Poisson Learning: A framework for graph-based semi-supervised learning at very low label rates

Jeff Calder [1], Brendan Cook [1], Matthew Thorpe [2], and Dejan Slepčev [3]

[1]School of Mathematics, University of Minnesota
[2]Department of Mathematics, University of Manchester
[3]Department of Mathematical Sciences, Carnegie Mellon University

Theory and Applications of Graph-Based Learning
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Outline

Graph-based semi-supervised learning

Graph: $G = (X, W)$

- $X = \{x_1, \dots, x_n\}$ are the vertices of the graph
- $W = (w_{ij})_{i,j=1}^n$ are nonnegative and symmetric ($w_{ij} = w_{ji}$) edge weights.
- $w_{ij} \approx 1$ if x_i, x_j similar, and $w_{ij} \approx 0$ when dissimilar.

Labels: We assume the first $m \ll n$ vertices are given labels

$$y_1, y_2, \dots, y_m \in \{\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_k\} \in \mathbb{R}^k.$$

Task: Extend the labels to the rest of the vertices $x_{m+1}, \dots, x_n$.

Semi-supervised smoothness assumption

Similar points $x_i, x_j \in X$ in high density regions of the graph should have similar labels.

Laplace Learning/Label Propagation:

- Original work [Zhu et al., 2003]
- Learning [Zhou et al., 2005]
- Manifold ranking [He et al, 2006, Zhou et al., 2011, Xu et al., 2011]

Laplace learning/Label propagation

Laplacian regularized semi-supervised learning solves the Laplace equation

$$\begin{cases} \mathcal{L}u(x_i) = 0, & \text{if } m+1 \leq i \leq n, \\ u(x_i) = y_i, & \text{if } 1 \leq i \leq m, \end{cases}$$

where $u : X \to \mathbb{R}^k$, and $\mathcal{L}$ is the graph Laplacian

$$\mathcal{L}u(x_i) = \sum_{j=1}^{n} w_{ij}(u(x_i) - u(x_j)).$$

The label decision for vertex x_i is determined by the largest component of $u(x_i)$

$$\ell(x_i) = \underset{j \in \{1,\ldots,k\}}{\text{argmax}} \{u_j(x)\}.$$

Label propagation

The solution of Laplace learning satisfies

$$\mathcal{L}u(x_i) = \sum_{j=1}^{n} w_{ij}(u(x_i) - u(x_j)) = 0. \qquad (m+1 \leq i \leq n)$$

Re-arranging, we see that u satisfies the mean-property

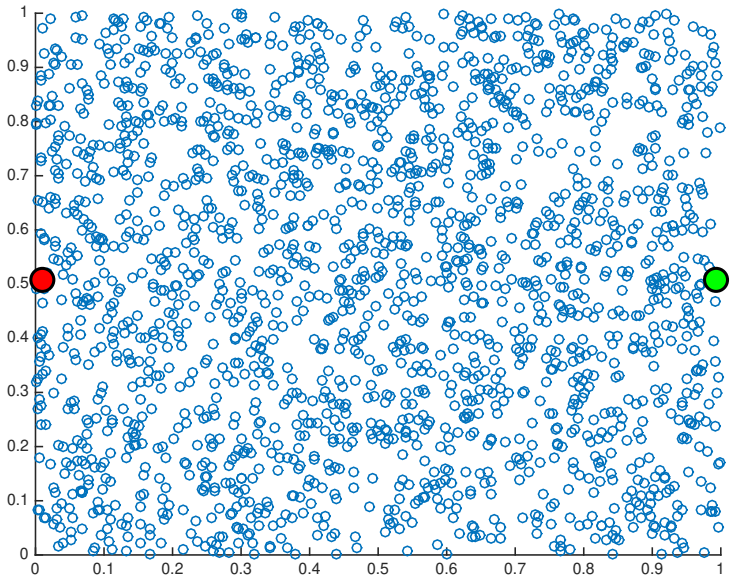
$$u(x_i) = \frac{\sum_{j=1}^{n} w_{ij}\, u(x_j)}{\sum_{j=1}^{n} w_{ij}}.$$

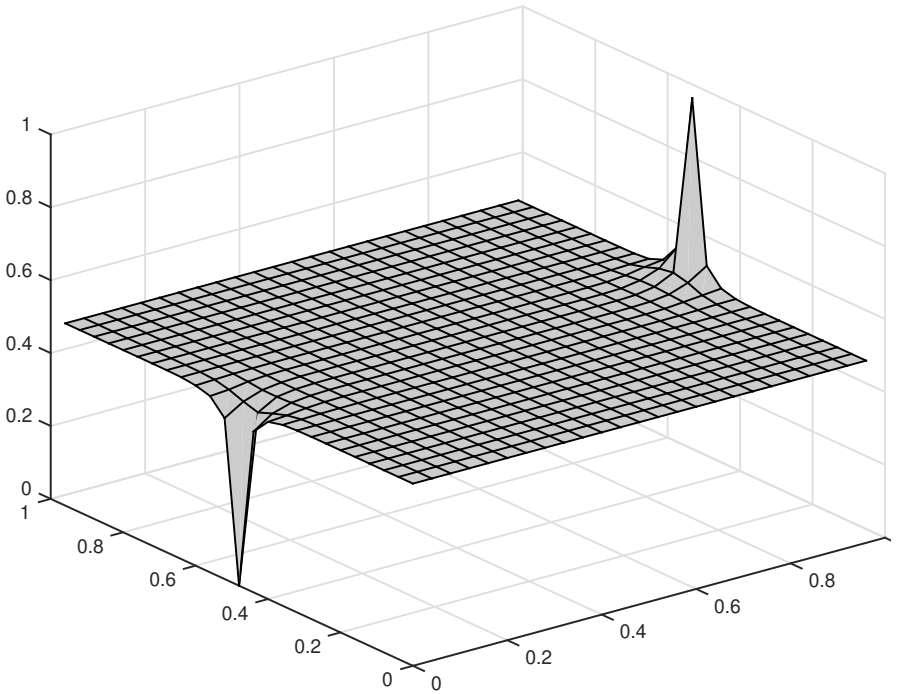
Label propagation [Zhu 2005] iterates

$$u^{k+1}(x_i) = \frac{\sum_{j=1}^{n} w_{ij}\, u^k(x_j)}{\sum_{j=1}^{n} w_{ij}},$$

and at convergence is equivalent to Laplace learning.

Ill-posed with small amount of labeled data

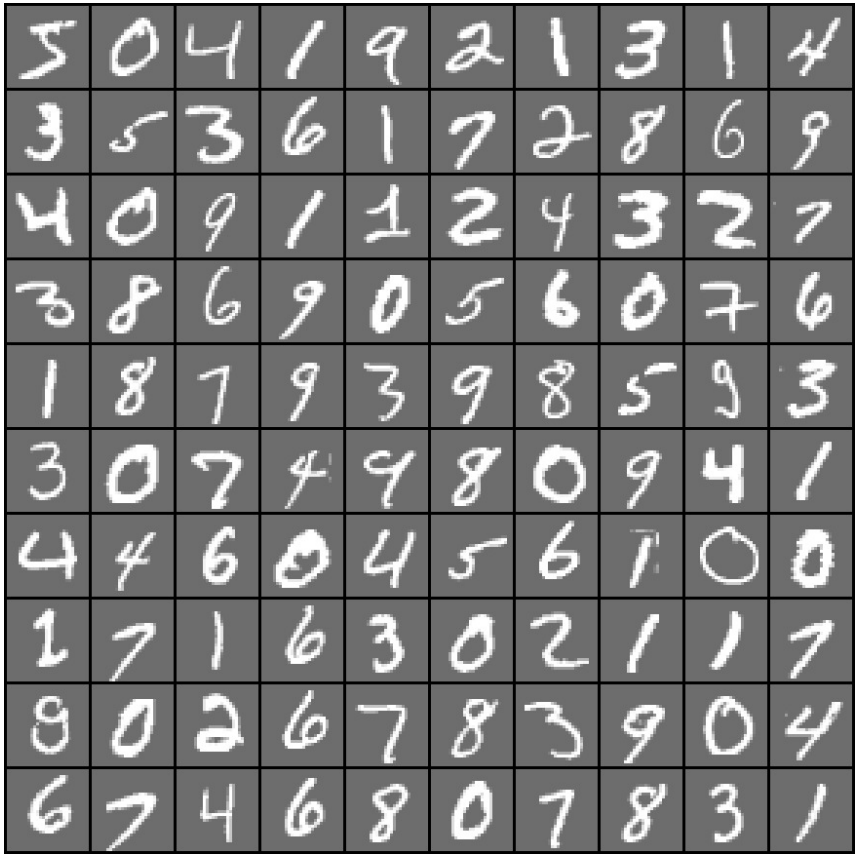




- Graph is $n = 10^5$ i.i.d. random variables uniformly drawn from $[0, 1]^2$.
- $w_{xy} = 1$ if $|x - y| < 0.01$ and $w_{xy} = 0$ otherwise.
- Two labels: $y_1 = 0$ at the Red point and $y_2 = 1$ at the Green point.
- Over 95% of labels in $[0.4975, 0.5025]$.

