

Lecture 3: Novelty Detection

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AGENDA

01 **Novelty Detection: Overview**

02 **Density-based Novelty Detection**

03 **Distance/Reconstruction-based ND**

04 **Model-based Novelty Detection**

Machine Learning

- Definition
 - ✓ A computer program is said to **learn** from experience **E** with respect to some class of tasks **T** and performance measure **P**, if its performance at task in T, as measured by P, improves with experience E” – Mitchell (1997)

Supervised Learning

- Goal: predict a single “target” or “outcome” variable
- Finds relations between X and Y
- Train (learn) data where target value is known
- Score data where target value is not known

Unsupervised Learning

- Explores intrinsic characteristics
- Estimates underlying distribution
- Segment data into meaningful groups or detect patterns
- There is no target (outcome) variable to predict or classify

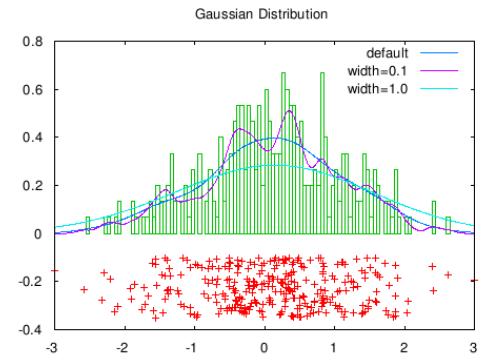
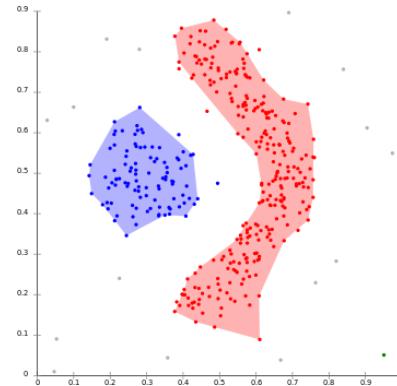
Unsupervised Learning

A given dataset \mathbf{X}

	Var. 1	Var. 2	...	Var. d
Ins. 1
Ins. 2
...
Ins. N

Unsupervised learning

- Explores intrinsic characteristics
- Estimates underlying distribution
- Density estimation, clustering, association rule mining, network (graph) analysis, etc.



이 책과 함께 구매한 도서

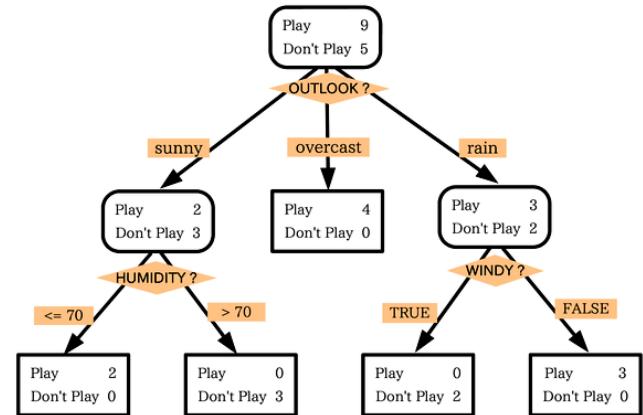


Supervised Learning

A given dataset \mathbf{X} & \mathbf{Y}

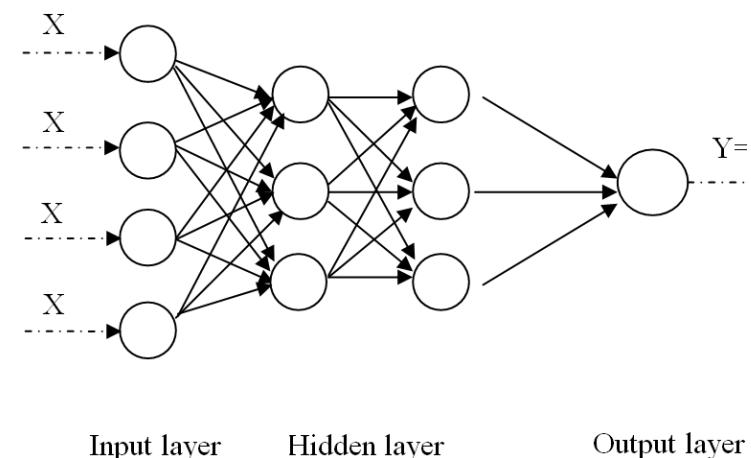
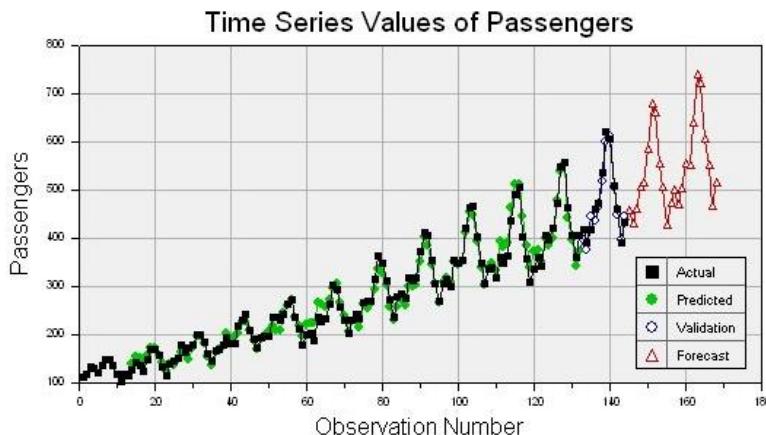
	Var. 1	Var. 2	...	Var. d	\rightarrow	\mathbf{Y}
Ins. 1
Ins. 2	$y = f(x)$..
...
Ins. N

Dependent variable: PLAY



Supervised learning

- Finds relations between \mathbf{X} and \mathbf{Y} : estimate the underlying function $y = f(x)$
- Classification, regression, novelty detection



Supervised Learning: Novelty Detection

- What is novel data (outliers)?

