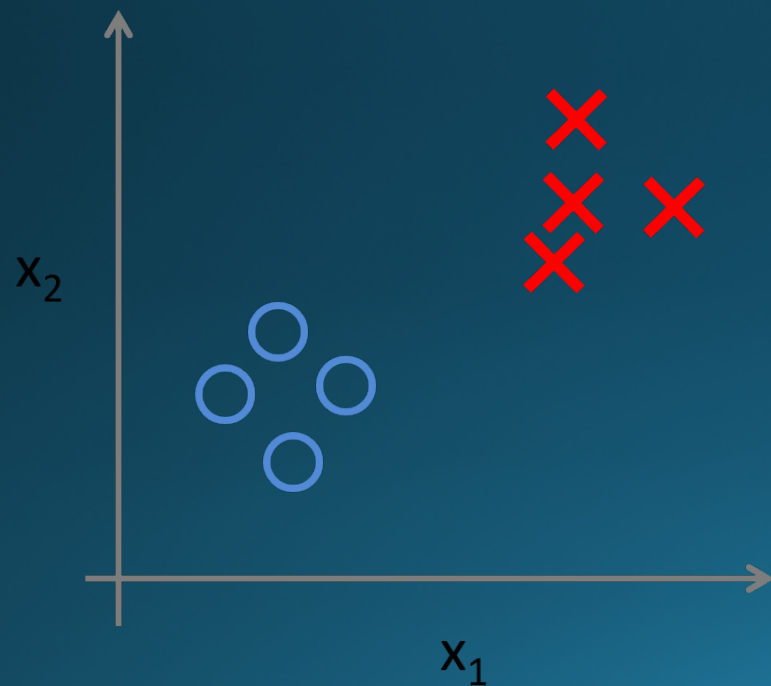


CSCI 4360/6360 Data Science II

Semi-Supervised Learning

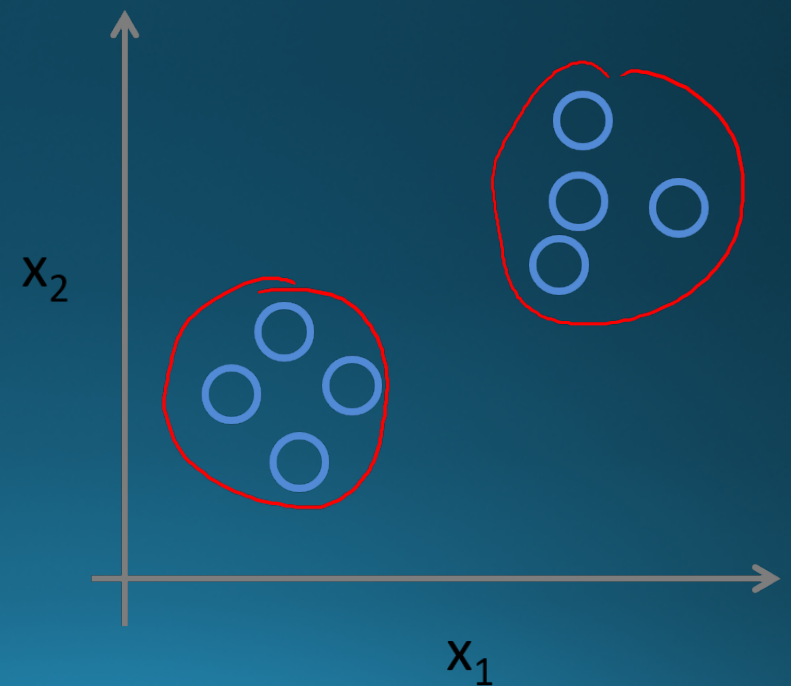
Supervised learning

Supervised Learning



Unsupervised learning

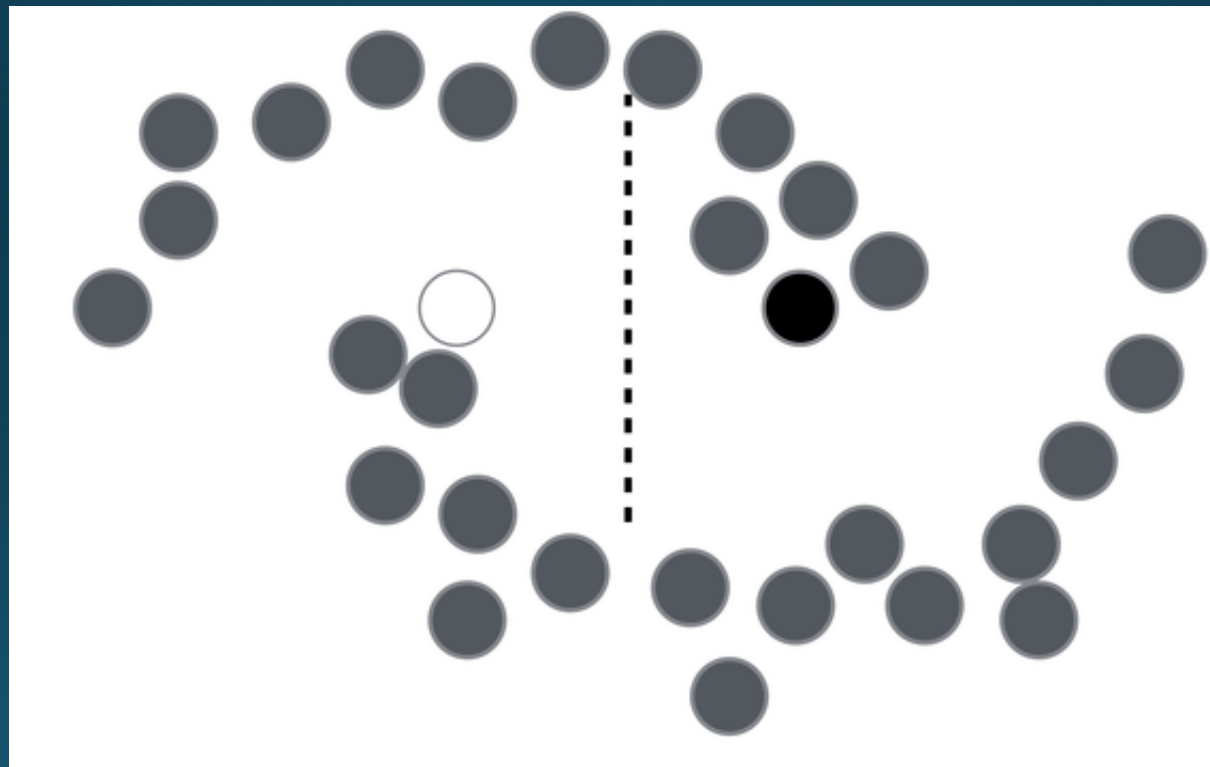
Unsupervised Learning



Semi-supervised learning

- Basically a hybrid!
- Given:
 - A pool of labeled examples L
 - A (usually larger) pool of unlabeled examples U
- **Can you improve accuracy somehow using U ?**

Semi-supervised Learning



Semi-Supervised Bootstrapped Learning/Self-training

Extract cities:

Paris
Pittsburgh
Seattle
Cupertino

San Francisco
Austin
denial

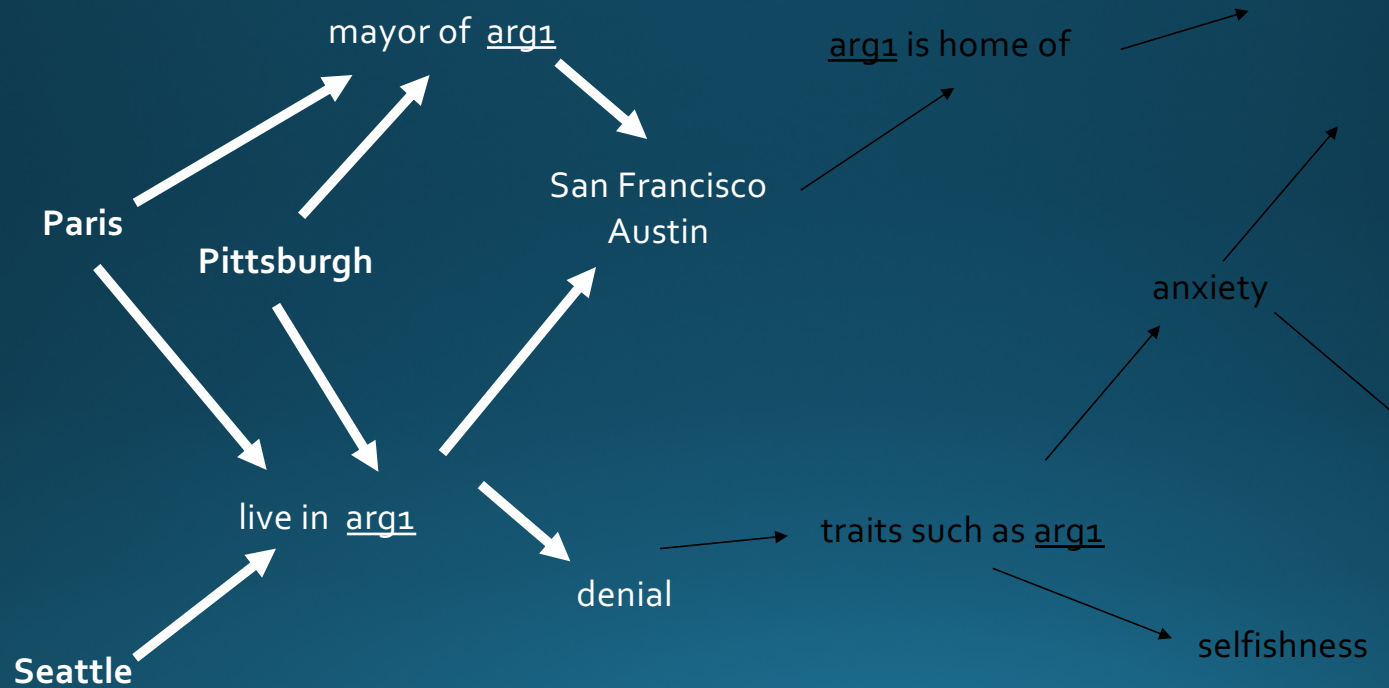
anxiety
selfishness
Berlin

mayor of arg1
live in arg1

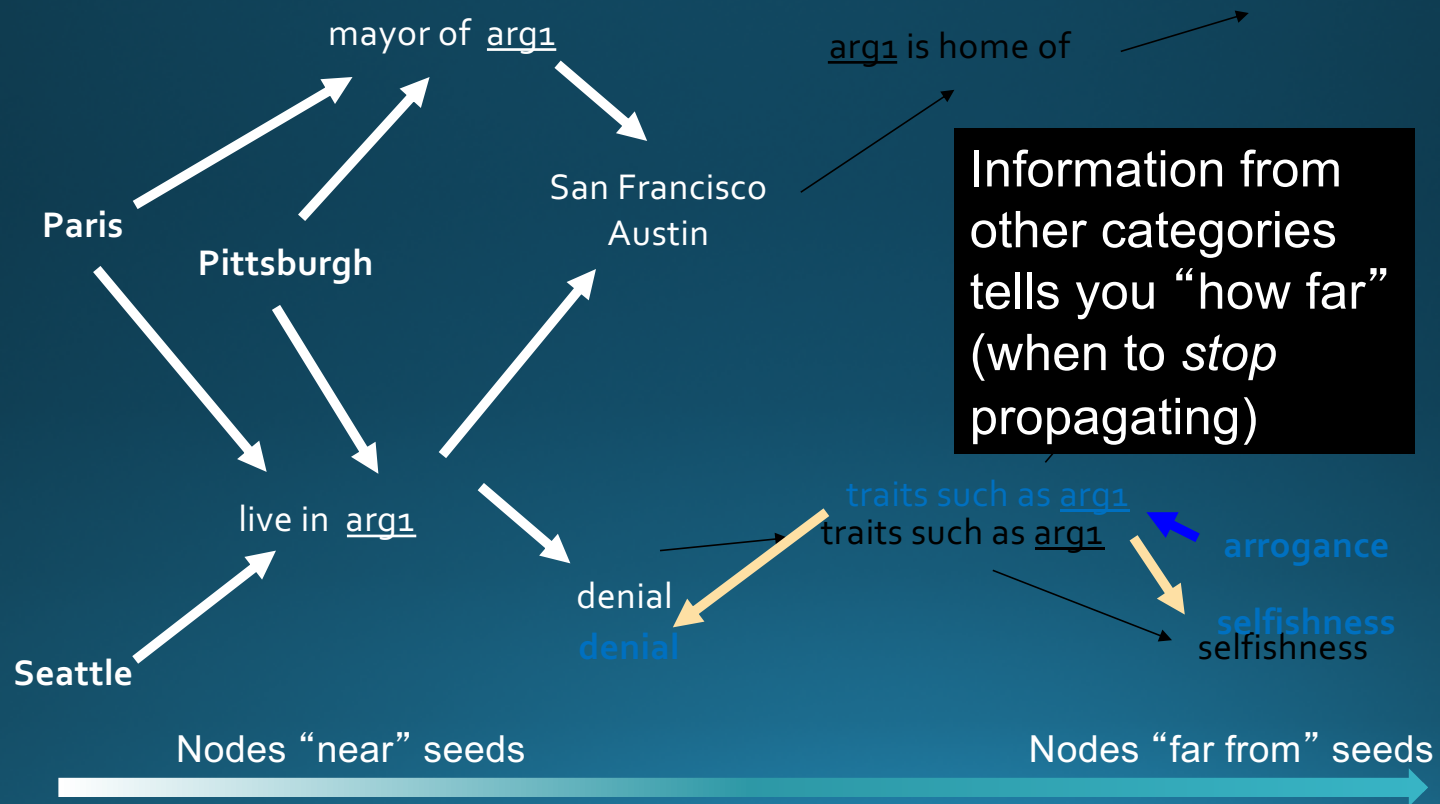
arg1 is home of
traits such as arg1



Semi-Supervised Bootstrapped Learning via Label Propagation

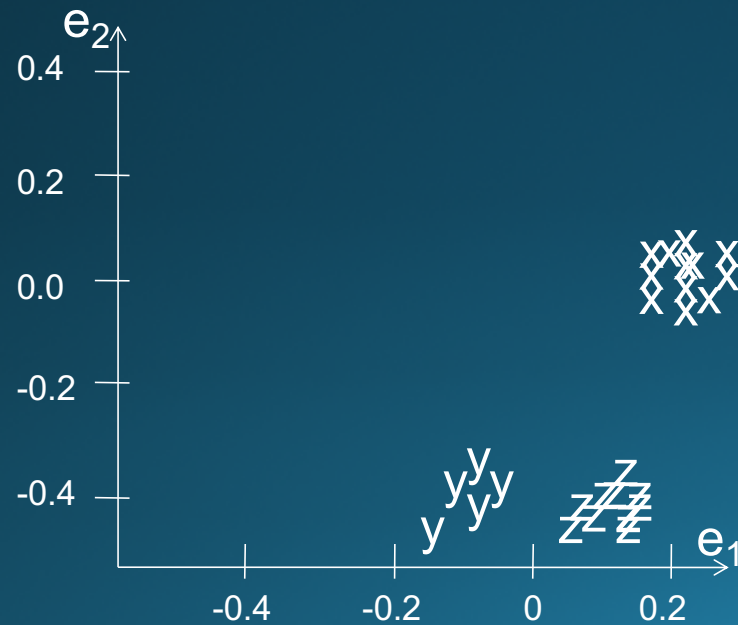


Semi-Supervised Bootstrapped Learning via Label Propagation

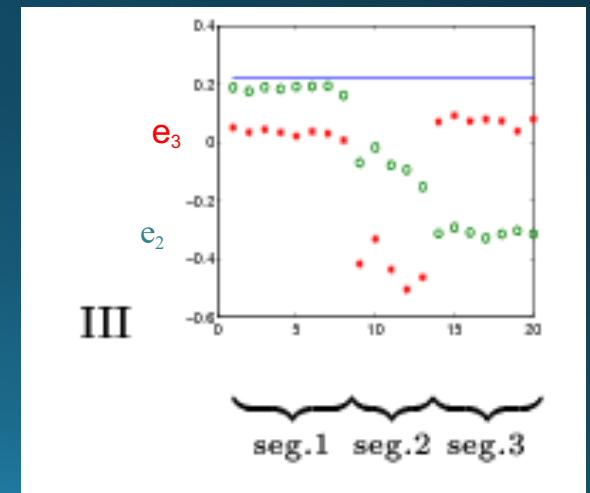
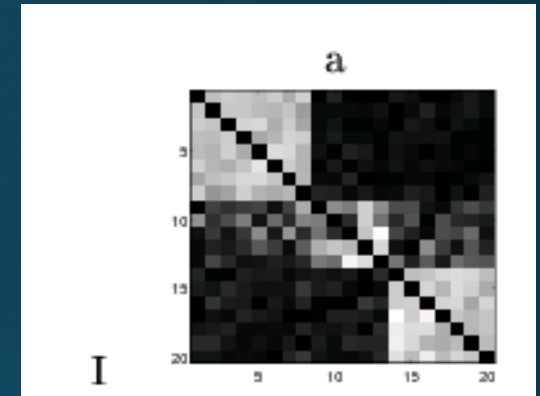


Spectral Clustering

- Graph = Matrix
 - $W \cdot v_1 = v_2$ "propogates weights from neighbors"

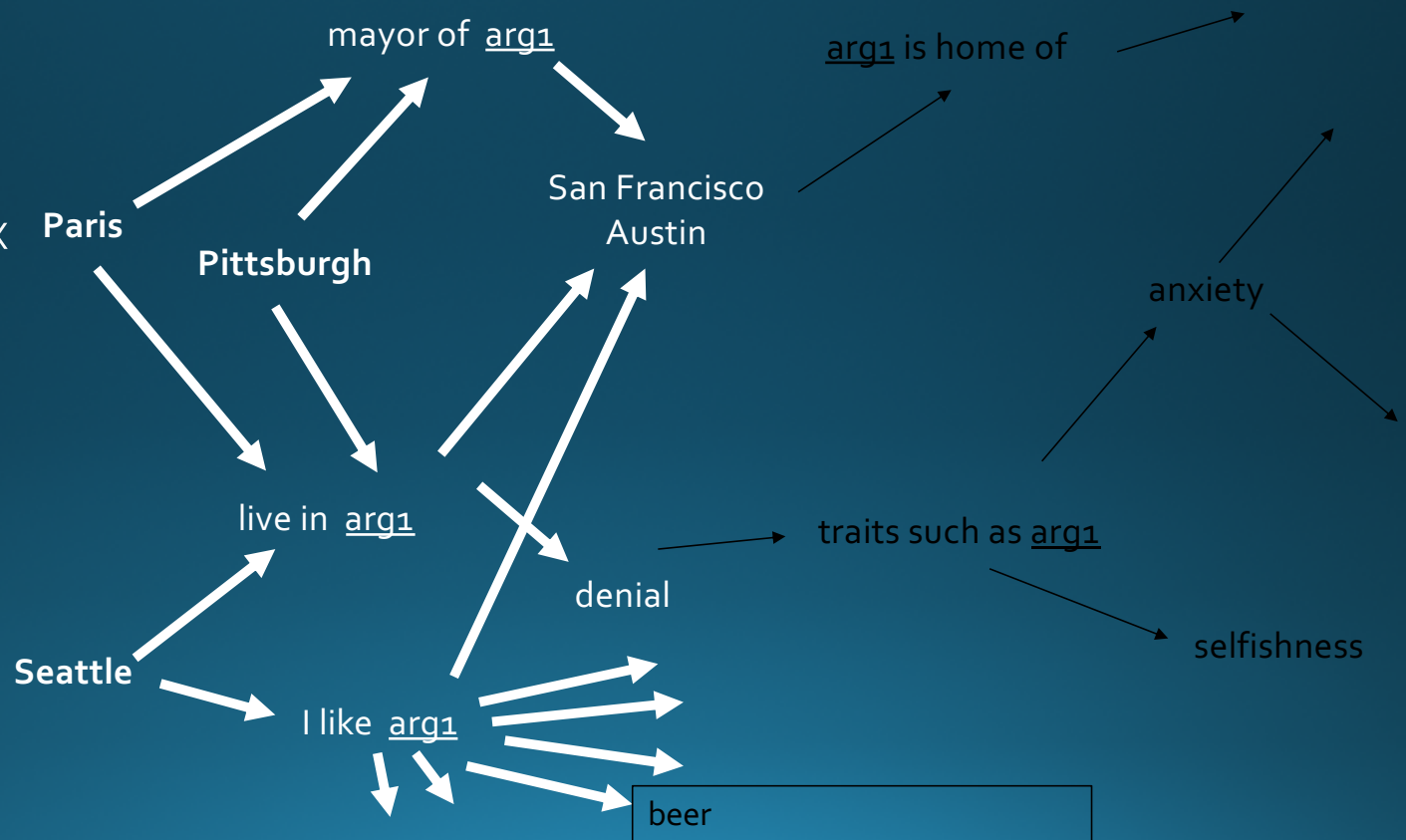


[Shi & Meila, 2002]