[Nadler et al., 2009, El Alaoui et al., 2016]

MNIST (70,000 28×28 pixel images of digits 0-9)



[Y. LeCun, L. Bottou, Y. Bengio, and P. Haffner. "Gradient-based learning applied to document recognition." Proceedings of the IEEE, 86(11):2278-2324, November 1998.]

Laplace learning on MNIST

# Labels/class	**1**	**2**	**3**	**4**	**5**
Laplace	16.1 (6.2)	28.2 (10)	42.0 (12)	57.8 (12)	69.5 (12)
Graph NN	58.8 (5.6)	66.6 (2.8)	70.2 (4)	71.3 (2.6)	73.4 (1.9)

# Labels/class	**10**	**50**	**100**	**500**	**1000**
Laplace	93.2 (2.3)	96.9 (0.1)	97.1 (0.1)	97.6 (0.1)	97.7 (0.0)
Graph NN	82.3 (1.0)	89.0 (0.5)	90.6 (0.4)	93.4 (0.1)	93.7 (0.1)

Average accuracy over 10 trials with standard deviation in brackets.

Graph NN: 1-nearest neighbor using graph geodesic distance.

Recent work

A lot of work since [Nadler 2009] has attempted to address this issue:

- Higher-order regularization: [Zhou and Belkin, 2011], [Dunlop et al., 2019]
- p-Laplace regularization: [Alaoui et al., 2016], [Calder 2018,2019], [Slepcev & Thorpe 2019]
- Re-weighted Laplacians: [Shi et al., 2017], [Calder & Slepcev, 2019]
- Centered kernel method: [Mai & Couillet, 2018]

In this talk:

1. We explain the degeneracy of Laplace learning in terms of random walks.
2. We propose a new algorithm: Poisson learning.

J. Calder, B. Cook, M. Thorpe, and D. Slepčev. **Poisson Learning: Graph based semi-supervised learning at very low label rates.** *International Conference on Machine Learning (ICML), PMLR 119:1306–1316*, 2020.

Outline

Poisson learning

We propose to replace Laplace learning

$$(1) \qquad \text{(Laplace equation)} \quad \begin{cases} \mathcal{L}u(x_i) = 0, & \text{if } m+1 \leq i \leq n, \\ u(x_i) = y_i, & \text{if } 1 \leq i \leq m, \end{cases}$$

with Poisson learning

$$\text{(Poisson equation)} \quad \mathcal{L}u(x_i) = \sum_{j=1}^{m} (y_j - \overline{y})\delta_{ij} \quad \text{for } i = 1, \ldots, n$$

subject to $\sum_{i=1}^{n} d_i u(x_i) = 0$, where $\overline{y} = \frac{1}{m}\sum_{i=1}^{m} y_i$.

In both cases, the label decision is the same:

$$\ell(x_i) = \underset{j \in \{1,\ldots,k\}}{\text{argmax}} \{u_j(x)\}.$$

Poisson learning

We propose to replace Laplace learning

$$(2) \qquad \text{(Laplace equation)} \quad \begin{cases} \mathcal{L}u(x_i) = 0, & \text{if } m+1 \leq i \leq n, \\ u(x_i) = y_i, & \text{if } 1 \leq i \leq m, \end{cases}$$

with Poisson learning

$$\text{(Poisson equation)} \quad \mathcal{L}u(x_i) = \sum_{j=1}^{m} (y_j - \overline{y})\delta_{ij} \quad \text{for } i = 1, \ldots, n$$

subject to $\sum_{i=1}^{n} d_i u(x_i) = 0$, where $\overline{y} = \frac{1}{m}\sum_{i=1}^{m} y_i$.

For Poisson learning, unbalanced class sizes can be incorporated:

$$\ell(x_i) = \operatorname*{argmax}_{j \in \{1,\ldots,k\}} \left\{ \frac{p_j}{n_j} u_j(x) \right\},$$

p_j = Fraction of data in class j

n_j = Fraction of training data from class j.

Random Walk Perspective

Suppose u solves the Laplace learning equation

$$\begin{cases} \mathcal{L}u(x_i) = 0, & \text{if } m+1 \leq i \leq n, \\ u(x_i) = y_i, & \text{if } 1 \leq i \leq m. \end{cases}$$

Let $x \in X$ and let $X_0, X_1, X_2, \ldots$ be a random walk on X with transition probabilities

$$\mathbb{P}(X_k = x_j \mid X_{k-1} = x_i) = \frac{w_{ij}}{d_i} \qquad \text{where } d_i = \sum_{j=1}^{n} w_{ij}.$$

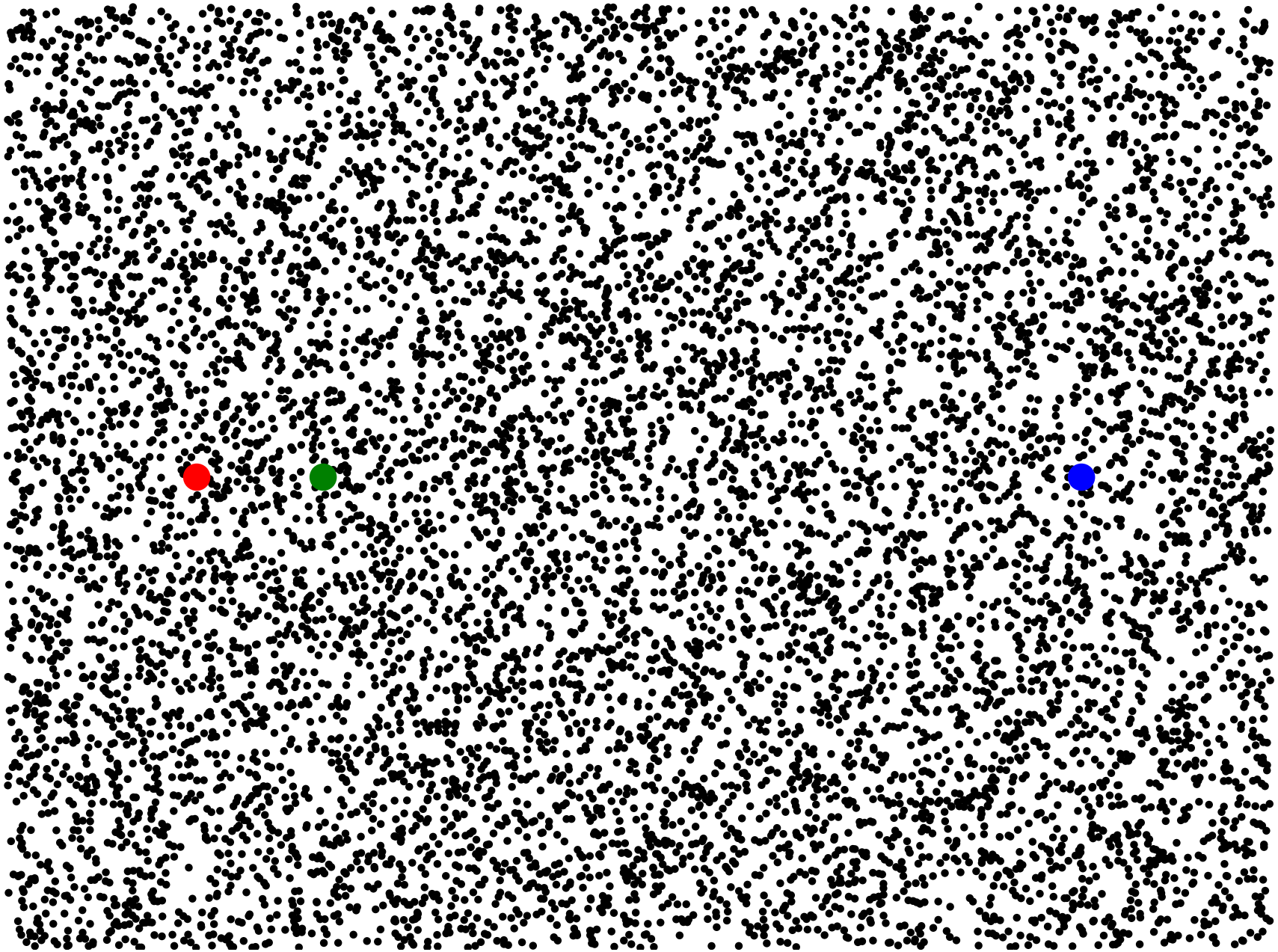
Define the stopping time to be the first time the walk hits a label, that is

