CPSC 340: Machine Learning and Data Mining

Multi-Dimensional Scaling

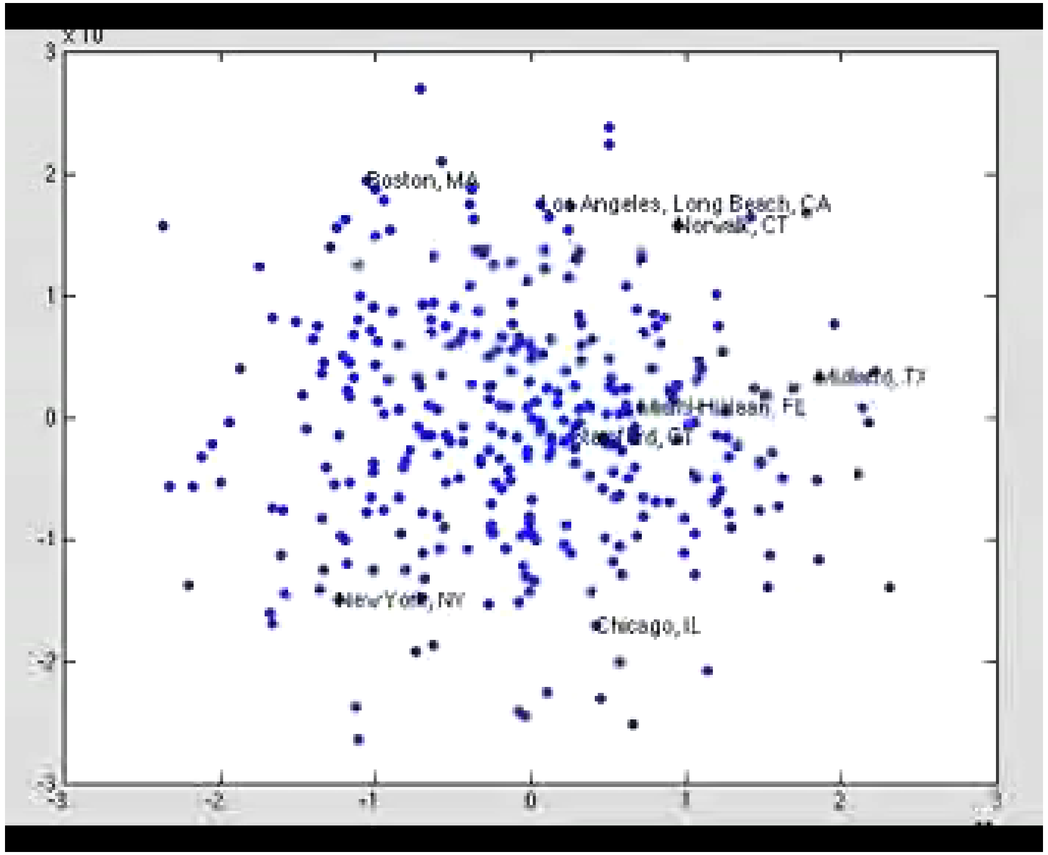
Summer 2021

Admin

- Assignment 6 out, due Friday 11:55pm
- Today is final exam coverage cut-off
- Final exam is next Wednesday (June 23)
  - Prep materials go up soon

- Course evaluation is open.
  - Please give me an honest feedback! How did I do?

Last Time: Multi-Dimensional Scaling

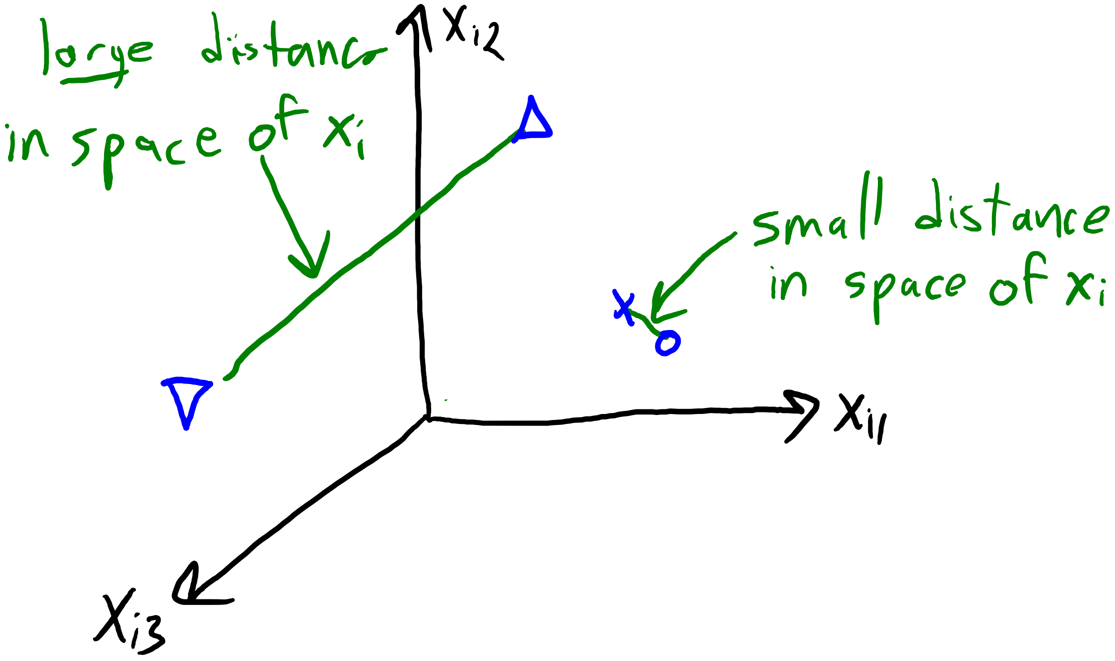


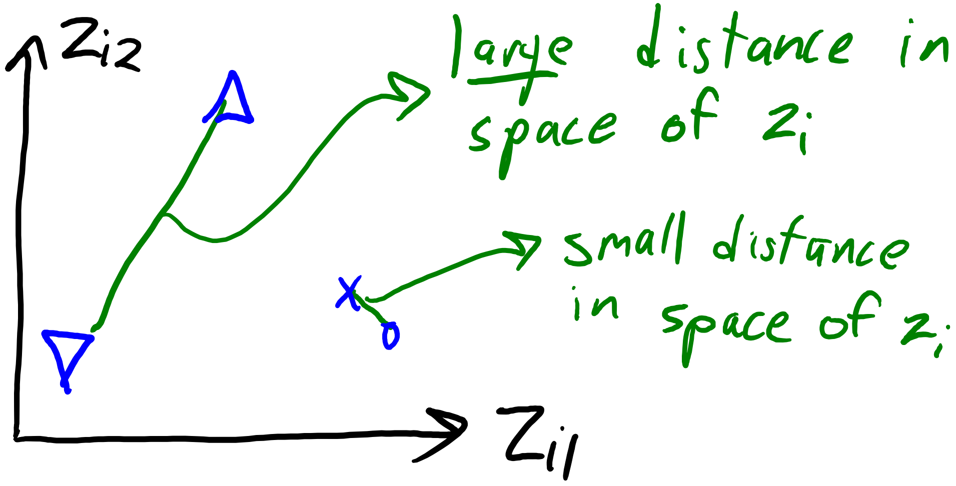
$$f(Z) = \underbrace{\sum_{i=1}^{n}\sum_{j=i+1}^{n}}_{\text{sum over pairs of examples}} \Big(\overbrace{\underbrace{\|z_i - z_j\|}_{\text{distance in scatterplot}} - \underbrace{\|x_i - x_j\|}_{\text{Distance between points in original 'd' dimensions}}}^{\text{"Try to make scatterplot distances match high-dimensional distance"}}\Big)^2$$

Multi-Dimensional Scaling

- Multi-dimensional scaling (MDS):
  - Optimize the final locations of the z_i values.

$$f(Z) = \sum_{i=1}^{n} \sum_{j=i+1}^{n} \left(\|z_i - z_j\| - \|x_i - x_j\| \right)^2$$


large distance in space of x_i
x_{i2}
small distance in space of x_i
x_{i1}
x_{i3}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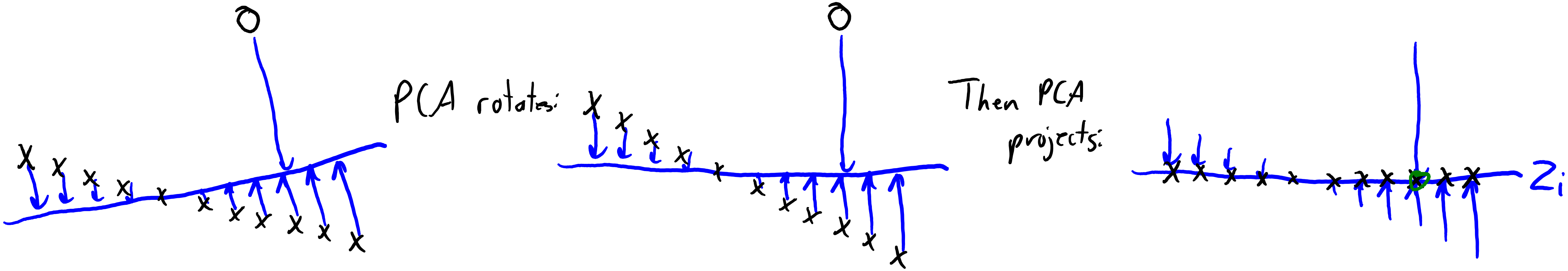
  - Non-parametric dimensionality reduction and visualization:
    - No ‘W’: just trying to make z_i preserve high-dimensional distances between x_i.



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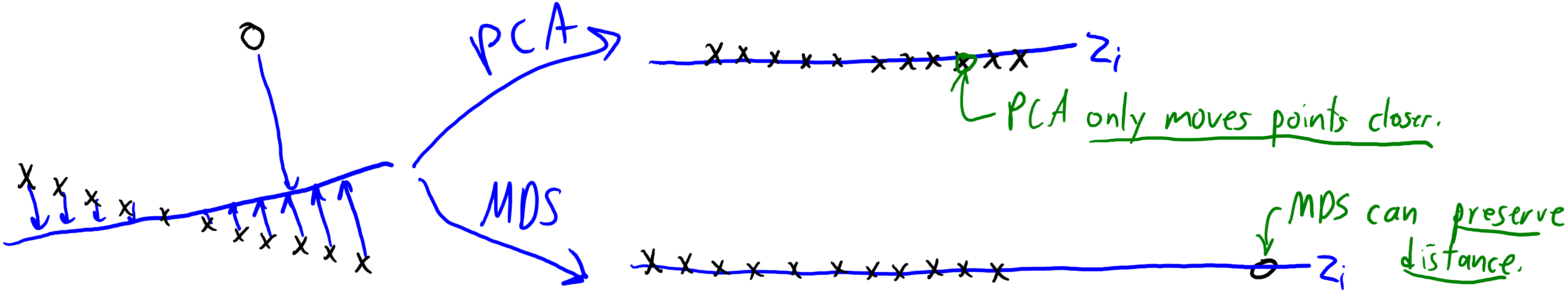

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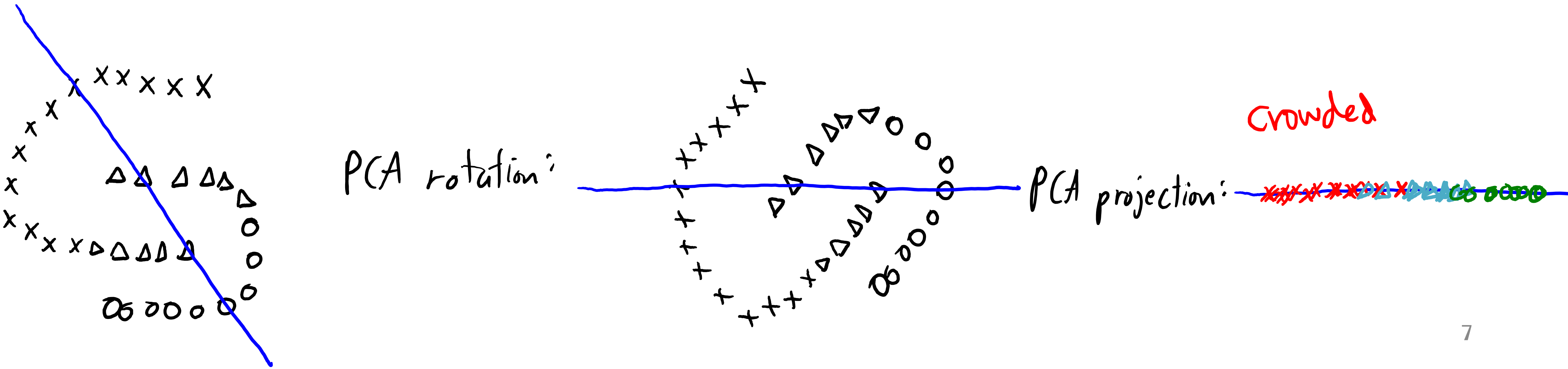

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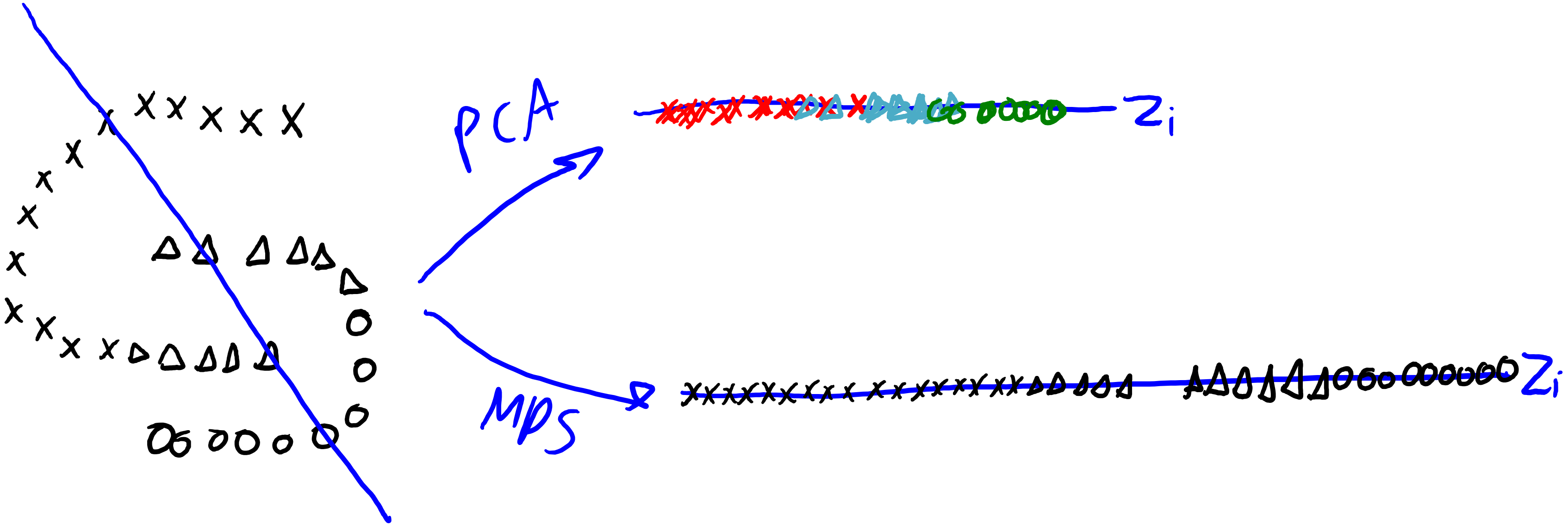

Multi-Dimensional Scaling

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$$f(Z) = \sum_{i=1}^{n} \sum_{j=i+1}^{n} (\|z_i - z_j\| - \|x_i - x_j\|)^2$$

- Cannot use SVD to compute solution:
  - Instead, do gradient descent on the z_i values.
  - You "learn" a scatterplot that tries to visualize high-dimensional data.
  - Not convex and sensitive to initialization.
    - And solution is not unique due to various factors like translation and rotation.

