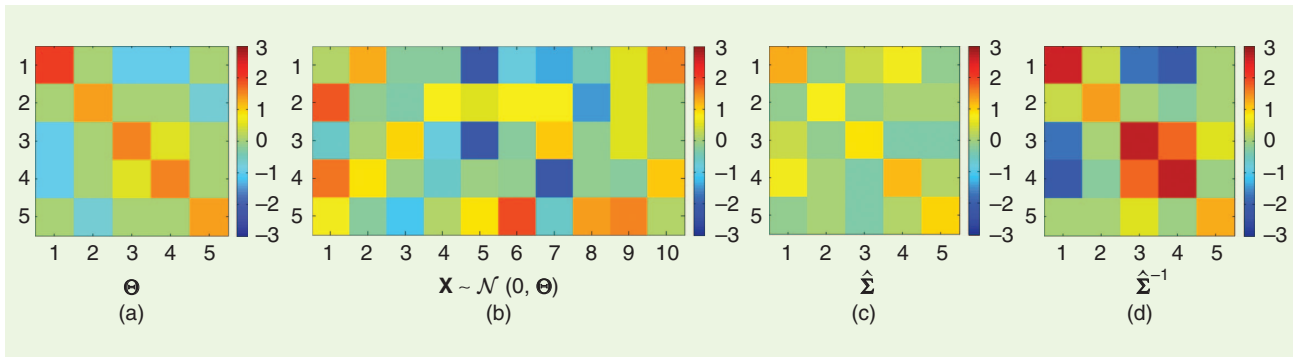


FIGURE 3. (a) A ground-truth precision Θ , (b) an observation matrix \mathbf{X} drawn from a multivariate Gaussian distribution with Θ , (c) the sample covariance $\hat{\Sigma}$, and (d) the inverse of the sample covariance $\hat{\Sigma}^{-1}$.

where Θ is the inverse covariance or precision matrix. In this context, learning the graph structure boils down to learning the matrix Θ , which encodes pairwise conditional independence between the variables. It is typical to assume, or take as a prior, that Θ is sparse because 1) real-world interactions are typically local and 2) the sparsity assumption makes learning computationally more tractable. We now review some key developments in learning Gaussian and discrete MRFs.

To learn GMRFs, one of the first approaches is suggested in [18], where the author has proposed learning Θ by sequentially pruning the smallest elements in the inverse of the sample covariance matrix $\hat{\Sigma} = (1/(M-1))\mathbf{X}\mathbf{X}^T$ (see Figure 3). Although it is based on a simple and effective rule, this method does not perform well when the sample covariance is not a good approximation of the “true” covariance, often due to a small number of samples. In fact, this method cannot even be applied when the sample size is smaller than the number of variables, in which case, the sample covariance matrix is not invertible.

Since a graph is a representation of a pairwise relationship, it is clear that learning a graph is equivalent to learning a neighborhood for each vertex, i.e., the other vertices to which it is connected. In this case, it is natural to assume that the observation at a particular vertex may be represented by observations at the neighboring vertices. Based on this assumption, the authors in [14] have proposed approximating the observation at each variable as a sparse linear combination of the observations at other variables. For a variable x_1 , for instance, this

approximation leads to a Lasso regression problem [19] of the form

$$\underset{\beta_1}{\text{minimize}} \|\mathbf{X}_1 - \mathbf{X}_{\setminus 1}\beta_1\|_2^2 + \lambda \|\beta_1\|_1, \quad (4)$$

where \mathbf{X}_1 and $\mathbf{X}_{\setminus 1}$ represent the observations on the variable x_1 (i.e., transpose of the first row of \mathbf{X}) and the rest of the variables, respectively, and $\beta_1 \in \mathbb{R}^{N-1}$ is a vector of coefficients for x_1 [see Figure 4(a) and (b)]. In (4), the first term can be interpreted as a local log-likelihood of β_1 , and the L^1 penalty is added to enforce its sparsity, with a regularization parameter λ balancing the two terms. The same procedure is then repeated for all of the variables (or vertices). Finally, the connection between a pair of vertices, v_i and v_j , is given by $\theta_{ij} = \theta_{ji} = \max(|\beta_{ij}|, |\beta_{ji}|)$. This neighborhood selection approach using the Lasso is intuitive with certain theoretical guarantees; however, due to the Lasso formulation, it does not work well with observations that are not independent and identically distributed (i.i.d.).

Instead of per-node neighborhood selection, the works in [6], [15], and [20] have proposed a popular method for estimating an inverse covariance or precision matrix at once, which is based on maximum-likelihood estimation. Specifically, the so-called graphical Lasso method aims to solve the following problem:

$$\underset{\Theta}{\text{maximize}} \log \det \Theta - \text{tr}(\hat{\Sigma}\Theta) - \rho \|\Theta\|_1, \quad (5)$$

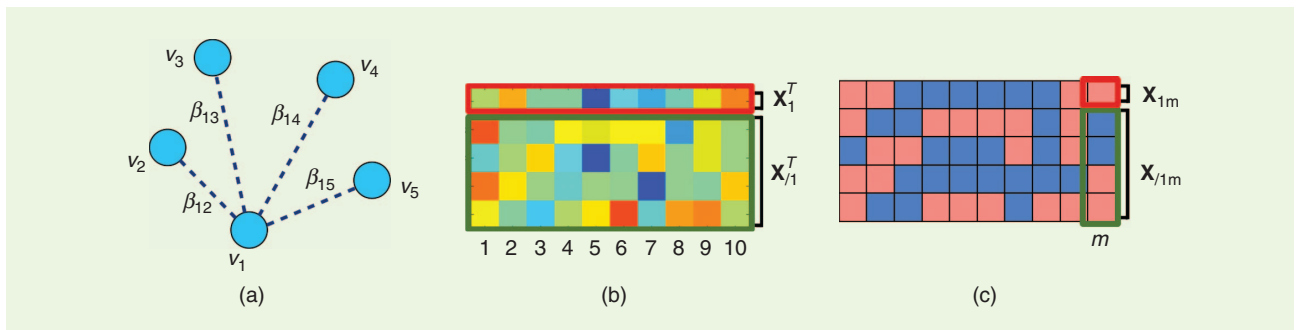


FIGURE 4. (a) Learning graphical models by neighborhood selection, (b) neighborhood selection via the Lasso regression for GMRFs, and (c) neighborhood selection via logistic regression for discrete MRFs.

where $\hat{\Sigma}$ is the sample covariance matrix (see Figure 3), and $\det(\cdot)$ and $\text{tr}(\cdot)$ represent the determinant and trace operators, respectively. The first two terms together can be interpreted as the log-likelihood under a GMRF, and the entry-wise L^1 norm of Θ is added to enforce sparsity of the connections with a regularization parameter, ρ . The main difference between this approach and the neighborhood selection method of [14] is that the optimization in the latter is decoupled for each vertex, while the one in the graphical Lasso is coupled, which can be essential for stability under noise. Although the problem of (5) is convex, log-determinant programs are, in general, computationally demanding. Nevertheless, a number of efficient approaches have been proposed specifically for the graphical Lasso. For example, the work in [16] proposes a quadratic approximation of the Gaussian negative log-likelihood that can significantly speed up optimization.

Unlike the GMRFs, variables in discrete MRFs take discrete values; one popular example is the binary Ising model [21]. Various learning methods may be applied in such cases, and one notable example is the approach proposed in [22], based on the idea of neighborhood selection similar to that in [14]. Specifically, given the exponential family distribution previously introduced, it is easy to verify that the conditional probability of one variable given the rest, e.g., $p(\mathbf{X}_{lm}|\mathbf{X}_{\setminus lm})$ for variable x_1 , where \mathbf{X}_{lm} and $\mathbf{X}_{\setminus lm}$, respectively, represent the first entry and the rest of the m th column of \mathbf{X} [see Figure 4(c)], follows the form of a logistic function. Therefore, x_1 can be considered as the dependent variable in a logistic regression where all of the other variables serve as independent variables. To learn sparse connections within the neighborhood of this vertex, the authors of [22] have proposed solving an L^1 -regularized logistic regression

$$\underset{\beta_1}{\text{maximize}} \log p_{\beta_1}(\mathbf{X}_{lm}|\mathbf{X}_{\setminus lm}) - \lambda \|\beta_1\|_1. \quad (6)$$

The same procedure is then repeated for the rest of the vertices to compute the final connection matrix, similar to that in [14].

Most previous approaches for learning GMRFs recover a precision matrix with both positive and negative entries. A positive off-diagonal entry in the precision matrix implies a negative partial correlation between the two random variables, which is difficult to interpret in some contexts, such as road traffic networks. For such application settings, it is, therefore, desirable to learn a graph topology with nonnegative weights. To this end, the authors in [23] have proposed selecting the precision matrix from the family of the so-called M-matrices [24], which are symmetric and positive definite matrices with nonpositive off-diagonal entries leading to the attractive GMRFs. Because the graph Laplacian matrix \mathbf{L} is a (singular) M-matrix that uniquely determines the adjacency matrix \mathbf{W} , it is a popular modeling choice, and numerous papers have focused on learning \mathbf{L} as a specific instance of the precision matrices.

One notable example is the work in [25], which has adapted the graphical Lasso formulation of (5) and proposed solv-

ing (7), which is slightly different from but equivalent to the optimization problem in [25], because of the following relationship: $\|\Theta\|_1 = \|\mathbf{L}\|_1 + (1/\sigma^2)N = 2\|\mathbf{W}\|_1 + (1/\sigma^2)N$. We therefore choose the formulation in (7) because it illustrates the connection with the graphical Lasso formulation in a straightforward way

$$\begin{aligned} & \underset{\Theta, \sigma^2}{\text{maximize}} \quad \log \det \Theta - \text{tr}\left(\frac{1}{M}\mathbf{X}\mathbf{X}^T\Theta\right) - \rho \|\Theta\|_1, \\ & \text{subject to} \quad \Theta = \mathbf{L} + \frac{1}{\sigma^2}\mathbf{I}, \mathbf{L} \in \mathcal{L}, \end{aligned} \quad (7)$$

where \mathbf{I} is the identity matrix, $\sigma^2 > 0$ is the a priori feature variance, \mathcal{L} is the set of valid graph Laplacian matrices, and $\|\cdot\|_1$ represents the entry-wise L^1 norm. In (7), the precision matrix Θ is modeled as a regularized graph Laplacian matrix (hence, full rank). By solving for it, the authors obtain the graph Laplacian matrix, or equivalently, an adjacency matrix with nonnegative weights.