$$\tau = \inf\{k \geq 0 \,:\, X_k \in \{x_1, x_2, \ldots, x_m\}\}.$$

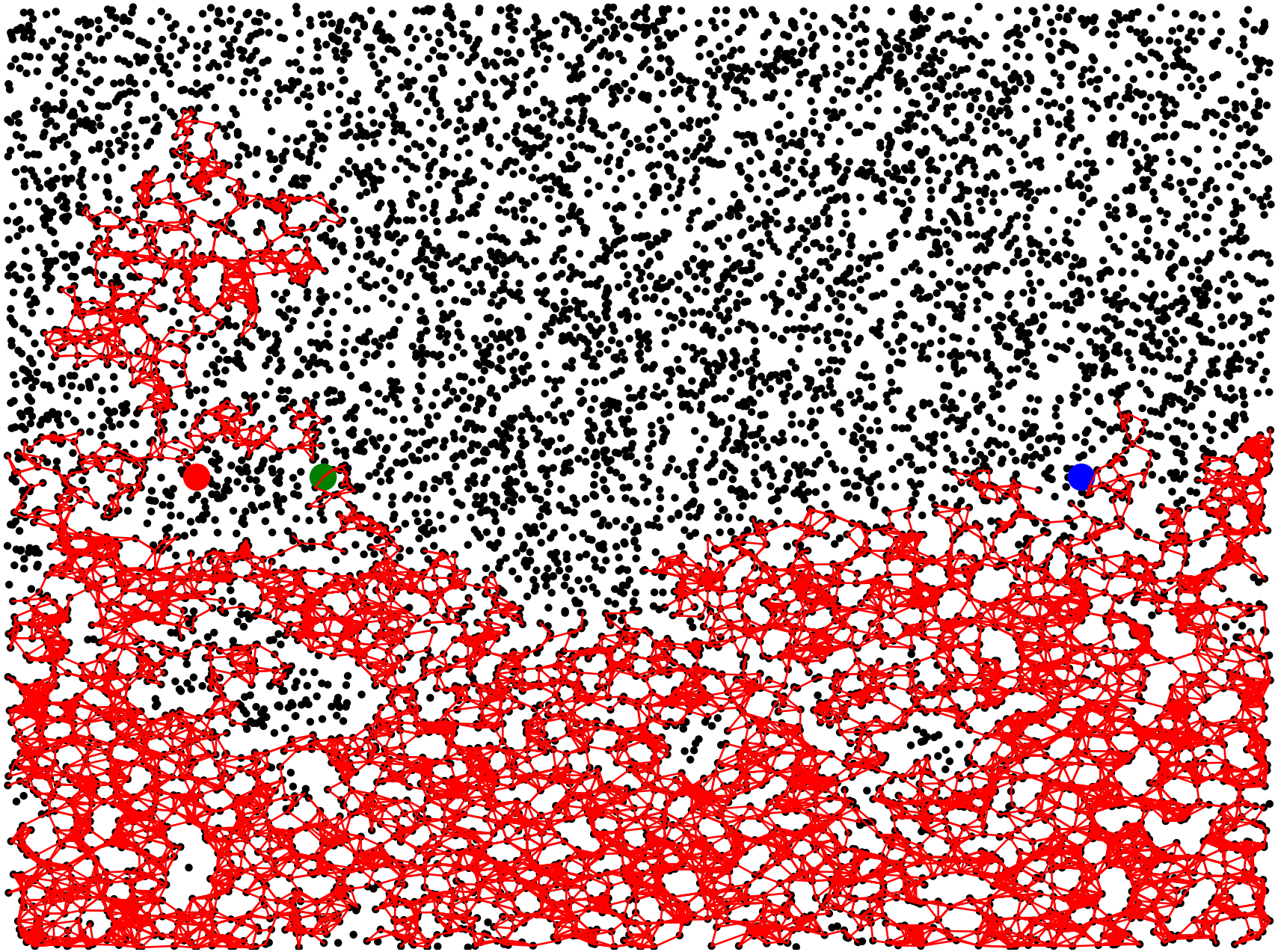
Let $i_\tau \leq m$ so that $X_\tau = x_{i_\tau}$. Then (by Doob's optimal stopping theorem)

(3) $$\boxed{u(x) = \mathbb{E}[y_{i_\tau} \mid X_0 = x].}$$

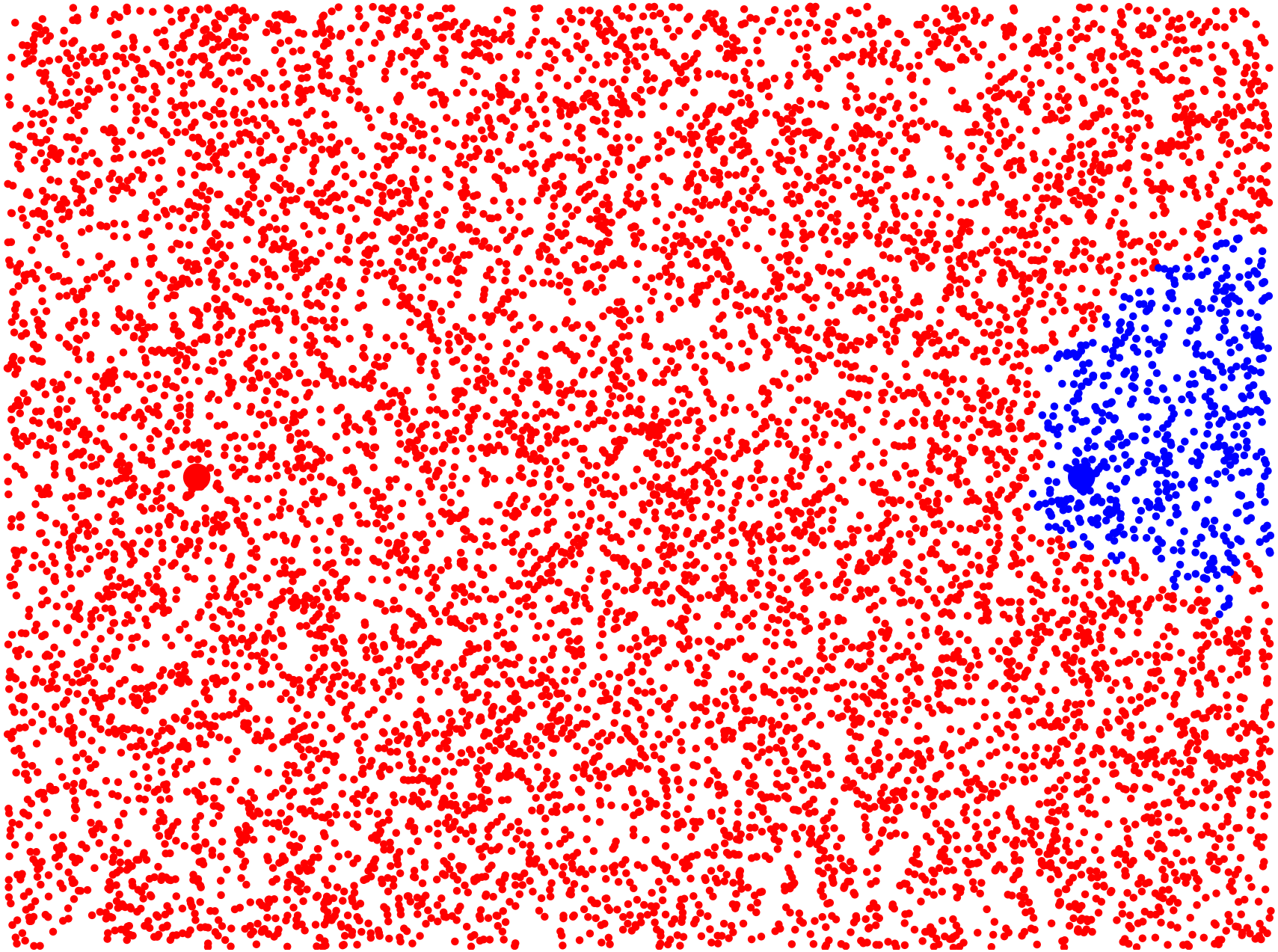
Classification experiment



Random walk experiment



Classification experiment



The Random walk perspective

At low label rates, the random walker reaches the mixing time before hitting a label.

- The label eventually hit is largely independent of where the walker starts.

After walking for a long time, the probability distribution of the walker approaches the invariant distribution π given by

$$\pi_i = \frac{d_i}{\sum_{j=1}^n d_j}.$$

Thus, the solution of Laplace learning is approximately

$$u(x_i) = \mathbb{E}[y_{i_\tau} \mid X_0 = x_i] \approx \frac{\sum_{j=1}^n d_j y_j}{\sum_{j=1}^n d_j} =: c \in \mathbb{R}^k.$$

Bottom line: Nearly everything is labeled by the one-hot vector closest to c!