In This Lecture

1. Multi-Dimensional Scaling
   - Euclidean MDS
   - Sammon Mapping
   - Geodesic MDS (ISOMAP)

2. Latent Factors for Language (Bonus)

Coming Up Next

EUCLIDEAN MDS VARIANTS

Different MDS Cost Functions

- MDS default objective: squared difference of Euclidean norms:

$$f(Z)=\sum_{i=1}^{n}\sum_{j=i+1}^{n}\Big(\overbrace{\underbrace{\|z_i-z_j\|}_{d_2}-\underbrace{\|x_i-x_j\|}_{d_1}}^{d_3}\Big)^2$$

Q: How many distance functions are involved here?

Q: Can we generalize this to other measures of distance?

Different MDS Cost Functions

- MDS default objective function with general distances/similarities:

$$f(Z) = \sum_{i=1}^{n} \sum_{j=i+1}^{n} d_3(d_2(z_i, z_j) - d_1(x_i, x_j))$$

  - Functions are not necessarily the same:
    - d_1 := high-dimensional distance we want to match.

$$d_1 : \mathbb{R}^d \times \mathbb{R}^d \longrightarrow \mathbb{R}$$

    - d_2 := low-dimensional distance we can control.

$$d_2 : \mathbb{R}^2 \times \mathbb{R}^2 \longrightarrow \mathbb{R}$$

    - d_3 := how we compare high-/low-dimensional distances.

$$d_3 : \mathbb{R} \times \mathbb{R} \longrightarrow \mathbb{R}$$

Different MDS Cost Functions

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$$f(Z) = \sum_{i=1}^{n} \sum_{j=i+1}^{n} d_3(d_2(z_i, z_j) - d_1(x_i, x_j))$$

- “Classic” MDS:
  - $d_1(x_i,x_j) = x_i^T x_j$, $d_2(z_i,z_j) = z_i^T z_j$, $d_3(a, b) = (a - b)^2$
  - This is a factorless version of PCA.
  - Not a great choice because it’s linear model.

Different MDS Cost Functions

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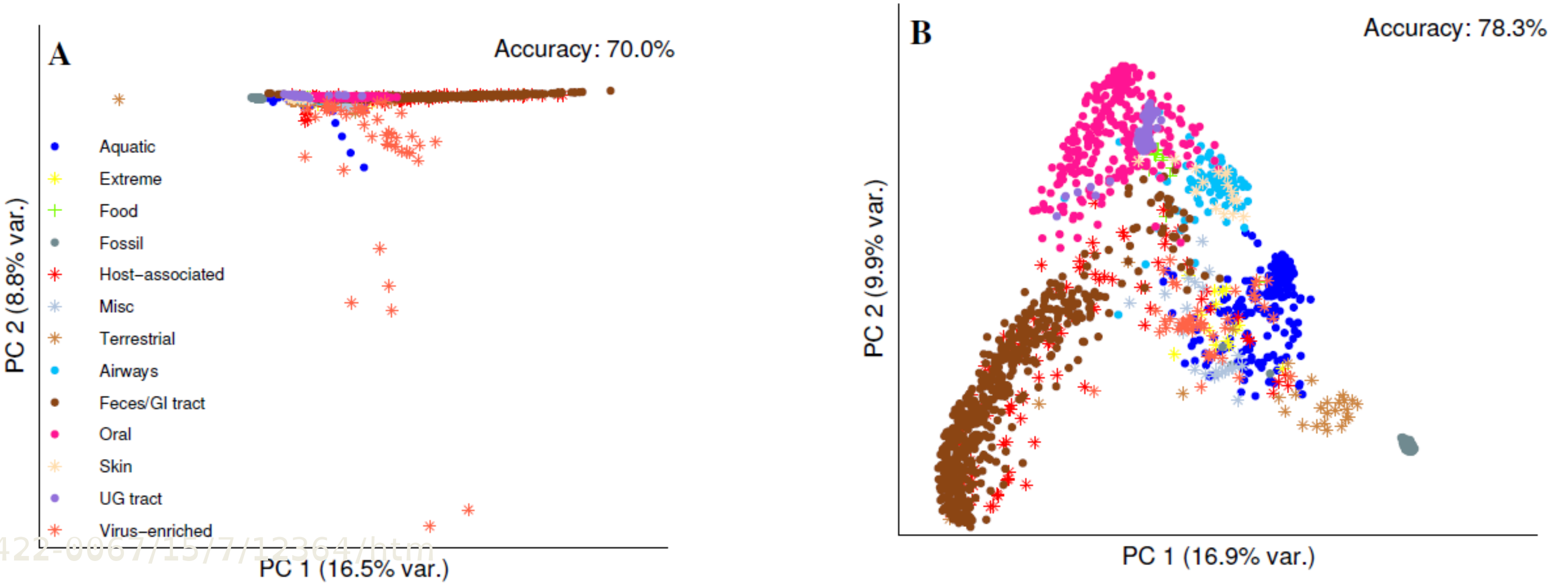
$$f(Z) = \sum_{i=1}^{n} \sum_{j=i+1}^{n} d_3(d_2(z_i, z_j) - d_1(x_i, x_j))$$

d_3: L2-norm.

d_1 is large → d_3 is large

⇒ reduce d_3 by increasing d_2.

- Another possibility: $d_1(x_i,x_j) = ||x_i - x_j||_1$ and $d_2(z_i,z_j) = ||z_i - z_j||$.
  - z_i approximates high-dimensional L_1-norm distances.



http://www.mdpi.com/1422-0067/15/7/12364/htm

Sammon’s Mapping

- Challenge for most MDS models: they focus on large distances.
  - Leads to “crowding” effect like with PCA.
- Early attempt to address this is Sammon’s mapping:
  - Weighted MDS so large/small distances are more comparable.

$$f(Z) = \sum_{i=1}^{n} \sum_{j=i+1}^{n} \left(\frac{d_2(z_i, z_j) - d_1(x_i, x_j)}{d_1(x_i, x_j)} \right)^2$$

  - Denominator reduces focus on large distances.

http://www.mdpi.com/1422-0067/15/7/12364/htm

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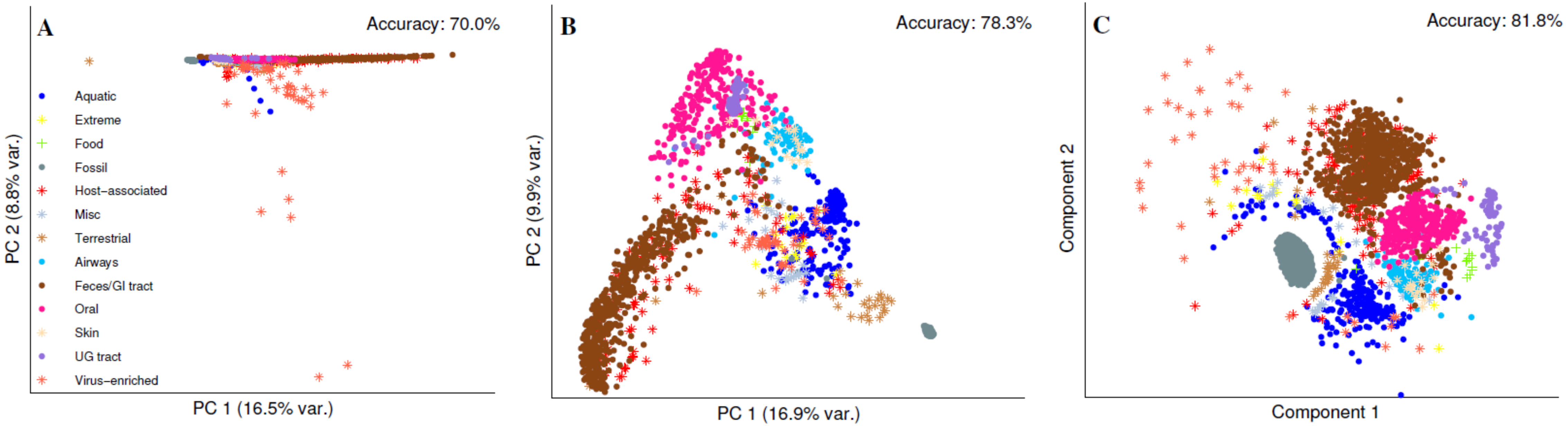

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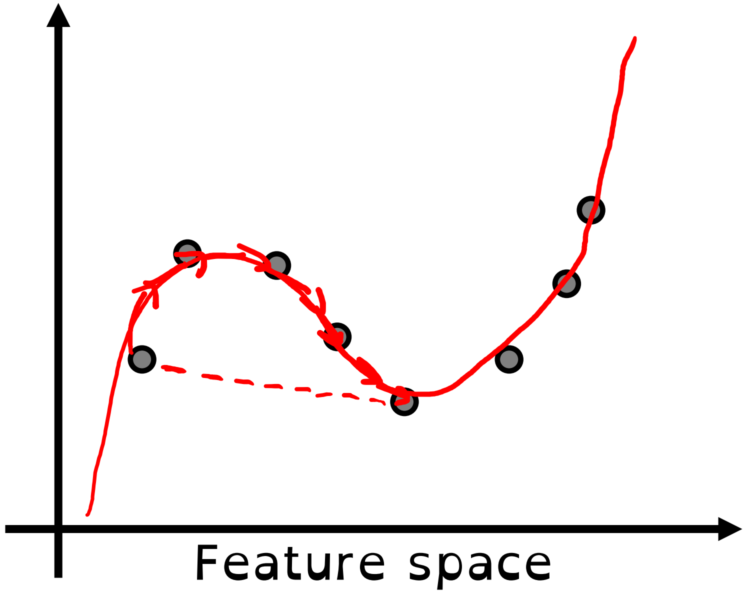
Coming Up Next

MANIFOLDS

“Manifold”

- “Manifold” := non-Euclidean subspace of feature space where datapoints live

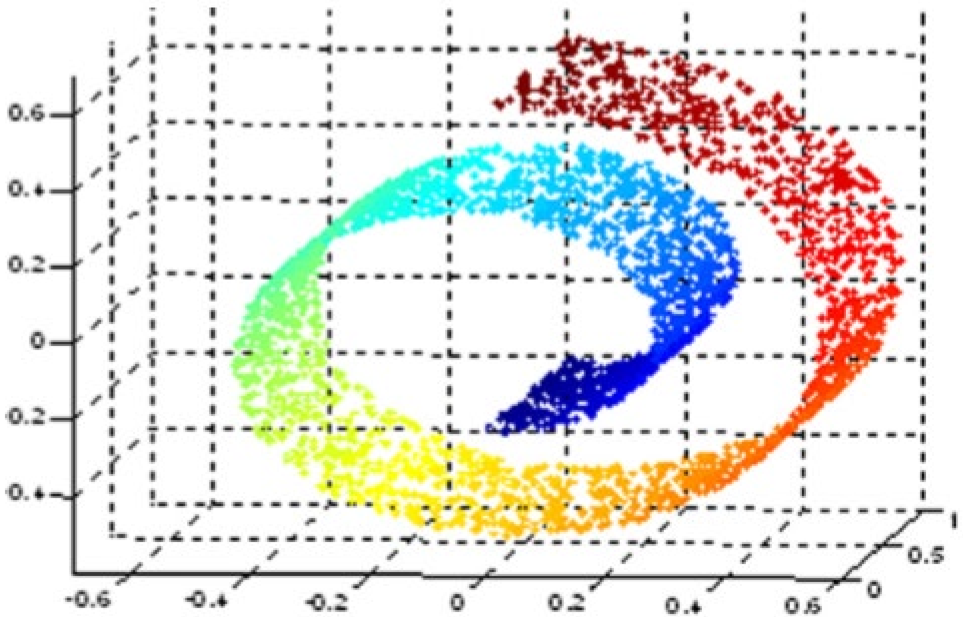


- Assumption: most data live on a manifold, not a true Euclidean feature space!

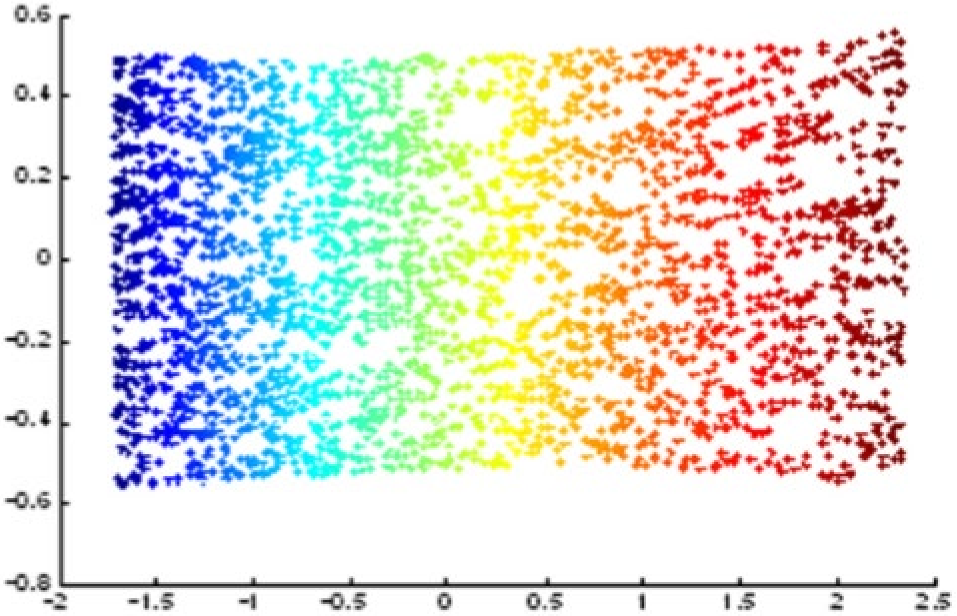
Learning Manifolds

- Consider data that lives on a low-dimensional “manifold”.
- e.g. ‘Swiss roll’:

Original data



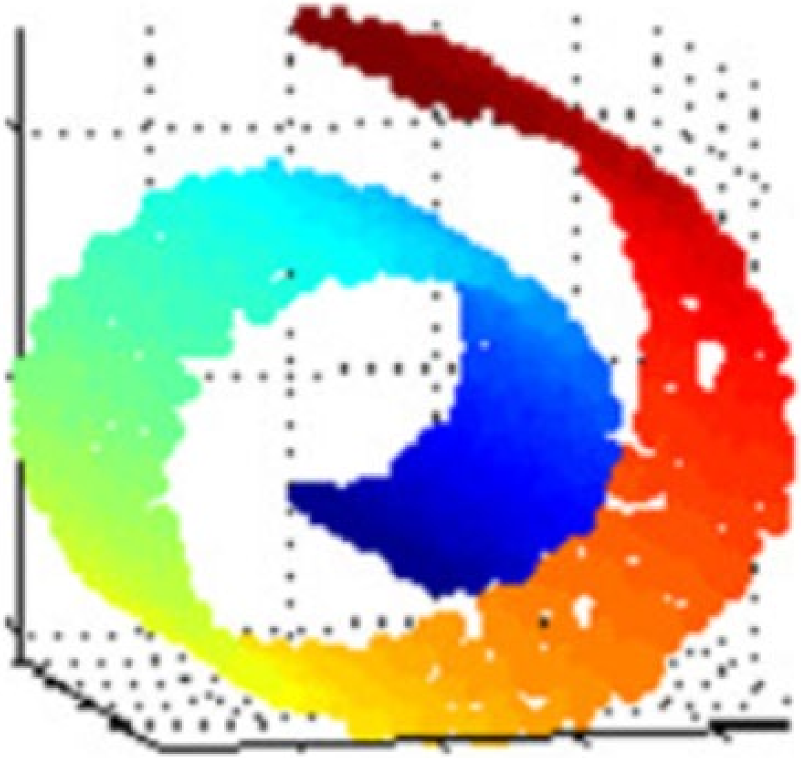
Two-dimensional manifold



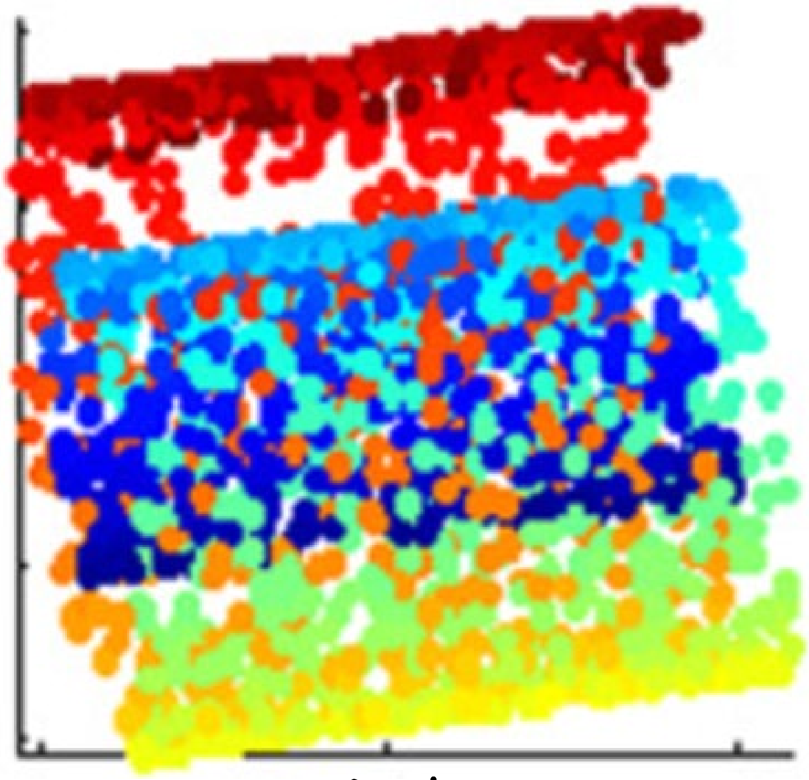
http://www.biomedcentral.com/content/pdf/1471-2105-13-S7-S3.pdf

Learning Manifolds

- Consider data that lives on a low-dimensional “manifold”.
  - With usual distances, PCA/MDS will not discover non-linear manifolds.



Original data

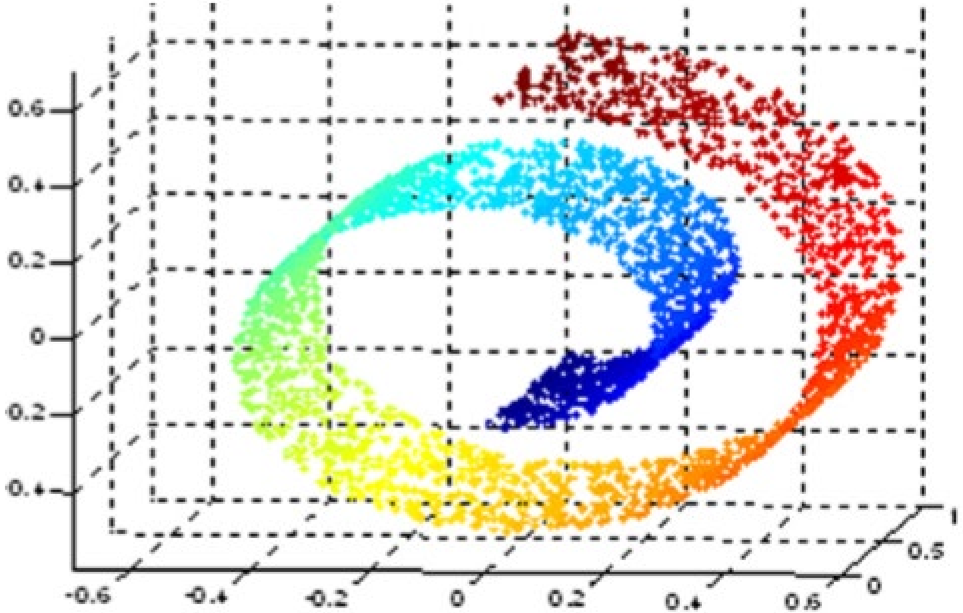


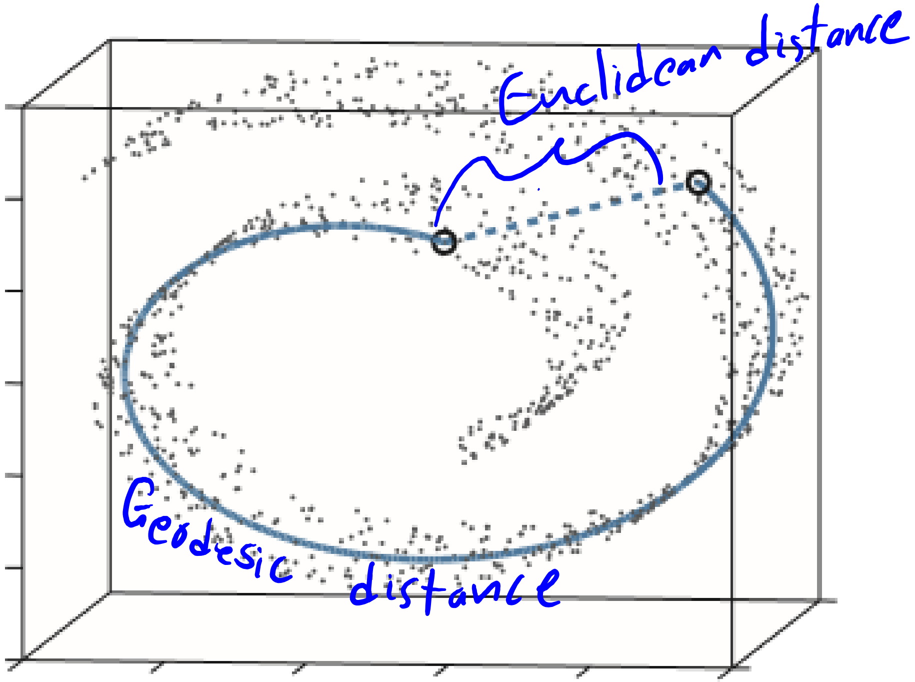
PCA

http://www.peh-med.com/content/9/1/12/figure/F1

Learning Manifolds

- Consider data that lives on a low-dimensional "manifold".
  - With usual distances, PCA/MDS will not discover non-linear manifolds.
- We need geodesic distance: the distance through the manifold.





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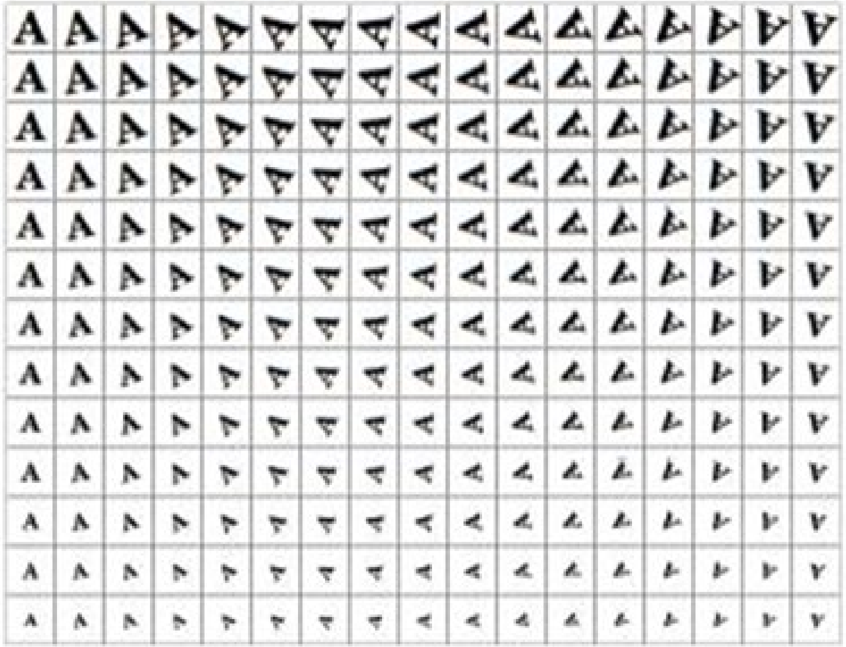
http://wearables.cc.gatech.edu/paper_of_week/isomap.pdf

Manifolds in Image Space

- Consider slowly-varying transformation of image:



- Images are on a manifold in the high-dimensional space.
  - Euclidean distance doesn’t reflect manifold structure.
  - Geodesic distance is distance through space of rotations/resizings.

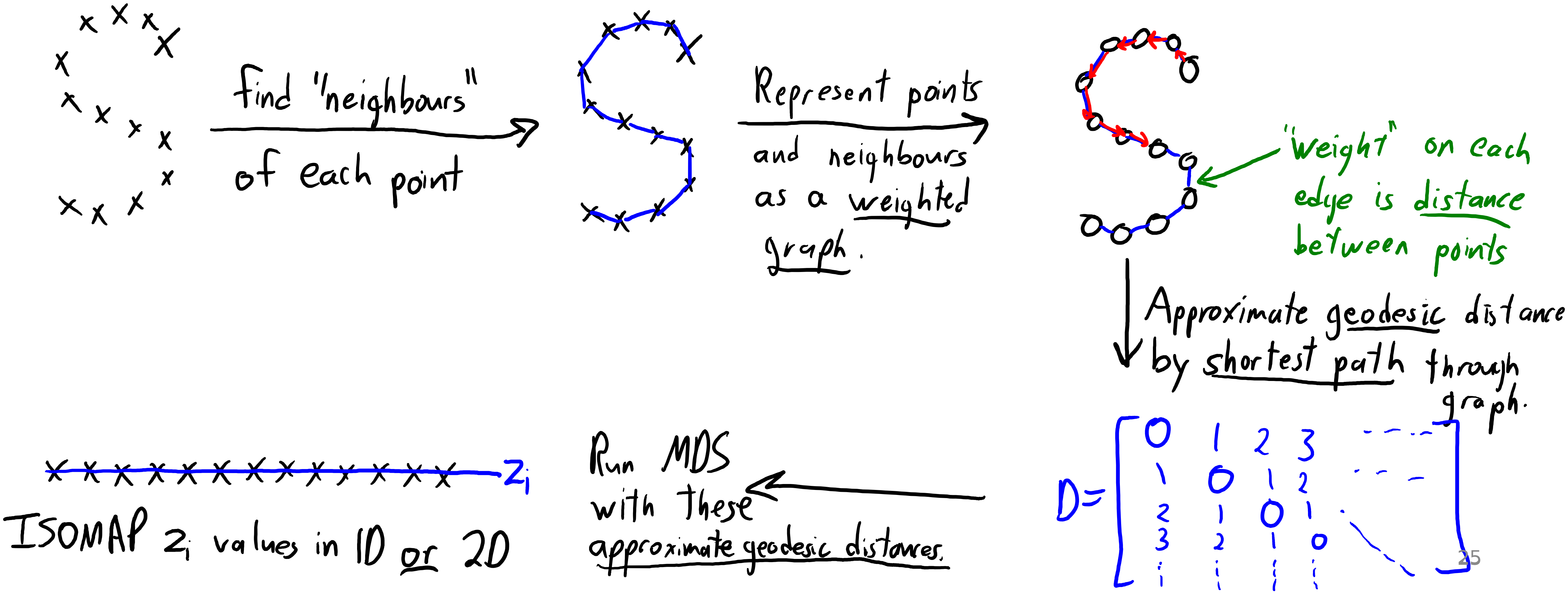
https://en.wikipedia.org/wiki/Nonlinear_dimensionality_reduction

Coming Up Next

ISOMAP

ISOMAP

- ISOMAP is MDS on manifolds:



find "neighbours" of each point

Represent points and neighbours as a weighted graph.

"weight" on each edge is distance between points

Approximate geodesic distance by shortest path through graph.

$$D = \begin{bmatrix} 0 & 1 & 2 & 3 & \cdots \\ 1 & 0 & 1 & 2 & \cdots \\ 2 & 1 & 0 & 1 & \ddots \\ 3 & 2 & 1 & 0 & \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

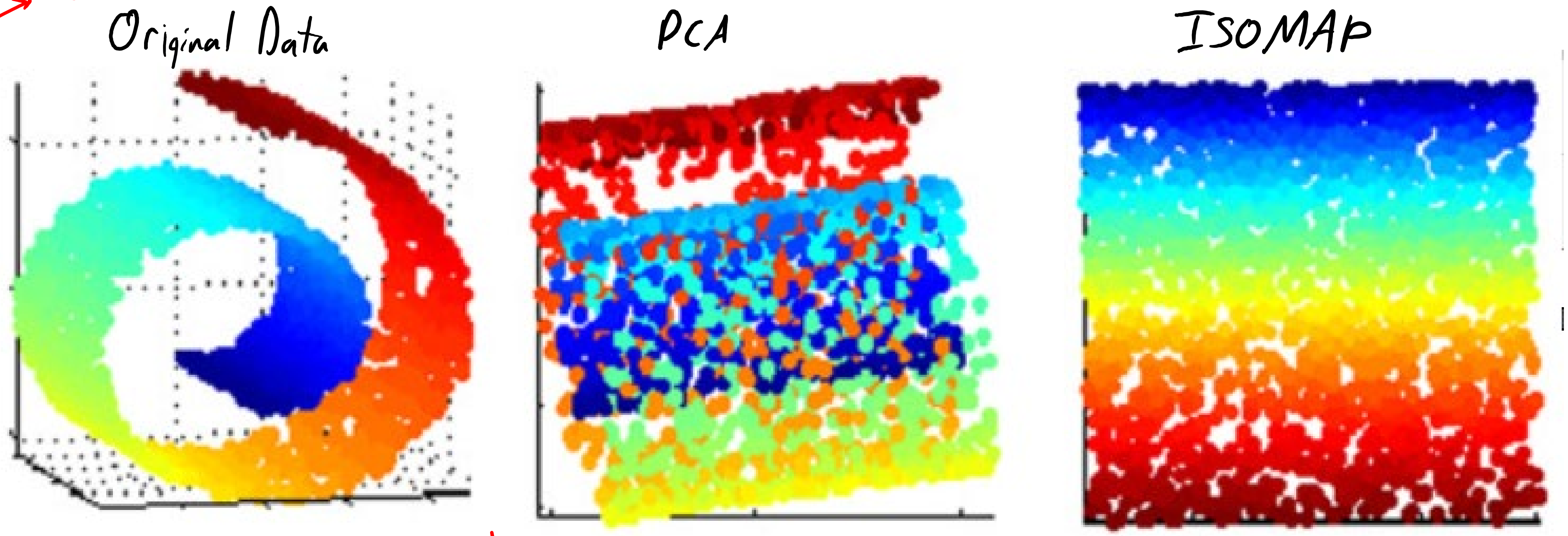
Run MDS with these approximate geodesic distances.