Note that the trace term in (7) includes the so-called Laplacian quadratic form $\mathbf{X}^T\mathbf{L}\mathbf{X}$, which measures the smoothness of the data on the graph and has also been used in other approaches that are not necessarily developed from the viewpoint of inverse covariance estimation. For instance, the works in [26] and [27] have proposed learning the graph by minimizing quadratic forms that involve powers of the graph Laplacian matrix \mathbf{L} . When the power of the Laplacian is set to two, this is equivalent to the locally linear embedding criterion proposed in [28] for nonlinear dimensionality reduction. As shown later, the criterion of signal smoothness has also been adopted in one of the GSP models for graph inference.

Physically motivated models

While the aforementioned methods mostly exploit statistical properties for graph inference, in particular, the conditional independence structure between random variables, another family of approaches tackles the problem by taking a physically motivated perspective. In this case, the observations, \mathbf{X} , are considered outcomes of some physical phenomena on the graph specified by the function $\mathcal{F}(\mathcal{G})$; the inference problem consists in capturing the structure inherent to the physics of the observed data. Two examples of such methods are 1) network tomography, where the physical process models data actually transmitted in a communication network, and 2) epidemic or information propagation models, where the physical process represents a disease spreading over a contact network or a meme spreading over social media.

The field of network tomography broadly concerns methods for inferring properties of networks from indirect observations [29]. It is most commonly used in the context of telecommunication networks, where the information to be inferred may include the network routes, or properties such as the available bandwidth or the reliability of each link in the network. For example, end-to-end measurements are acquired by sending a sequence of packets from one source to many destinations, and sequences of received

packets are used to infer the internal network topology. The seminal work on this problem aimed to infer the routing tree from one source to multiple destinations [30]. Subsequent work considered interleaving measurements from multiple sources to the same destinations simultaneously to infer general topologies [31]. These methods can be interpreted as choosing the function $\mathcal{F}(\mathcal{G})$ in our formulation as one that measures network responses by exhaustively sending probes between all possible pairs of end hosts. Consequently, this may impose a significant amount of measurement traffic on the network. To reduce this traffic, approaches based on active sampling have also been proposed [32].

Information propagation models have been applied to infer latent biological, social, and financial networks based on observations of epidemics, memes, or other signals diffusing over them (e.g., [7]–[10]). For simplicity and consistency, in this discussion, we adopt the terminology of epidemiology. These types of models are characterized by three main components: 1) the nodes, 2) an infection process (i.e., the change in the state of the node that is transferred by neighboring nodes in the network), and 3) the causality (i.e., the underlying graph structure based on which the infection is propagated). Given a known graph structure, epidemic processes over graphs have been well studied through popular models in which nodes may be susceptible, infected, and possibly recovered [33]. On the other hand, when the structure is not known beforehand, it may be inferred by considering the propagation of contagions over the edges of an unknown network, given usually only the time steps when nodes became infected.

A (fully observed) cascade may be represented by the sequence of triples $\{(v'_p, v_p, t_p)\}_{p=0}^P$, where $P \leq N$, representing that node v'_p infected its neighbor v_p at time t_p . In many applications, one may observe when a node becomes infected, but not which neighbor infected it, as shown in Figure 5. Then, the task is to recover an underlying graph, \mathcal{G} , given the (partial) observations $\{(v_p, t_p)\}_{p=0}^P$, usually for a number of such cascades. In this case, the set of nodes is given and the goal is to recover the edge structure. The common convention is to shift the infection times so that the initial infection in each cascade always occurs at time $t_0 = 0$. Equivalently, let \mathbf{x} denote a length- N vector where x_i is the time when v_i is infected, using the convention $x_i = \infty$ if v_i is not infected in this cascade. The observations from M cascades can then be represented in a N -by- M matrix, $\mathbf{X} = \mathcal{F}(\mathcal{G})$.

Methods for inferring networks from information cascades can be generally divided into two main categories depending on whether they are based on homogeneous or heterogeneous models. Methods based on homogeneous models assume that cascades propagate in a statistically identical manner across all edges. For example, one model treats entries w_{ij} of the (unknown) adjacency matrix as representing the conditional probability that v_i infects v_j , given v_i is infected [8]. In addition, a transmission time model, $h(t)$, is assumed known such that the likelihood that v_i infects v_j at time x_j , given that v_i was infected at time $x_i < x_j$, is

$$p(x_j | x_i, w_{ij}) = h(x_j - x_i) w_{ij}. \quad (8)$$

Here, $h(t)$ is taken to be zero for $t < 0$ and typically decays to zero as $t \rightarrow \infty$.

Assuming that the function $h(t)$ is given, the inference problem reduces to finding the conditional probabilities w_{ij} . Given the set of nodes infected as well as the time of infection in each observed cascade, and assuming that cascades are independent and identically distributed, the likelihood of a graph with adjacency matrix \mathbf{W} (with w_{ij} being the ij th entry) is derived explicitly in [8], and it is further shown that maximizing this likelihood can be recast as an equivalent geometric program so that convex optimization techniques can be applied to the problem of inferring \mathbf{W} .

A similar model is considered in [7], in which the conditional transmission probabilities are taken to be the same on all edges, i.e., $w_{ij} = \beta \cdot \mathbf{1}\{(v_i, v_j) \in \mathcal{E}\}$, where $\mathbf{1}\{\cdot\}$ is an indicator function, for a given constant $\beta \in (0, 1)$. The task, therefore, reduces to determining where there are edges, which is a discrete optimization problem. The maximum-likelihood objective is shown to be submodular in [7], and an edge selection scheme based on greedy optimization obtains the optimal likelihood up to a constant factor. Clearly, the main drawbacks of homogeneous methods are the strong underlying assumption that cascades propagate in an identical manner across all edges in the network.

Methods based on heterogeneous models relax these requirements and allow for cascades to propagate at different rates across different edges. The NETRATE algorithm [9] is a prototypical example of this category, in which one assumes a parametric form for

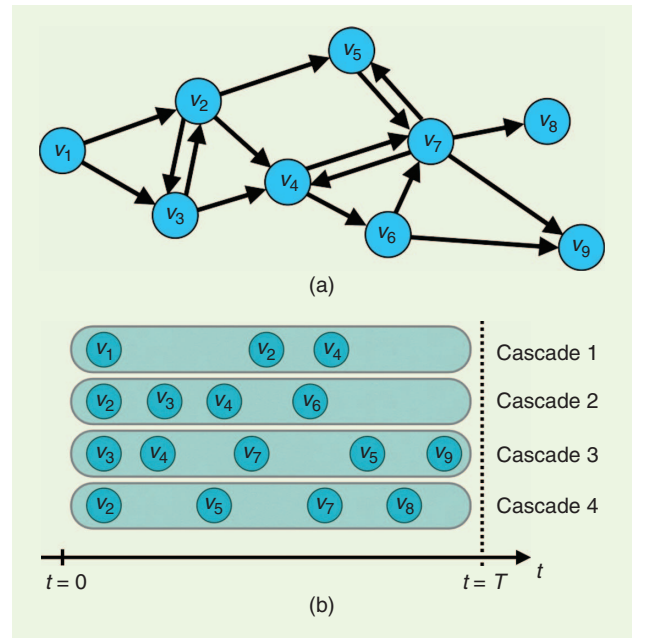


FIGURE 5. (a) An underlying graph with directed edges indicating possible directions of spreading and (b) observations of cascades spreading over the graph. We observe the times when nodes became infected (i.e., the cascade reached a node) but do not observe from which neighbor it was infected. (This figure was inspired by [9, Fig. 1].)

the edge conditional likelihood $p(x_j|x_i, w_{ij})$. For example, in an exponential model, $p(x_j|x_i, w_{ij}) = w_{ij}e^{-w_{ij}(x_j-x_i)} \cdot \mathbf{1}\{x_j > x_i\}$. If we write $P(x_j|x_i, w_{ij}) = \int_{x_i}^{x_j} p(t|x_i, w_{ij}) dt$ for the cumulative density function, then the survival function

$$\text{Sur}(x_j|x_i, w_{ij}) = 1 - P(x_j|x_i, w_{ij}) \quad (9)$$

is the probability that v_j is not infected by v_i by time x_j , given that v_i was infected at time x_i . Furthermore, the hazard function

$$\text{Haz}(x_j|x_i, w_{ij}) = \frac{p(x_j|x_i, w_{ij})}{\text{Sur}(x_j|x_i, w_{ij})}, \quad (10)$$

is the instantaneous probability at time x_j that v_j is infected by v_i , given that v_i was infected at time x_i .

With this notation, the likelihood of a given cascade observation \mathbf{x} that is observed up to time $T = \max\{x_v < \infty : v \in \mathcal{V}\}$, is [9]

$$p(\mathbf{x}|\mathbf{W}) = \prod_{i: x_i \leq T} \prod_{j: x_j > T} \text{Sur}(T|x_i, w_{ij}) \times \prod_{k: x_k < x_i} \text{Sur}(x_i|x_k, w_{ki}) \sum_{l: x_l < x_i} \text{Haz}(x_i|x_l, w_{li}). \quad (11)$$

When the survival and hazard functions are log-concave (which is the case for exponentially distributed edge conditional likelihoods as well as others), then the resulting maximum-likelihood inference problem is shown to be convex in [9]. In fact, the overall maximum-likelihood problem decomposes into per-node problems that can be solved using a soft-thresholding algorithm, in a manner similar to [14]. Furthermore, conditions are provided in [34] under which the resulting estimate is shown to be consistent (as the number of observed cascades tends to infinity), and sample complexity results are provided, quantifying how quickly the error decays as a function of the number of observed cascades.

The aforementioned heterogeneous approach requires adopting a parametric model for the edge conditional likelihood, which may be difficult to justify in some settings. The approach described in [10] uses kernel methods to estimate the edge conditional likelihoods in a nonparametric manner. More recently, a Bayesian approach that infers a graph topology from diffusion observations has been proposed in which the infection time is not directly observed [35], but rather the state of each node (susceptible or infected) is a latent variable affecting the statistics of the signal that is observed at each node.

In summary, many physically motivated approaches consider the function $\mathcal{F}(\mathcal{G})$ to be an information propagation model on the network and generally fall under the bigger umbrella of probabilistic inference of the network of diffusion or epidemic data. Note, however, that despite its probabilistic nature, such an inference is carried out with a specific model of the physical phenomena in mind, instead of using a general probability distribution of the observations considered by statistical models in the previous section. In addition, for both methods in network tomography and those based on information propa-

gation models, the recovered network typically indicates only the existence of edges and does not promote a specific graph signal structure. As we shall see, this is a clear difference from the GSP models that are discussed in the following section.

Graph learning: A signal representation perspective

There is a growing interest in the signal processing community to analyze signals that are supported on the vertex set of weighted graphs, leading to the fast-growing field of GSP [3], [12]. GSP enables the processing and analysis of signals that lie on structured but irregular domains by generalizing classical signal processing concepts, tools, and methods, such as time-frequency analysis and filtering, on graphs [3], [12], [13].