“Observations that deviate so much from other observations as to arouse suspicions that they were generated by a different mechanism (Hawkins, 1980)”
“Instances that their true probability density is very low (Harmeling et al., 2006)”

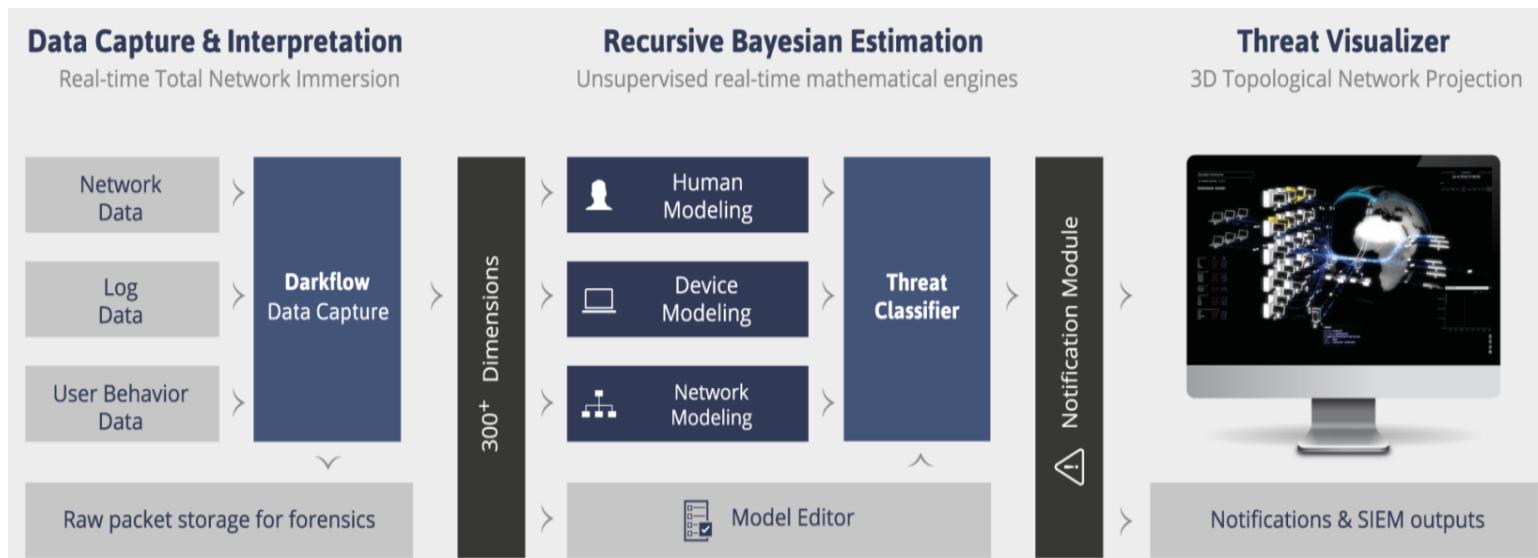
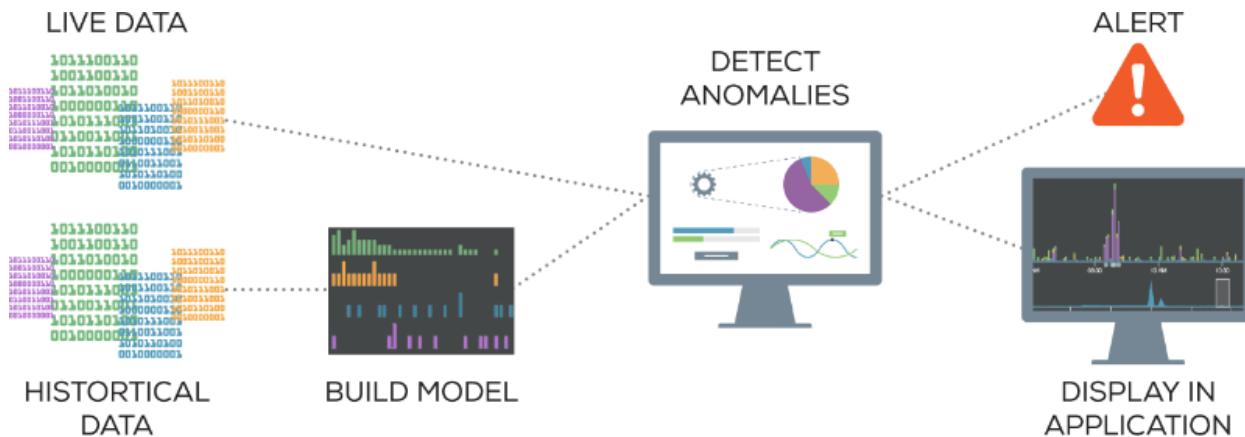
- Outliers are different from noise data
 - ✓ Noise is random error or variance in a measured variable
 - ✓ Noise should be removed before outlier detection
- Outliers are interesting
 - ✓ It violates the mechanism that generates the normal data

Supervised Learning: Novelty Detection

- Applications
 - ✓ Industrial monitoring
 - ✓ IT security
 - ✓ Healthcare informatics
 - ✓ Sensor network
 - ✓ Computer vision
 - ✓ Credit card fraud detection
 - ✓ Telecom fraud detection
 - ✓ Customer segmentation/Medical analysis

Supervised Learning: Novelty Detection

- Applications: System Security



Supervised Learning: Novelty Detection

Data Preparation

ADFA-LD Dataset

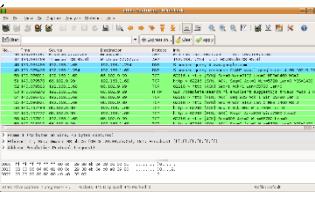
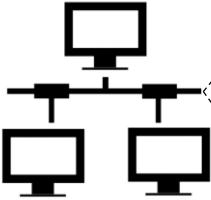
Syscall Trace

265	104	265	104	3	175
104	142	3	3	3	104
265	104	142	142	175	
146	142	146	142	265	3
175	175	142	142	175	
119	265	142	146	265	
146	119	142	146	142	
142	142	142	146	104	
265	3	119	3	265	119
146	146	146	265	146	
142	142	146	142	119	