Semi-Supervised Learning as Label Propagation on a Graph

- Propagate label to "nearby" nodes
 - X is "near" Y if there is a high probability of reaching Y from X
- Propagation methods
 - Personalized PageRank
 - Random walk
- Rewards multiple paths
- Penalizes longer and "high fanout" paths



Semi-Supervised Classification of Network Data Using Very Few Labels

Frank Lin

Carnegie Mellon University, Pittsburgh, Pennsylvania

Email: frank@cs.cmu.edu

William W. Cohen

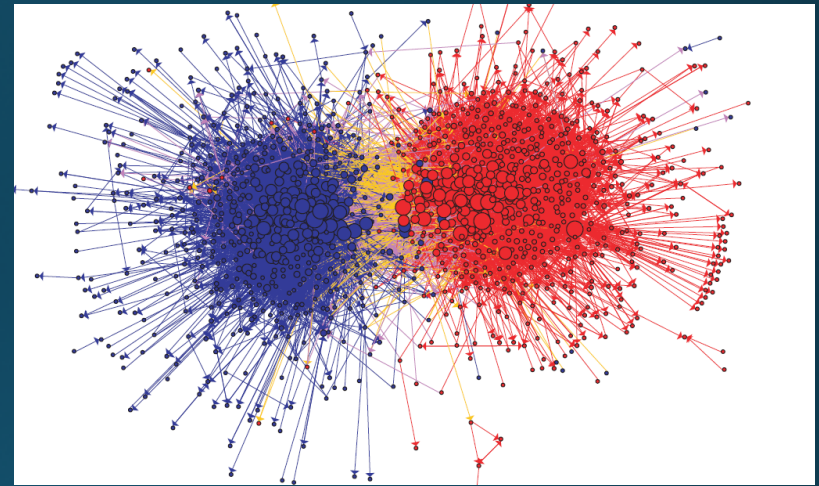
Carnegie Mellon University, Pittsburgh, Pennsylvania

Email: wcohen@cs.cmu.edu

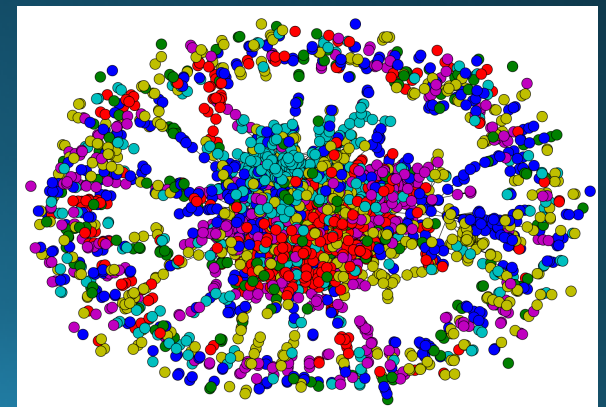
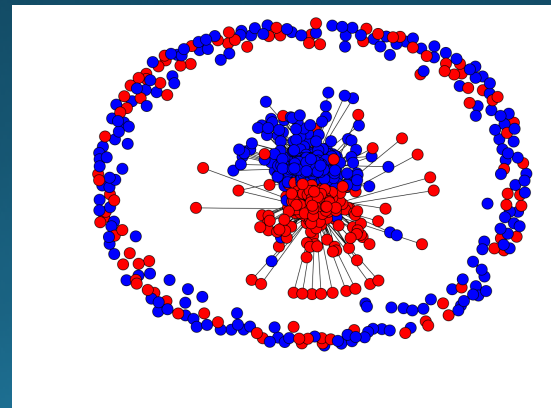
ASONAM-2010 (Advances in Social Networks Analysis and Mining)

Network Datasets with Known Classes

- UBMCBlog
- AGBlog
- MSPBlog
- Cora
- Citeseer



	Nodes	Edges	Density
UMBCBlog	404	2725	0.01670
AGBlog	1222	19021	0.01274
MSPBlog	1031	9316	0.00876
Cora	2485	5209	0.00084
CiteSeer	2110	3757	0.00084



MultiRankWalk

- Seed Selection
 - Order by PageRank or degree, or even randomly
 - Traverse list until you have k examples/class

$$\vec{r} = (1 - d)\vec{u} + dW\vec{r}$$

Given: A graph $G = (V, E)$, corresponding to nodes in G are instances X , composed of unlabeled instances X^U and labeled instances X^L with corresponding labels Y^L , and a damping factor d .
Returns: Labels Y^U for unlabeled nodes X^U .

For each class c

- 1) Set $\mathbf{u}_i \leftarrow 1, \forall Y_i^L = c$
- 2) Normalize \mathbf{u} such that $\|\mathbf{u}\|_1 = 1$
- 3) Set $R_c \leftarrow \text{RandomWalk}(G, \mathbf{u}, d)$

For each instance i

- Set $X_i^U \leftarrow \text{argmax}_c(R_{ci})$

Fig. 1. The MultiRankWalk algorithm.

Comparison: wvRN

- One definition [MacSkassy & Provost, JMLR 2007]:...

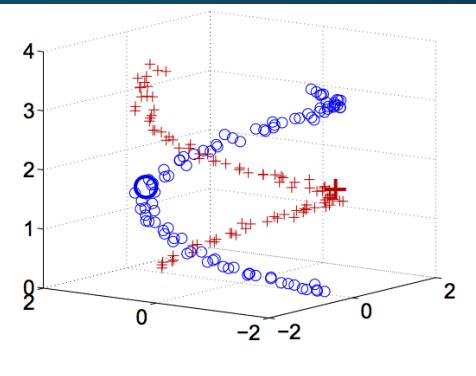
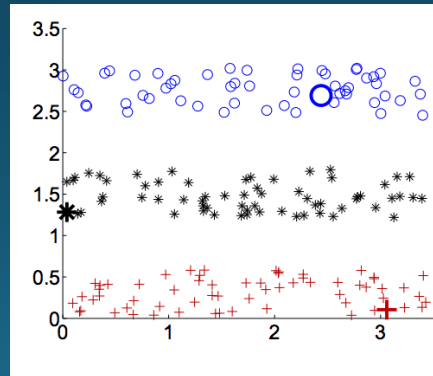
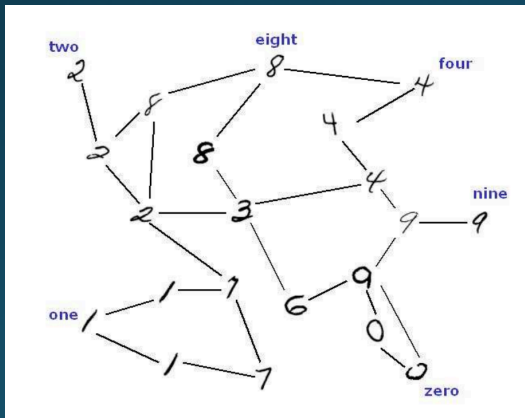
Definition. Given $v_i \in \mathbf{V}^U$, the weighted-vote relational-neighbor classifier (wvRN) estimates $P(x_i|\mathcal{N}_i)$ as the (weighted) mean of the class-membership probabilities of the entities in \mathcal{N}_i :

$$P(x_i = c|\mathcal{N}_i) = \frac{1}{Z} \sum_{v_j \in \mathcal{N}_i} w_{i,j} \cdot P(x_j = c|\mathcal{N}_j),$$