Consider a weighted graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$ with the vertex set \mathcal{V} of cardinality N and edge set \mathcal{E} . A graph signal is defined as a function $\mathbf{x}: \mathcal{V} \rightarrow \mathbb{R}^N$ that assigns a scalar value to each vertex. When the graph is undirected, the combinatorial or unnormalized graph Laplacian matrix \mathbf{L} is defined as

$$\mathbf{L} = \mathbf{D} - \mathbf{W}, \quad (12)$$

where \mathbf{D} is the degree matrix that contains the degrees of the vertices along the diagonal, and \mathbf{W} is the weighted adjacency matrix of \mathcal{G} . Since \mathbf{L} is a real and symmetric matrix, it admits a complete set of orthonormal eigenvectors with the associated eigenvalues via the eigencomposition

$$\mathbf{L} = \boldsymbol{\chi} \boldsymbol{\Lambda} \boldsymbol{\chi}^T, \quad (13)$$

where $\boldsymbol{\chi}$ is the eigenvector matrix that contains the eigenvectors as columns, and $\boldsymbol{\Lambda}$ is the eigenvalue matrix $\text{diag}(\lambda_0, \lambda_1, \dots, \lambda_{N-1})$ that contains the eigenvalues along the diagonal. Conventionally, the eigenvalues are sorted in an increasing order, and we have for a connected graph: $0 = \lambda_0 < \lambda_1 \leq \dots \leq \lambda_{N-1}$. The Laplacian matrix \mathbf{L} enables a generalization of the notion of frequency and the definition of a graph Fourier transform (GFT) [36]. Alternatively, a GFT may also be defined using the adjacency matrix \mathbf{W} , and this definition can be used in directed graphs [12]. Furthermore, both \mathbf{L} and \mathbf{W} can be interpreted as a general class of shift operators on graphs [12].

These operators are used to represent and process signals on a graph in a way similar to that in traditional signal processing. To see this more clearly, consider two equations of central importance in signal processing: $\mathcal{D}\mathbf{c} = \mathbf{x}$ for the synthesis view and $\mathcal{A}\mathbf{x} = \mathbf{b}$ for the analysis view. In the synthesis view, the signal \mathbf{x} is represented as a linear combination of atoms that are columns of a representation matrix \mathcal{D} , with \mathbf{c} being the coefficient vector. In the context of GSP, the representation \mathcal{D} of a signal on the graph \mathcal{G} is realized via $\mathcal{F}(\mathcal{G})$, i.e., a function of \mathcal{G} . In the analysis view of GSP, given \mathcal{G} and \mathbf{x} and with a design for \mathcal{F} (that defines \mathcal{A}), we study the characteristics of \mathbf{x} encoded in \mathbf{b} . Examples include the generalization of the Fourier and wavelet transforms for graph signals [12], [36], which are defined based on mathematical properties of a given graph, \mathcal{G} . Alternatively, graph dictionaries can be

trained by taking into account information from both \mathcal{G} and \mathbf{x} [37], [38].

Although most GSP approaches focus on developing techniques for analyzing signals on a predefined or known graph, there is growing interest in addressing the problem of learning graph topologies from observed signals, especially in the case when the topology is not readily available (i.e., not predefined given the application domain). This offers a new perspective on the problem of graph learning, especially by focusing on the representation of the observed signals on the learned graph. Indeed, this corresponds to a synthesis view of the signal processing model: given \mathbf{x} , with some designs for \mathcal{F} and \mathbf{c} , we would like to infer \mathcal{G} . Of crucial importance is, therefore, a model that captures the relationship between the signal representation and the graph, which, together with graph operators such as the adjacency/Laplacian matrices or the graph shift operators [12], contributes to specific designs for \mathcal{F} . Moreover, assumptions on the structure or properties of \mathbf{c} also play an important role in determining the characteristics of the resulting signal representation. Graph-learning frameworks that are developed from a signal representation perspective therefore have the unique advantage of enforcing certain desirable representations of the observed signals by exploiting the notions of frequency-domain analysis and filtering operations on graphs.

A graph signal representation perspective is complementary to the existing perspectives that we discussed in the previous sections. For instance, from the statistical perspective, the majority of approaches for learning graphical models do not lead directly to a graph topology with nonnegative edge weights, a property that is often desirable in real-world applications, and very little work has studied the case of inferring attractive GMRFs. Furthermore, the joint distribution of the random variables is mostly imposed in a global manner, while it is not easy to encourage localized behavior (i.e., about a subset of the variables) on the learned graph. The physics perspective, on the other hand, mostly focuses on a few conventional models such as network diffusion and cascades. It remains, however, an open question how observations that do not necessarily come from a well-defined physical phenomenon can be exploited to infer the underlying structure of the data. The GSP viewpoint introduces one more important ingredient that can be used as a regularizer for complicated inference problems: the frequency or spectral representation of the observations. In the following sections, we review three models for signal representation on graphs, which lead to various methodologies for inferring graph topologies from the observed signals.

Models based on signal smoothness

The first model we consider is a smoothness model, under which the signal takes similar values at neighboring vertices. Practical examples of this model could be temperature observed at different locations in a flat geographical region or ratings on movies

by individuals in a social network. The measure of smoothness of a signal \mathbf{x} on the graph \mathcal{G} is usually defined by the so-called Laplacian quadratic form

$$Q(\mathbf{L}) = \mathbf{x}^T \mathbf{L} \mathbf{x} = \frac{1}{2} \sum_{i,j} w_{ij} (\mathbf{x}(i) - \mathbf{x}(j))^2, \quad (14)$$

where w_{ij} is the ij th entry of the adjacency matrix \mathbf{W} and \mathbf{L} is the Laplacian matrix. Clearly, $Q(\mathbf{L}) = 0$ when \mathbf{x} is a constant signal over the graph (i.e., a dc signal with no variation). More generally, we can see that given the same L^2 -norm, the smaller the value $Q(\mathbf{L})$, the more similar the signal values at neighboring vertices (i.e., the lower the variation of \mathbf{x} with respect to \mathcal{G}). One natural criterion is therefore to learn a graph (or, equivalently, its Laplacian matrix \mathbf{L}) such that the signal variation on the resulting graph, i.e., the Laplacian quadratic $Q(\mathbf{L})$, is small. As an example, for the same signal, learning a graph in Figure 6(a) leads to a smoother signal representation in terms of $Q(\mathbf{L})$ than that by learning a graph in Figure 6(c). The criterion of minimizing $Q(\mathbf{L})$ or its variants with powers of \mathbf{L} has been proposed in a number of existing approaches, such as the ones in [25]–[27].

A procedure to infer a graph that favors the smoothness of the graph signals can be obtained using the synthesis model $\mathcal{F}(\mathcal{G})\mathbf{c} = \mathbf{x}$, and this is the idea behind the approaches in [39] and [40]. Specifically, consider a factor analysis model with the choice of $\mathcal{F}(\mathcal{G}) = \chi$ and

$$\mathbf{x} = \chi \mathbf{c} + \boldsymbol{\epsilon}, \quad (15)$$

where χ is the eigenvector matrix of the Laplacian \mathbf{L} and $\boldsymbol{\epsilon} \sim \mathcal{N}(\mathbf{0}, \sigma_{\epsilon}^2 \mathbf{I})$ is additive Gaussian noise. With further assumptions that \mathbf{c} follows a Gaussian distribution with a precision matrix $\boldsymbol{\Lambda}$

$$\mathbf{c} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Lambda}^{\dagger}), \quad (16)$$

where $\boldsymbol{\Lambda}^{\dagger}$ is the Moore–Penrose pseudoinverse of the eigenvalue matrix of \mathbf{L} , and that \mathbf{c} and $\boldsymbol{\epsilon}$ are statistically independent, it is shown in [39] that the signal \mathbf{x} follows a GMRF model

$$\mathbf{x} \sim \mathcal{N}(\mathbf{0}, \mathbf{L}^{\dagger} + \sigma_{\epsilon}^2 \mathbf{I}). \quad (17)$$

This leads to formulating the problem of jointly inferring the graph Laplacian and the latent variable \mathbf{c} as

$$\underset{\chi, \mathbf{A}, \mathbf{c}}{\text{minimize}} \|\mathbf{x} - \chi \mathbf{c}\|_2^2 + \alpha \mathbf{c}^T \boldsymbol{\Lambda} \mathbf{c}, \quad (18)$$

where α is a nonnegative regularization parameter related to the assumed noise level σ_{ϵ}^2 . By making the change of variables $\mathbf{y} = \chi \mathbf{c}$ and recalling that the matrix of Laplacian eigenvectors χ is orthonormal, one arrives at the equivalent problem

$$\underset{\mathbf{L}, \mathbf{y}}{\text{minimize}} \|\mathbf{x} - \mathbf{y}\|_2^2 + \alpha \mathbf{y}^T \mathbf{L} \mathbf{y}, \quad (19)$$

in which the Laplacian quadratic form appears. Therefore, these particular modeling choices for \mathcal{F} and \mathbf{c} lead to a procedure for inferring a graph over which the observation \mathbf{x} is smooth. Note that there is a one-to-one mapping between the Laplacian matrix \mathbf{L} and a weighted undirected graph, so inferring \mathbf{L} is equivalent to inferring \mathcal{G} .

By taking the matrix form of the observations and adding an L^2 penalty, the authors of [39] have proposed solving the following optimization problem

$$\begin{aligned} & \underset{\mathbf{L}, \mathbf{Y}}{\text{minimize}} && \|\mathbf{X} - \mathbf{Y}\|_F^2 + \alpha \text{tr}(\mathbf{Y}^T \mathbf{L} \mathbf{Y}) + \beta \|\mathbf{L}\|_F^2, \\ & \text{subject to} && \text{tr}(\mathbf{L}) = N, \quad \mathbf{L} \in \mathcal{L}, \end{aligned} \quad (20)$$

where $\text{tr}(\cdot)$ and $\|\cdot\|_F$ represent the trace and Frobenius norm of a matrix, respectively, and α and β are nonnegative regularization

parameters. The trace constraint acts as a normalization factor that fixes the volume of the graph, and \mathcal{L} is the set of valid Laplacian matrices. This constitutes the problem of finding \mathbf{Y} that is close to the data observations \mathbf{X} , while ensuring at the same time that \mathbf{Y} is smooth on the learned graph, represented by its Laplacian matrix, \mathbf{L} . The Frobenius norm of \mathbf{L} is added to control the distribution of the edge weights and is inspired by the approach in [27]. The problem is solved via alternating minimization in [39], in which the step of solving for \mathbf{L} bears similarity to the optimization in [27]. A formulation similar to (20) has further been studied in [40], where reformulating the problem in terms of the adjacency matrix \mathbf{W} leads to a more efficient algorithm computationally. Both works emphasize the characteristics of GSP-based graph-learning approaches, i.e., enforcing desirable signal representations through the learning process.