The random walk perspective

Let $X_0^{x_j}, X_1^{x_j}, X_2^{x_j}$ be a random walk on the graph X starting from $x_j \in X$, and define

$$u_T(x_i) = \mathbb{E}\left[\sum_{k=0}^{T}\sum_{j=1}^{m} y_j \mathbb{1}_{\{X_k^{x_j} = x_i\}}\right].$$

Idea: We release random walkers from the labeled nodes, and record how often each label's walker visits x_i.

We can write

$$u_T(x_i) = \sum_{j=1}^{m} y_j \sum_{k=0}^{T} \mathbb{P}(X_k^{x_j} = x_i).$$

The inner term is a Green's function for a random walk. As $T \to \infty$, $u_T \to \infty$.

We center u_T by its mean value:

$$\sum_{i=1}^{n} u_T(x_i) = \sum_{k=0}^{T}\sum_{j=1}^{m} y_j = \sum_{k=0}^{T} m\overline{y}, \qquad \text{where } \overline{y} = \frac{1}{m}\sum_{j=1}^{m} y_j.$$

The random walk perspective

Subtracting off the mean of u_T, and normalizing by d_i, we arrive at

$$u_T(x_i) := \mathbb{E}\left[\sum_{k=0}^{T} \frac{1}{d_i} \sum_{j=1}^{m} (y_j - \overline{y}) \mathbb{1}_{\{X_k^{x_j} = x_i\}}\right], \quad \text{where } \overline{y} = \frac{1}{m}\sum_{j=1}^{m} y_j.$$

Theorem

For every $T \geq 0$ we have

$$u_{T+1}(x_i) = u_T(x_i) + \frac{1}{d_i}\left(\sum_{j=1}^{m}(y_j - \overline{y})\delta_{ij} - \mathcal{L}u_T(x_i)\right).$$

If the graph G is connected and the Markov chain induced by the random walk is aperiodic, then $u_T \to u$ as $T \to \infty$, where $u : X \to \mathbb{R}$ is the solution of

$$\mathcal{L}u(x_i) = \sum_{j=1}^{m}(y_j - \overline{y})\delta_{ij} \quad \text{for } i = 1, \ldots, n$$

satisfying $\sum_{i=1}^{n} d_i u(x_i) = 0$.

The variational interpretation

We define the space of weighted mean-zero functions

$$\ell_0^2(X) = \left\{ u : X \to \mathbb{R} \, : \, \sum_{i=1}^{n} d_i \, u(x_i) = 0 \right\}.$$

Consider the variational problem

$$\min_{u \in \ell_0^2(X)} \left\{ \sum_{i,j=1}^{n} w_{ij} |u(x_i) - u(x_j)|^2 - \sum_{j=1}^{m} (y_j - \overline{y}) \cdot u(x_j) \right\}, \tag{4}$$

where $\overline{y} = \frac{1}{m} \sum_{i=1}^{m} y_i$.

Theorem

Assume G is connected. Then there exists a unique solution $u \in \ell_0^2(X)$ of (4), and furthermore, u satisfies the Poisson equation

$$\mathcal{L} u(x_i) = \sum_{j=1}^{m} (y_j - \overline{y}) \delta_{ij}.$$

Poisson vs Laplace

The variational interpretation of Poisson learning is

$$\min_{u \in \ell_0^2(X)} \left\{ \sum_{i,j=1}^{n} w_{ij} |u(x_i) - u(x_j)|^2 - \sum_{j=1}^{m} (y_j - \overline{y}) \cdot u(x_j) \right\}.$$

We compare this with the variational interpretation for Laplace learning, which is

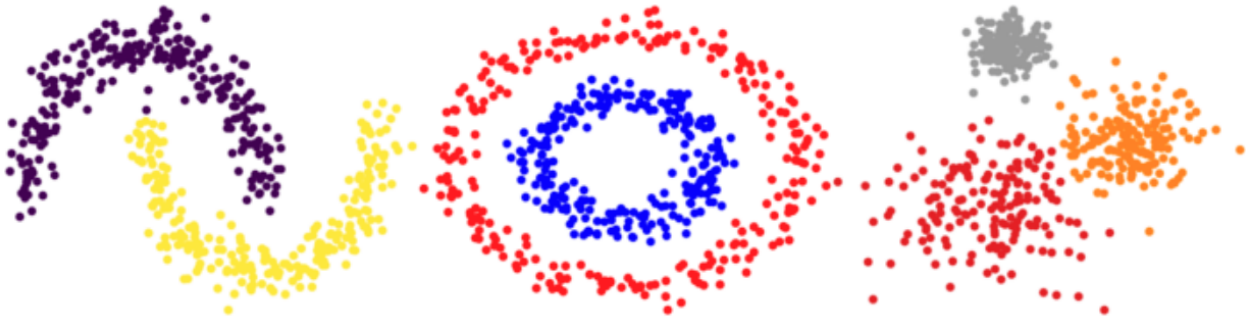
$$\min_{u \in \ell^2(X)} \left\{ \sum_{i,j=1}^{n} w_{ij} |u(x_i) - u(x_j)|^2 \ : \ u(x_i) = y_i \text{ for } i = 1, \dots, m \right\}.$$

Takeaway: Instead of hard constraints, Poisson equations use soft constraints that are affine functions of the label values.

Outline

GraphLearning Python Package

Graph-based Clustering and Semi-Supervised Learning



This python package is devoted to efficient implementations of modern graph-based learning algorithms for both semi-supervised learning and clustering. The package implements many popular datasets (currently MNIST, FashionMNIST, cifar-10, and WEBKB) in a way that makes it simple for users to test out new algorithms and rapidly compare against existing methods.

This package reproduces experiments from the paper

Calder, Cook, Thorpe, Slepcev. Poisson Learning: Graph Based Semi-Supervised Learning at Very Low Label Rates., Proceedings of the 37th International Conference on Machine Learning, PMLR 119:1306-1316, 2020.

Installation

Install with

```
pip install graphlearning
```

https://github.com/jwcalder/GraphLearning

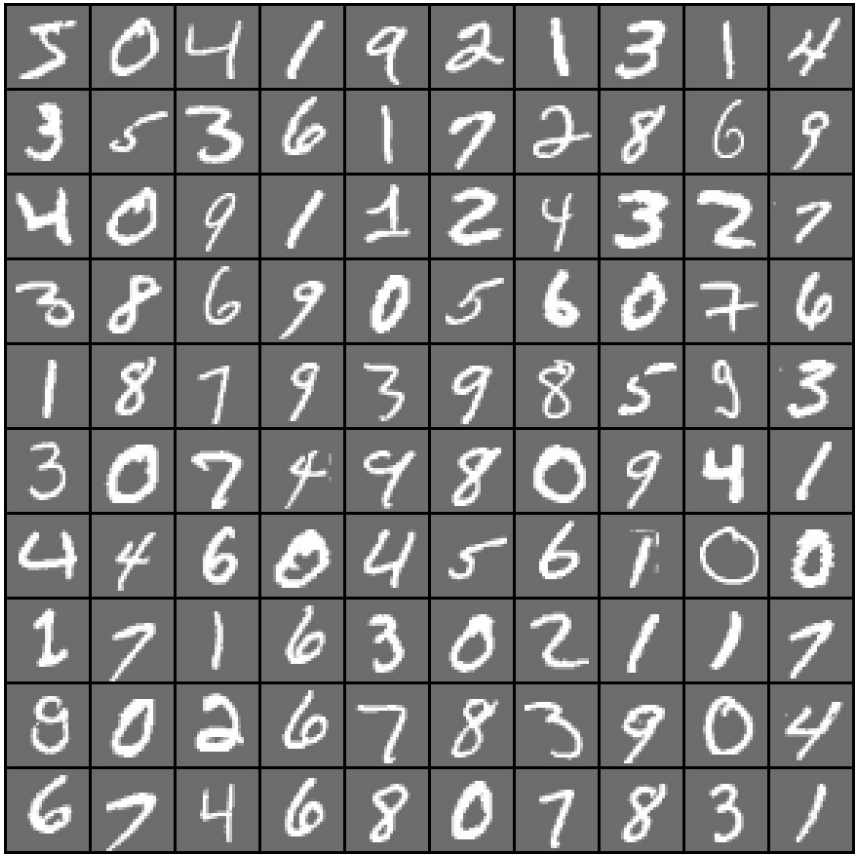
Algorithmic details

Algorithm 1 Poisson Learning

Input: $\mathbf{W}, \mathbf{F}, \mathbf{b}, T$ $\{\mathbf{F} \in \mathbb{R}^{k\times m}$ are label vectors, $\mathbf{b} \in \mathbb{R}^k$ are class sizes.$\}$
Output: $\mathbf{U} \in \mathbb{R}^{n\times k}$
$\mathbf{D} \leftarrow \text{diag}(\mathbf{W}\mathbb{1})$
$\mathbf{L} \leftarrow \mathbf{D} - \mathbf{W}$
$\mathbf{c} \leftarrow \frac{1}{m}\mathbf{F}\mathbb{1}$
$\mathbf{B} \leftarrow [\mathbf{F} - \mathbf{c}, \textbf{zeros}(k, n-m)]$
$\mathbf{U} \leftarrow \textbf{zeros}(n, k)$
for $i = 1$ **to** T **do**
    $\mathbf{U} \leftarrow \mathbf{U} + \mathbf{D}^{-1}(\mathbf{B}^T - \mathbf{L}\mathbf{U})$
end for
$\mathbf{U} \leftarrow \mathbf{U} \cdot \text{diag}(\mathbf{b}/\mathbf{c})$ $\{$Accounts for unbalanced class sizes.$\}$