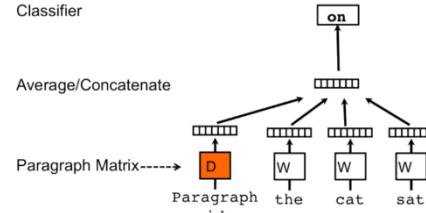
CICIDS2017 Dataset

Packet Capture

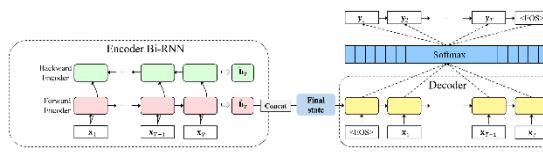


Vectorization

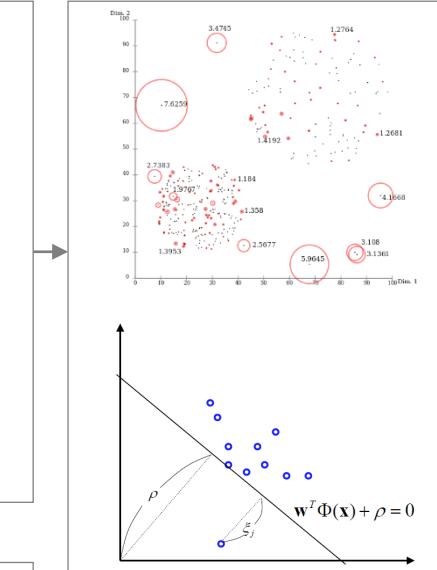
Doc2vec



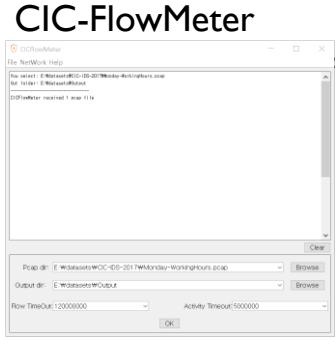
RNN-AutoEncoder



D-dimensional vector



Features

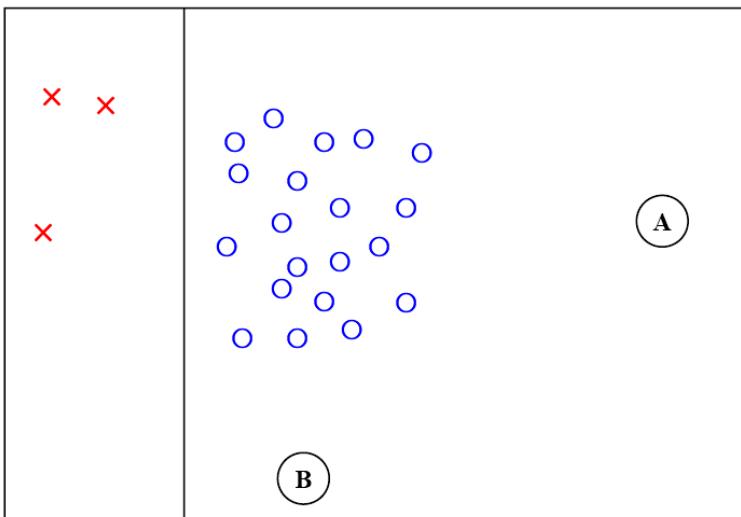


CSV Format

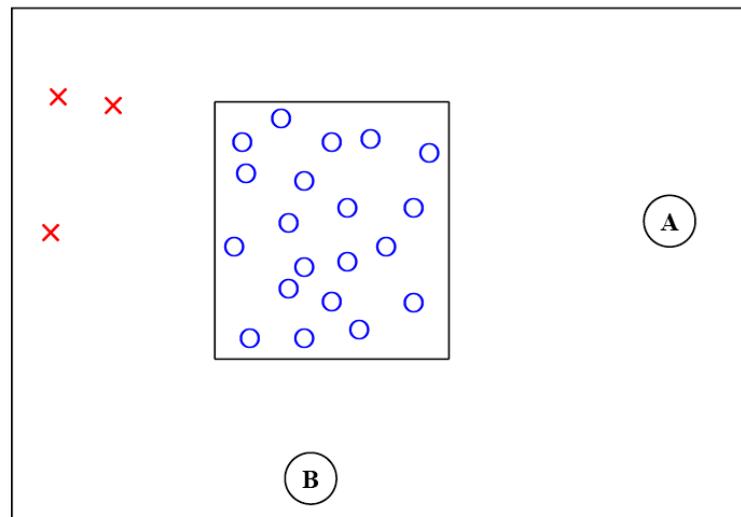
A	B	C	D	E	F	G	H	I	J	K	L	M	N
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2	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	4	2	0	12	0	6	
3	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	4	2	0	12	0	6	
4	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	4	2	0	12	0	6	
5	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	4	2	0	12	0	6	
6	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	4	2	0	12	0	6	
7	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	4	2	0	12	0	6	
8	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	4	2	0	12	0	6	
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10	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	609	7	4	484	414	233	
11	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	876	9	4	696	1064	313	
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15	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	1170	9	4	3160	3069	1965	
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22	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	973	9	4	3112	3012	1561	
23	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	7	4	2114	2336	1398		
24	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	1703	13	11	4122	1038	1660	
25	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	85	4	484	270	2465		
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39	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	951	7	4	2114	2336	1398	
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43	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	951	7	4	2114	2336	1398	
44	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	7033	13	11	4122	1038	1660	
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62	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	85	4	484	270	2465		
63	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	951	7	4	2114	2336	1398	
64	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	7033	13	11	4122	1038	1660	
65	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	85	4	484	270	2465		
66	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	85	4	484	270	2465		
67	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	951	7	4	2114	2336	1398	
68	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	7033	13	11	4122	1038	1660	
69	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	85	4	484	270	2465		
70	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	85	4	484	270	2465		
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74	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	85	4	484	270	2465		
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79	192.168.1.10	192.168.1.100	80	HTTP	GET	6/30/2021	951	7	4	2114	2336	1398	
80	192.168.1.10	192.168.1.100	80										