ISOMAP z_i values in 1D or 2D

ISOMAP

- ISOMAP can "unwrap" the roll:
  - shortest paths are approximations to geodesic distances.

Dijkstra's



- Sensitive to having the right graph:
  - Points off of manifold and gaps in manifold cause problems.

http://www.peh-med.com/content/9/1/12/figure/F1

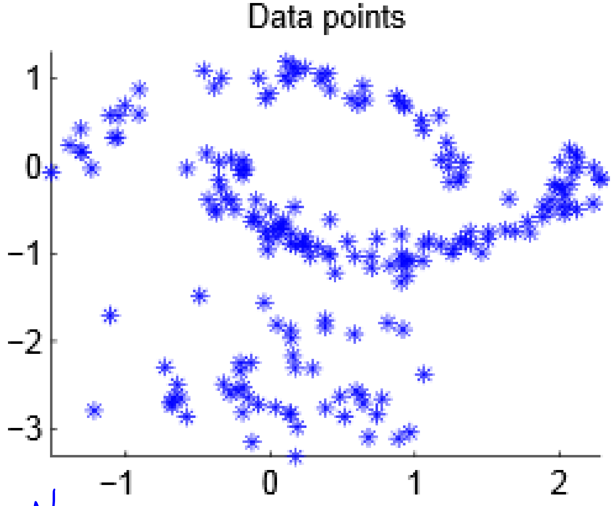
Constructing Neighbour Graphs

- Sometimes you can define the graph/distance without features:
  - Facebook friend graph.
  - Connect YouTube videos if one video tends to follow another.

- But we can also convert from features x_i to a "neighbour" graph (A6):
  - Approach 1 ("epsilon graph"): connect x_i to all x_j within some threshold ε.
    - Like we did with density-based clustering.
  - Approach 2a ("KNN graph"): connect x_i to x_j if:
    - x_j is a KNN of x_i **OR** x_i is a KNN of x_j.
  - Approach 2b ("mutual KNN graph"): connect x_i to x_j if:
    - x_j is a KNN of x_i **AND** x_i is a KNN of x_j.

http://ai.stanford.edu/~ang/papers/nips01-spectral.pdf

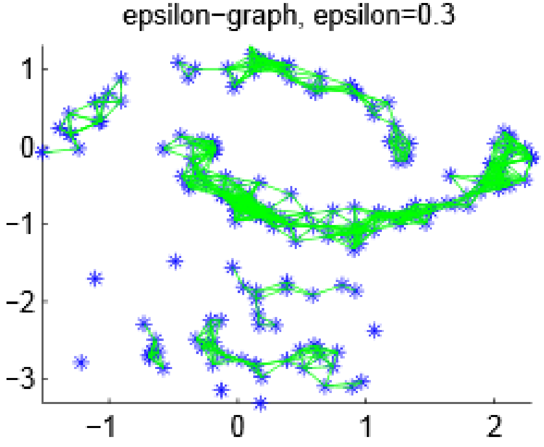
Converting from Features to Graph

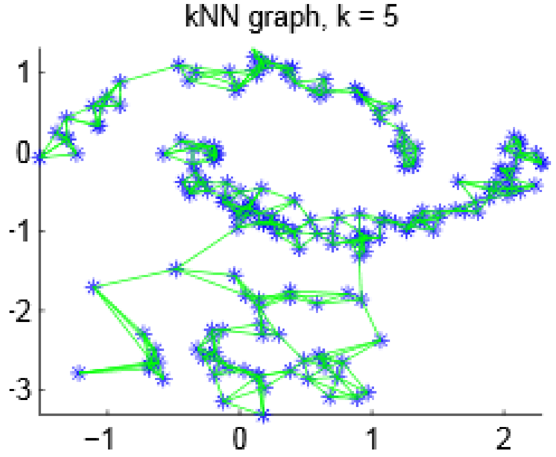

Data points

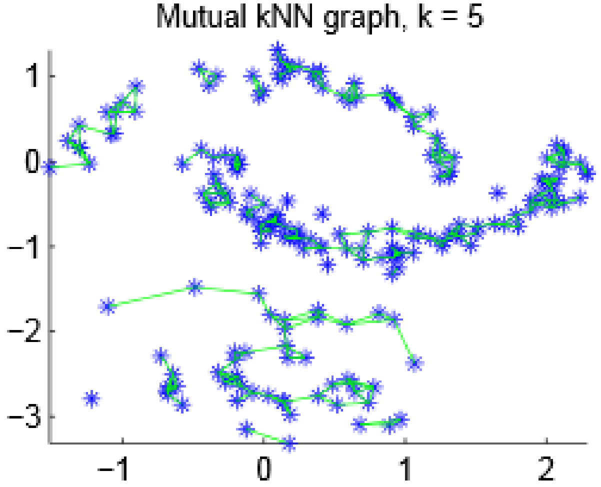
add edge if $\|x_i - x_j\| \leq 0{,}3$

add edge if 'i' is 5-NN of 'j' $\underline{\text{or}}$ 'j' is 5-NN of 'i'

add edge if 'i' and 'j' are KNNs of each other.


epsilon−graph, epsilon=0.3

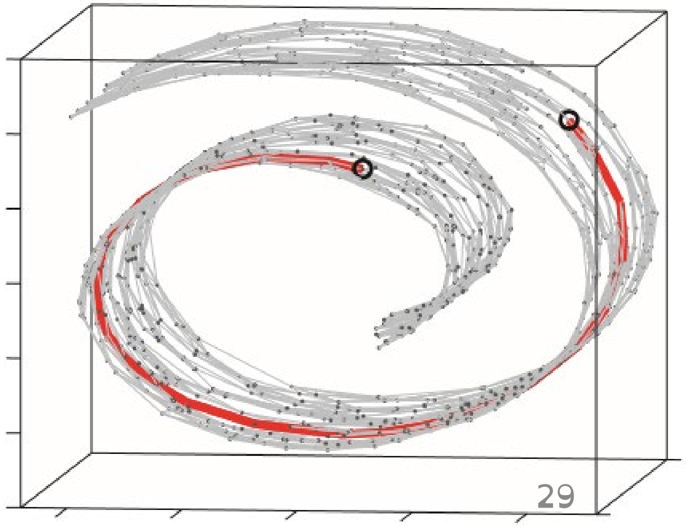

kNN graph, k = 5


Mutual kNN graph, k = 5

http://www.kyb.mpg.de/fileadmin/user_upload/files/publications/attachments/Luxburg07_tutorial_4488%5
B0%5D.pdf

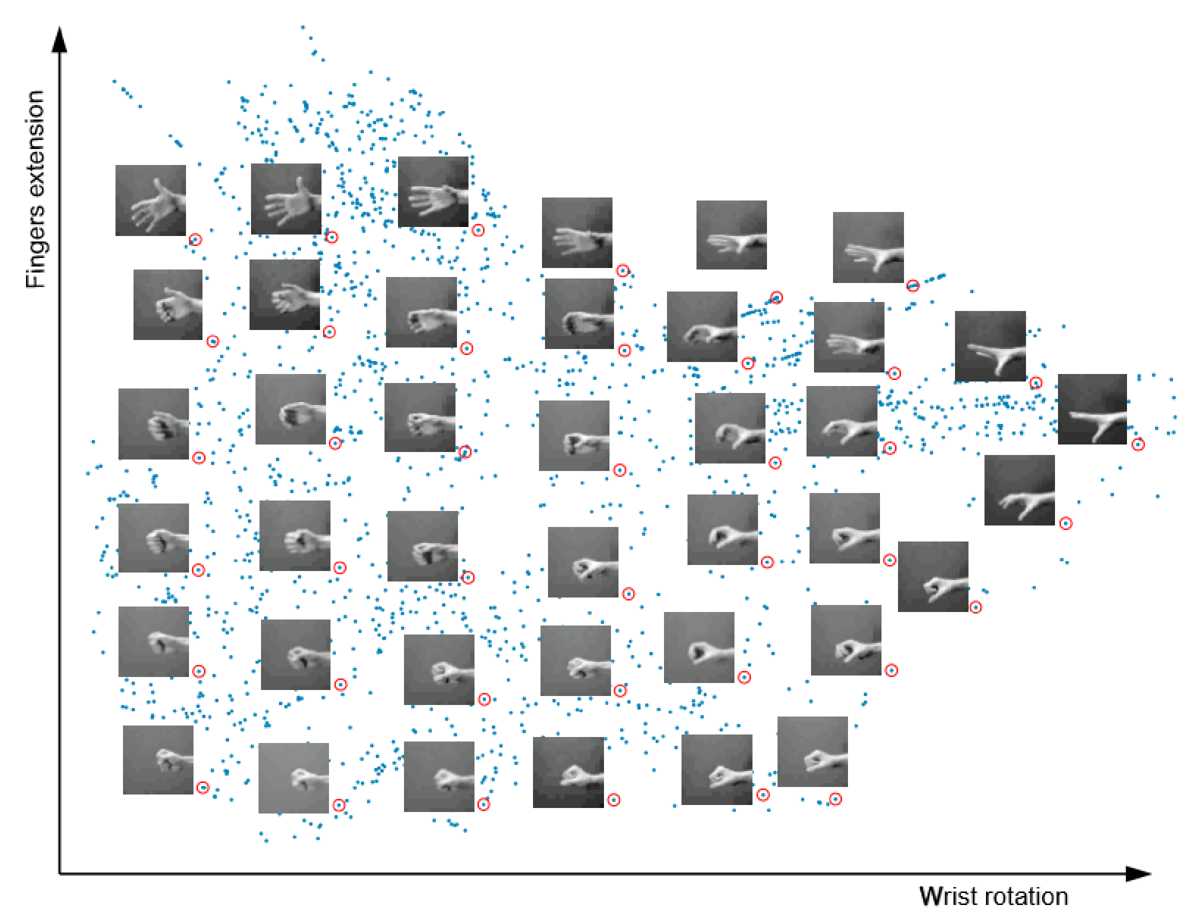
ISOMAP

- ISOMAP is latent-factor model for visualizing data on manifolds:
  1. Find the neighbours of each point.
     - Usually "k-nearest neighbours graph", or "epsilon graph".
  2. Compute edge weights:
     - Usually distance between neighbours.
  3. Compute weighted shortest path between all points
     - Dijkstra or other shortest path algorithm.
  4. Run MDS using these distances.



http://wearables.cc.gatech.edu/paper_of_week/isomap.pdf

ISOMAP on Hand Images



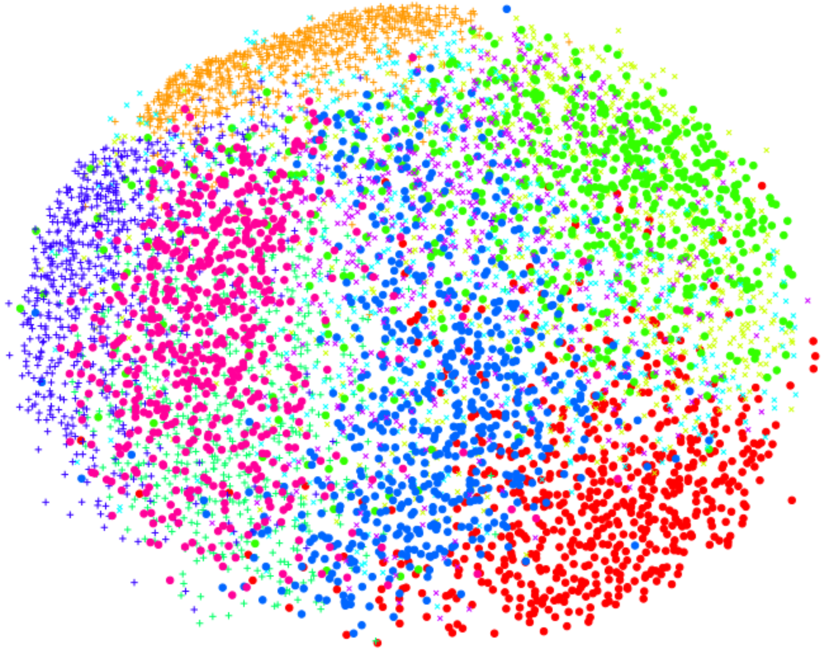
- Related method is “local linear embedding”.