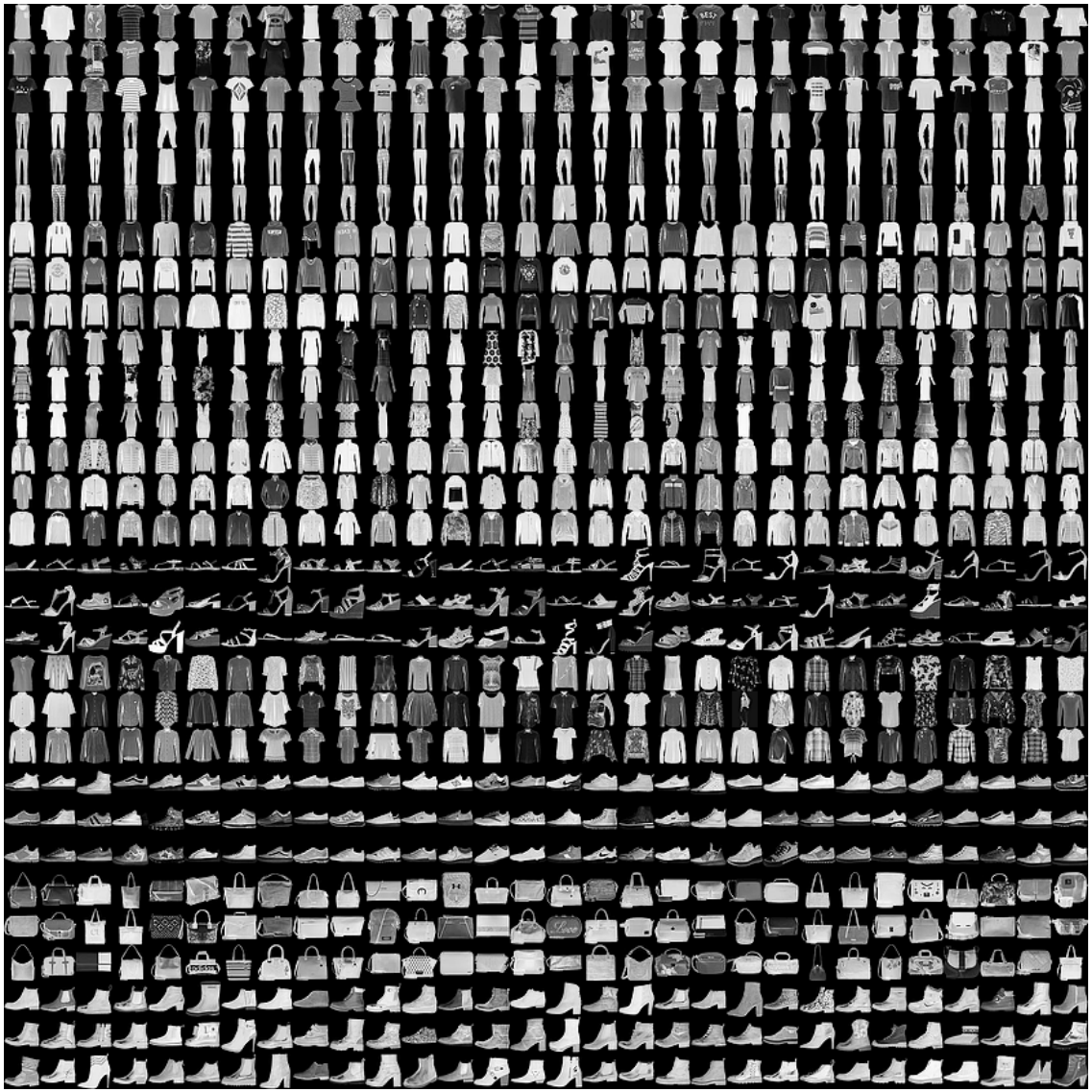
1. We only need about $T = 100$ iterations on MNIST, FashionMNIST, CIFAR-10, to get good results. CPU Time: 8 seconds on CPU, 1 second on GPU.

MNIST (70,000 28×28 pixel images of digits 0-9)



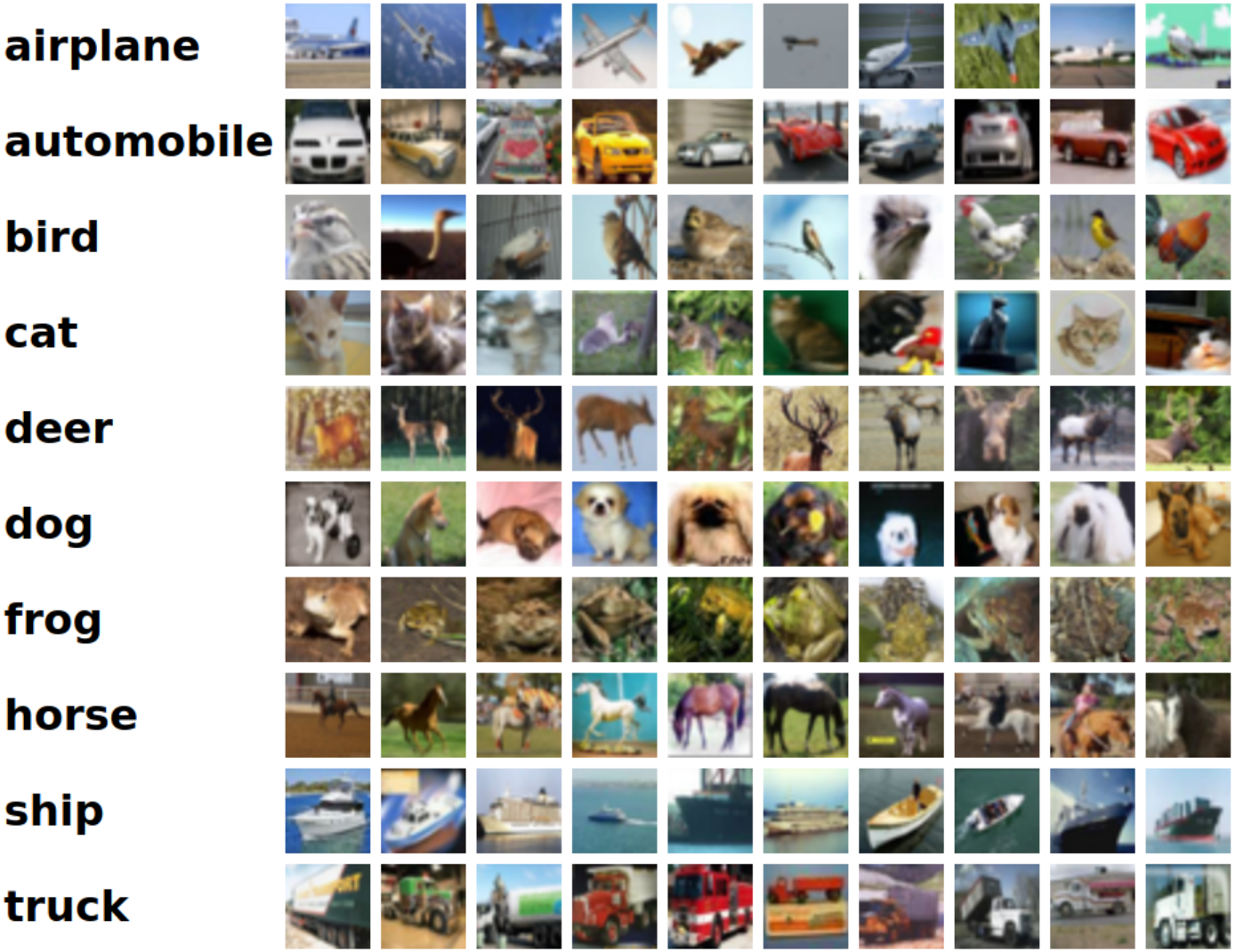
[Y. LeCun, L. Bottou, Y. Bengio, and P. Haffner. "Gradient-based learning applied to document recognition." Proceedings of the IEEE, 86(11):2278-2324, November 1998.]