Supervised Learning: Novelty Detection

- Classification vs. Novelty Detection



Binary classification

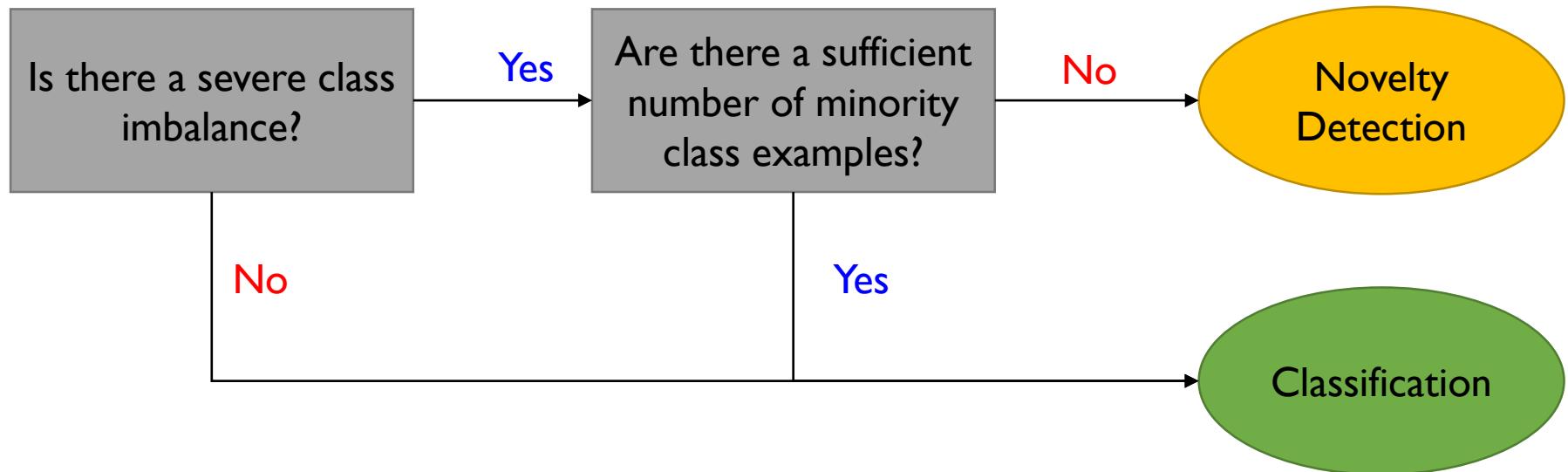


Novelty detection

Supervised Learning: Novelty Detection

- Classification vs. Novelty Detection

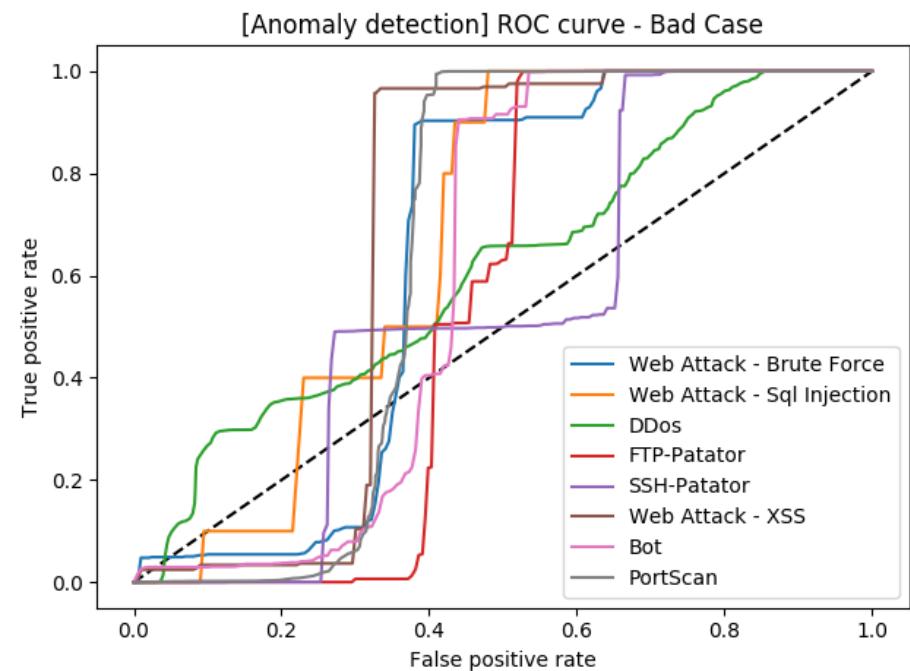
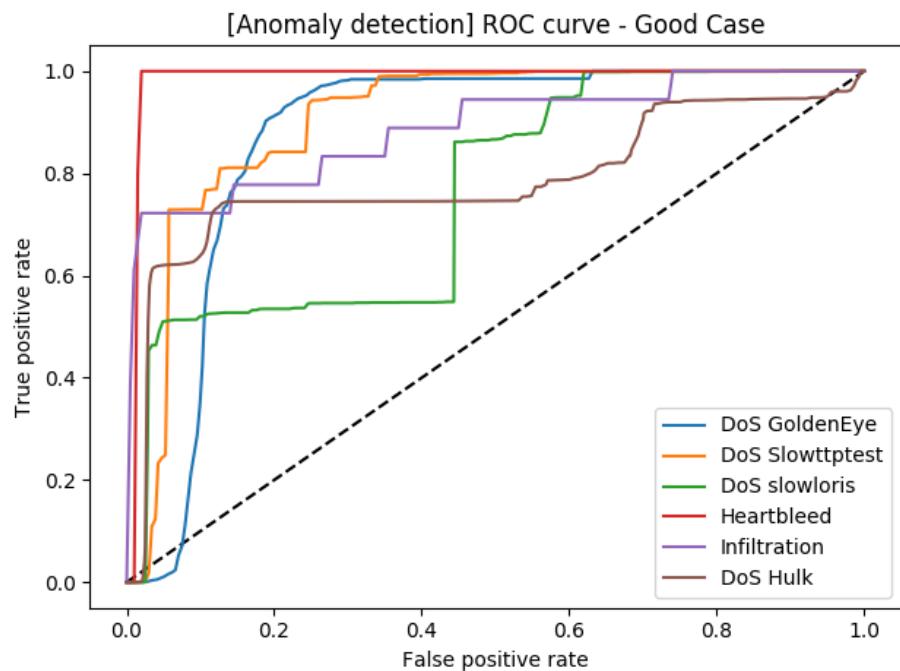
✓ Which one to use?