- Does this look familiar?
- **Homophily!**

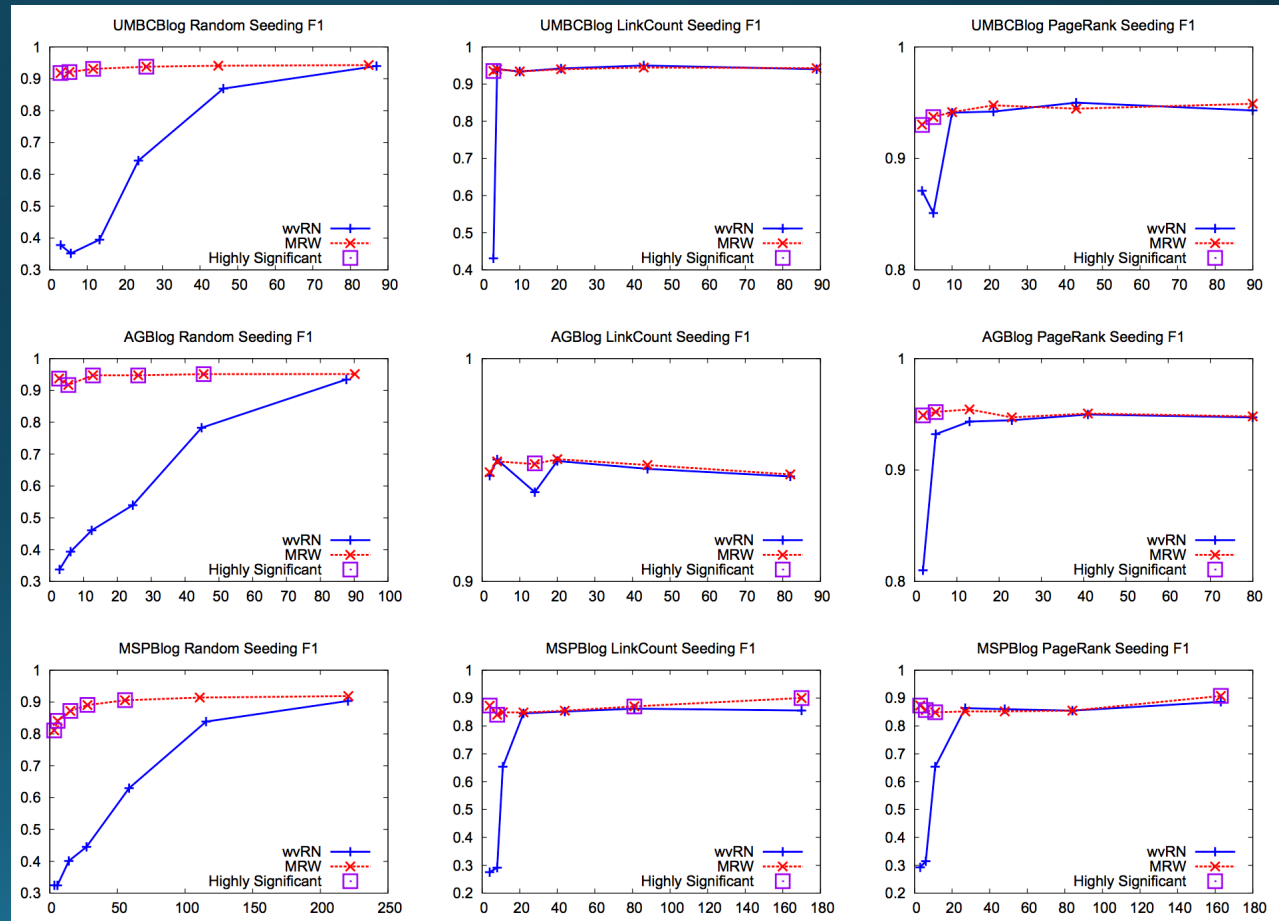
Comparison: HF

- Another definition in [X. Zhu, Z. Ghahramani, and J. Lafferty, ICML 2003]
- A **harmonic field** – the score of each node in the graph is the harmonic, or linearly weighted, average of its neighbors' scores (harmonic field, HF)



MRW versus wvRN

- MRW is easily the method to beat
- wvRN matches MRW **only** when seeding is **not** random
- Still takes a larger number of labeled instances compared to MRW



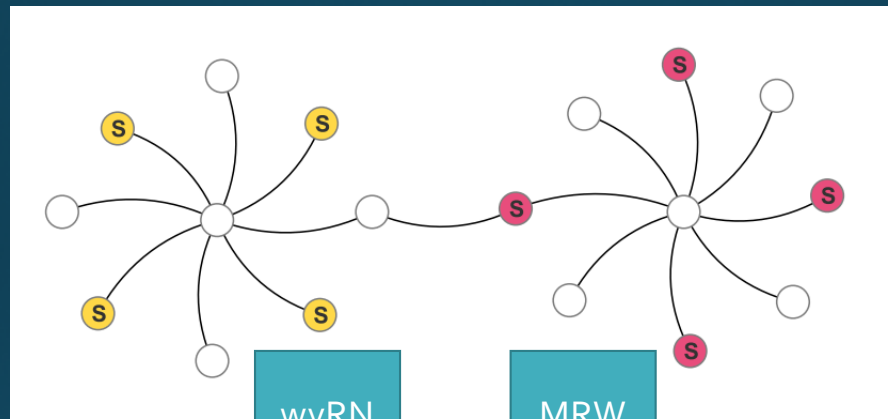
Why is MRW > wvRN?

- Start with wvRN & HF objectives
- Do not account for graph *structure*
 - Or location of seeds
- **Graph-walk methods do not have these constraints**
 - And directly account for graph structure

$$(6.2) \quad P(x_i = c | N_i) = \frac{1}{Z} \sum_{v_j \in N_i} w_{i,j} \cdot P(x_j = c | N_j)$$

$$(6.3) \quad f(j) = \frac{1}{d_j} \sum_{i \sim j} w_{i,j} \cdot f(i)$$

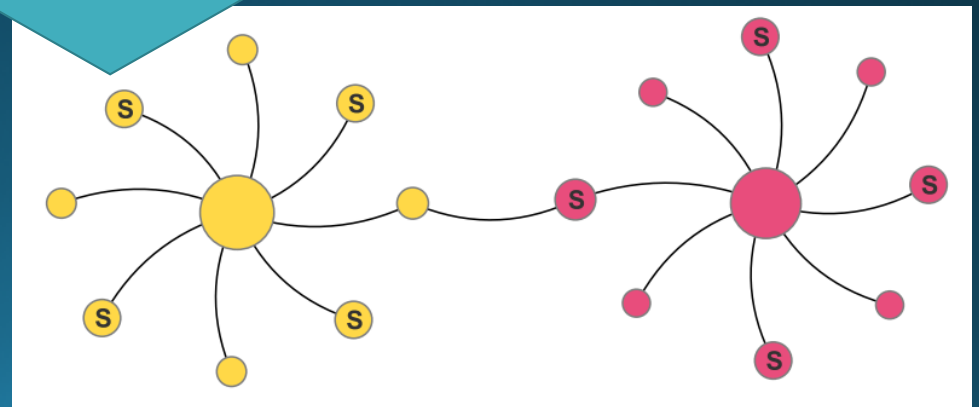
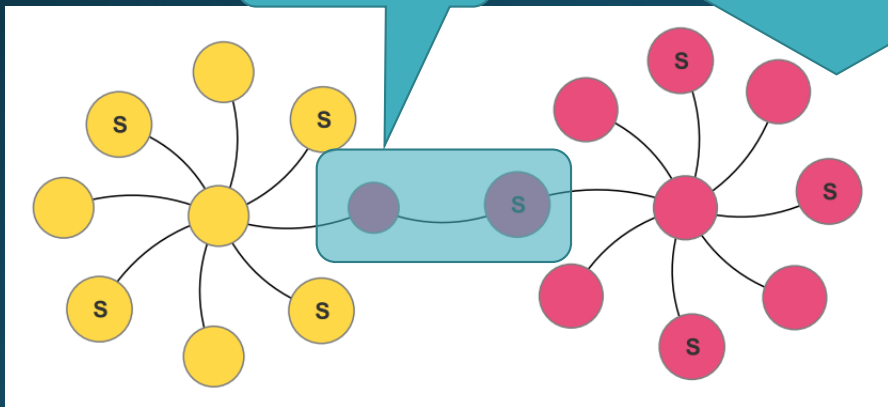
Why is MRW > wvRN?



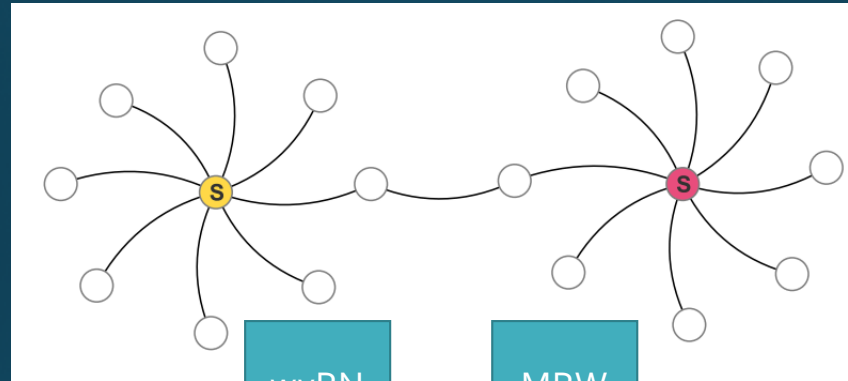
Oops...

wvRN

MRW

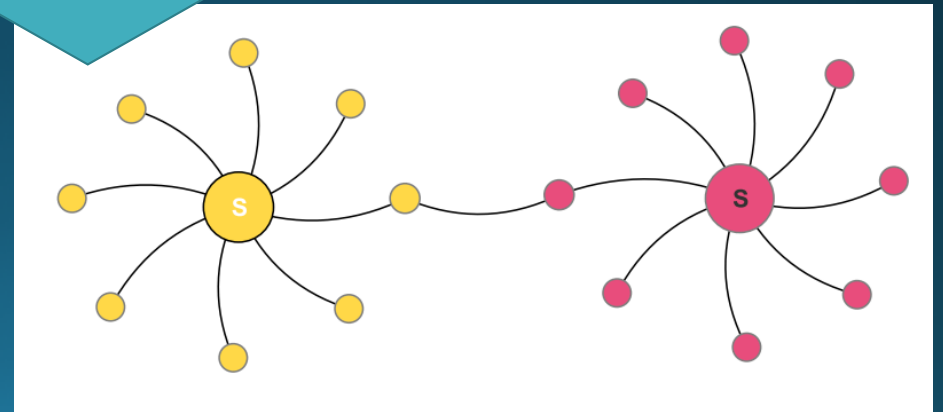
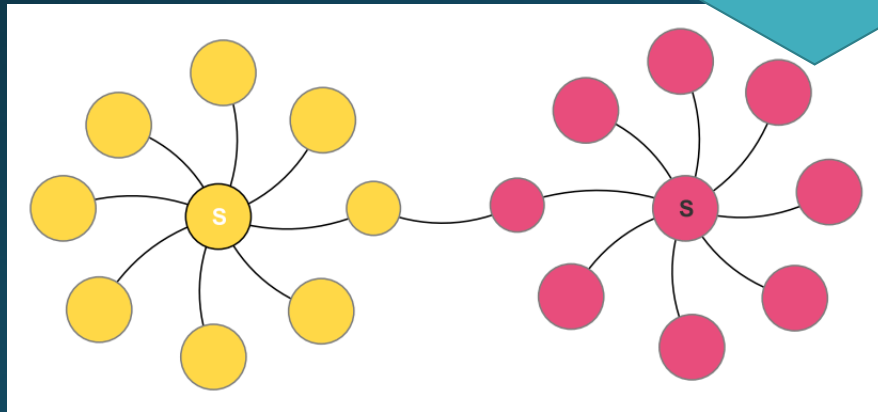