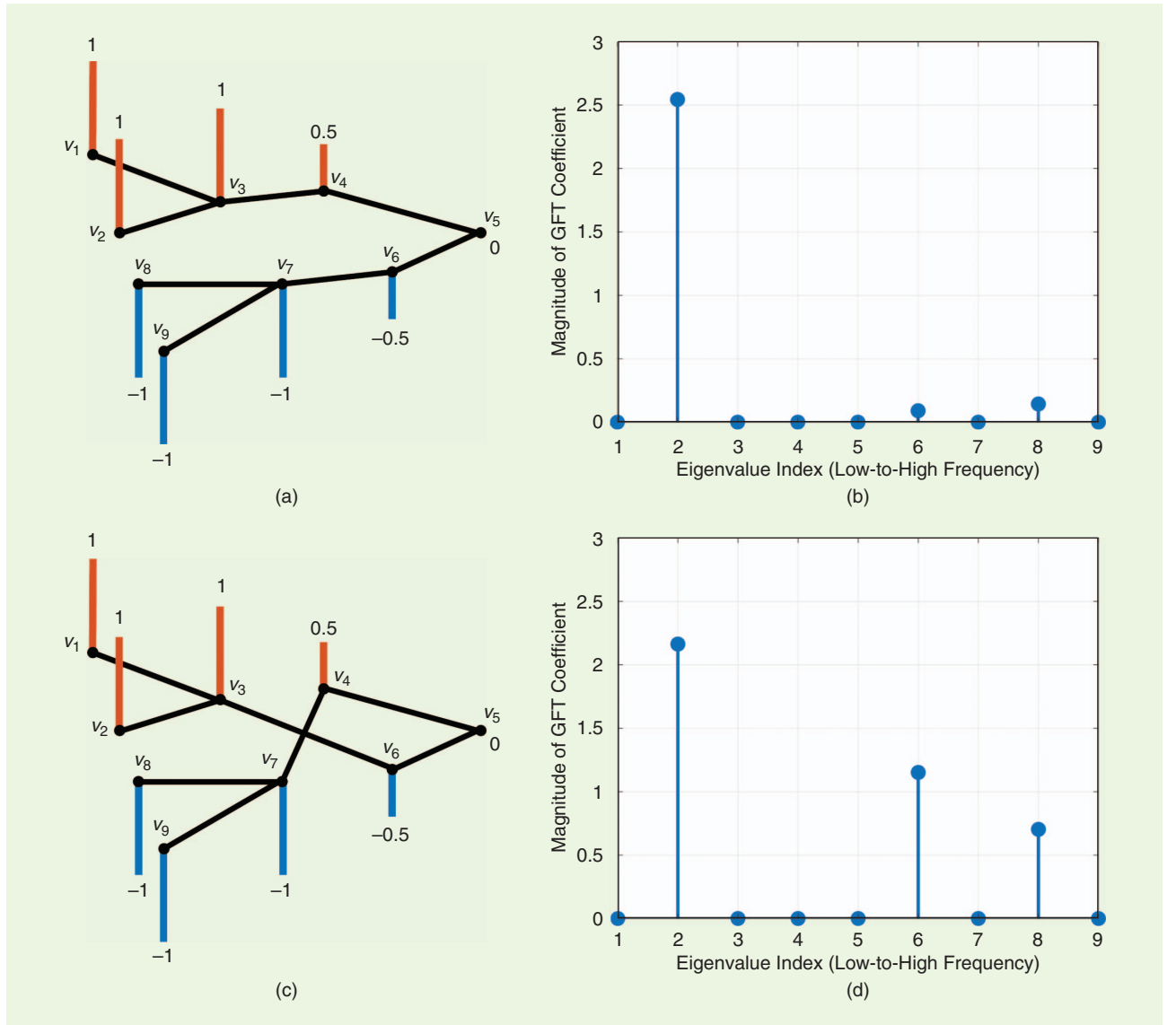


FIGURE 6. (a) A smooth signal on the graph with $Q(\mathbf{L})=1$ and (b) its GFT [36] coefficients in the graph spectral domain. The signal forms a smooth representation on the graph as its values vary slowly along the edges of the graph, and it mainly consists of low-frequency components in the graph spectral domain. (c) A less smooth signal on the graph with $Q(\mathbf{L})=5$ and (d) its GFT [36] coefficients in the graph spectral domain. A different choice of the graph leads to a different representation of the same signal.

As we have seen, the smoothness property of the graph signal is associated with a multivariate Gaussian distribution, which is also behind the idea of classical approaches for learning graphical models, such as the graphical Lasso. Following the same design for \mathcal{F} and slightly different designs for Λ as compared to those in [39] and [40], the authors of [41] have proposed solving a similar objective compared to the graphical Lasso but with the constraints that the solutions correspond to different types of graph Laplacian matrices (e.g., the combinatorial or generalized Laplacian). The basic idea in the latter approach is to identify GMRF models so that the precision matrix has the form of a graph Laplacian. Their work generalizes the classical graphical Lasso formulation and the formulation proposed in [25] to precision matrices restricted to having a Laplacian form. From a probabilistic perspective, the problems of interest correspond to a maximum a posteriori parameter estimation of GMRF models, whose precision matrix is a graph Laplacian. In addition, the proposed approach allows for incorporating prior knowledge on graph connectivity, which, if applicable, can help improve the performance of the graph-inference algorithm.

It is also worth mentioning that the approaches in [39]–[41] learn a graph topology without any explicit constraint on the density of the edges in the learned graph. This information, if available, can be incorporated into the learning process. For example, the work of [42] has proposed learning a graph with a targeted number of edges by selecting the ones that lead to the smallest $Q(\mathbf{L})$.

To summarize, in the global smoothness model, the objective of minimizing the original or a variant of the Laplacian quadratic form of $Q(\mathbf{L})$ can be interpreted as having $\mathcal{F}(\mathcal{G}) = \chi$ and \mathbf{c} following a multivariate Gaussian distribution. However, different learning algorithms may vary in both the output of the algorithm and the computational complexity. For instance, the approaches in [40] and [42] learn an adjacency matrix, while the approaches in [39] and [41] learn a graph Laplacian matrix or its variants. In terms of complexity, the approaches in [39]–[41] all solve a quadratic program, with efficient implementations provided in the latter two based on primal-dual techniques and block-coordinate-descent algorithms, respectively. On the other hand, the method in [42] involves a sorting algorithm that scales with the desired number of edges.

Finally, it is important to notice that $Q(\mathbf{L})$ is a measure of global smoothness on \mathcal{G} in the sense that a small $Q(\mathbf{L})$ implies a small variation of signal values along all of the edges in the graph, and the signal energy is mostly concentrated in the low-frequency components in the graph spectral domain. Although global smoothness is often a desirable property for the signal representation, it can also be limiting in other scenarios. The second class of models that we introduce in the following section relaxes this constraint by allowing for a

more flexible representation of the signal in terms of its spectral characteristics.

Models based on spectral filtering of graph signals

The second graph signal model that we consider goes beyond the global smoothness of the signal on the graph and focuses more on the general family of graph signals that are generated by applying a filtering operation to a latent (input) signal. In particular, the filtering operation may correspond to the diffusion of an input signal on the graph. Depending on the type of graph filter and input signal, the generated signal can have different frequency characteristics (e.g., bandpass signals) and localization properties (e.g., locally smooth signals). Moreover, this family of algorithms is more appropriate than the one based on a globally smooth signal model for learning graph topologies when the observations are the result of a diffusion process on a graph. Particularly, the graph diffusion model can be widely applied in real-world scenarios to understand the distribution of heat (sources) [43], such as the propagation of a heat wave in geographical spaces, the movement of people in buildings or vehicles in cities, and the shift of people's interest toward certain subjects on social media platforms [44].

In these types of models, the graph filters and input signals may be interpreted as the functions $\mathcal{F}(\mathcal{G})$ and the coefficients \mathbf{c} in our synthesis model, respectively. The existing methods in the literature therefore differ in the assumption on \mathcal{F} as well as the distribution of \mathbf{c} . In particular, \mathcal{F} may be defined as an arbitrary (polynomial) function of a matrix related to the graph [45], [46], or a well-known diffusion kernel, such as the heat diffusion kernel [47] (see Figure 7 for two examples). The assumptions on \mathbf{c} can also vary, with the most prevalent ones being zero-mean Gaussian distribution and sparsity. Broadly speaking, we can distinguish the graph-learning algorithms belonging to this family in two different categories. The first category models the graph signals as stationary processes on graphs, where the eigenvectors of a graph operator, such as the adjacency/Laplacian matrix or a shift operator, are estimated from the sample covariance matrix of the observations in the first step. The eigenvalues are then estimated in the second step to obtain the operator. The second category poses the graph-learning problem as a dictionary-learning problem with a prior on the coefficients \mathbf{c} . In the following sections, we give a few representative examples of both categories, which differ in terms of graph filters as well as input signal characteristics.

Stationarity-based learning frameworks

The main characteristic of this line of work is that, given a stationarity assumption, the eigenvectors of a graph operator are estimated by the empirical covariance matrix of the observations. In particular, the graph signal \mathbf{x} can be generated from

Graph-learning frameworks that are developed from a signal representation perspective therefore have the unique advantage of enforcing certain desirable representations of the observed signals by exploiting the notions of frequency-domain analysis and filtering operations on graphs.