Supervised Learning: Novelty Detection

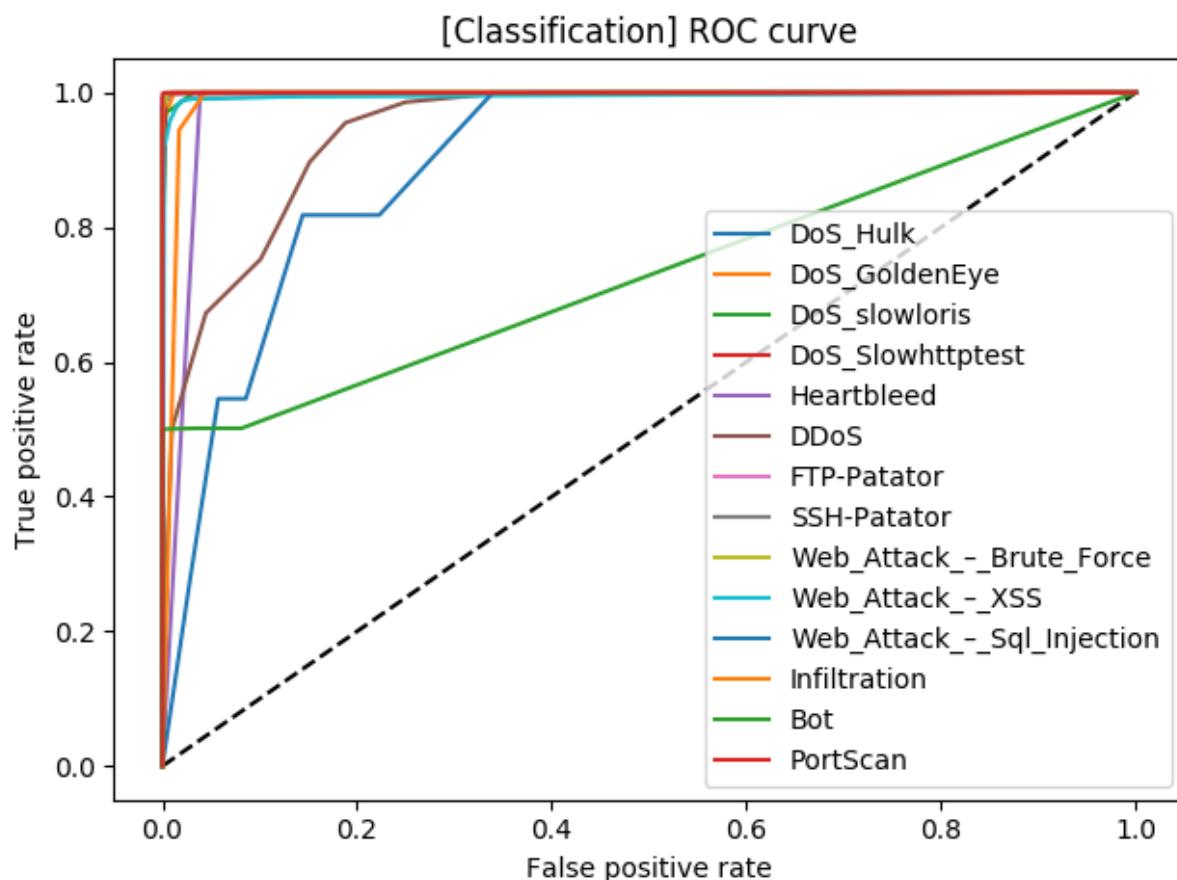
- Classification vs. Novelty Detection

- ✓ Performance comparison for network traffic anomaly detection

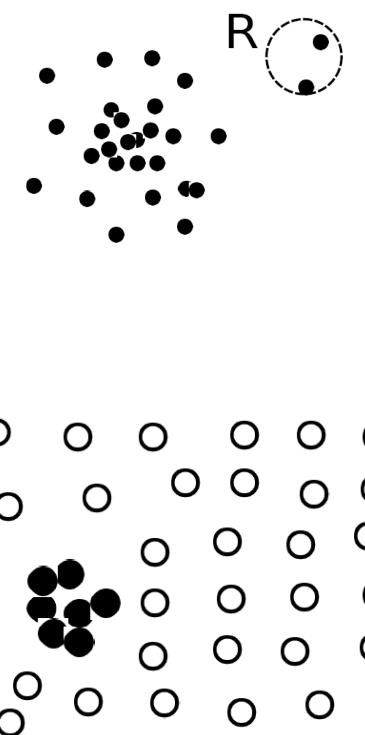


Supervised Learning: Novelty Detection

- Classification vs. Novelty Detection
 - ✓ Performance comparison for network traffic anomaly detection

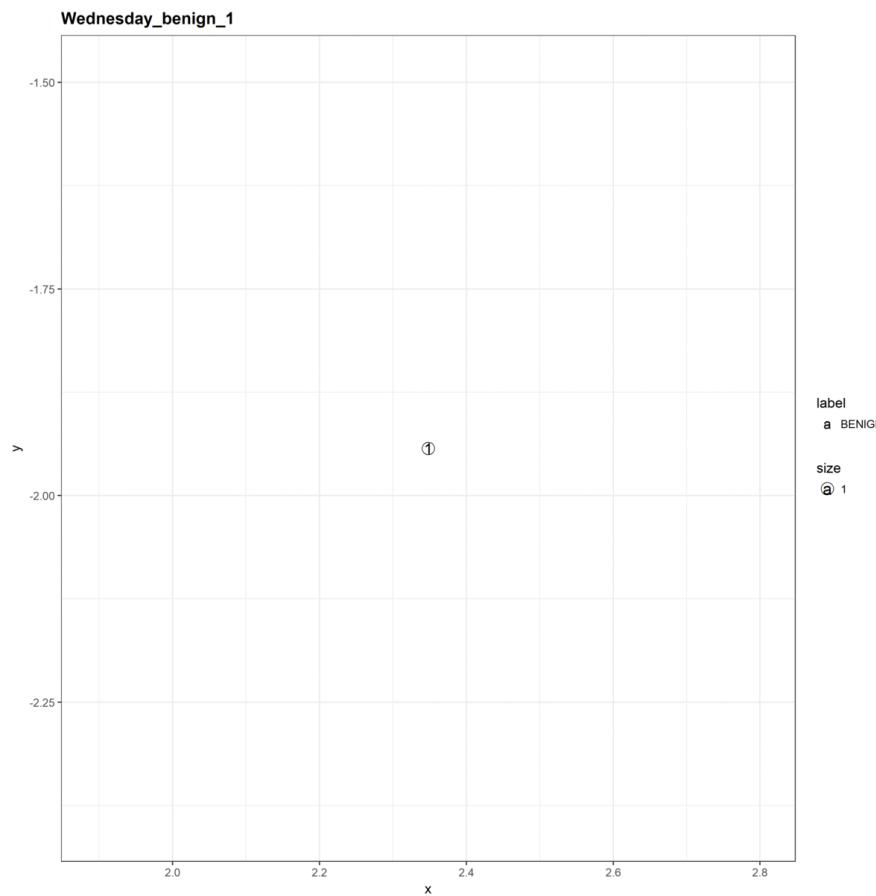


Type of Novel Data (Outliers)

- Global outlier
 - ✓ Object that significantly deviates from the rest of the data set
 - ✓ Ex) Credit card fraud detection
 - ✓ Issue: find an appropriate measurement of deviation
 - Contextual outlier (local outlier)
 - ✓ Object that deviates significantly based on a selected context
 - ✓ Ex) 30°C in Alaska vs. 30°C in Sahara
 - ✓ Issue: How to define or formulate meaningful context?
 - Collective outlier
 - ✓ A subset of data objects collectively deviate significantly from the whole data set, even if the individual data objects may not be outliers
 - ✓ Ex) Denial-of-Service (DoS) attack
- 
- The diagram consists of two parts. The top part shows a scatter plot of data points. A cluster of dark grey dots is labeled 'R' with a dashed circle around it, representing a global outlier. The bottom part shows a grid of data points. A small cluster of dark grey dots is highlighted with a dashed circle, representing a collective outlier.