Why is MRW > wvRN?



wvRN

MRW



Notations

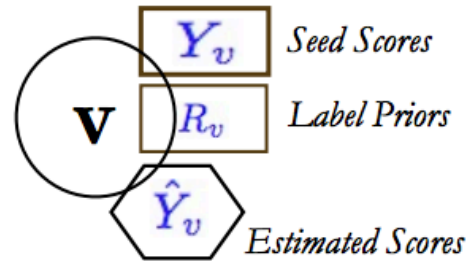
$\hat{Y}_{v,l}$: score of estimated label l on node v

$Y_{v,l}$: score of seed label l on node v

$R_{v,l}$: regularization target for label l on node v

S : seed node indicator (diagonal matrix)

W_{uv} : weight of edge (u, v) in the graph



LP-ZGL (Zhu et al., ICML 2003)

Smooth

$$\arg \min_{\hat{Y}} \sum_{l=1}^m W_{uv} (\hat{Y}_{ul} - \hat{Y}_{vl})^2 = \sum_{l=1}^m \hat{Y}_l^T L \hat{Y}_l$$

Graph Laplacian
 $L = D - W$ (PSD)

such that $Y_{ul} = \hat{Y}_{ul}, \forall S_{uu} = 1$

Match Seeds (hard)

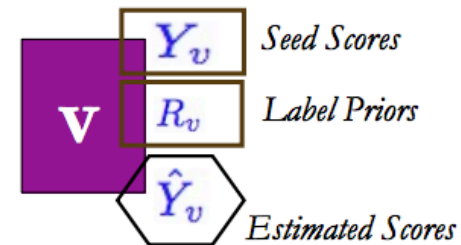
- Smoothness
 - two nodes connected by an edge with high weight should be assigned similar labels
- Solution satisfies harmonic property

Modified Adsorption (MAD)

[Talukdar and Crammer, ECML 2009]

$$\arg \min_{\hat{\mathbf{Y}}} \sum_{l=1}^{m+1} \left[\|\mathbf{S}\hat{\mathbf{Y}}_l - \mathbf{S}\mathbf{Y}_l\|^2 + \mu_1 \sum_{u,v} M_{uv} (\hat{Y}_{ul} - \hat{Y}_{vl})^2 + \mu_2 \|\hat{\mathbf{Y}}_l - \mathbf{R}_l\|^2 \right]$$

- m labels, +1 dummy label
- $\mathbf{M} = \mathbf{W}^\top + \mathbf{W}'$ is the symmetrized weight matrix
- \hat{Y}_{vl} : weight of label l on node v
- Y_{vl} : seed weight for label l on node v
- \mathbf{S} : diagonal matrix, nonzero for seed nodes
- \mathbf{R}_{vl} : regularization target for label l on node v



Modified Adsorption (MAD)

[Talukdar and Crammer, ECML 2009]

$$\arg \min_{\hat{\mathbf{Y}}} \sum_{l=1}^{m+1} \left[\|\mathbf{S}\hat{\mathbf{Y}}_l - \mathbf{S}\mathbf{Y}_l\|^2 + \mu_1 \sum_{u,v} M_{uv} (\hat{\mathbf{Y}}_{ul} - \hat{\mathbf{Y}}_{vl})^2 + \mu_2 \|\hat{\mathbf{Y}}_l - \mathbf{R}_l\|^2 \right]$$

How to do this minimization?

First, differentiate to find min is at

$$(\mu_1 \mathbf{S} + \mu_2 \mathbf{L} + \mu_3 \mathbf{I}) \hat{\mathbf{Y}}_l = (\mu_1 \mathbf{S}\mathbf{Y}_l + \mu_3 \mathbf{R}_l).$$

Jacobi method:

- To solve $Ax=b$ for x

- Iterate:

$$\mathbf{x}^{(k+1)} = D^{-1}(\mathbf{b} - R\mathbf{x}^{(k)}).$$

- ... or:

$$x_i^{(k+1)} = \frac{1}{a_{ii}} \left(b_i - \sum_{j \neq i} a_{ij} x_j^{(k)} \right), \quad i = 1, 2, \dots, n.$$

Inputs $\mathbf{Y}, \mathbf{R} : |V| \times (|L| + 1)$, $\mathbf{W} : |V| \times |V|$, $\mathbf{S} : |V| \times |V|$ diagonal

$\hat{\mathbf{Y}} \leftarrow \mathbf{Y}$

$\mathbf{M} = \mathbf{W}' + \mathbf{W}^\dagger$

$Z_v \leftarrow \mathbf{S}_{vv} + \mu_1 \sum_{u \neq v} \mathbf{M}_{vu} + \mu_2 \quad \forall v \in V$

repeat

 for all $v \in V$ do

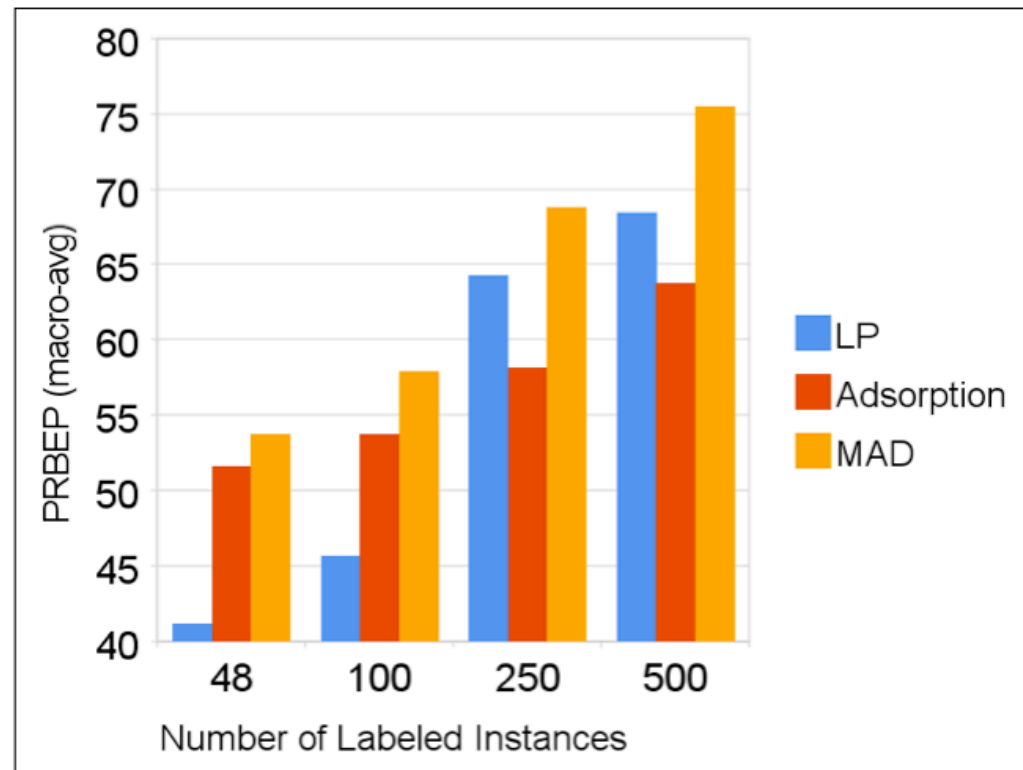
$\hat{\mathbf{Y}}_v \leftarrow \frac{1}{Z_v} \left((\mathbf{S}\mathbf{Y})_v + \mu_1 \mathbf{M}_v \cdot \hat{\mathbf{Y}} + \mu_2 \mathbf{R}_v \right)$

 end for

until convergence

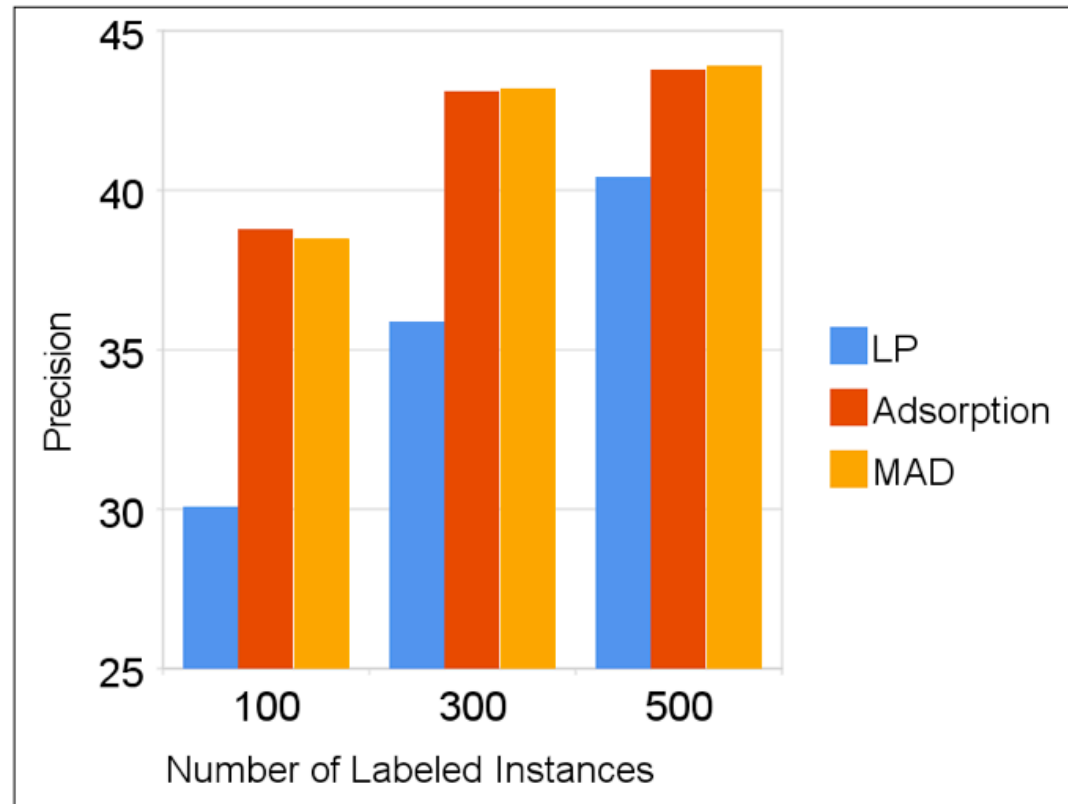
- Extends Adsorption with well-defined optimization
- Importance of a node can be discounted
- Easily Parallelizable: Scalable