FashionMNIST (70,000 28×28 images of fashion items)



[Xiao, Han, Kashif Rasul, and Roland Vollgraf. "Fashion-mnist: a novel image dataset for benchmarking machine learning algorithms." arXiv preprint arXiv:1708.07747 (2017).]

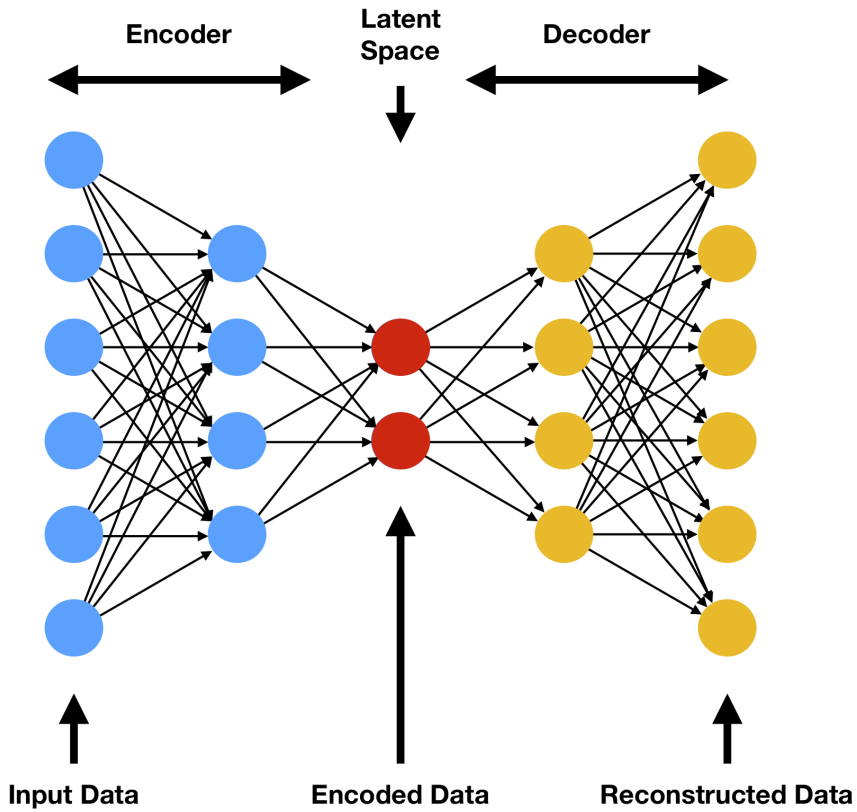
CIFAR-10



[Krizhevsky, Alex, and Geoffrey Hinton. "Learning multiple layers of features from tiny images." (2009): 7.]

Autoencoders

For each dataset, we build the graph by training autoencoders.



`www.compthree.com`

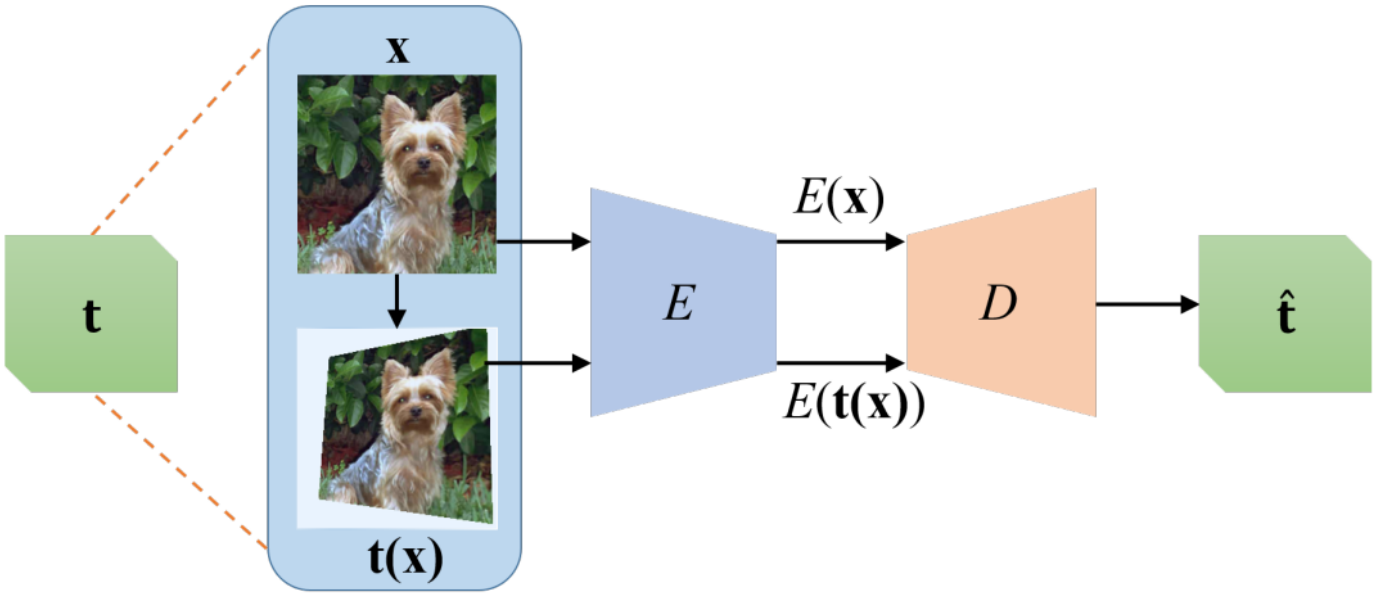
Autoencoders are "Nonlinear versions of PCA"

Building graphs from autoencoders

For MNIST and FashionMNIST, we use a 4-layer variational autoencoder with 30 latent variables:

[Kingma and Welling. Auto-encoding variational Bayes. ICML 2014]

For CIFAR-10, we use the autoencoding framework from [Zhang et al. AutoEncoding Transformations (AET), CVPR 2019] with 12,288 latent variables.



Building graphs from autoencoders

After training autoencoders, we build a $k = 10$ nearest neighbor graphs in the latent space with Gaussian weights

$$w_{ij} = \exp\left(-\frac{4|x_i - x_j|^2}{d_k(x_i)^2}\right),$$

where $d_k(x_i)$ is the distance in the latent space between x_i and its k^{th} nearest neighbor. The weight matrix was then symmetrized by replacing W with $W + W^T$.

For CIFAR-10, the latent feature vectors were normalized to unit norm (equivalent to using an angular similarity).

First comparison

We compared against many other graph-based learning algorithms

- Laplace/Label propagation: [Zhu et al., 2003]
- Graph nearest neighbor (using Dijkstra)
- Lazy random walks: [Zhou et al., 2004]
- Mutli-class MBO: [Garcia-Cardona et al., 2014]
- Centered kernel method: [Mai & Couillet, 2018]
- Sparse Label Propagation: [Jung et al., 2016]
- Weighted Nonlocal Laplacian (WNLL): [Shi et al., 2017]
- p-Laplace regularization: [Flores et al. 2019]

MNIST results

Table: Average (standard deviation) classification accuracy over 100 trials.

# Labels per class	**1**	**2**	**3**	**4**	**5**
Laplace/LP	16.1 (6.2)	28.2 (10.3)	42.0 (12.4)	57.8 (12.3)	69.5 (12.2)
Nearest Neighbor	65.4 (5.2)	74.2 (3.3)	77.8 (2.6)	80.7 (2.0)	82.1 (2.0)
Random Walk	66.4 (5.3)	76.2 (3.3)	80.0 (2.7)	82.8 (2.3)	84.5 (2.0)
MBO	19.4 (6.2)	29.3 (6.9)	40.2 (7.4)	50.7 (6.0)	59.2 (6.0)
Centered Kernel	19.1 (1.9)	24.2 (2.3)	28.8 (3.4)	32.6 (4.1)	35.6 (4.6)
Sparse Label Prop.	14.0 (5.5)	14.0 (4.0)	14.5 (4.0)	18.0 (5.9)	16.2 (4.2)
WNLL	55.8 (15.2)	82.8 (7.6)	90.5 (3.3)	93.6 (1.5)	94.6 (1.1)
p-Laplace	72.3 (9.1)	86.5 (3.9)	89.7 (1.6)	90.3 (1.6)	91.9 (1.0)
Poisson	**90.2 (4.0)**	**93.6 (1.6)**	**94.5 (1.1)**	**94.9 (0.8)**	**95.3 (0.7)**

FashionMNIST results

Table: Average (standard deviation) classification accuracy over 100 trials.