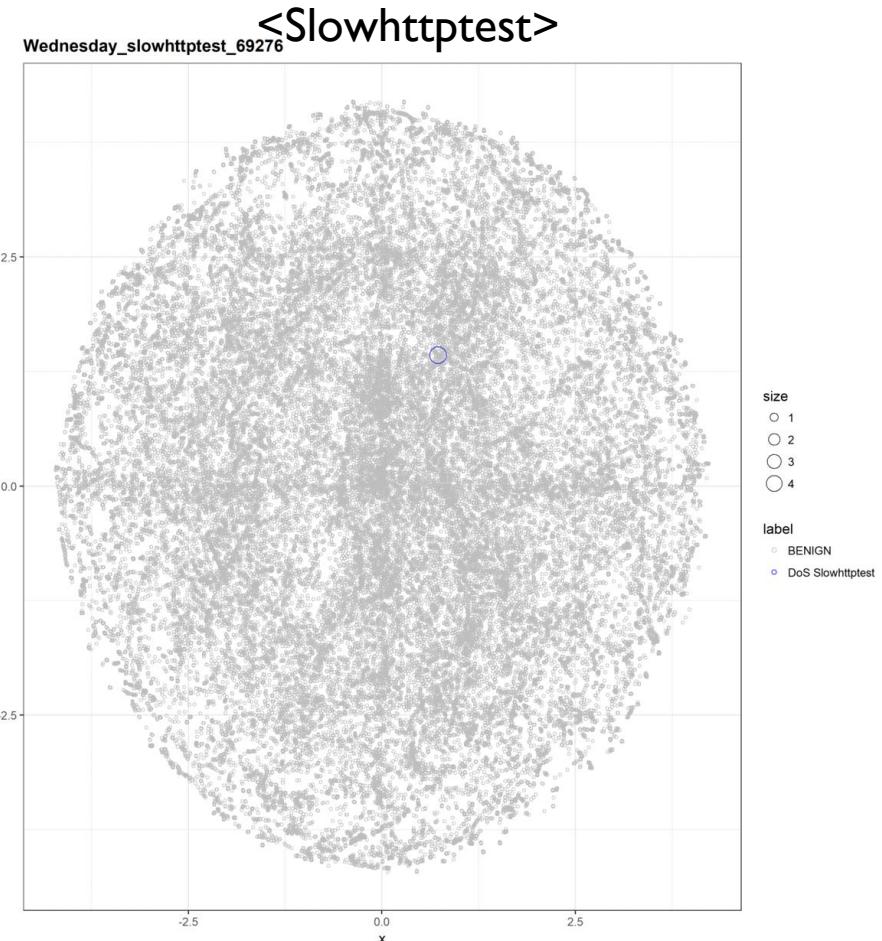
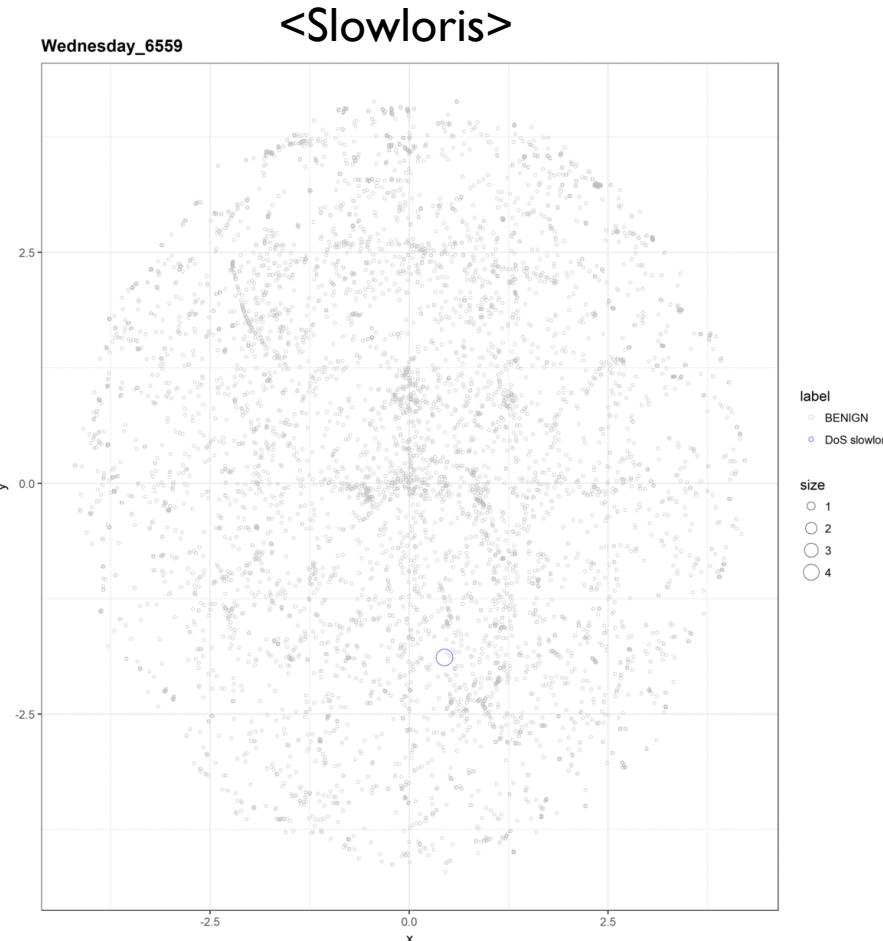
Type of Novel Data (Outliers)

- Collective outlier: An example
 - ✓ Normal traffic (animation by Minsik Park)



Type of Novel Data (Outliers)

- Collective outlier: An example
 - ✓ DoS traffic (animation by Minsik Park)