Text Classification



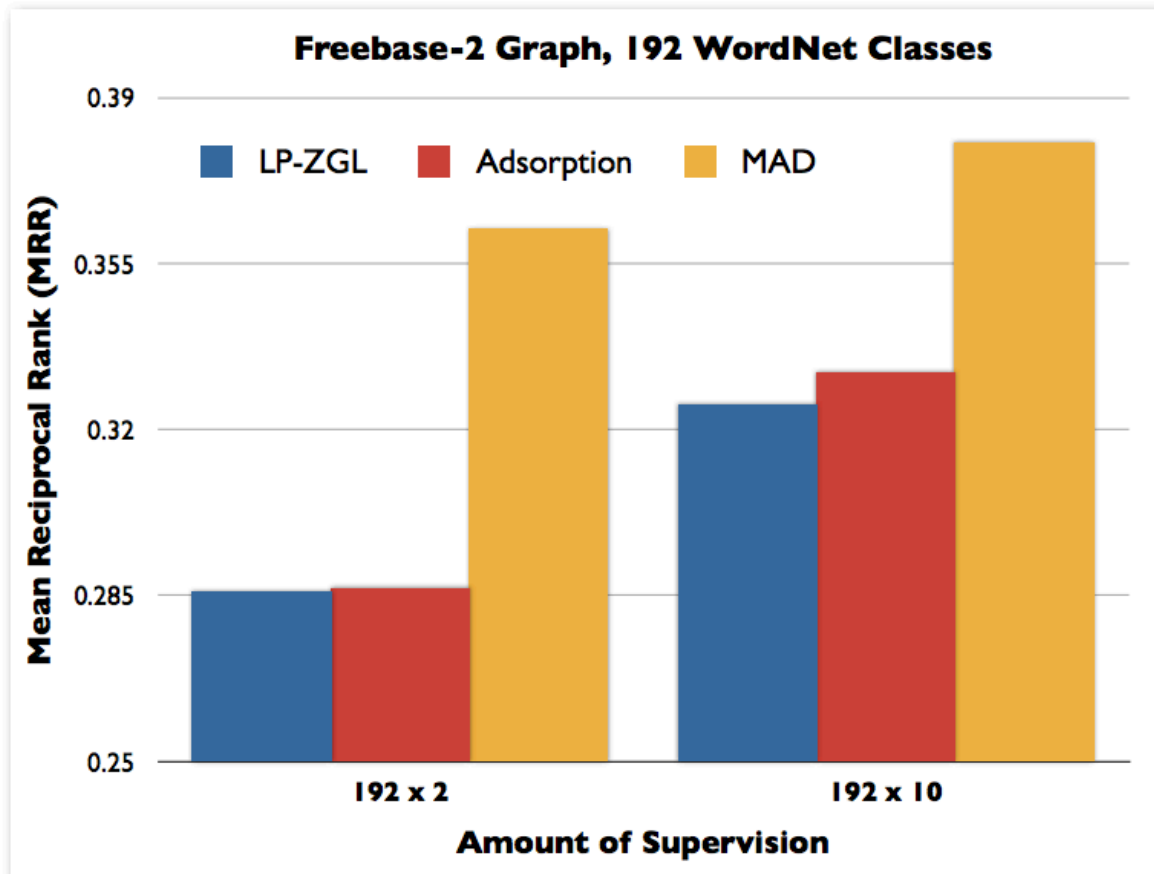
**PRBEP (macro-averaged) on WebKB
Dataset, 3148 test instances**

Sentiment Classification



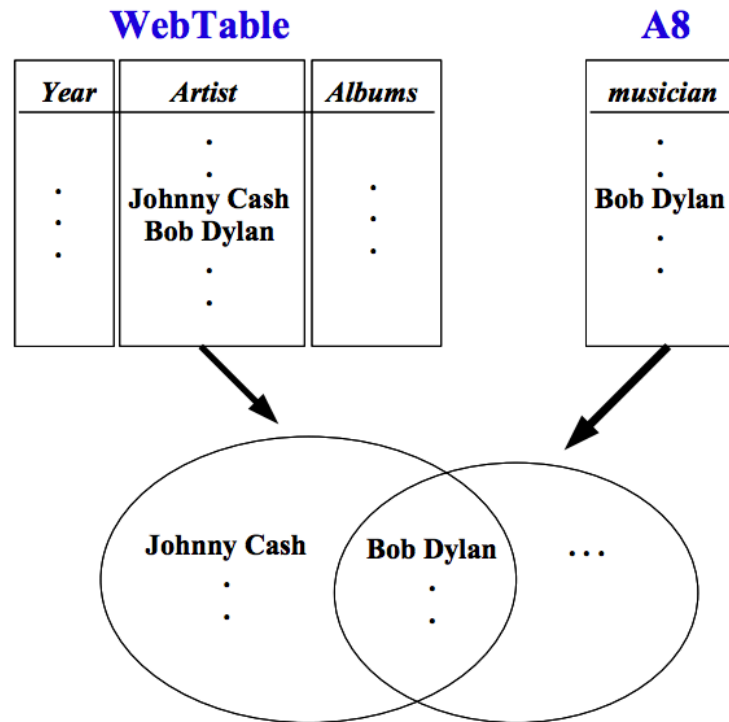
Precision on 3568 Sentiment test instances

Class-Instance Acquisition

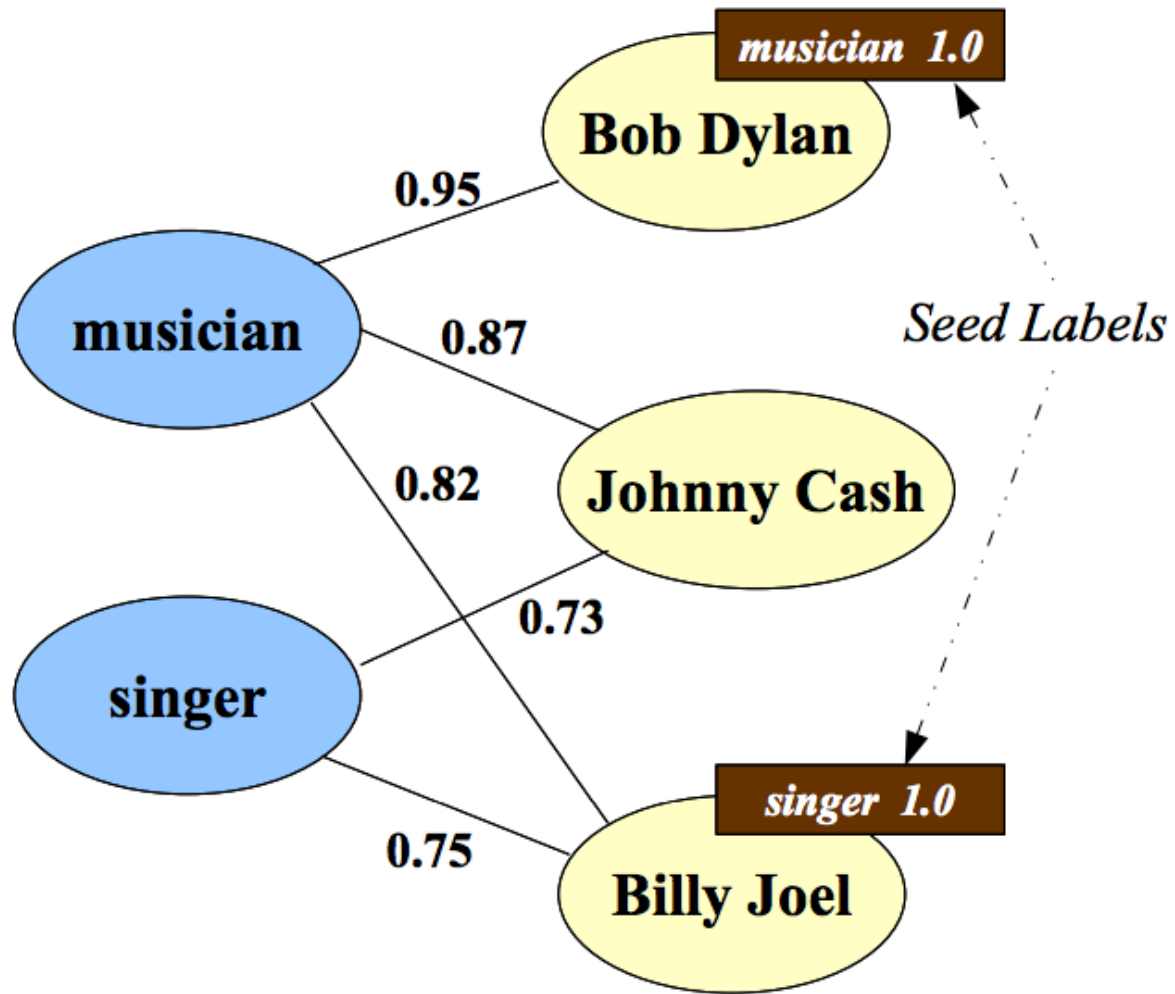


Graph with
303k nodes,
2.3m edges.