# Labels per class	**1**	**2**	**3**	**4**	**5**
Laplace/LP	18.4 (7.3)	32.5 (8.2)	44.0 (8.6)	52.2 (6.2)	57.9 (6.7)
Nearest Neighbor	46.6 (4.7)	53.5 (3.6)	57.2 (3.0)	59.3 (2.6)	61.1 (2.8)
Random Walk	49.0 (4.4)	55.6 (3.8)	59.4 (3.0)	61.6 (2.5)	63.4 (2.5)
MBO	15.7 (4.1)	20.1 (4.6)	25.7 (4.9)	30.7 (4.9)	34.8 (4.3)
Centered Kernel	11.8 (0.4)	13.1 (0.7)	14.3 (0.8)	15.2 (0.9)	16.3 (1.1)
Sparse Label Prop.	14.1 (3.8)	16.5 (2.0)	13.7 (3.3)	13.8 (3.3)	16.1 (2.5)
WNLL	44.6 (7.1)	59.1 (4.7)	64.7 (3.5)	67.4 (3.3)	70.0 (2.8)
p-Laplace	54.6 (4.0)	57.4 (3.8)	65.4 (2.8)	68.0 (2.9)	68.4 (0.5)
Poisson	**60.8 (4.6)**	**66.1 (3.9)**	**69.6 (2.6)**	**71.2 (2.2)**	**72.4 (2.3)**

Compare to clustering result of 67.2% [McConville et al., 2019]

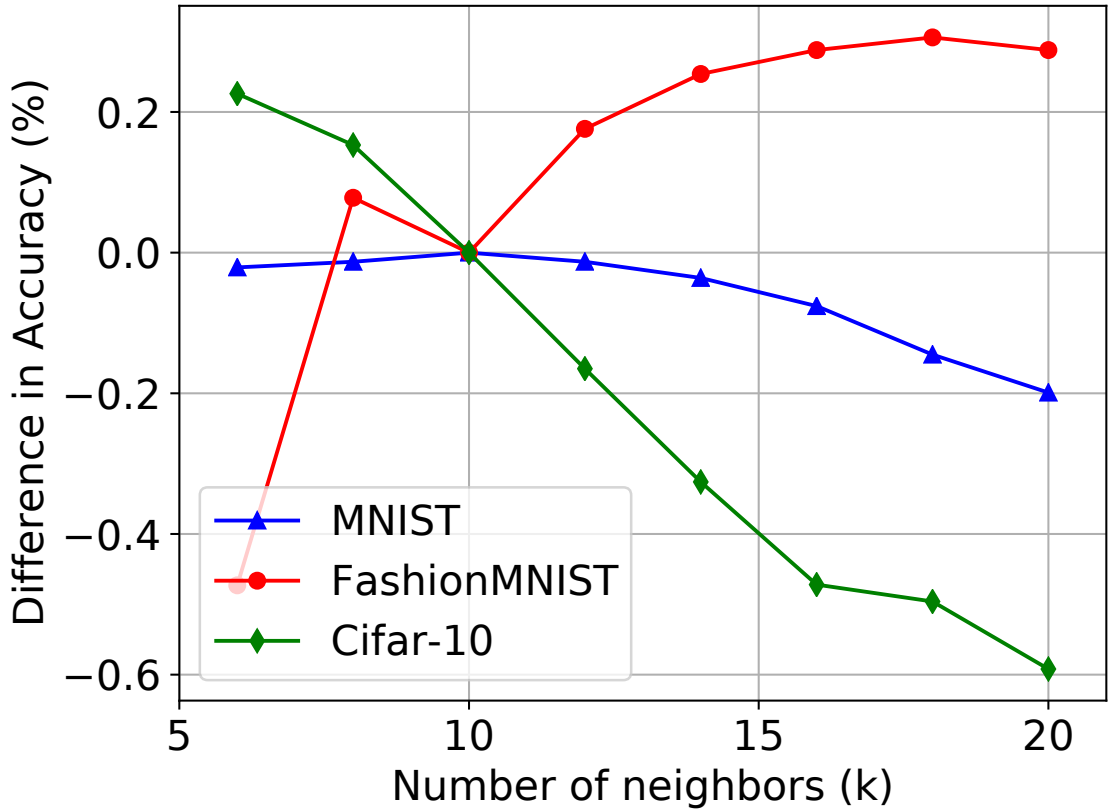
CIFAR-10 results

Table: Average (standard deviation) classification accuracy over 100 trials.

# Labels per class	**1**	**2**	**3**	**4**	**5**
Laplace/LP	10.4 (1.3)	11.0 (2.1)	11.6 (2.7)	12.9 (3.9)	14.1 (5.0)
Nearest Neighbor	33.1 (4.3)	37.3 (4.1)	39.7 (3.0)	41.7 (2.8)	43.0 (2.5)
Random Walk	36.4 (4.9)	42.0 (4.4)	45.1 (3.3)	47.5 (2.9)	49.0 (2.6)
MBO	14.2 (4.1)	19.3 (5.2)	24.3 (5.6)	28.5 (5.6)	33.5 (5.7)
Centered Kernel	15.4 (1.6)	16.9 (2.0)	18.8 (2.1)	19.9 (2.0)	21.7 (2.2)
Sparse Label Prop.	11.8 (2.4)	12.3 (2.4)	11.1 (3.3)	14.4 (3.5)	11.0 (2.9)
WNLL	16.6 (5.2)	26.2 (6.8)	33.2 (7.0)	39.0 (6.2)	44.0 (5.5)
p-Laplace	26.0 (6.7)	35.0 (5.4)	42.1 (3.1)	48.1 (2.6)	49.7 (3.8)
Poisson	**40.7 (5.5)**	**46.5 (5.1)**	**49.9 (3.4)**	**52.3 (3.1)**	**53.8 (2.6)**

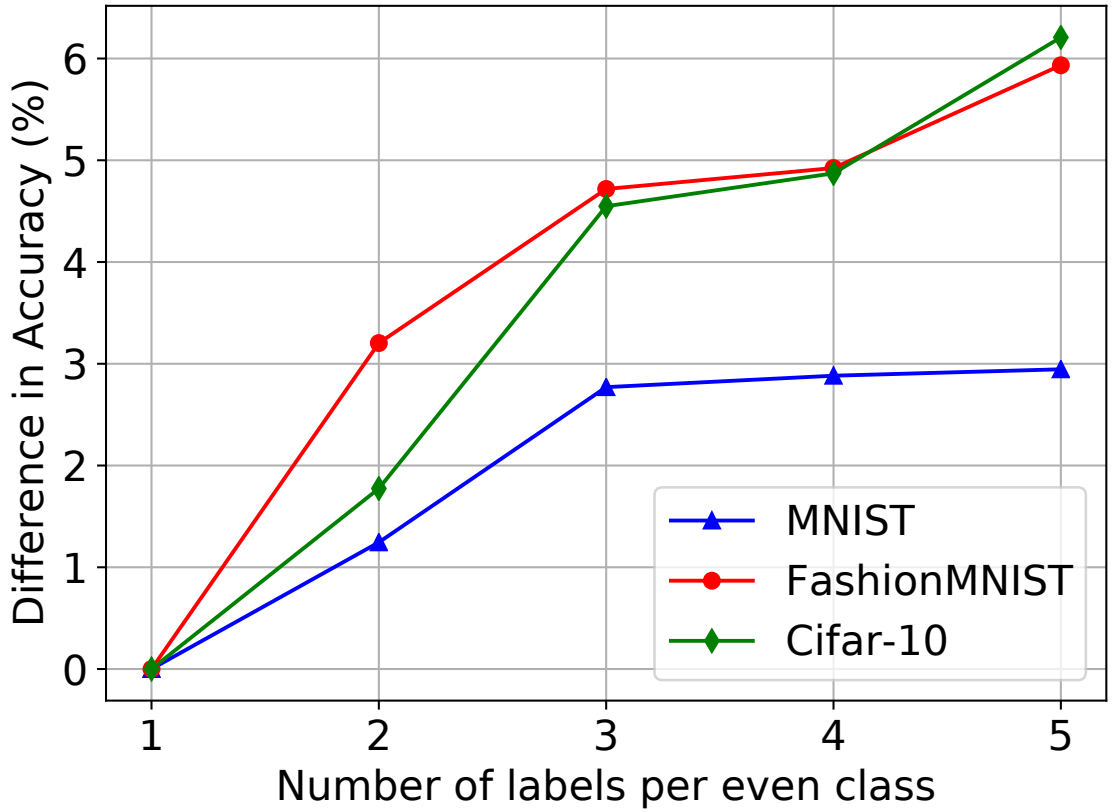
Compare to clustering result of 41.2% [Mukherjee et al., ClusterGAN, CVPR 2019].