http://wearables.cc.gatech.edu/paper_of_week/isomap.pdf

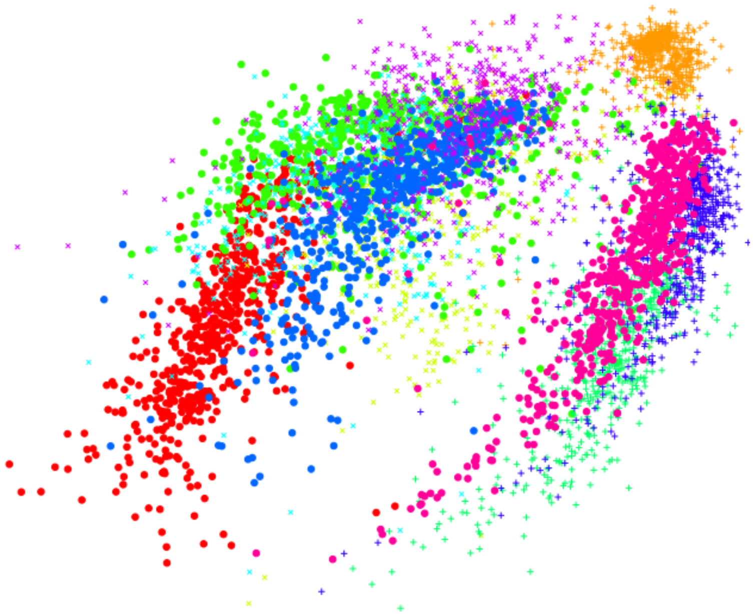
Sammon's Map vs. ISOMAP vs. PCA

● 0
+ 1
× 2
● 3
+ 4
× 5
● 6
+ 7
× 8
● 9

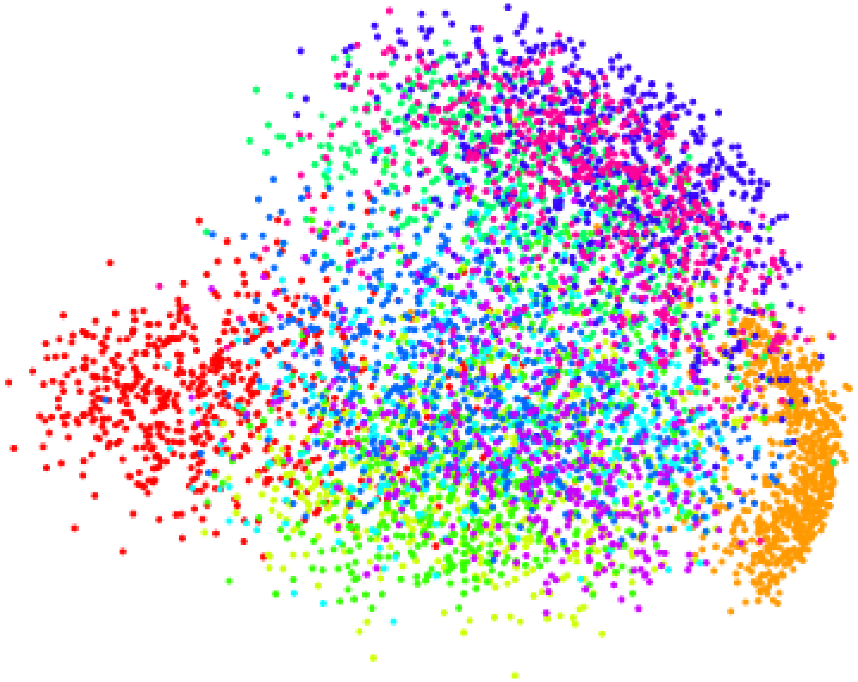
Sammon Map



ISOMAP

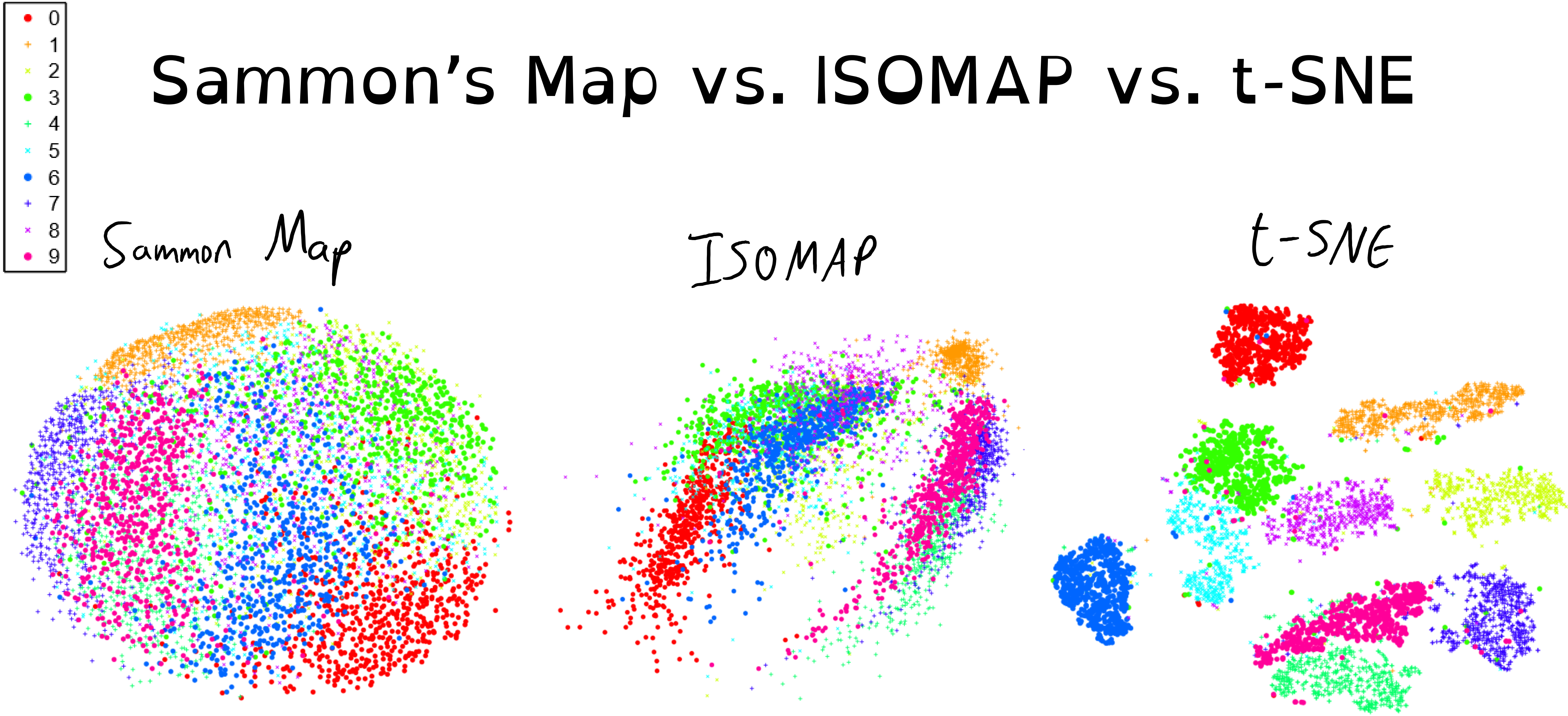


PCA



http://lvdmaaten.github.io/publications/papers/JMLR_2008.pdf

Sammon’s Map vs. ISOMAP vs. t-SNE



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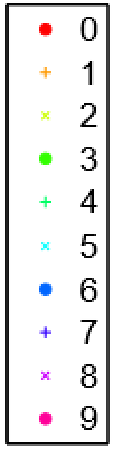

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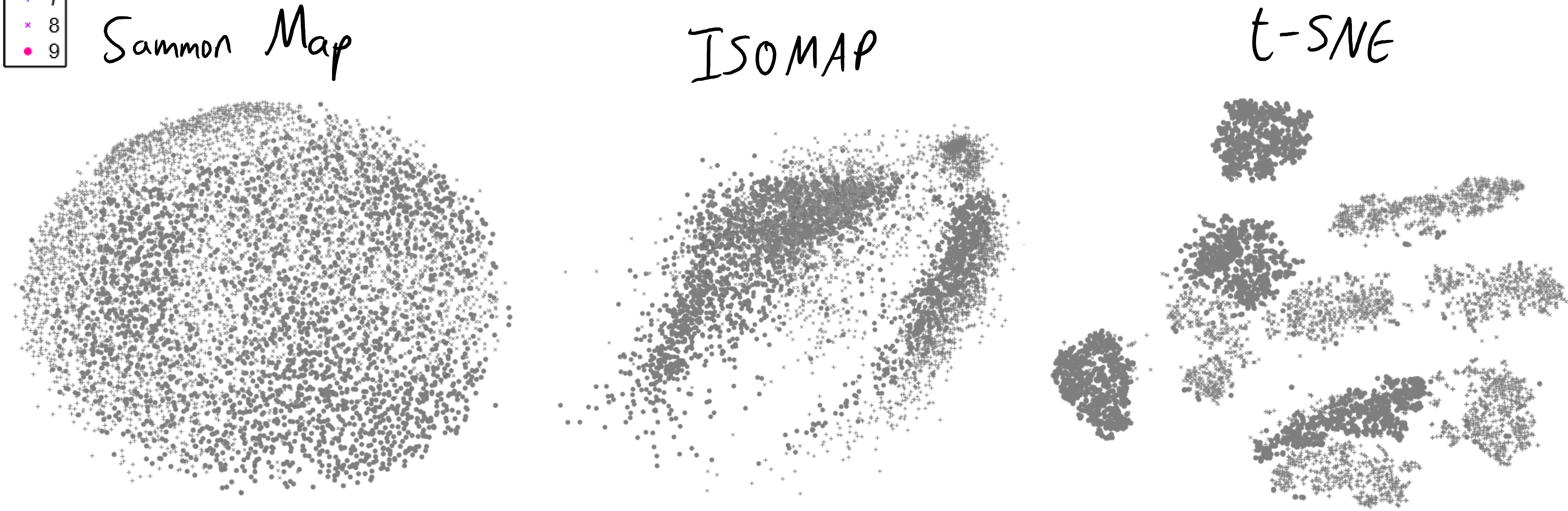

Remember this is unsupervised, algorithms do not know the labels.

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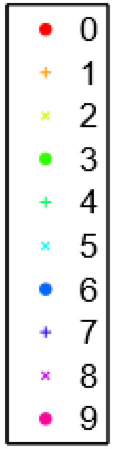

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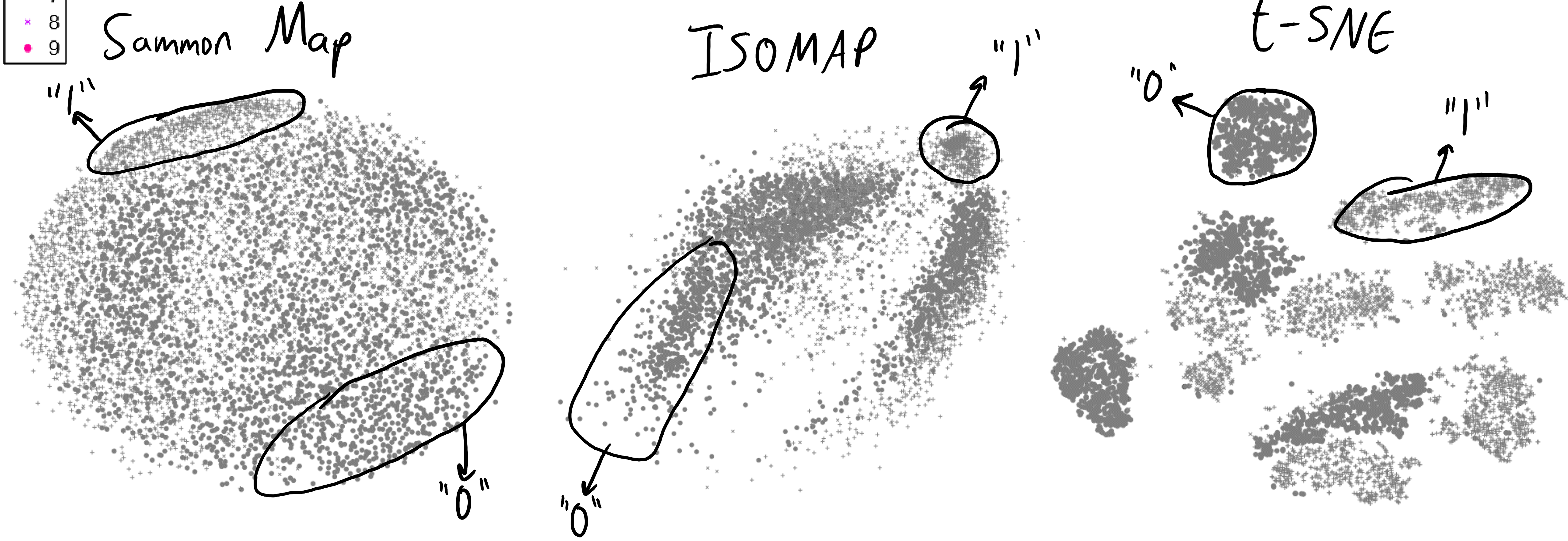

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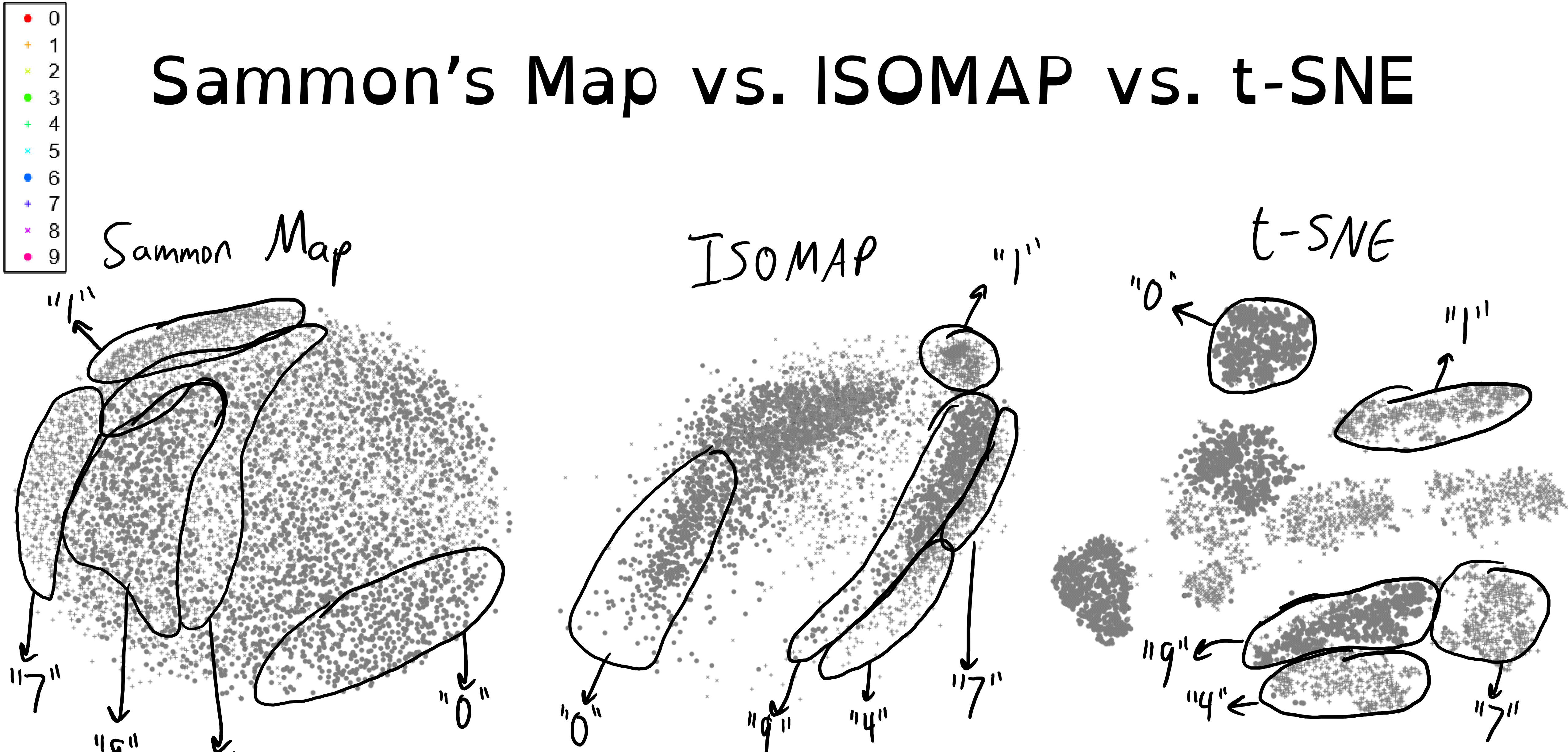
Sammon's Map vs. ISOMAP vs. t-SNE



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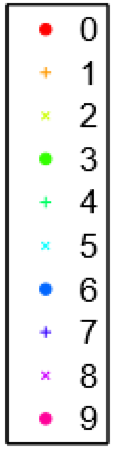