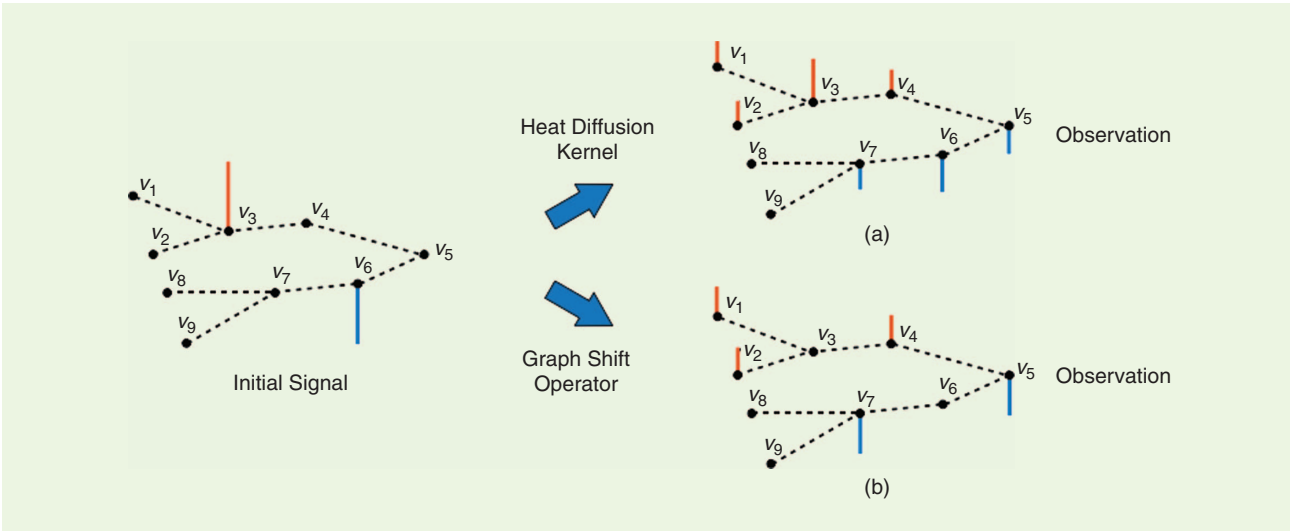


FIGURE 7. Diffusion processes on the graph defined by (a) a heat diffusion kernel and (b) a graph shift operator.

$$\mathbf{x} = \beta_0 \prod_{k=1}^{\infty} (\mathbf{I} - \beta_k \mathbf{S}) \mathbf{c} = \sum_{k=0}^{\infty} \alpha_k \mathbf{S}^k \mathbf{c}, \quad (21)$$

for some sets of the parameters $\{\alpha\}$ and $\{\beta\}$. The latter implies that there exists an underlying diffusion process in the graph operator \mathbf{S} , which can be the adjacency matrix, Laplacian, or a variation thereof, that produces the signal \mathbf{x} from the input signal \mathbf{c} . By assuming a finite polynomial degree K , the generative signal model becomes

$$\mathbf{x} = \mathcal{F}(\mathcal{G}) \mathbf{c} = \sum_{k=0}^K \alpha_k \mathbf{S}^k \mathbf{c}, \quad (22)$$

where the connectivity matrix of \mathcal{G} is captured through the graph operator \mathbf{S} . Usually, \mathbf{c} is assumed to be a zero-mean graph signal with the covariance matrix $\Sigma_{\mathbf{c}} = \mathbb{E}[\mathbf{c}\mathbf{c}^T]$. In addition, if \mathbf{c} is white and $\Sigma_{\mathbf{c}} = \mathbf{I}$, (21) is equivalent to assuming that the graph process \mathbf{x} is stationary in \mathbf{S} . This assumption of stationarity is important for estimating the eigenvectors of the graph operator. Indeed, since the graph operator \mathbf{S} is often a real and symmetric matrix, its eigenvectors are also eigenvectors of the covariance matrix $\Sigma_{\mathbf{x}}$. As a matter of fact,

$$\begin{aligned} \Sigma_{\mathbf{x}} &= \mathbb{E}[\mathbf{x}\mathbf{x}^T] = \mathbb{E}\left[\sum_{k=0}^K \alpha_k \mathbf{S}^k \mathbf{c} \left(\sum_{k=0}^K \alpha_k \mathbf{S}^k \mathbf{c}\right)^T\right] \\ &= \sum_{k=0}^K \alpha_k \mathbf{S}^k \left(\sum_{k=0}^K \alpha_k \mathbf{S}^k\right)^T = \chi \left(\sum_{k=0}^K \alpha_k \Lambda^k\right)^2 \chi^T, \end{aligned} \quad (23)$$

where we have used the assumption that $\Sigma_{\mathbf{c}} = \mathbf{I}$ and the eigen-decomposition $\mathbf{S} = \chi \Lambda \chi^T$. Given a sufficient number of graph signals, the eigenvectors of the graph operator \mathbf{S} can therefore be approximated by the eigenvectors of the empirical covariance matrix of the observations. To recover \mathbf{S} , the second step of the process would then be to learn its eigenvalues.

The authors in [46] have followed the aforementioned reasoning and modeled the diffusion process by powers of the

normalized Laplacian matrix. More precisely, they propose an algorithm for characterizing and then computing a set of admissible diffusion matrices, which defines a polytope. In general, this polytope corresponds to a continuum of graphs that are all consistent with the observations. To obtain a particular solution, an additional criterion is required. Two such criteria are one that encourages the resulting graph to be sparse and another that encourages the recovered graph to be simple (i.e., a graph in which no vertex has a connection to itself, hence an adjacency matrix with only zeros along the diagonal).

Similarly, in [45], after obtaining the eigenvectors of a graph shift operator, the graph-learning problem is equivalent to learning its eigenvalues under the constraints that the shift operator obeys some desired properties, such as sparsity. The optimization problem of [45] can be written as

$$\begin{aligned} &\underset{\mathbf{S}, \Psi}{\text{minimize}} && f(\mathbf{S}, \Psi), \\ &\text{subject to} && \mathbf{S} = \chi \Psi \chi^T, \mathbf{S} \in \mathcal{S}, \end{aligned} \quad (24)$$

where $f(\cdot)$ is a convex function applied on \mathbf{S} that imposes the desired properties of \mathbf{S} , e.g., sparsity via an entry-wise L^1 -norm, and \mathcal{S} is the constraint set of \mathbf{S} being a valid graph operator, e.g., nonnegativity of the edge weights. The stationarity assumption is further relaxed in [48]. However, all of these approaches are based on the assumption that the sample covariance of the observed data and the graph operator have the same set of eigenvectors. Thus, their performance depends on the accuracy of eigenvectors obtained from the sample covariance of data, which can be difficult to guarantee especially when the number of data samples is small relative to the number of vertices in the graph.

Given the limitation in estimating the eigenvectors of the graph operator from the sample covariance, the work of [49] has proposed a different approach. They have formulated the problem of graph learning as a graph system identification problem where, by assuming that the observed signals are outputs of a system with a graph-based filter given certain input, the

goal is to learn a weighted graph (a graph Laplacian matrix) and the graph-based filter (a function of the graph Laplacian matrices). This algorithm is based on the minimization of a regularized maximum-likelihood criterion, and it is valid under the assumption that the graph filters are one-to-one functions, i.e., increasing or decreasing in the space of eigenvalues, such as a heat diffusion kernel. More specifically, the system input is assumed to be multivariate white Gaussian noise (hence the stationarity assumption on the observed signals), and (23) is again used for computing an initial estimate of the eigenvectors. However, different from [45] and [46], where these eigenvectors are used directly in forming the graph operators, in [49], they are used to compute the graph Laplacian. After initializing the filter parameter, the algorithm iterates until convergence between the following three steps: 1) prefilter the sample covariance using the inverse of the graph filter; 2) estimate a graph Laplacian from the prefiltered covariance matrix by solving a maximum-likelihood optimization criterion using an algorithm proposed in [41]; and 3) update the filter parameter based on the current estimate of the graph Laplacian. Compared to [45] and [46], this approach may therefore lead to a more accurate inference of the graph operator (in this case, graph Laplacian).

Graph dictionary-based learning frameworks

Methods belonging to this category are based on the notion of spectral graph dictionaries used for efficient signal representation. Specifically, the authors in [47] and [50] assume a different graph signal diffusion model, where the data consist of (sparse) combinations of overlapping local patterns that reside on the graph. These patterns may describe localized events or specific processes appearing at different vertices of the graph, such as traffic bottlenecks in transportation networks or rumor sources in social networks. The graph signals are then viewed as observations at different time instants of a few processes that start at different nodes of an unknown graph and diffuse with time. Such signals can be represented as the combination of graph heat kernels or, more generally, of localized graph kernels. Both algorithms can be considered as a generalization of dictionary learning to graph signals. Dictionary learning [51], [52] is an area of research in signal processing and machine learning where the signals are represented as a linear combination of simple components, i.e., atoms, in an (often) overcomplete basis. Signal decompositions with over-

complete dictionaries offer a way to efficiently approximate or process signals, such that the important characteristics are revealed by the sparse signal representation. Because of these desirable properties, dictionary learning has been extended to the representation of graph signals and eventually has been applied to the problem of graph inference.

Next, we provide more details on one of the aforementioned algorithms. The authors in [47] have focused on graph signals generated from heat diffusion processes, which are useful in identifying processes evolving near a starting seed node. An illustrative example of such a signal can be found in Figure 8, in which case the graph Laplacian matrix is used to model the diffusion of the heat throughout a graph. The concatenation of a set of heat diffusion operators at different time instances defines a graph dictionary that is further on used to represent the graph signals. Hence, the graph signal model becomes

$$\mathbf{x} = \mathcal{F}(\mathcal{G})\mathbf{c} = [e^{-\tau_1\mathbf{L}} e^{-\tau_2\mathbf{L}} \dots e^{-\tau_S\mathbf{L}}]\mathbf{c} = \sum_{s=1}^S e^{-\tau_s\mathbf{L}}\mathbf{c}_s, \quad (25)$$

which is a linear combination of different heat diffusion processes evolving on the graph. In this synthesis model, the coefficients \mathbf{c}_s corresponding to a subdictionary $e^{-\tau_s\mathbf{L}}$ can be seen as a graph signal that goes through a heat diffusion process on the graph. The signal component $e^{-\tau_s\mathbf{L}}\mathbf{c}_s$ can then be interpreted as the result of this diffusion process at time τ_s . It is interesting to note that the parameter τ_s in the model carries a notion of scale. In particular, when τ_s is small, the i th column of $e^{-\tau_s\mathbf{L}}$, i.e., the atom centered at node v_i of the graph, is mainly localized in a small neighborhood of v_i . As τ_s becomes larger, it reflects information about the graph at a larger scale around v_i . Thus, the signal model can be seen as an additive model of diffusion processes of S initial graph signals, which undergo a diffusion model with different diffusion times.