Challenges

- Modeling normal objects and outliers properly
 - ✓ The border between normal and outlier objects is often a gray area
- Application-specific outlier detection
 - ✓ Choice of distance measure among objects and the model of relationship among objects are often application-dependent
 - ✓ E.g., clinic data: a small deviation could be an outlier; while in marketing analysis, larger fluctuations
- Understandability
 - ✓ Understand why these are outliers: Justification of the detection
 - ✓ Specify the degree of an outlier: the unlikelihood of the object being generated by a normal mechanism

Challenges

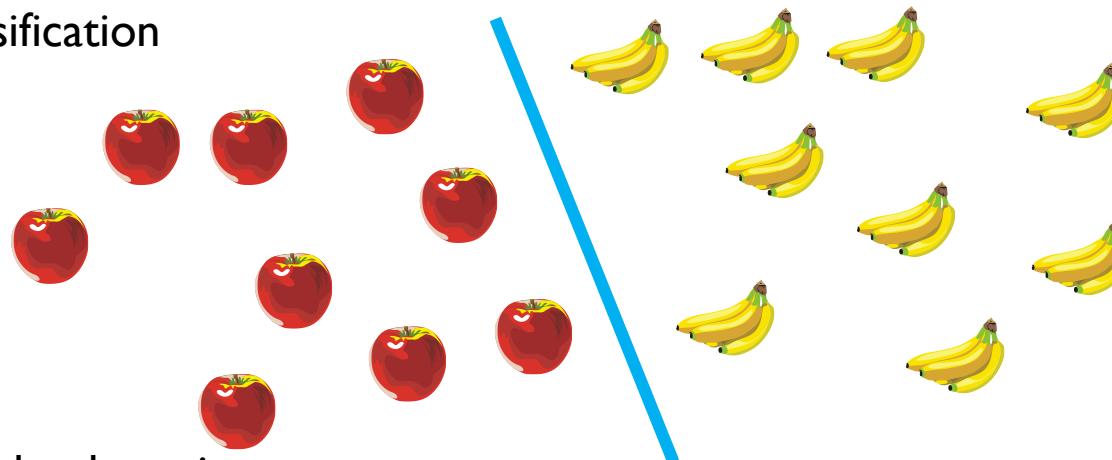
- Novelty detection actually matters

- 분석목표 : 제품 원료품질 검사 데이터(X)로 제품불량(Y)을 예측
- 데이터 분포
 - X 변수 : 재료 품질검사 데이터 560 개 항목
 - Y 범주 : 불량, 정상
 - 비중 : 정상 93%, 불량 7%
- 분석기법
 - 지도학습 : KNN, Random Forest
 - 비지도학습 : Gaussian Mixture 모델
- 분석과정 및 결과
 - 1) 전체 데이터로 학습
 - Accuracy 93%
 - 문제점 : 불량데이터에 대한 예측성능이 매우 낮음 (Precision 0.38, Recall 0.01, f1-score 0.02)
 - 2) 정상, 불량 학습데이터 비중을 맞춤 (1 : 1)
 - Accuracy 66%
 - 문제점 : 불량데이터 예측성능은 향상되었으나 (Precision 0.38, Recall 0.71), 전체 Accuracy 낮아짐 (66%)
 - 3) 이상치 탐지 분석 (가우시안 혼합모델)
 - 비정상 데이터에 대한 예측성능이 지도학습과 유사한 수준으로 낮음
 - 4) PolyNomial 방법
 - X 변수를 증가시키는 방법 : 분류분석이고, 이미 X변수가 많아서 시도하지 않음
- 문의사항
 - 판단기준 : 편중된 데이터에 대해서 어느 정도의 수치가 나왔을 때 연관성이 있다고 판단해야 할지 판단기준은?
 - 분석방향 : 편중된 데이터에 대해서 불량(이상치)을 예측할 수 있도록 모델학습 시, 시도해 볼만한 방법은?