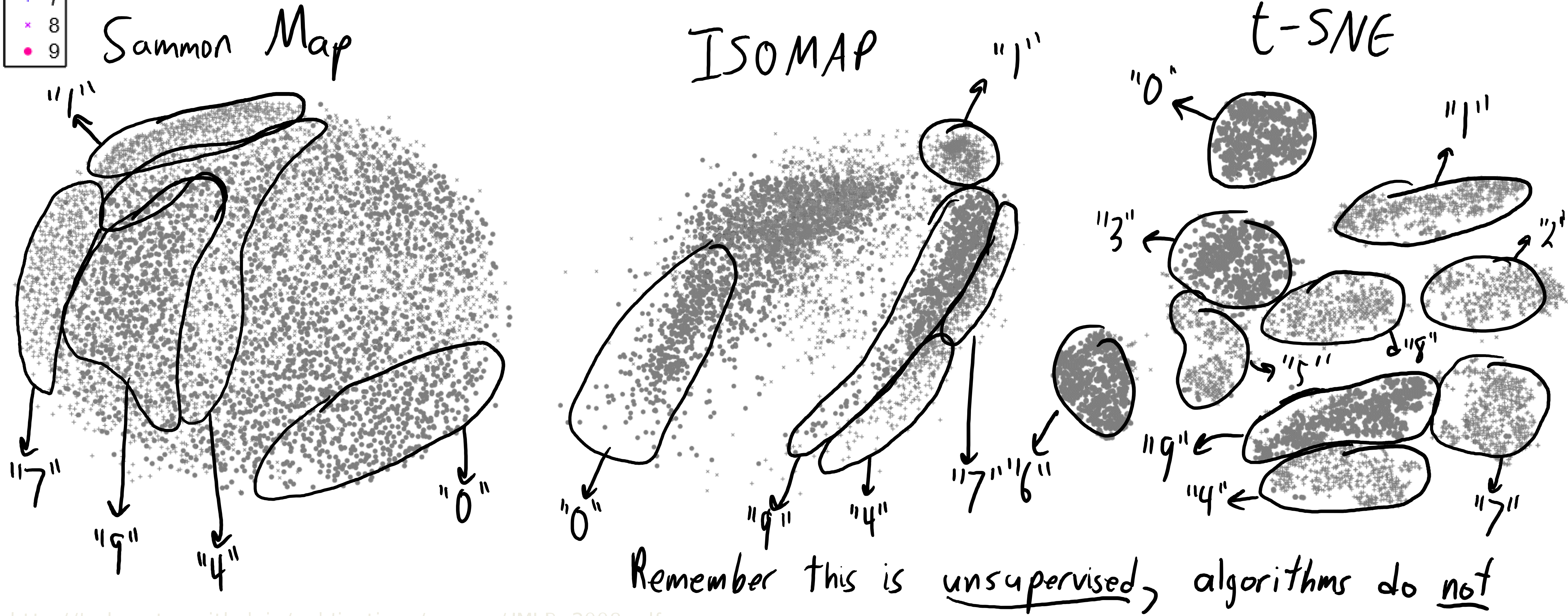

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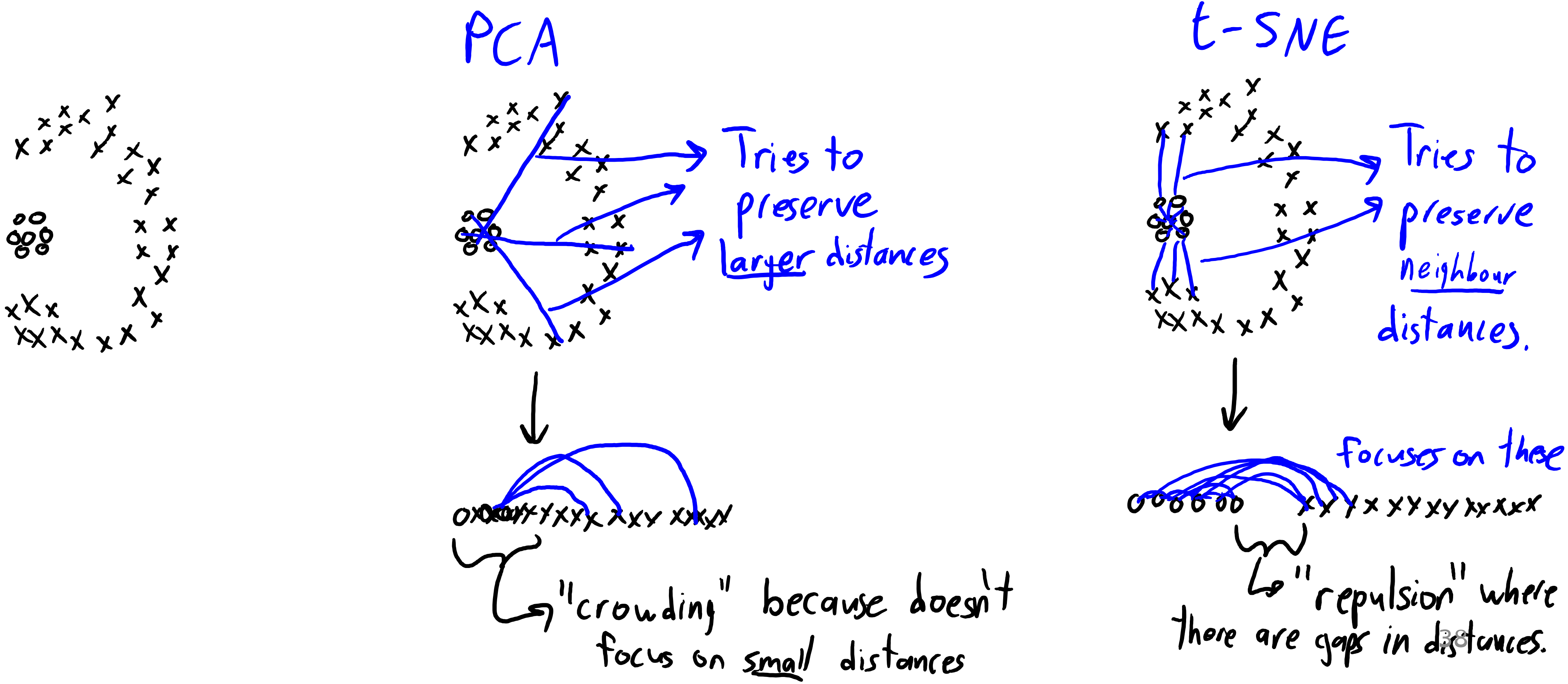
Coming Up Next

T-SNE

t-Distributed Stochastic Neighbour Embedding

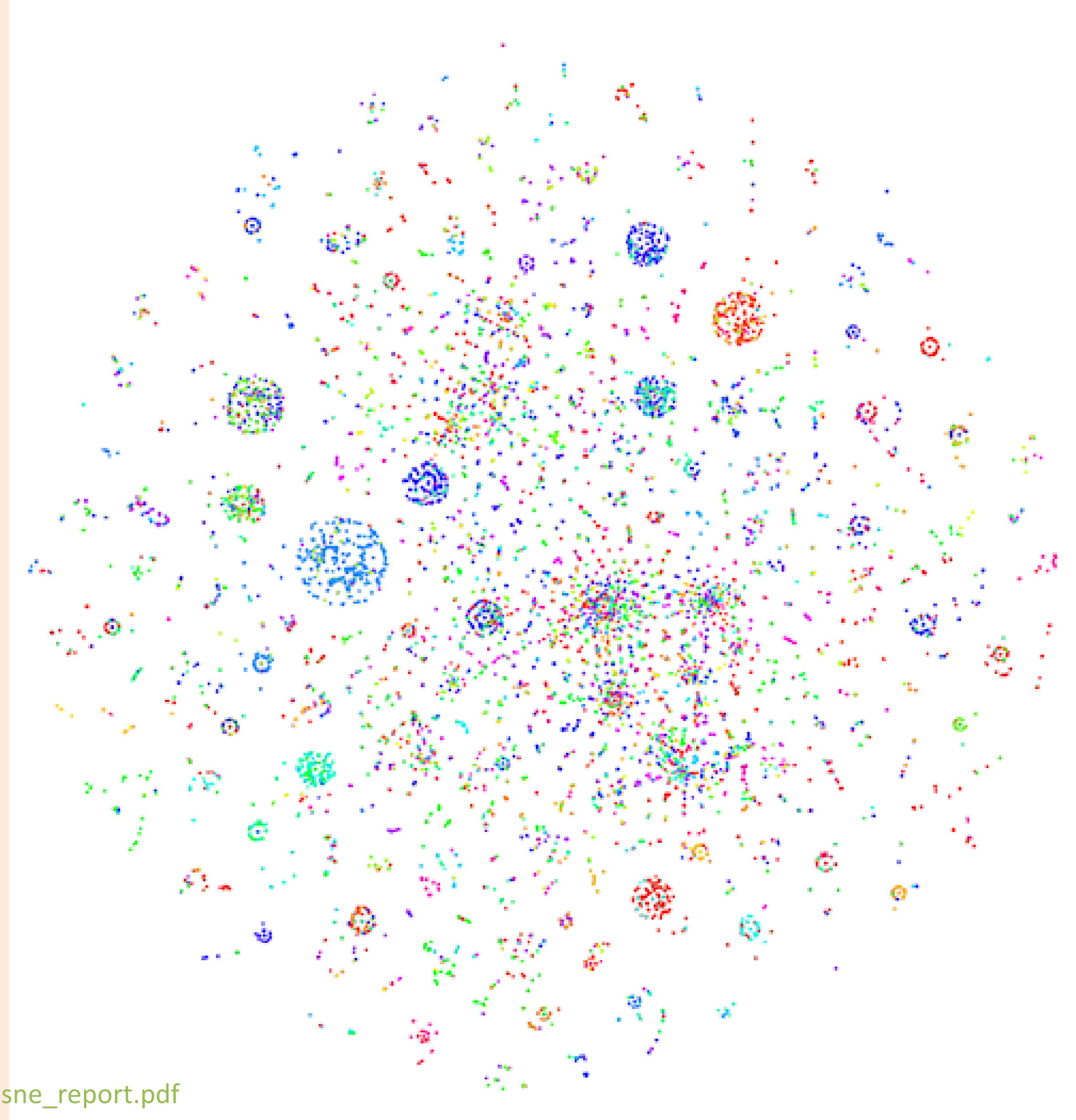
- One key idea in t-SNE:
  - Focus on distance to “neighbours”
    (allow large variance in other distances)


PCA
t-SNE
Tries to preserve larger distances
Tries to preserve neighbour distances.
"crowding" because doesn't focus on small distances
Focuses on these
"repulsion" where there are gaps in distances.

t-Distributed Stochastic Neighbour Embedding

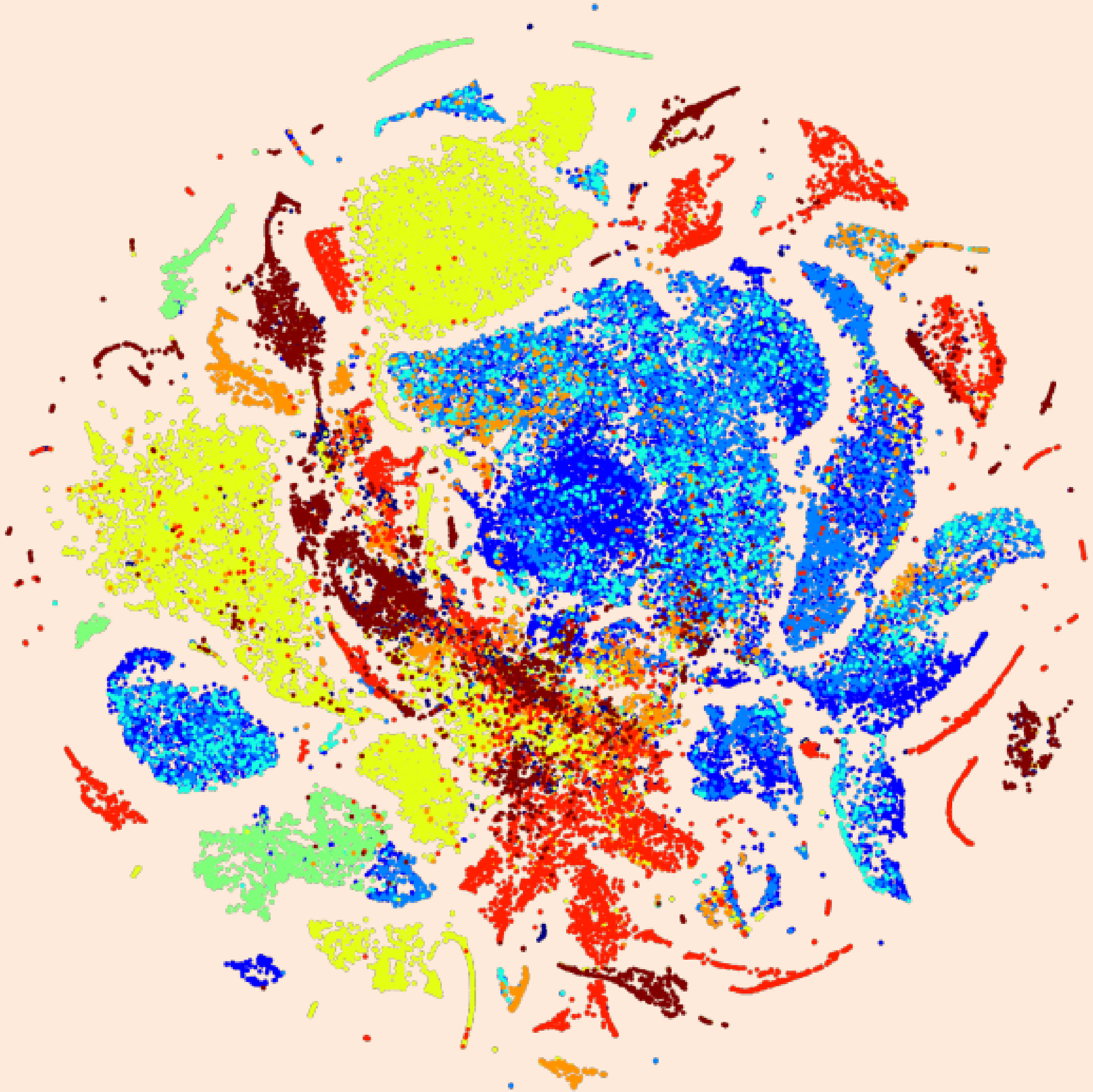
- t-SNE is a special case of MDS (specific d_1, d_2, and d_3 choices):
  - d_1: for each x_i, compute 'neighbour-ness' of each x_j
  - Computation is similar to k-means++, but most weight to close points (Gaussian).
    - Doesn't require explicit graph.
  - d_2: for each z_i, compute 'neighbour-ness' of each z_j.
    - Similar to above, but use student's t (grows really slowly with distance).
    - Avoids 'crowding', because you have a huge range that large distances can fill.
  - d_3: Compare x_i and z_i using an entropy-like measure:
    - How much 'randomness' is in probabilities of x_i if you know the z_i (and vice versa)?
- Interactive demo: https://distill.pub/2016/misread-tsne