ASSIGNING CLASS LABELS TO WEBTABLE INSTANCES



Score (musician, Johnny Cash) = 0.87



New (Class, Instance) Pairs Found

Class	A few non-seed Instances found by Adsorption
Scientific Journals	Journal of Physics, Nature, Structural and Molecular Biology, Sciences Sociales et sante, Kidney and Blood Pressure Research, American Journal of Physiology-Cell Physiology, ...
NFL Players	Tony Gonzales, Thabiti Davis, Taylor Stubblefield, Ron Dixon, Rodney Hannan, ...
Book Publishers	Small Night Shade Books, House of Ansari Press, Highwater Books, Distributed Art Publishers, Cooper Canyon Press, ...

17

Total classes: **9081**

Modern SSL

- Graph Laplacians
 - Enforces graph structure
 - Imposes smoothness on labels
- Graph embeddings
 - “Embedding” ~ “context”
- Transductive -> Inductive
 - Transductive: learns the unlabeled data from the labeled data + structure
 - Inductive: generalizes to completely unobserved data

Graph Laplacians

- Reformulate SSL objective as two distinct terms:

$$f^T L f = \frac{1}{2} \sum_{i,j} W_{ij} (f(i) - f(j))^2$$

Weighted sum of supervised loss over *labeled* instances

$$J(f) = f^T L f + \sum_{i=1}^l \lambda (f(i) - y_i)^2 = f^T L f + (f - y)^T \Lambda (f - y)$$

Graph Laplacian regularization term

Graph Embeddings

- Remember word embeddings with word2vec?

- **Context!**

- Estimate "context" of each node with a random walk over neighborhood of a fixed window size
- Skipgram-based model, DeepWalk

$$-\sum_{(i,c)} \log p(c|i) = -\sum_{(i,c)} \left(\mathbf{w}_c^T \mathbf{e}_i - \log \sum_{c' \in \mathcal{C}} \exp(\mathbf{w}_{c'}^T \mathbf{e}_i) \right)$$

- \mathcal{C} is set of all possible context
- w 's are parameters of Skipgram
- e_i is embedding of node i

Inductive SSL

- You start with X^l (labeled) and X^u (unlabeled), hoping their combination will result in a superior model
- Semi-supervised learning yields predictions on X^u
 - Transductive learning
- What if a *completely unobserved* data point shows up?
 - Inductive learning—a concept often left out in SSL literature
- **Convert your SSL framework to classification!**

Transductive learning (note embeddings)

$$p(y|\mathbf{x}, \mathbf{e}) = \frac{\exp[\mathbf{h}^k(\mathbf{x})^T, \mathbf{h}^l(\mathbf{e})^T] \mathbf{w}_y}{\sum_{y'} \exp[\mathbf{h}^k(\mathbf{x})^T, \mathbf{h}^l(\mathbf{e})^T] \mathbf{w}_{y'}}$$

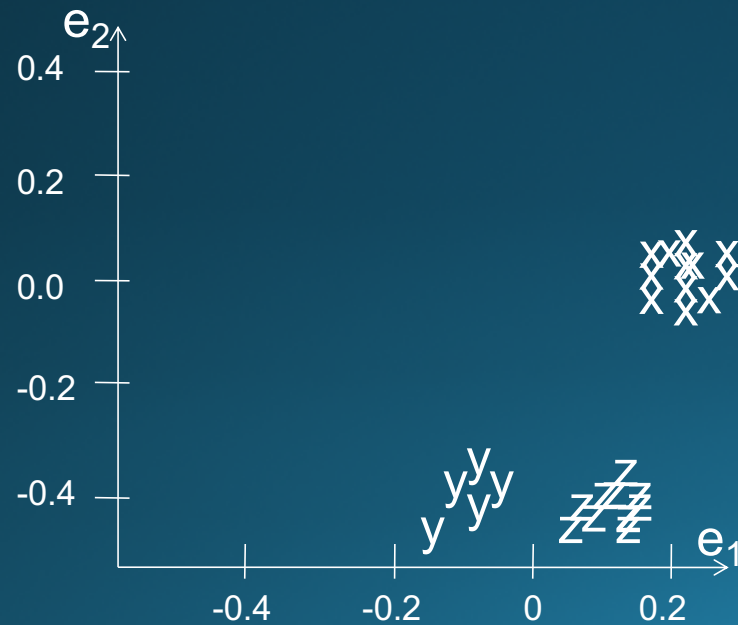
Inductive learning (dependent only on \mathbf{x})

$$p(y|\mathbf{x}) = \frac{\exp[\mathbf{h}^k(\mathbf{x})^T, \mathbf{h}^l(\mathbf{x})^T] \mathbf{w}_y}{\sum_{y'} \exp[\mathbf{h}^k(\mathbf{x})^T, \mathbf{h}^l(\mathbf{x})^T] \mathbf{w}_{y'}}$$

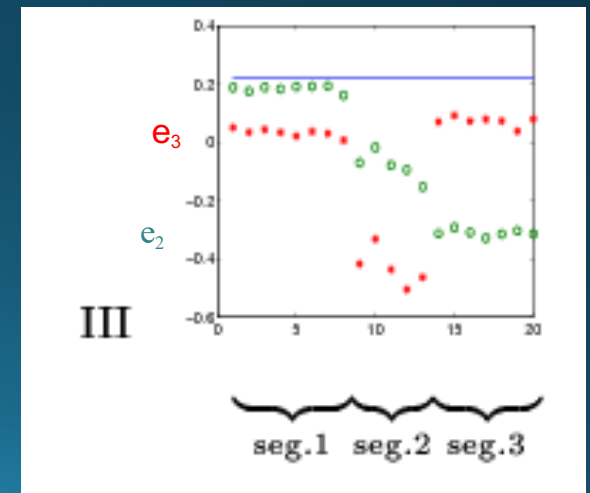
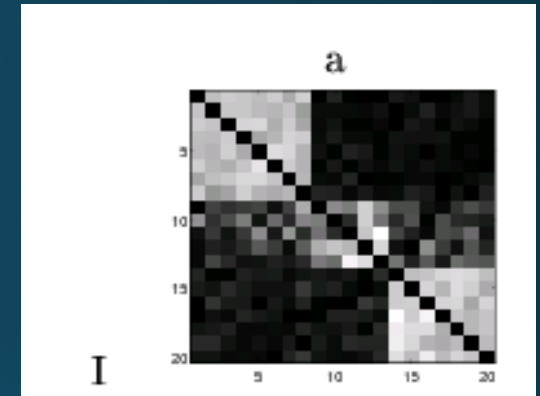
Quick digression to unsupervised learning...

Spectral Clustering

- Graph = Matrix
 - $W \cdot v_1 = v_2$ "propogates weights from neighbors"



[Shi & Meila, 2002]

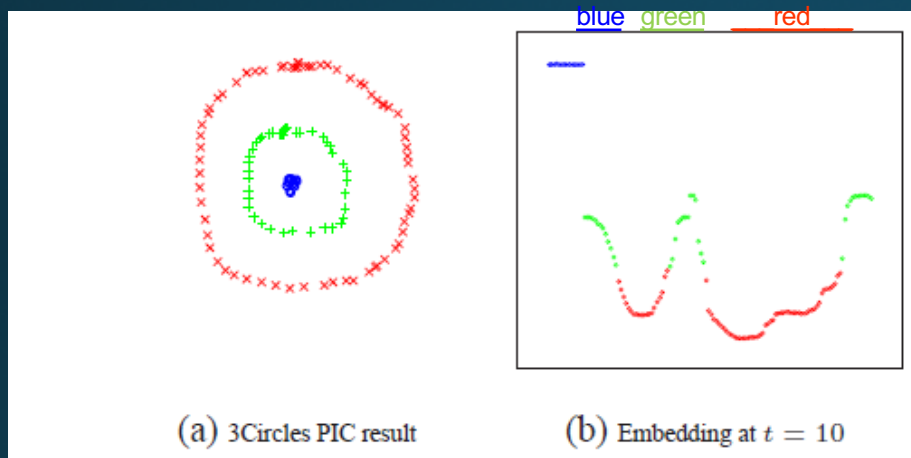


Repeated averaging with neighbors as a clustering method

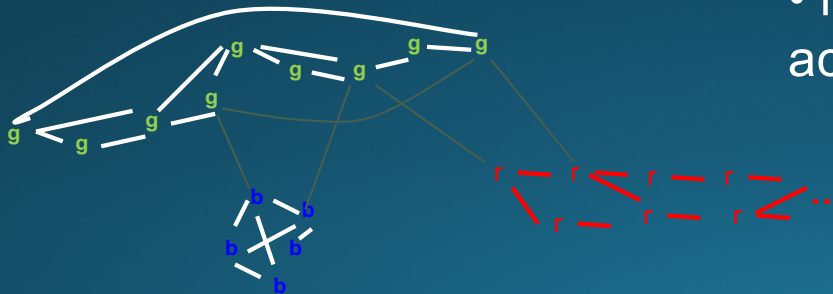
- Pick a vector v^0 (maybe at random)
- Compute $v^1 = Wv^0$
 - i.e., replace $v^0[x]$ with *weighted average* of $v^0[y]$ for the neighbors y of x
- Plot $v^1[x]$ for each x
- Repeat for v^2, v^3, \dots

- Variants widely used for *semi-supervised* learning
 - clamping of labels for nodes with known labels
- Without clamping, will converge to constant v^t
- What are the *dynamics* of this process?