Varying number of neighbors k



5 labels per class for all classes.

Unbalanced training data



Odd numbered classes got 1 label per class.

Volume constrained semi-supervised learning

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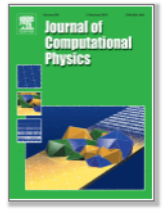

Auction dynamics: A volume constrained MBO scheme

Matt Jacobs, Ekaterina Merkurjev, Selim Esedoğlu

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Classification results can be improved by incorporating prior knowledge of class sizes through volume constraints.

PoissonMBO: Volume constrained Poisson learning

Observation 1: The Poisson learning iteration with a fixed time step

$$u_{T+1}(x) = u_T(x) + dt\left(\sum_{y\in\Gamma}(g(y)-\overline{y})\delta_{ij} - \mathcal{L}u_T(x)\right)$$

is **volume preserving**. That is $\sum_{x\in\mathcal{X}} u_{T+1}(x) = \sum_{x\in\mathcal{X}} u_T(x)$.

Observation 2: We can easily perform a volume constrained label projection

$$\ell(x_i) = \underset{j\in\{1,\dots,k\}}{\text{argmax}} \{s_j\, u_j(x)\}.$$

We adjust the weights s_j to grow/shrink each region to achieve the correct class sizes.

Named after the Merriman-Bence-Osher (MBO) scheme for curvature motion, which has been used before in graph-based learning [Garcia, et al., 2014, Jacobs et al., 2018].

Easy to add volume constraints

Algorithm 2 Poisson MBO

1: **Input:** $\mathbf{W}, \mathbf{F}, N_{\text{inner}}, N_{\text{outer}}, \mathbf{b}, \mu, T > 0$
2: **Output:** $\mathbf{U} \in \mathbb{R}^{n \times k}$
3: $\mathbf{U} \leftarrow \text{PoissonLearning}(\mathbf{W}, \mathbf{F}, \mathbf{b}, T)$
4: $\mathrm{d}t \leftarrow 1/\max_{1 \leq i \leq n} \mathbf{D}_{ii}$
5: **for** $i = 1$ **to** N_{outer} **do**
6: **for** $j = 1$ **to** N_{inner} **do**
7: $\mathbf{U} \leftarrow \mathbf{U} - \mathrm{d}t(\mathbf{L}\mathbf{U} - \mu \mathbf{B}^T)$
8: **end for**
9: $\mathbf{U} \leftarrow \text{VolumeConstrainedLabelProjection}(\mathbf{U}, \mathbf{b})$
10: **end for**

1. The iterations in Steps 7-9 are volume preserving.

MNIST results

Table: Average (standard deviation) classification accuracy over 100 trials.

# Labels per class	**1**	**2**	**3**	**4**	**5**
Laplace/LP	16.1 (6.2)	28.2 (10.3)	42.0 (12.4)	57.8 (12.3)	69.5 (12.2)
WNLL	55.8 (15.2)	82.8 (7.6)	90.5 (3.3)	93.6 (1.5)	94.6 (1.1)
p-Laplace	72.3 (9.1)	86.5 (3.9)	89.7 (1.6)	90.3 (1.6)	91.9 (1.0)
VolumeMBO	89.9 (7.3)	95.6 (1.9)	96.2 (1.2)	96.6 (0.6)	96.7 (0.6)
Poisson	90.2 (4.0)	93.6 (1.6)	94.5 (1.1)	94.9 (0.8)	95.3 (0.7)
PoissonMBO	**96.5 (2.6)**	**97.2 (0.1)**	**97.2 (0.1)**	**97.2 (0.1)**	**97.2 (0.1)**
# Labels per class	**10**	**20**	**40**	**80**	**160**
Laplace/LP	91.3 (3.7)	95.8 (0.6)	96.5 (0.2)	96.8 (0.1)	97.0 (0.1)
WNLL	95.6 (0.5)	96.1 (0.3)	96.3 (0.2)	96.4 (0.1)	96.3 (0.1)
p-Laplace	94.0 (0.8)	95.1 (0.4)	95.5 (0.1)	96.0 (0.2)	96.2 (0.1)
VolumeMBO	96.9 (0.2)	97.0 (0.1)	97.1 (0.1)	97.2 (0.1)	**97.3 (0.1)**
Poisson	95.9 (0.4)	96.3 (0.3)	96.6 (0.2)	96.8 (0.1)	96.9 (0.1)
PoissonMBO	**97.2 (0.1)**	**97.2 (0.1)**	**97.2 (0.1)**	**97.2 (0.1)**	97.2 (0.1)

FashionMNIST results

Table: Average (standard deviation) classification accuracy over 100 trials.

# Labels per class	**1**	**2**	**3**	**4**	**5**
Laplace/LP	18.4 (7.3)	32.5 (8.2)	44.0 (8.6)	52.2 (6.2)	57.9 (6.7)
WNLL	44.6 (7.1)	59.1 (4.7)	64.7 (3.5)	67.4 (3.3)	70.0 (2.8)
p-Laplace	54.6 (4.0)	57.4 (3.8)	65.4 (2.8)	68.0 (2.9)	68.4 (0.5)
VolumeMBO	54.7 (5.2)	61.7 (4.4)	66.1 (3.3)	68.5 (2.8)	70.1 (2.8)
Poisson	60.8 (4.6)	66.1 (3.9)	69.6 (2.6)	71.2 (2.2)	72.4 (2.3)
PoissonMBO	**62.0 (5.7)**	**67.2 (4.8)**	**70.4 (2.9)**	**72.1 (2.5)**	**73.1 (2.7)**
# Labels per class	**10**	**20**	**40**	**80**	**160**
Laplace/LP	70.6 (3.1)	76.5 (1.4)	79.2 (0.7)	80.9 (0.5)	**82.3 (0.3)**
WNLL	74.4 (1.6)	77.6 (1.1)	79.4 (0.6)	80.6 (0.4)	81.5 (0.3)
p-Laplace	73.0 (0.9)	76.2 (0.8)	78.0 (0.3)	79.7 (0.5)	80.9 (0.3)
VolumeMBO	74.4 (1.5)	77.4 (1.0)	79.5 (0.7)	**81.0 (0.5)**	82.1 (0.3)
Poisson	75.2 (1.5)	77.3 (1.1)	78.8 (0.7)	79.9 (0.6)	80.7 (0.5)
PoissonMBO	**76.1 (1.4)**	**78.2 (1.1)**	**79.5 (0.7)**	80.7 (0.6)	81.6 (0.5)

CIFAR-10 results

Table: Average (standard deviation) classification accuracy over 100 trials.

# Labels per class	**1**	**2**	**3**	**4**	**5**
Laplace/LP	10.4 (1.3)	11.0 (2.1)	11.6 (2.7)	12.9 (3.9)	14.1 (5.0)
WNLL	16.6 (5.2)	26.2 (6.8)	33.2 (7.0)	39.0 (6.2)	44.0 (5.5)
p-Laplace	26.0 (6.7)	35.0 (5.4)	42.1 (3.1)	48.1 (2.6)	49.7 (3.8)
VolumeMBO	38.0 (7.2)	46.4 (7.2)	50.1 (5.7)	53.3 (4.4)	55.3 (3.8)
Poisson	40.7 (5.5)	46.5 (5.1)	49.9 (3.4)	52.3 (3.1)	53.8 (2.6)
PoissonMBO	**41.8 (6.5)**	**50.2 (6.0)**	**53.5 (4.4)**	**56.5 (3.5)**	**57.9 (3.2)**
# Labels per class	**10**	**20**	**40**	**80**	**160**
Laplace/LP	21.8 (7.4)	38.6 (8.2)	54.8 (4.4)	62.7 (1.4)	66.6 (0.7)
WNLL	54.0 (2.8)	60.3 (1.6)	64.2 (0.7)	66.6 (0.6)	68.2 (0.4)
p-Laplace	56.4 (1.8)	60.4 (1.2)	63.8 (0.6)	66.3 (0.6)	68.7 (0.3)
VolumeMBO	59.2 (3.2)	61.8 (2.0)	63.6 (1.4)	64.5 (1.3)	65.8 (0.9)
Poisson	58.3 (1.7)	61.5 (1.3)	63.8 (0.8)	65.6 (0.6)	67.3 (0.4)
PoissonMBO	**61.8 (2.2)**	**64.5 (1.6)**	**66.9 (0.8)**	**68.7 (0.6)**	**70.3 (0.4)**

References

References:

1. J. Calder, B. Cook, M. Thorpe, and D. Slepčev. **Poisson Learning: Graph based semi-supervised learning at very low label rates.** *International Conference on Machine Learning (ICML), PMLR 119:1306–1316*, 2020.

Code: `https://github.com/jwcalder/GraphLearning` (pip install graphlearning)