t-SNE on Wikipedia Articles



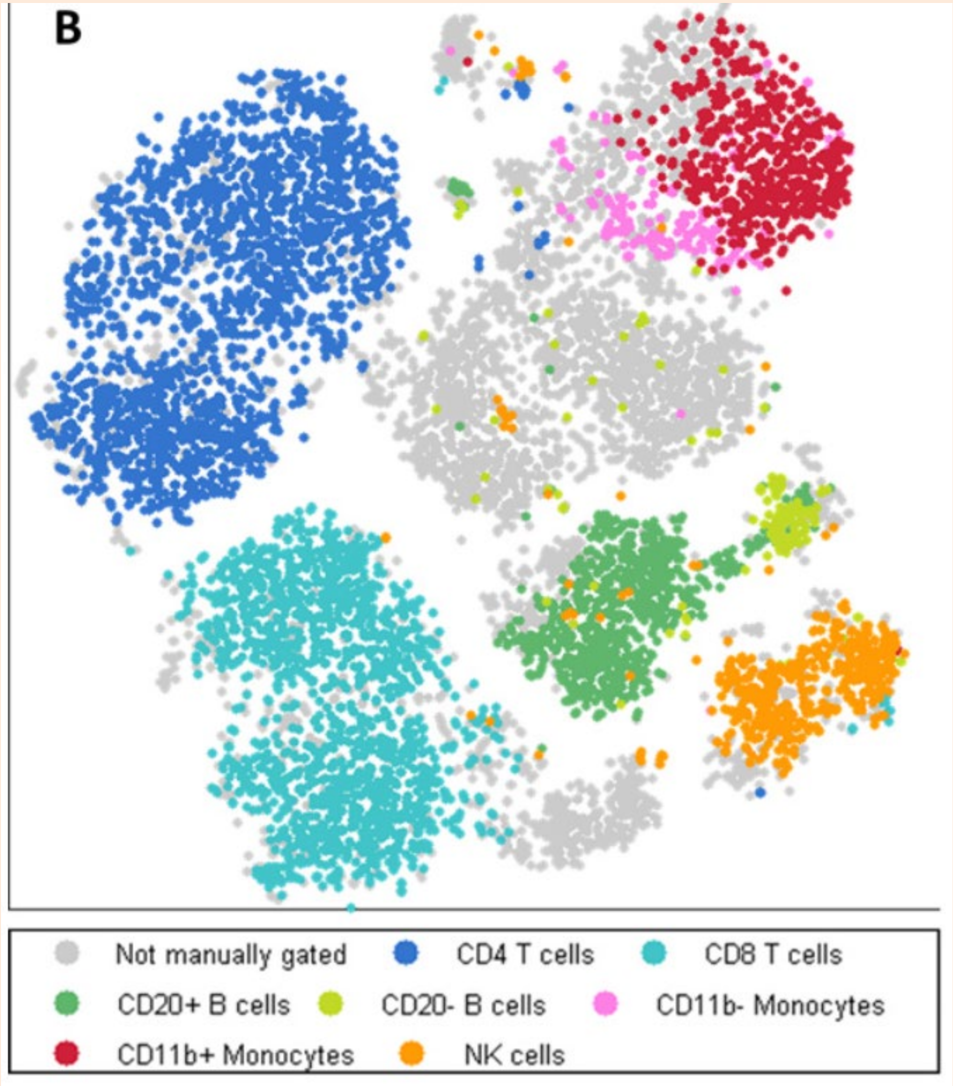
http://jasneetsabharwal.com/assets/files/wiki_tsne_report.pdf

t-SNE on Product Features



http://blog.kaggle.com/2015/06/09/otto-product-classification-winners-interview-2nd-place-alexander-guschin/

t-SNE on Leukemia Heterogeneity



http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4076922/

End of Part 4: Latent Factor Models

End of Part 4: Key Concepts

- We discussed linear latent-factor models:

$$f(W,Z) = \sum_{i=1}^{n} \sum_{j=1}^{d} (\langle w^j, z_i \rangle - x_{ij})^2$$

$$= \sum_{i=1}^{n} \| W^T z_i - x_i \|^2$$

$$= \| ZW - X \|_F^2$$

- Represent ‘X’ as linear combination of latent factors ‘w_c’.
  - Latent features ‘z_i’ give a lower-dimensional version of each ‘x_i’.
  - When k=1, finds direction that minimizes squared orthogonal distance.
- Applications:
  - Outlier detection, dimensionality reduction, data compression, features for linear models, visualization, factor discovery, filling in missing entries.

End of Part 4: Key Concepts

- We discussed linear latent-factor models:

$$f(W,Z) = \sum_{i=1}^{n} \sum_{j=1}^{d} (\langle w^j, z_i \rangle - x_{ij})^2$$

- Principal component analysis (PCA):
  - Often uses orthogonal factors and fits them sequentially (via SVD).
- Non-negative matrix factorization:
  - Uses non-negative factors giving sparsity.
  - Can be minimized with projected gradient.
- Many variations are possible:
  - Different regularizers (sparse coding) or loss functions (robust/binary PCA).
  - Missing values (recommender systems) or change of basis (kernel PCA).

End of Part 4: Key Concepts

- We discussed multi-dimensional scaling (MDS):
  - Non-parametric method for high-dimensional data visualization.
  - Tries to match distance/similarity in high-/low-dimensions.
    - "Gradient descent on scatterplot points".
- Main challenge in MDS methods is "crowding" effect:
  - Methods focus on large distances and lose local structure.
- Common solutions:
  - Sammon mapping: use weighted cost function.
  - ISOMAP: approximate geodesic distance using via shortest paths in graph.
  - T-SNE: give up on large distances and focus on neighbour distances.

Summary

- Different MDS distances/losses/weights usually gives better results.
- Manifold learning focuses on low-dimensional curved structures.
- ISOMAP is most common approach:
  - Approximates geodesic distance by shortest path in weighted graph.
- t-SNE is promising new data MDS method.

- Next time: deep learning.

$$G = \begin{bmatrix} & & 0 \\ 0 & & \\ & 0 & \end{bmatrix} \quad \underset{n \times n}{D} = \begin{bmatrix} 0 & & & \infty \\ & 0 & & \\ \infty & & \ddots & \\ & \infty & & 0 \end{bmatrix} \longrightarrow D = \begin{bmatrix} 0 & & & 99999 \\ & 0 & & \\ 99999 & & \ddots & \\ & 99999 & & 0 \end{bmatrix}$$

Please Do Course Evaluation!

Review Questions

- Q1: Is MDS sensitive to initialization? Why?

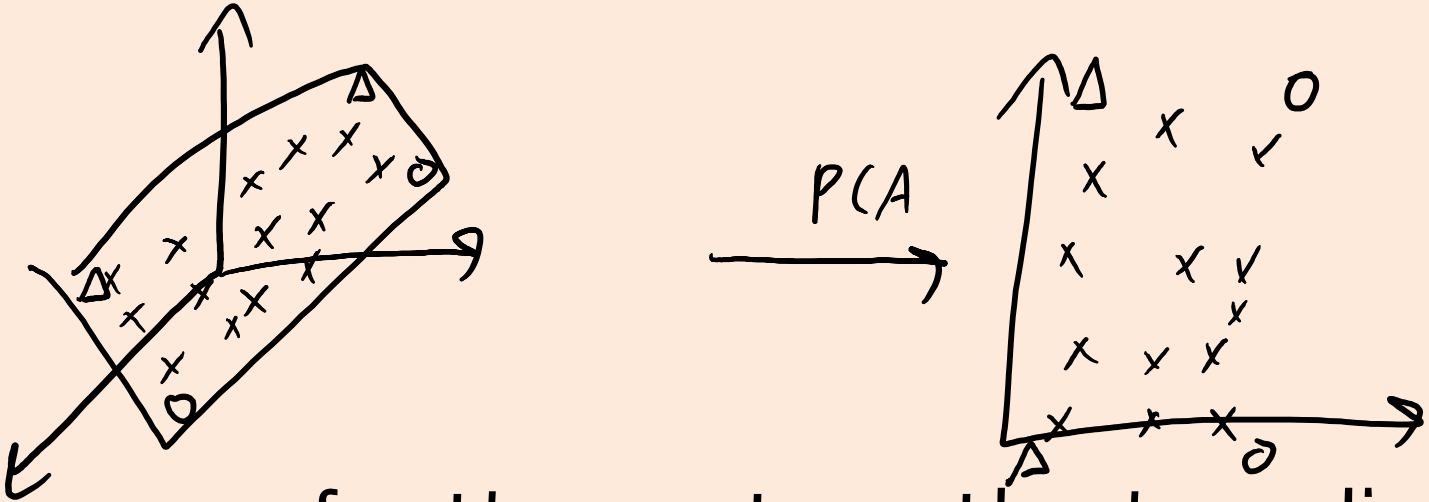
- Q2: What is the problem with using linear dimensionality reduction for data on manifold?

- Q3: How does ISOMAP compute pair-wise distances among examples?

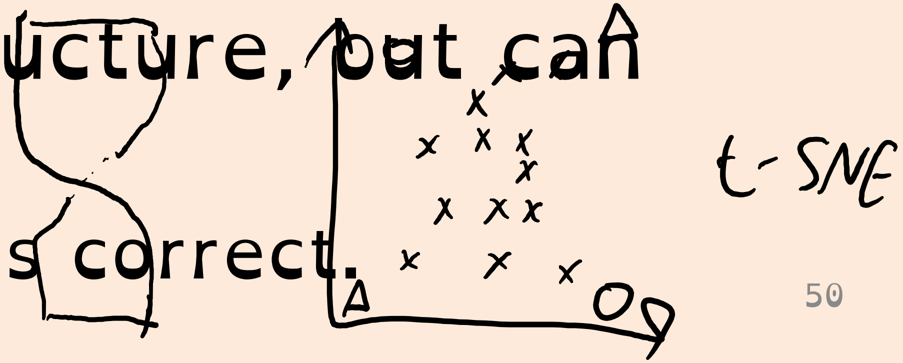
- Q4: What is the key idea behind t-SNE in terms of preserving distances in 2D?

Does t-SNE always outperform PCA?

- Consider 3D data living on a 2D hyper-plane:

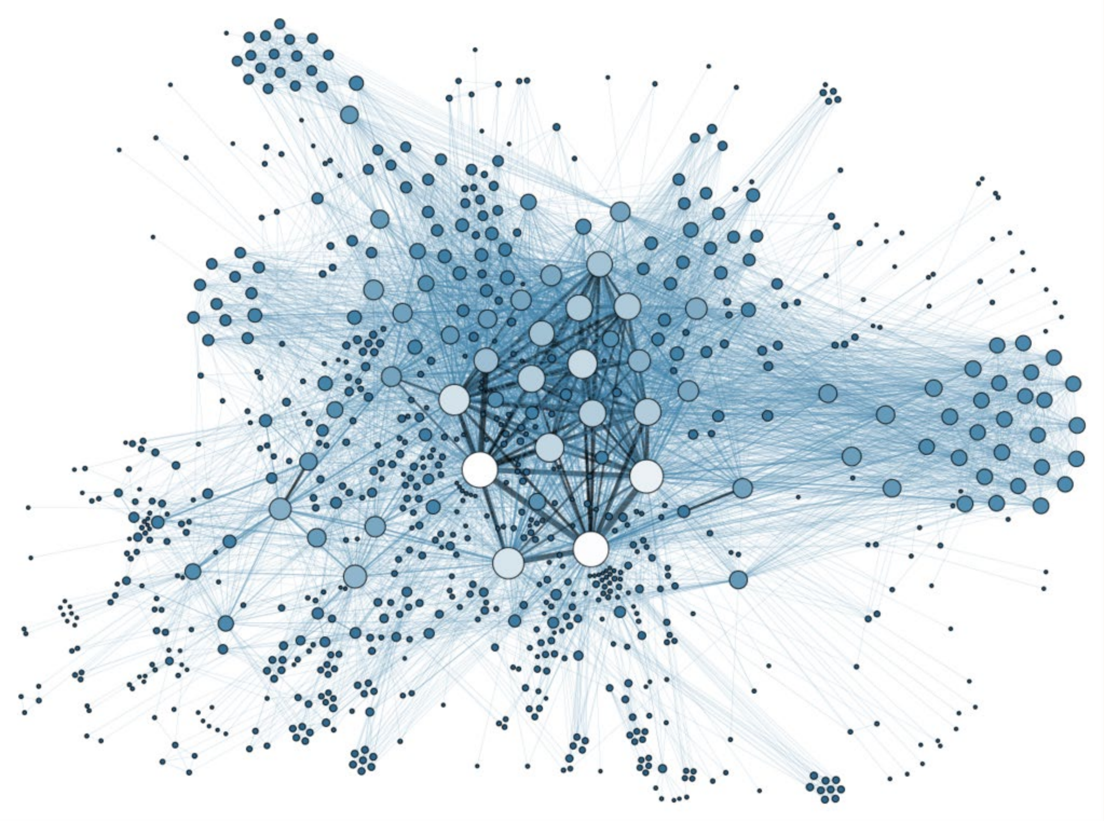


- PCA can perfectly capture the low-dimensional structure.
- T-SNE can capture the local structure, but can “twist” the plane.
  - It doesn’t try to get long distances correct.



Graph Drawing

- A closely-related topic to MDS is graph drawing:
  - Given a graph, how should we display it?
  - Lots of interesting methods: https://en.wikipedia.org/wiki/Graph_drawing



Bonus Slide: Multivariate Chain Rule

- Recall the univariate chain rule: $\frac{d}{dw}\left[f(g(w))\right] = f'(g(w))\,g'(w)$
- The multivariate chain rule: $\underbrace{\nabla\left[f(g(w))\right]}_{d \times 1} = \underbrace{f'(g(w))}_{1 \times 1}\underbrace{\nabla g(w)}_{d \times 1}$
- Example:

$$\nabla\left[\tfrac{1}{2}(w^T x_i - y_i)^2\right]$$

$$= \nabla\left[f(g(w))\right]$$

$$\begin{tikzcd}
\text{with } g(w) = w^T x_i - y_i \arrow[r] & \nabla g(w) = x_i \arrow[dr] & \\
 & & \nabla\left[f(g(w))\right] = r_i \; x_i \\
\text{and } f(r_i) = \tfrac{1}{2} r_i^2 \arrow[r] & f'(r_i) = r_i \arrow[ur] &
\end{tikzcd}$$

$$= (w^T x_i - y_i) x_i$$

Bonus Slide: Multivariate Chain Rule for MDS

- General MDS formulation:

$$\underset{Z\in\mathbb{R}^{n\times k}}{\operatorname{argmin}} \sum_{i=1}^{n}\sum_{j=i+1}^{n} g(d_1(x_i,x_j), d_2(z_i,z_j))$$

- Using multivariate chain rule we have:

$$\nabla_{z_i} g(d_1(x_i,x_j), d_2(z_i,z_j)) = g'(d_1(x_i,x_j), d_2(z_i,z_j))\nabla_{z_i} d_2(z_i,z_j)$$

- Example: If $d_1(x_i,x_j) = \|x_i - x_j\|$ and $d_2(z_i,z_j) = \|z_i - z_j\|$ and $g(d_1,d_2) = \frac{1}{2}(d_1-d_2)^2$

$$\nabla_{z_i} g(d_1(x_i,x_j), d_2(z_i,z_j)) = \underbrace{-(d_1(x_i,x_j) - d_2(z_i,z_j))}_{\substack{g'(d_1,d_2) \\ \text{(move distances closer)}}}\underbrace{\left[-\frac{(z_i - z_j)}{2\|z_i - z_j\|}\right]}_{\text{(how distance changes in } z\text{-space)}\ \to\ \nabla_{z_i} d_2(z_i,z_j)}$$

↳ Assuming $z_i \neq z_j$

Latent-Factor Representation of Words

- For natural language, we often represent words by an index.
  - E.g., “cat” is word 124056 among a “bag of words”.

- But this may be inefficient:
  - Should “cat” and “kitten” share parameters in some way?

Latent-Factor Representation of Words

- Latent-factor representation of individual words:
  - Closeness in latent space should indicate similarity.
  - Distances could represent meaning?

- Recent alternative to PCA/NMF is word2vec…

Using Context

- Consider these phrases:
  - “the <u>cat</u> purred”
  - “the <u>kitten</u> purred”

  - “black <u>cat</u> ran”
  - “black <u>kitten</u> ran”

- Words that occur in the same context likely have similar meanings.

- Word2vec uses this insight to design an MDS distance function.

Word2Vec

- Two common word2vec approaches:
  1. Try to predict word from surrounding words (continuous bag of words).
  2. Try to predict surrounding words from word (skip-gram).