An additional assumption in this signal model is that the diffusion processes are expected to start from only a few nodes of the graph, at specific times, and spread over the entire graph over time. This assumption can be formally captured by imposing a sparsity constraint on the latent variable \mathbf{c} . The graph-learning problem can be cast as a structured dictionary-learning problem, where the dictionary is defined by the unknown graph Laplacian matrix. The latter can then be estimated as a solution of the following optimization problem:

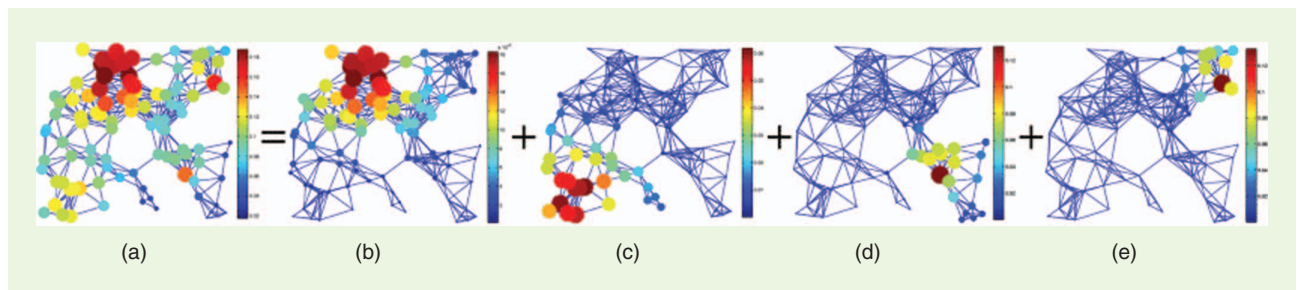


FIGURE 8. (a) A graph signal. (b)–(e) Its decomposition in four localized simple components. Each component is a heat-diffusion process ($e^{-\tau_s\mathbf{L}}$) at time τ_s that has started from different network nodes. The size and the color of each ball indicate the value of the signal at each vertex of the graph [47].

$$\begin{aligned}
& \underset{\mathbf{L}, \mathbf{C}, \tau_s}{\text{minimize}} && \|\mathbf{X} - \mathbf{D}\mathbf{C}\|_F^2 + \alpha \sum_{m=1}^M \|\mathbf{c}_m\|_1 + \beta \|\mathbf{L}\|_F^2, \\
& \text{subject to} && \mathbf{D} = [e^{-\tau_1 \mathbf{L}} \ e^{-\tau_2 \mathbf{L}} \ \dots \ e^{-\tau_S \mathbf{L}}], \ \{\tau_s\}_{s=1}^S \geq 0, \\
& && \text{tr}(\mathbf{L}) = N, \ \mathbf{L} \in \mathcal{L},
\end{aligned} \tag{26}$$

where \mathbf{c}_m is the m th column of the coefficient matrix \mathbf{C} , and the constraints on \mathcal{L} are the same as those in (20). Following the same reasoning, the work in [50] extends the heat diffusion dictionary to the more general family of polynomial graph kernels. In summary, these approaches propose recovering the graph Laplacian matrix by assuming that the graph signals can be sparsely represented by a dictionary that consists of graph diffusion kernels. Note that, when no locality assumptions are imposed (e.g., large τ_s) and a single diffusion kernel is used in the dictionary, the model reduces to a global smoothness model.

In summary, from the perspective of spectral filtering, and in particular, network diffusion, the function $\mathcal{F}(\mathcal{G})$ is one that helps define a meaningful diffusion process on the graph via the graph Laplacian, heat diffusion kernel, or other more general graph shift operators. This directly leads to the slightly different output of the learning algorithms in [45]–[47]. The choice of the coefficients \mathbf{c} , on the other hand, determines specific characteristics of the graph signals, such as stationarity or sparsity. In terms of computational complexity, the methods in [45]–[47] all involve the computation of eigenvectors, followed by solving either a linear program [45] or a semidefinite program [46], [47].

Models based on causal dependencies on graphs

The models described in the previous two sections are mainly designed for learning undirected graphs, which is also the predominant consideration in the current GSP literature. Undirected graphs are associated with symmetric Laplacian matrices \mathbf{L} , which admit a complete set of orthonormal eigenvalues and eigenvectors that conveniently provide a notion of frequency for signals on graphs. It is often the case, however, that in some application domains learning directed graphs is more desirable as in those cases where the directions of edges may be interpreted as causal dependencies between the variables that the vertices represent. For example, in brain analysis, even though the inference of an undirected functional connectivity between the regions of interest is certainly of interest, a directed effective connectivity may reveal extra information about the causal dependencies between those regions [53], [54]. The third class of models that

we discuss is therefore one that allows for the inference of these directed dependencies.

The authors of [55] have proposed a causal graph process based on the idea of sparse vector autoregressive (SVAR) estimation [56], [57]. In their model, the signal at time step t , $\mathbf{x}[t]$, is represented as a linear combination of its observations in the past T time steps and a random noise process $\mathbf{n}[t]$

$$\begin{aligned}
\mathbf{x}[t] &= \mathbf{n}[t] + \sum_{j=1}^T P_j(\mathbf{W})\mathbf{x}[t-j] \\
&= \mathbf{n}[t] + \sum_{j=1}^T \sum_{k=0}^j a_{jk} \mathbf{W}^k \mathbf{x}[t-j],
\end{aligned} \tag{27}$$

where $P_j(\mathbf{W})$ is a degree j polynomial of the (possibly directed) adjacency matrix \mathbf{W} with coefficients a_{jk} (see Figure 9). Clearly, this model admits the design of $\mathcal{F}(\mathcal{G}) = P_j(\mathbf{W})$ and $\mathbf{c} = \mathbf{x}[t-i]$ in forming one time-lagged copy of the signal $\mathbf{x}[t]$. For temporal observations $\mathbf{X} = (\mathbf{x}[0] \ \mathbf{x}[1] \ \dots \ \mathbf{x}[M-1])$, the authors have therefore proposed solving the following optimization problem:

$$\begin{aligned}
& \underset{\mathbf{W}, \mathbf{a}}{\text{minimize}} && \frac{1}{2} \sum_{t=T}^{M-1} \left\| \mathbf{x}[t] - \sum_{j=1}^T P_j(\mathbf{W})\mathbf{x}[t-j] \right\|_2^2 + \alpha \|\text{vec}(\mathbf{W})\|_1 \\
& && + \beta \|\mathbf{a}\|_1,
\end{aligned} \tag{28}$$

where $\text{vec}(\mathbf{W})$ is the vectorized form of \mathbf{W} , $\mathbf{a} = (a_{10} \ a_{11} \ \dots \ a_{jk} \ \dots \ a_{TT})$ is a vector of all the polynomial coefficients a_{jk} , and the entry-wise L^1 -norm is imposed on \mathbf{W} and \mathbf{a} for promoting sparsity. Because of nonconvexity introduced by the matrix polynomials, the problem in (28) is solved in three steps, i.e., solving sequentially for $P_j(\mathbf{W})$, \mathbf{W} , and \mathbf{a} . In summary, in the SVAR model, the specific designs of \mathcal{F} and \mathbf{c} lead to a particular generative process of the observed signals on the learned graph. Similar ideas can also be found in the Granger causality or vector autoregressive models (VARMs) [58], [59].

Structural equation models (SEMs) are another popular approach for inferring directed graphs [60], [61]. In the SEMs, the signal observation \mathbf{x} at time step t is modeled as

$$\mathbf{x}[t] = \mathbf{W}\mathbf{x}[t] + \mathbf{E}\mathbf{y}[t] + \mathbf{n}[t], \tag{29}$$

where the first term in (29) consists of endogenous variables, which define the signal value at each variable as a linear combination of

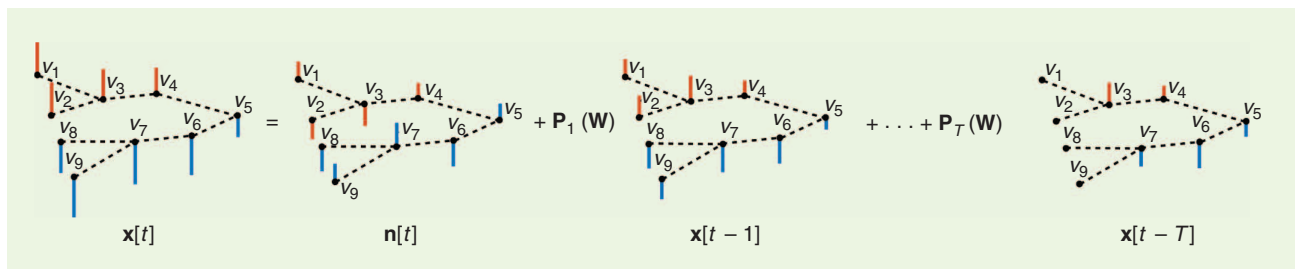


FIGURE 9. A graph signal \mathbf{x} at time step t is modeled as a linear combination of its observations in the past T time steps and a random noise process $\mathbf{n}[t]$.

the values at its neighbors in the graph, and the second term represents exogenous variables $\mathbf{y}[t]$ with a coefficient matrix \mathbf{E} . The third term represents observation noise similar to that in (27). The endogenous component of the signal implies a choice of $\mathcal{F}(\mathcal{G}) = \mathbf{W}$ (which can again be directed) and $\mathbf{c} = \mathbf{x}[t]$, and, similar to the SVAR model, enforces a certain generative process of the signal on the learned graph.

As we can see, causal dependencies on the graph, either between different components of the signal or between its present and past observations, can be conveniently modeled in a straightforward manner by choosing $\mathcal{F}(\mathcal{G})$ as a polynomial of the adjacency matrix of a directed graph and choosing the coefficients \mathbf{c} as the present or past signal observations. As a consequence, methods in [54], [55], and [62] are all able to learn an asymmetric graph adjacency matrix, which is a potential advantage compared to methods based on the previous two models. Furthermore, the SEMs can be extended to track network topologies that evolve dynamically [62] and deal with highly correlated data [63] or can be combined with the SVAR model, which leads to the structural vector autoregressive models (SVARMs) [64]. Interested readers are referred to [65] for a recent review of the related models. In these extensions of the classical models, the designs of \mathcal{F} and \mathbf{c} can be generalized accordingly to link the signal representation and learned graph topology. Finally, as an overall comparison, the differences between methods that are based on the three models discussed in this review are summarized in Table 1.

Connections with the broader literature

We have seen that GSP-based approaches can be unified by the viewpoint of learning graph topologies that enforce desirable representations of the signals on the learned graph. This offers a new interpretation of the traditional statistical and physically motivated models. First, as a typical example of approaches for learning graphical models, the graphical Lasso solves the optimization problem of (5) in which the trace term $\text{tr}(\tilde{\Sigma}\Theta) = (1/(M-1))\text{tr}(\mathbf{X}^T\Theta\mathbf{X})$ bears similarity to the

Laplacian quadratic form $\mathbf{Q}(\mathbf{L})$ and the trace term in the problem of (20), when the precision matrix Θ is chosen to be the graph Laplacian \mathbf{L} . This is the case for the approach in [25], which has proposed considering $\Theta = \mathbf{L} + (1/\sigma^2)\mathbf{I}$ in (7) as a regularized Laplacian to fit into the formulation of (5). The graphical Lasso approach, therefore, can be interpreted as one that promotes global smoothness of the signals on the learned topology.