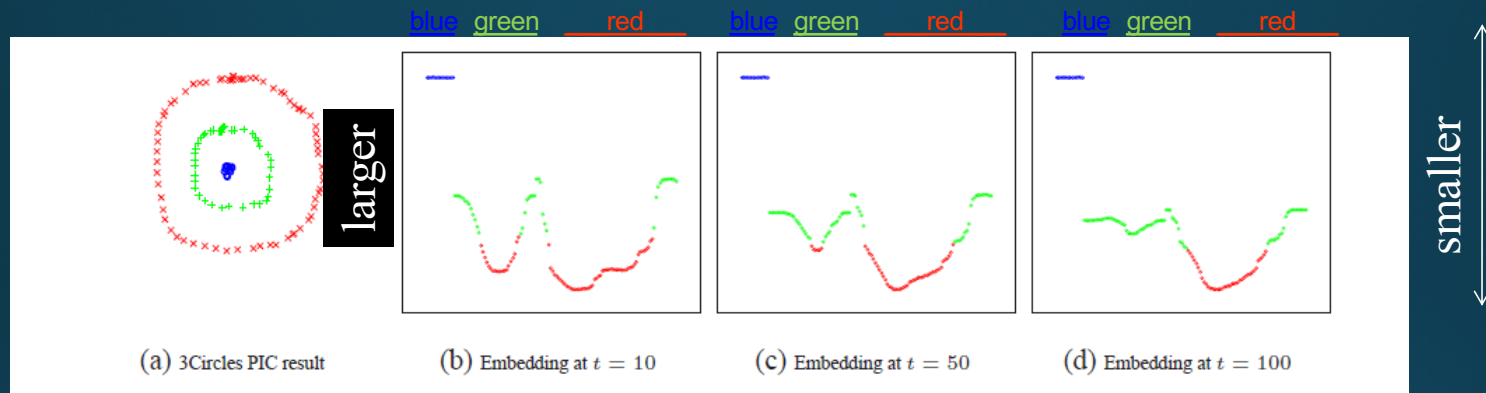
Repeated averaging with neighbors on a sample problem...



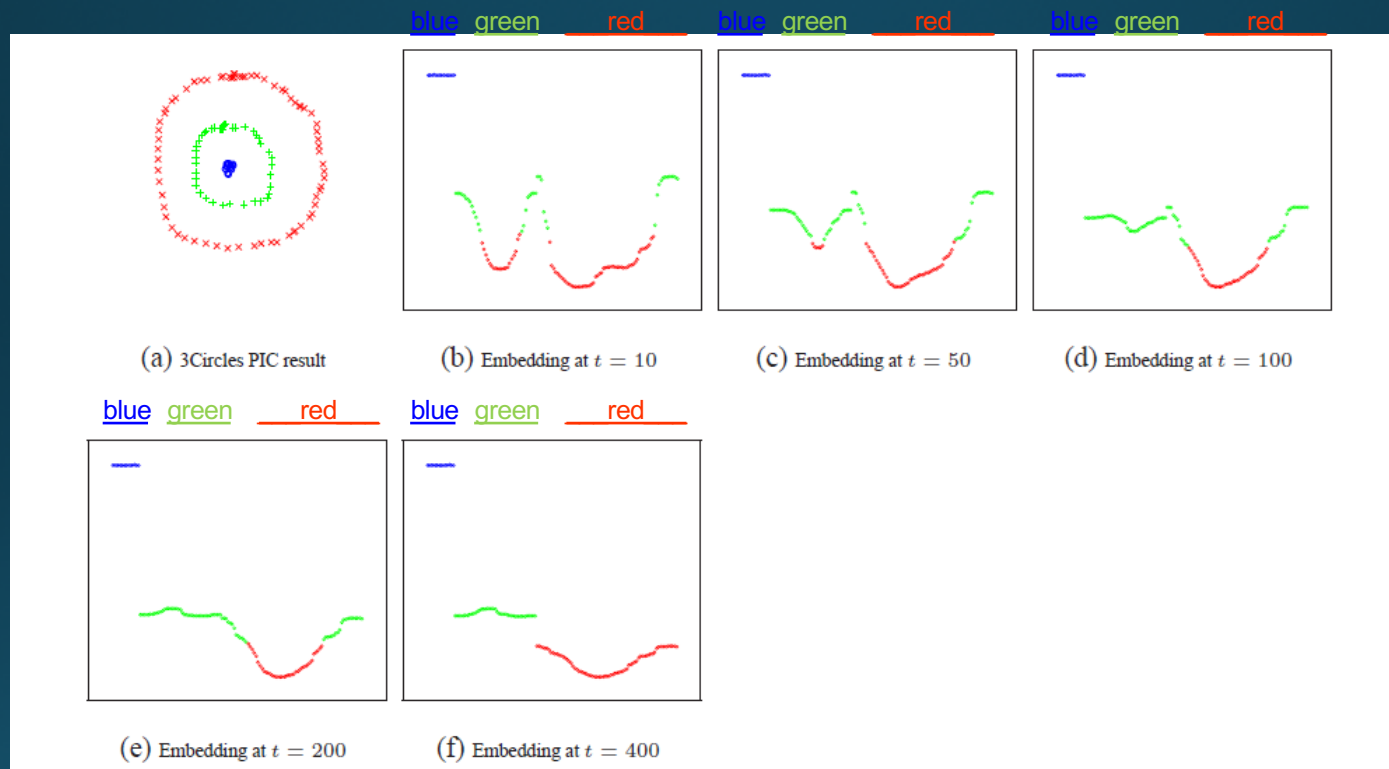
- Create a graph, connecting all points in the 2-D initial space to all other points
 - Weighted by distance
- Run power iteration for 10 steps
- Plot node id x vs $v^{10}(x)$
 - nodes are ordered by actual cluster number



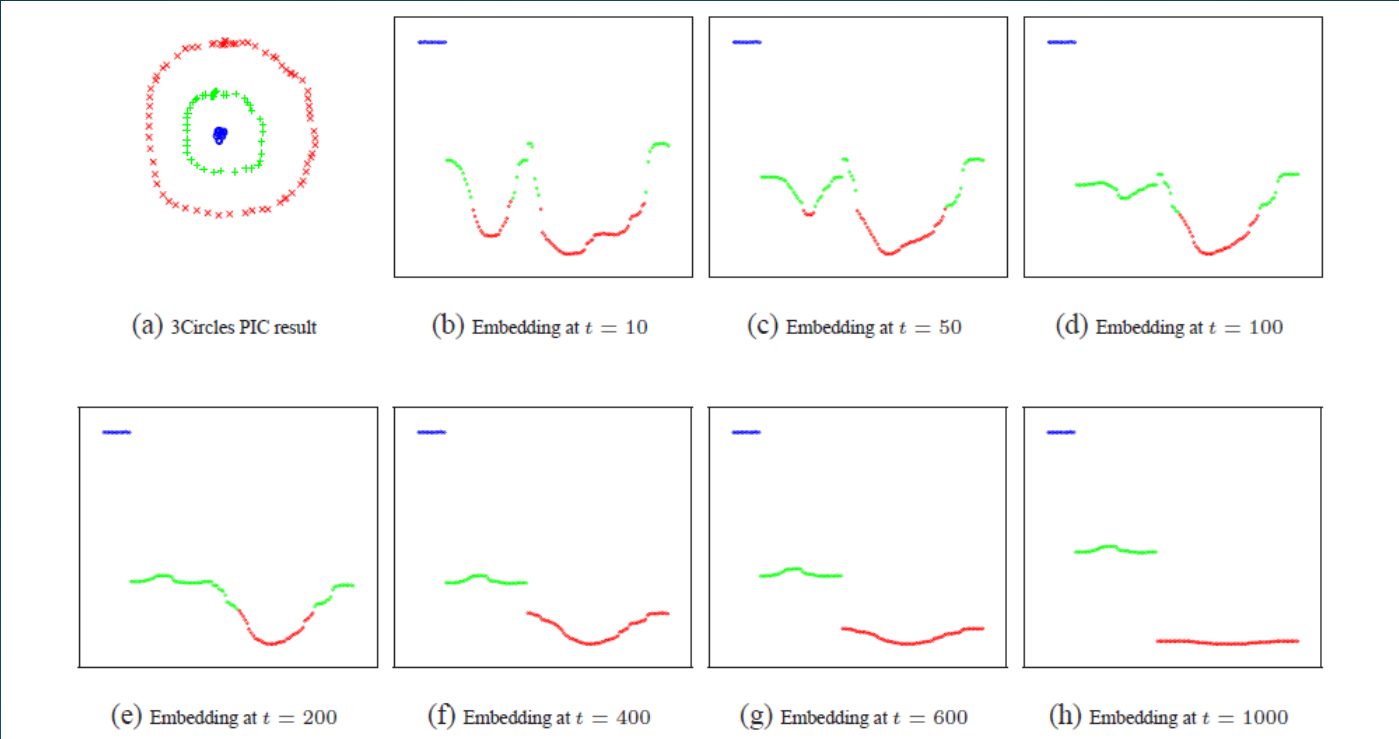
Repeated averaging with neighbors on a sample problem...



Repeated averaging with neighbors on a sample problem...



Repeated averaging with neighbors on a sample problem...



very small

PIC: Power Iteration Clustering

- Run power iteration (repeated averaging w/ neighbors) with early stopping

1. Pick an initial vector \mathbf{v}^0 .
2. Set $\mathbf{v}^{t+1} \leftarrow \frac{W\mathbf{v}^t}{\|W\mathbf{v}^t\|_1}$ and $\delta^{t+1} \leftarrow |\mathbf{v}^{t+1} - \mathbf{v}^t|$.
3. Increment t and repeat above step until $|\delta^t - \delta^{t-1}| \simeq 0$.
4. Use k -means to cluster points on \mathbf{v}^t and return clusters C_1, C_2, \dots, C_k .

- \mathbf{v}^0 : random start, or “degree matrix” D , or others
- Easy to implement, and relatively efficient (& easily parallelized!)
- Empirically, often **better** than traditional spectral methods
 - Surprising given embedded space is 1-dimensional!

References

- “Semi-Supervised Classification of Network Data Using Very Few Labels”,
<https://lti.cs.cmu.edu/sites/default/files/research/reports/2009/cmultiog017.pdf>
- “New Regularized Algorithms for Transductive Learning”,
<http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.220.42&rep=rep1&type=pdf>
- “Semi-supervised Learning in Gigantic Image Collections”,
<http://papers.nips.cc/paper/3633-semi-supervised-learning-in-gigantic-image-collections.pdf>
- “Revisiting Semi-Supervised Learning with Graph Embeddings”,
<http://proceedings.mlr.press/v48/yanga16.pdf>