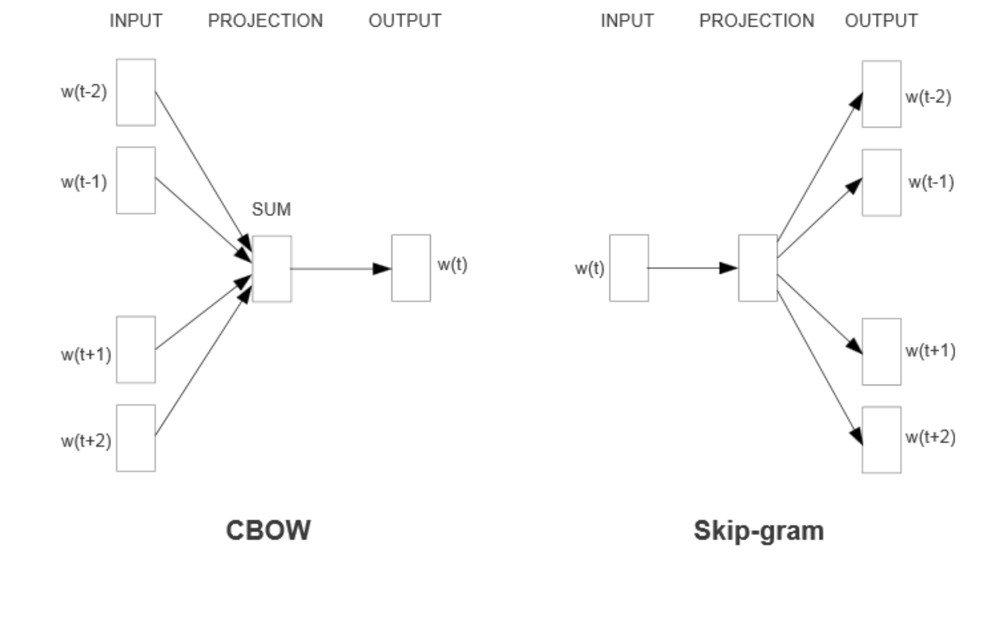


Figure 1: New model architectures. The CBOW architecture predicts the current word based on the context, and the Skip-gram predicts surrounding words given the current word.

- Train latent-factors to solve one of these supervised learning tasks.

https://arxiv.org/pdf/1301.3781.pdf

Word2Vec

- In both cases, each word ‘i’ is represented by a vector z_i.
- In continuous bag of words (CBOW), we optimize the following likelihood:

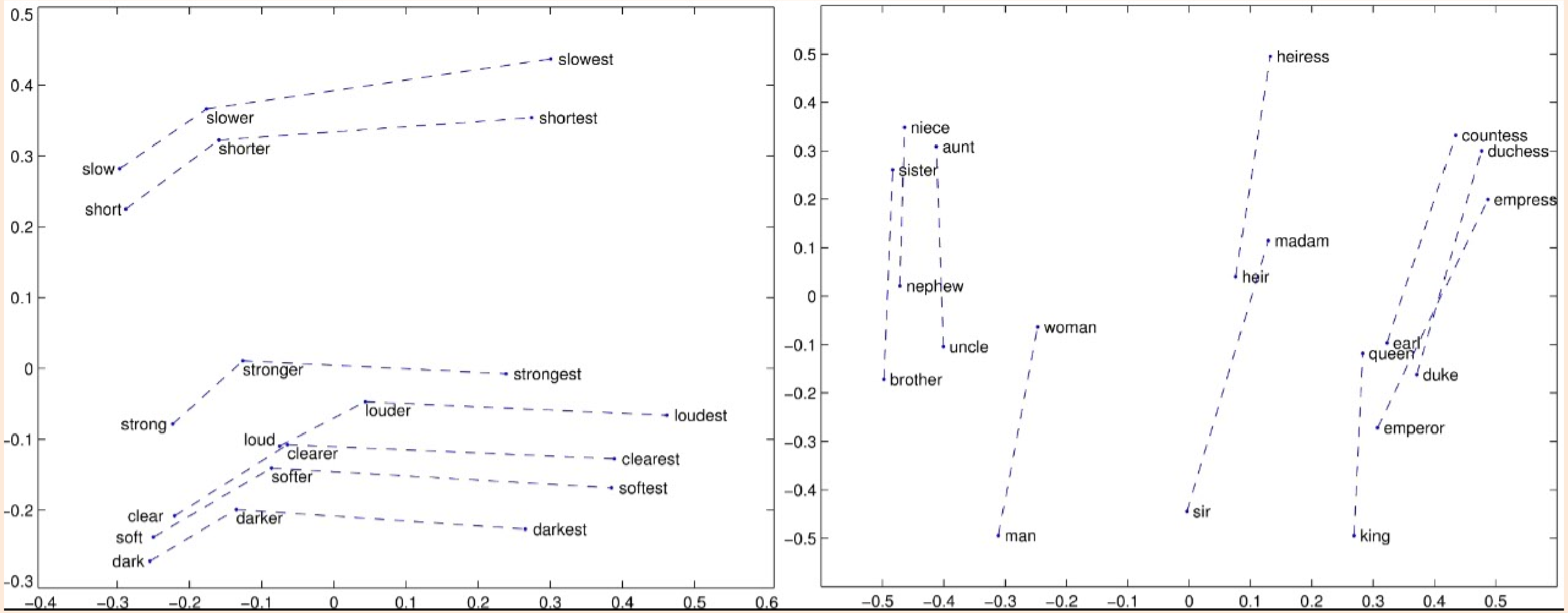
$$p(x_i \mid x_{surround}) = \prod_{j \in surround} p(x_i \mid x_j) \quad \text{(independence assumption)}$$

$$= \prod_{j \in surround} \frac{\exp(z_i^T z_j)}{\sum_{c=1}^{k} \exp(z_c^T z_j)} \quad \text{(softmax over all words)}$$

- Apply gradient descent to logarithm:
  - Encourages $z_i^T z_j$ to be big for words in same context (making z_i close to z_j).
  - Encourages $z_i^T z_j$ to be small for words not appearing in same context (makes z_i and z_j far).
- For CBOW, denominator sums over all words.
- For skip-gram it will be over all possible surrounding words.
  - Common trick to speed things up: sample terms in denominator (“negative sampling”).

Word2Vec Example

- MDS visualization of a set of related words:



- Distances between vectors might represent semantics.

http://sebastianruder.com/secret-word2vec

Word2Vec

- Subtracting word vectors to find related vectors.

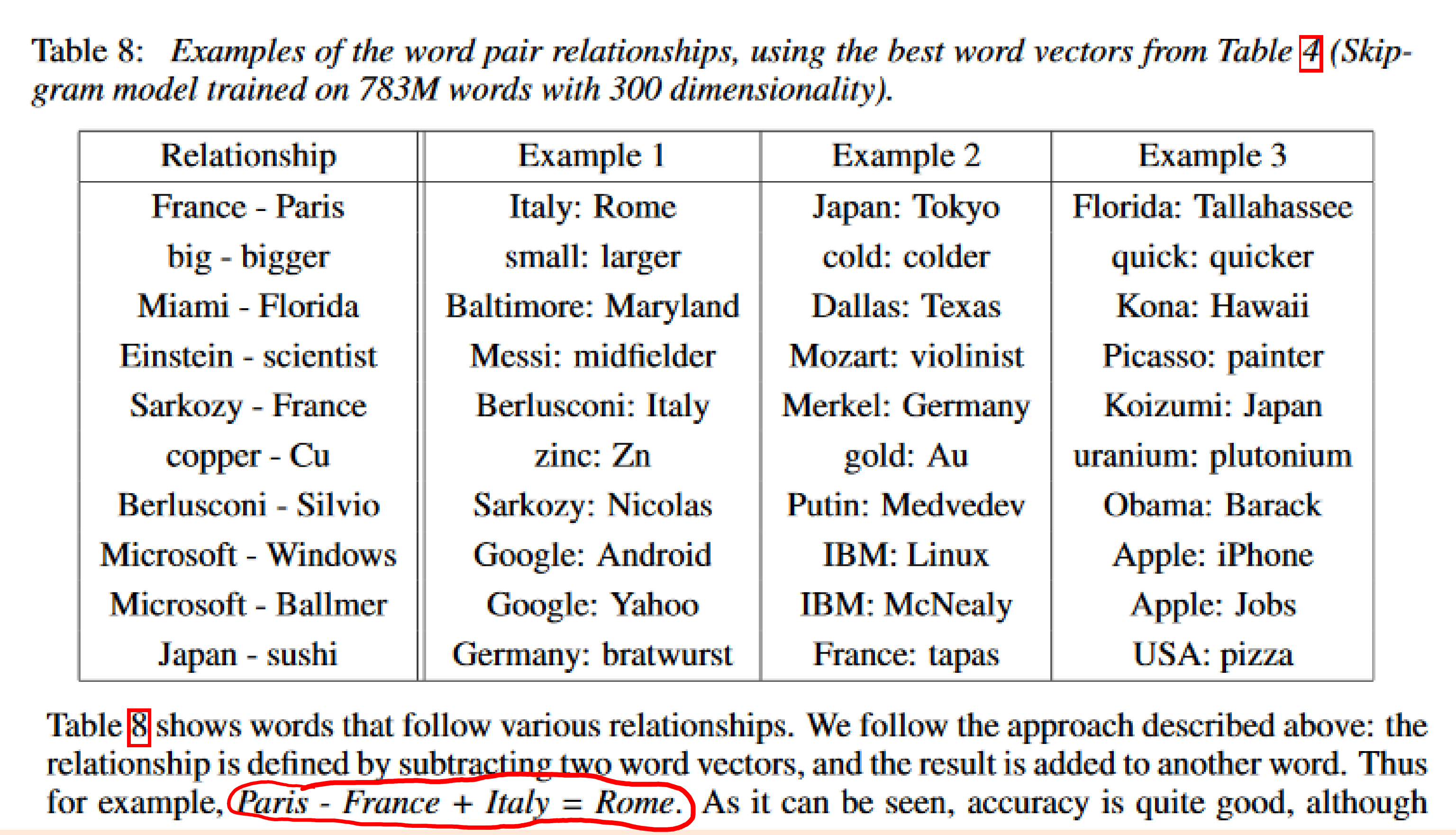


Table 8: *Examples of the word pair relationships, using the best word vectors from Table 4 (Skip-gram model trained on 783M words with 300 dimensionality).*

Relationship	Example 1	Example 2	Example 3
France - Paris	Italy: Rome	Japan: Tokyo	Florida: Tallahassee
big - bigger	small: larger	cold: colder	quick: quicker
Miami - Florida	Baltimore: Maryland	Dallas: Texas	Kona: Hawaii
Einstein - scientist	Messi: midfielder	Mozart: violinist	Picasso: painter
Sarkozy - France	Berlusconi: Italy	Merkel: Germany	Koizumi: Japan
copper - Cu	zinc: Zn	gold: Au	uranium: plutonium
Berlusconi - Silvio	Sarkozy: Nicolas	Putin: Medvedev	Obama: Barack
Microsoft - Windows	Google: Android	IBM: Linux	Apple: iPhone
Microsoft - Ballmer	Google: Yahoo	IBM: McNealy	Apple: Jobs
Japan - sushi	Germany: bratwurst	France: tapas	USA: pizza

Table 8 shows words that follow various relationships. We follow the approach described above: the relationship is defined by subtracting two word vectors, and the result is added to another word. Thus for example, *Paris - France + Italy = Rome*. As it can be seen, accuracy is quite good, although

- Word vectors for 157 languages here.

https://arxiv.org/pdf/1301.3781.pdf

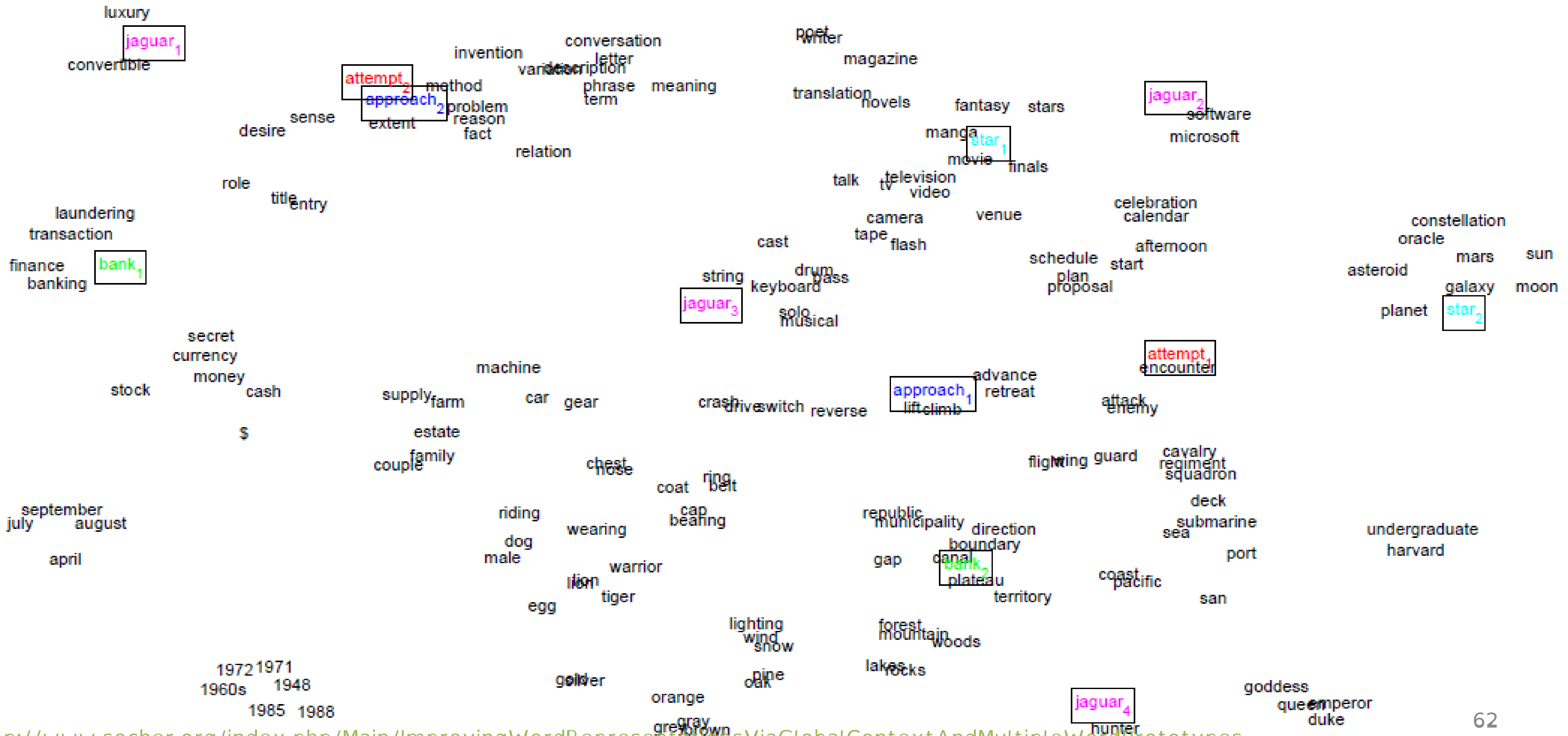
Multiple Word Prototypes

- What about homonyms and polysemy?
  - The word vectors would need to account for all meanings.

- More recent approaches:
  - Try to cluster the different contexts where words appear.
  - Use different vectors for different contexts.

$$X_{jaguar} = \left[\begin{array}{c} \cdots \\ \cdots \\ \end{array}\right] \begin{array}{l} z_{j1} \\ z_{j2} \\ z_{j3} \end{array}$$

Multiple Word Prototypes



http://www.socher.org/index.php/Main/ImprovingWordRepresentationsViaGlobalContextAndMultipleWordPrototypes