Second, models based on spectral filtering and causal dependencies on graphs can generally be thought of as the ones that define generative processes of the observed signals, in particular the diffusion processes on the graph. This is achieved either explicitly by choosing $\mathcal{F}(\mathcal{G})$ as diffusion matrices, as described in the “Models Based on Spectral Filtering of Graph Signals” section, or implicitly by defining the causal processes of signal generation, as described in the “Models Based on Causal Dependencies on Graphs” section. Both types of models share similar philosophies to the ones developed from a physics viewpoint in the “Physically Motivated Models” section, in that they all propose inferring the graph topologies by modeling signals as outcomes of physical processes on the graph, especially the diffusion and cascading processes.

It is also interesting to note that certain models can be interpreted from all three viewpoints, an example being the global smoothness model. Indeed, in addition to the statistical and GSP perspectives described previously, the property of global smoothness can also be observed in a square-lattice Ising model [21], hence admitting a physical interpretation. Despite the connections with traditional approaches, however, GSP-based approaches offer some unique advantages compared to the classical methods. On the one hand, the flexibility in designing the function $\mathcal{F}(\mathcal{G})$ allows for statistical properties of the observed signals that are not limited to a Gaussian distribution, which is, however, the predominant choice in many statistical machine-learning methods. On the other hand, this also makes it easier to consider models that

Table 1. Comparisons between different GSP-based approaches to graph learning.

Method	Signal Model	Assumption		Learning Output	Edge Directionality
		$\mathcal{F}(\mathcal{G})$	\mathbf{c}		
Dong et al. [39]	Global smoothness	Eigenvector matrix	i.i.d. Gaussian	Laplacian	Undirected
Kalofolias et al. [40]	Global smoothness	Eigenvector matrix	i.i.d. Gaussian	Adjacency matrix	Undirected
Egilmez et al. [41]	Global smoothness	Eigenvector matrix	i.i.d. Gaussian	Generalized Laplacian	Undirected
Chepur et al. [42]	Global smoothness	Eigenvector matrix	i.i.d. Gaussian	Adjacency matrix	Undirected
Pasdeloup et al. [46]	Spectral filtering (diffusion by adjacency)	Normalized adjacency matrix	i.i.d. Gaussian	Normalized adjacency matrix normalized Laplacian	Undirected
Segarra et al. [45]	Spectral filtering (diffusion by graph shift operator)	Graph shift operator	i.i.d. Gaussian	Graph shift operator	Undirected
Thanou et al. [47]	Spectral filtering (heat diffusion)	Heat kernel	Sparsity	Laplacian	Undirected
Mei and Moura [55]	Causal dependency (SVAR)	Polynomials of adjacency matrix	Past signals	Adjacency matrix	Directed
Baingana et al. [62]	Causal dependency (SEM)	Adjacency matrix	Present signal	Time-varying adjacency matrix	Directed
Shen et al. [54]	Causal dependency (SVARM)	Polynomials of adjacency matrix	Past and present signals	Adjacency matrix	Directed

go beyond a simple diffusion or cascade model. For example, by the sparsity assumption on the coefficients \mathbf{c} , the method in [47] defines the signals as the outcomes of possibly more than one diffusion process that originates at different parts of the graph after potentially different time steps. Similarly, by choosing different $\mathcal{F}(\mathcal{G})$ and \mathbf{c} , the SVAR models [55] and the SEMs [62] correspond to different generative processes of the signals, one based on the static network structure and the other on temporal dynamics. These design flexibilities provide more powerful modeling of the signal representation for the graph-inference process.

Applications of GSP-based graph-learning methods

The field of GSP is strongly motivated by a wide range of applications where there exist inherent structures behind data observations. Naturally, GSP-based graph-learning methods are appealing in areas where learning hidden structures behind data has been of constant interest. In particular, the emphasis on the modeling of the signal representation within the learning process has made them increasingly popular in a growing number of applications. Currently, these methods mainly find applications in image coding and compression, brain signal analysis, and a few other diverse areas.

Image coding and compression

Image representation and coding has been one main area of interest for GSP-based methods. Images can be naturally thought of as graph signals defined on a regular grid structure, where the nodes are the image pixels and the edge weights capture the similarity between adjacent pixels. The design of new, flexible graph signal representations has opened the door to new, structure-aware transform-coding techniques, and eventually to more efficient image-compression frameworks [66]. Such representation permits going beyond traditional transform coding by moving from classical fixed transforms such as the discrete cosine transform to graph-based transforms that are better adapted to the actual image structure.

The design of the graph and the corresponding transform remains, however, one of the biggest challenges in graph-based image compression. A suitable graph for effective transform coding should lead to easily compressible signal coefficients at the cost of a small overhead for coding the graph. Most graph-based coding techniques focus mainly on images, and they construct the graph by considering pairwise similarities among pixel intensities. A few attempts at adapting the graph topology and, consequently, the graph transform, exist in the literature [67], [68]; however, they rely on selecting an efficient graph for compression from a set of representative graph templates without being fully adapted to the image signals.

Graph learning has been introduced only recently for these types of problems. A learning model based on signal smoothness, inspired by [39] and [70], has been further extended to design a graph-based coding framework that takes into account the coding of the signal values as well as the cost of transmitting the graph in rate distortion terms [69]. In particular, the cost of coding the image signal is minimized by

promoting its smoothness on the learned topology. The transmission cost of the graph itself is further controlled by adding an additional term in the optimization problem, which penalizes the sparsity of the graph Fourier coefficients of the edge weight signal.

An illustrative example of the graph-based transform coding proposed in [69] as well as its application to image compression is shown in Figure 10. Briefly, the compression algorithm consists of three important parts. First, the solution to an optimization problem that takes into account the rate approximation of the image signal at a patch level, as well as the cost of transmitting the graph, provides a graph topology [Figure 10(a)] that defines the optimal coding strategy. Second, the GFT coefficients of the image signal on the learned graph can be used to efficiently compress the image. As we can see in Figure 10(b), the decay of these coefficients (in terms of their log magnitude) is much faster than the decay of the GFT coefficients corresponding to the four nearest-neighbor grid graph that does not involve any learning. Finally, the weights of the learned graph are treated as a new edge weight signal that lies on a dual graph, whose nodes represent the edges in the learned graph, with the signal values on the nodes being the edge weights of the learned graph. Two nodes are connected in this dual graph if and only if the two corresponding edges share one common node in the learned graph. The learned graph is then transmitted by the GFT coefficients of this edge weight signal, where the decay of these coefficients is shown in Figure 10(c). The obtained results confirm that the GFT coefficients of the graph weights are concentrated on the low frequencies, which indicates a highly compressible graph.

Another example is the work in [71], which introduces an efficient graph-learning approach for fast graph Fourier transform, based on [41]. The authors have considered a maximum-likelihood estimation problem with additional constraints based on a matrix factorization of the graph Laplacian matrix, such that its eigenvector matrix is a product of a block diagonal matrix and a butterfly-like matrix. The learned graph leads to a fast, nonseparable transform for intrapredictive residual blocks in video compression. Such efforts confirm that learning a meaningful graph can have a significant impact in graph-based image compression. These are only a few first attempts, which leave much room for improvement, especially in terms of coding performance. Thus, we expect to see more future research efforts that fully exploit the potential of graph methods.

Brain signal analysis

GSP is a promising and powerful framework for brain network data, mainly because of its potential to jointly model brain structure as a graph and brain activities as signals residing on the nodes of the graph. The overview paper in [72] provides a summary of how a GSP view of brain signals can provide additional insights into the functionality of the brain.

Graph learning, in particular, has been successfully applied for inferring the structural and functional connectivity of the brain related to different diseases or external stimuli. For example, [27] introduced a graph regression model for learning

brain structural connectivity of patients with Alzheimer's disease, which is based on the signal smoothness model discussed in the "Models Based on Signal Smoothness" section. A similar framework [73] extended to the noisy settings has been applied on a set of magnetoencephalography signals to capture the brain activity in two categories of visual stimuli (e.g., the subject was viewing face or nonface images). In addition to the smoothness assumption, the proposed framework is based on the assumption that the perturbation on the low-rank components of the noisy signals is sparse. The recovered functional connectivity graphs under these assumptions are compatible with findings in the neuroscientific literature, which is a promising result indicating that graph learning can contribute to this application domain.

Instead of the smoothness model adopted in [27] and [73], the authors in [54] have utilized models on causal dependencies and proposed inferring effective connectivity networks of brain regions that may shed light on the understanding of the cause behind epilepsy. The signals that they use are electrocorticography time series data before and after ictal onset of seizures of epilepsy. All of these applications show the potential impact GSP-based graph-learning methods may have on the brain and,

more generally, biomedical data analysis, where the inference of hidden connections can be crucial.

Other application domains

In addition to image processing and biomedical analysis, GSP-based graph-learning methods have been applied to a number of other diverse areas. One notable example is meteorology, where it is of interest to understand the relationship between different locations based on the temperatures recorded at the weather stations in these locations. Interestingly, this is an area where all three major signal models introduced in this article may be employed to learn graphs that lead to different insights. For instance, the authors of [39] and [42] have proposed learning a network of weather stations using the signal smoothness model, which essentially captures the relationship between these stations in terms of their altitude. Alternatively, the work in [46] has adopted the heat diffusion model in which the evolution of temperatures in different regions is modeled as a diffusion process on the learned geographical graph. The authors of [55] have further developed a framework based on causal dependencies to infer a directed temperature propagation network

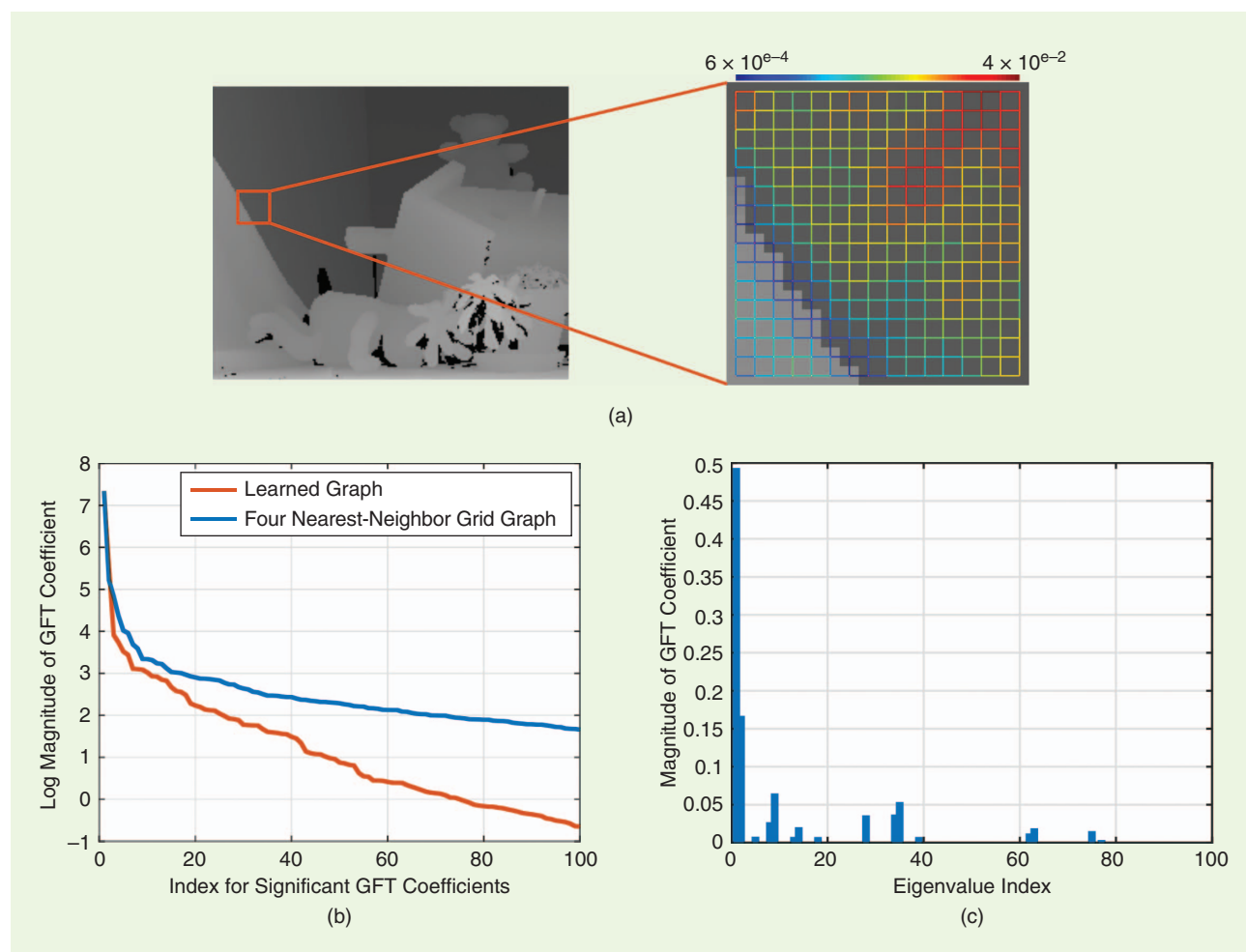


FIGURE 10. Inferring a graph for image coding. (a) The graph learned on a random patch of the image Teddy using [69]. (b) A comparison between the GFT coefficients of the image signal on the learned graph and the four nearest-neighbor grid graph. The coefficients are ordered decreasingly by log magnitude. (c) The GFT coefficients of the graph weights.

that is consistent with major wind directions over the United States. We note, however, that most of these studies are proof of concept, and future research is expected to focus more on the perspective of practical applications in meteorology.

Another area of interest is environmental monitoring. As an example, the author of [74] has proposed applying the GSP-based graph-learning framework of [70] for the analysis of exemplary environmental data of ozone concentration in Poland. More specifically, the paper has proposed learning a network that reflects the relationship between different regions in terms of ozone concentration. Such a relationship may be understood in a dynamic fashion using data from different temporal periods. Similarly, the work in [39] has analyzed evapotranspiration data collected in California to understand the relationship between regions of different geological features.

Finally, GSP-based methods have also been applied to infer graphs that reveal urban traffic flows [47], patterns of news propagation on the Internet [62], the interregion political relationship [39], similarities between animal species [41], and ontologies of concepts [25]. The diversity of these areas has demonstrated the potential of applying GSP-based graph-learning methods for understanding the hidden relationship behind data observations in real-world applications.

Concluding remarks and future directions

Learning structures and graphs from data observations is an important problem in modern data analytics, and the novel signal processing approaches reviewed in this article have both theoretical and practical significance. On the one hand, GSP provides a new theoretical framework for graph learning by utilizing signal processing tools, with a strong emphasis on the representation of the signals on the learned graph, which can be essential from a modeling viewpoint. As a result, the novel approaches developed in this field would benefit not only the inference of optimal graph topologies, but also the subsequent signal processing and data analysis tasks. On the other hand, the novel signal and graph models designed from a GSP perspective may contribute uniquely to the understanding of the often complex data structure and generative processes of the observations made in real-world application domains, such as brain and social network analysis. For these reasons, GSP-based approaches for graph learning have recently attracted increased interest. There exist, however, many open issues and questions that are worthy of further investigation. In the following sections, we discuss five general directions for future work.

Input signals of learning frameworks

The first important point that needs further investigation is the quality of the input signals. Most approaches in the literature have focused on the scenario where a complete set of data are observed for all the entities of interest (i.e., at all vertices in the

graph). However, there are often situations when observations are only partially available, either because of the failure to acquire data from some of the sensors or simply because of the costs associated with making full observations. For example, in large-scale social, biomedical, or environmental networks, sampling or active learning may need to be applied to select a limited number of sensors for observations [75]. It is a challenge to design graph-learning approaches that can handle such cases as well as to study the extent to which the partial or missing observations affect the learning performance. Another scenario is that of dealing with sequential input data that come in an online and adaptive fashion, which has been studied in the recent work of [76].

Outcome of learning frameworks

Compared to the input signals, it is arguably even more important to rethink the potential outcome of the learning frameworks.

Several important lines of thought remain largely unexplored in the current literature. First, while most of the existing work focuses on learning undirected graphs, it is certainly of interest to investigate approaches for learning directed ones. Methods described in the “Models Based on Causal Dependencies on Graphs” section, such as [54], [55], and [62], are able to achieve this since they do not explicitly rely on the notion of frequency provided by the eigendecomposition of the symmetric graph adjacency or Laplacian matrices. However, it is certainly possible and desirable to extend the frequency interpretation obtained with undirected graphs to the case of directed ones. For example, alternative definitions of frequencies of graph signals have been recently proposed based on normalization of the random walk Laplacian [77], novel definition of inner product of graph signals [78], and explicit optimization for an orthonormal basis on graphs [79], [80]. How to design techniques that learn directed graphs by making use of these new developments in the frequency interpretation of graph signals remains an interesting question.

Second, in many real-world applications, the network structure changes over time, particularly social network interactions or brain functional connectivities. It is, therefore, interesting to look into learning frameworks that can infer dynamic graph topologies. To this end, [62] has proposed a method to track network structure that can be switched between a number of different states. Alternatively, [70] and [88] have proposed approaches to infer dynamic networks from observations within different time windows, with a penalty term imposed on the similarity between consecutive networks to be inferred. Such a notion of temporal smoothness is certainly an interesting question to study and may draw inspiration from the visualizations of dynamic networks recently proposed in [81].

Third, although the current lines of work reviewed in this article mainly focus on the signal representation, it is also possible to put constraints directly on the learned graphs by

The novel approaches developed in this field would benefit not only the inference of optimal graph topologies, but also the subsequent signal processing and data analysis tasks.

enforcing certain graph properties that go beyond the common choice of sparsity, which has been adopted explicitly by the optimization problems in many existing methods [15], [25], [42], [45], [46], [55], [62]. One example is the work in [82], where the authors have proposed inferring graphs with monotone topology properties. Another example is the approach in [83], which learns a sparse graph with connected components. Learning graphs with desirable properties inspired by a specific application domain (e.g., community detection [2]) can also have great potential benefit, and it is a topic worth investigating.

Fourth, in some applications, it might not be necessary to learn the full graph topology, but rather, some other intermediate or graph-related representations. For example, this could be an embedding of the vertices in the graph for the purpose of clustering [84] or a function of the graph, such as graph filters, for the subsequent signal processing tasks [85]. Another possibility is to learn graph properties such as eigenvalues (for example, using the technique described in [46]), degree distribution, or templates that constitute local regions of the graph. Similar to the previous point, in these scenarios, the learning framework needs to be designed accordingly with the end objective or application in mind.

Finally, instead of learning a deterministic graph structure, as in most of the existing models, it would be interesting to explore the possibility of learning graphs in a probabilistic fashion, one in which we either specify the confidence in building an edge between each pair of the vertices or indicate the uncertainty of the inferred graph. This would benefit specific situations when a soft decision is preferred to a hard decision, possibly due to anticipated measurement errors in the observations or other constraints.

Signal models

Throughout this article, we have emphasized the importance of a properly defined signal model in the design of the graph-learning framework. The current literature predominantly focuses on either the globally or locally smooth models. Other models, such as bandlimited signals, i.e., those that have limited support in the graph spectral domain, may also be considered for inferring graph topologies [86]. Generally speaking, more flexible signal models that go beyond the smoothness-based criteria can be designed by taking into account general filtering operations of signals on the graph.

The learning framework may also need to adapt to the specific input and output, as outlined in the previous two sections. For instance, given only partially available observations, it might make sense to consider a signal model tailored for the observed, instead of the whole, region of the graph. Another scenario would be that, in learning dynamic graph topologies, the signal model employed needs to be consistent with the temporal smoothness criteria adopted to learn the sequence of graphs.

Performance guarantees

Graph inference is an inherently difficult problem given the large number of unknown variables (generally in the order of N^2) and the relatively small amount of observations. As a

result, learning algorithms must be designed with additional assumptions or priors. In this case, it is desirable to have theoretical guarantees of the performance of graph recovery under the specific model and prior. It would also be interesting to put the errors in graph recovery into the context of the subsequent data processing tasks and study their impact. Furthermore, for many graph-learning algorithms, in addition to the empirical performance, it is necessary to provide guarantees of the convergence when alternating minimization is employed as well as to study the computational complexity that can be essential for learning large-scale graphs. These theoretical considerations remain largely unexplored in the current literature and therefore require much further investigation, given their importance.

Objective of graph learning

The final comment on future work is a reflection on the objective of the graph-learning problem and, in particular, how to better integrate the inference framework with the subsequent data analysis tasks. Clearly, the learned graph may be readily used for classical machine-learning tasks such as clustering or semisupervised learning, but it may also directly benefit the processing and analysis of the graph signals. In this setting, it is often the case that a cost related to the application is directly incorporated into the optimization for graph learning. For instance, the work in [87] has proposed a method for inferring graph topologies with a joint goal of dictionary learning, whose cost function is incorporated into the optimization problem. In many applications, such as image coding, accuracy is not the only interesting performance metric. Typically, there exist different tradeoffs that are more complex and should be taken into consideration. For example, in image compression, the actual cost of coding the graph is at least as important as the cost of coding the image signal. Such constraints are indicated by the application, and they should be incorporated in the graph-learning framework (e.g., [69]) to make the learning framework more targeted to a specific application.

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