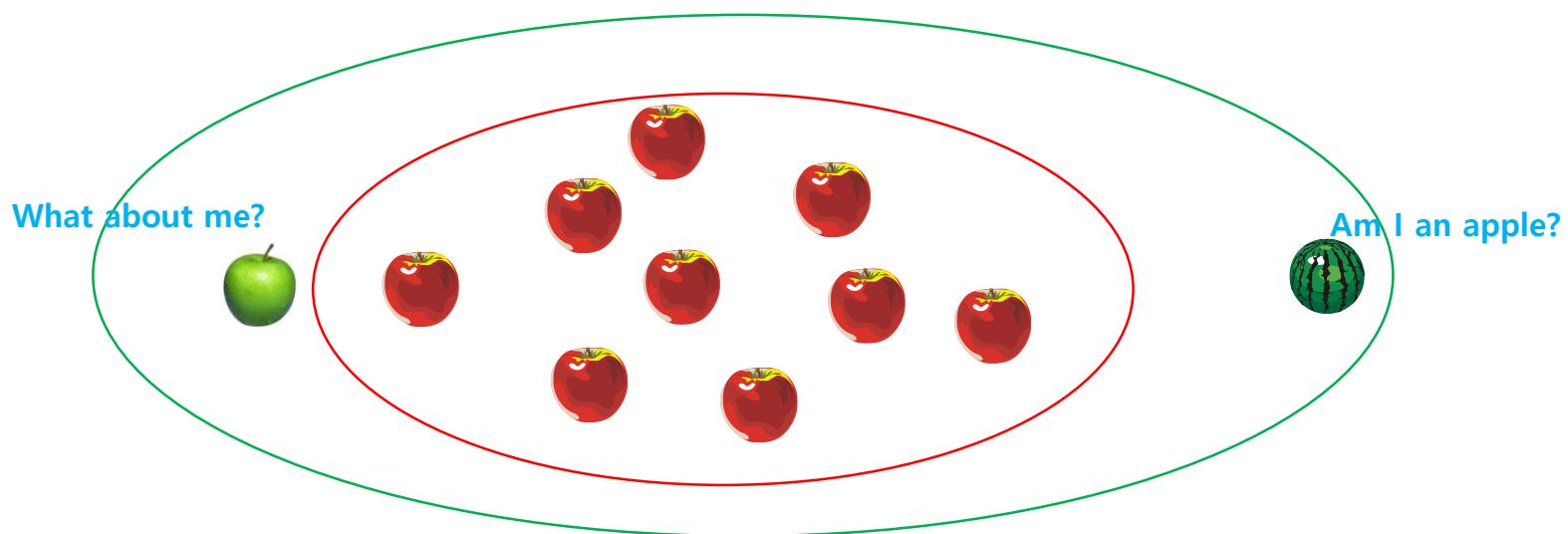
Supervised Learning: Novelty Detection

- The way by which the classification and novelty detection learns from data

✓ Classification

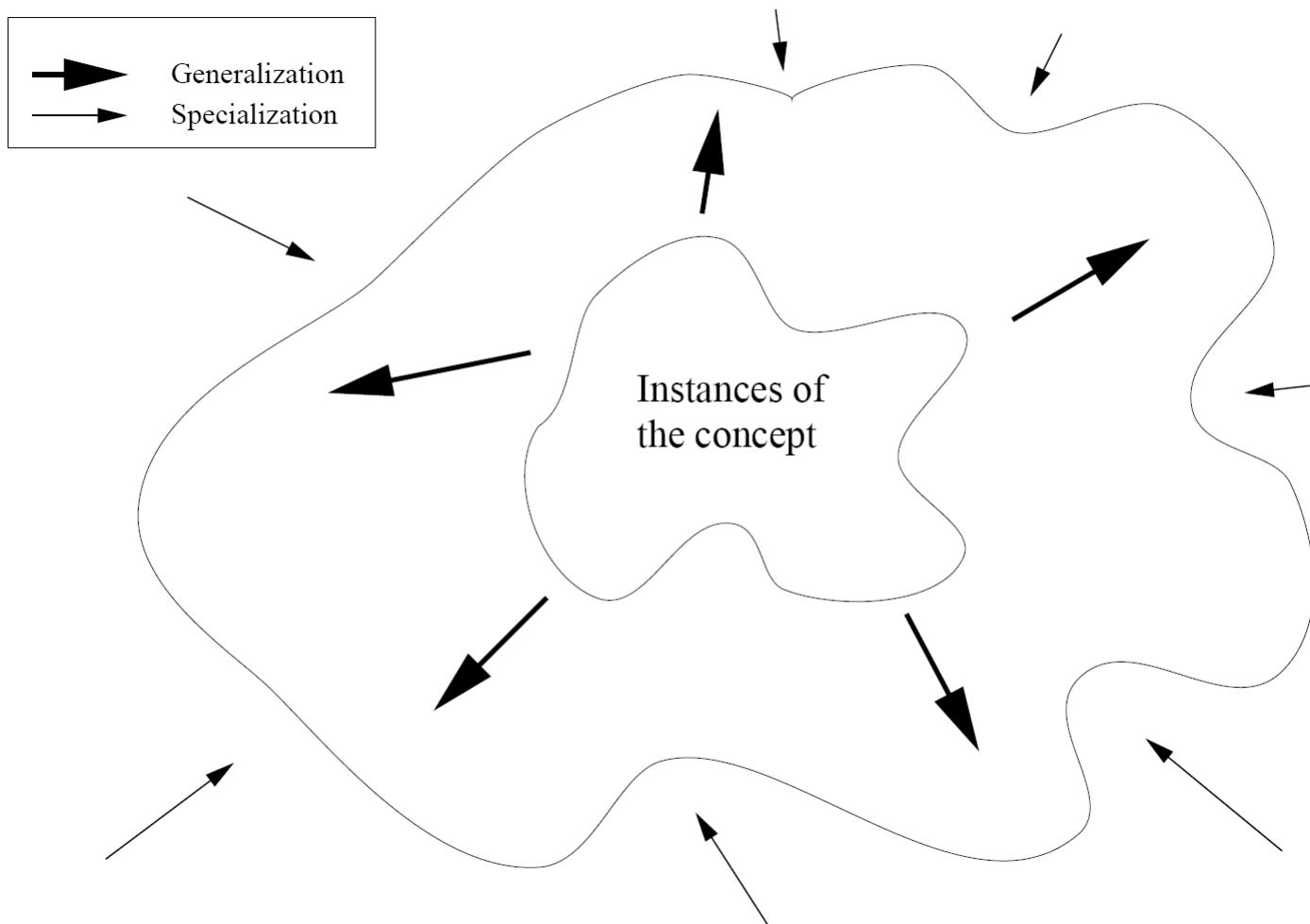


✓ Novelty detection



Supervised Learning: Novelty Detection

- Generalization vs. Specialization

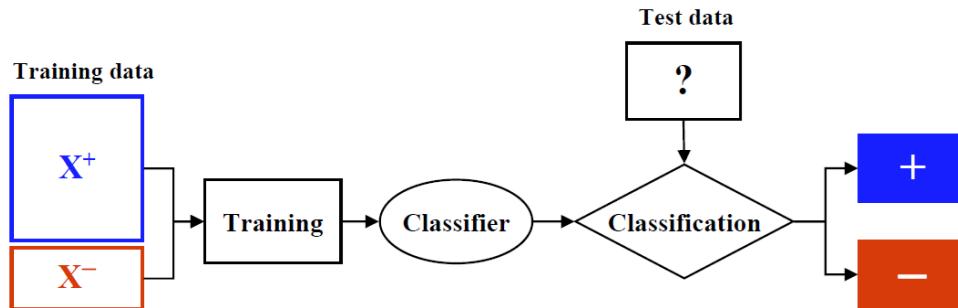


ND Approach

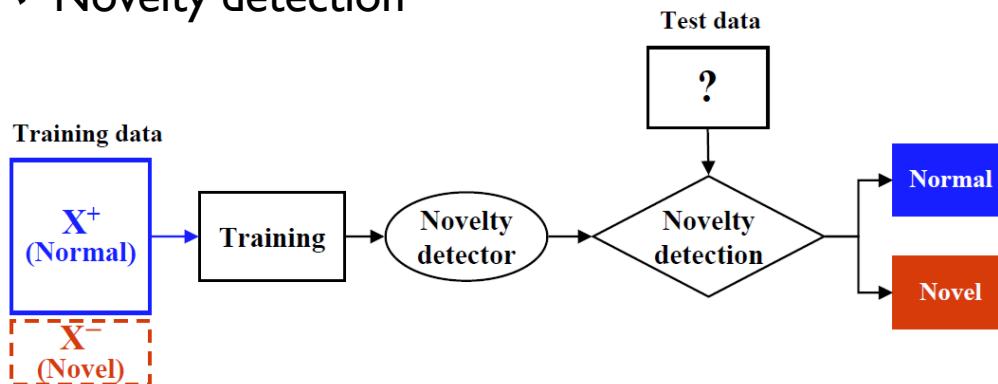
- Assumption

- ✓ There are considerably more “normal” observations than “abnormal” observations in the data

- ✓ Classification



- ✓ Novelty detection



Performance Measures

- Performance Measures
 - ✓ Confusion matrix for novelty detection

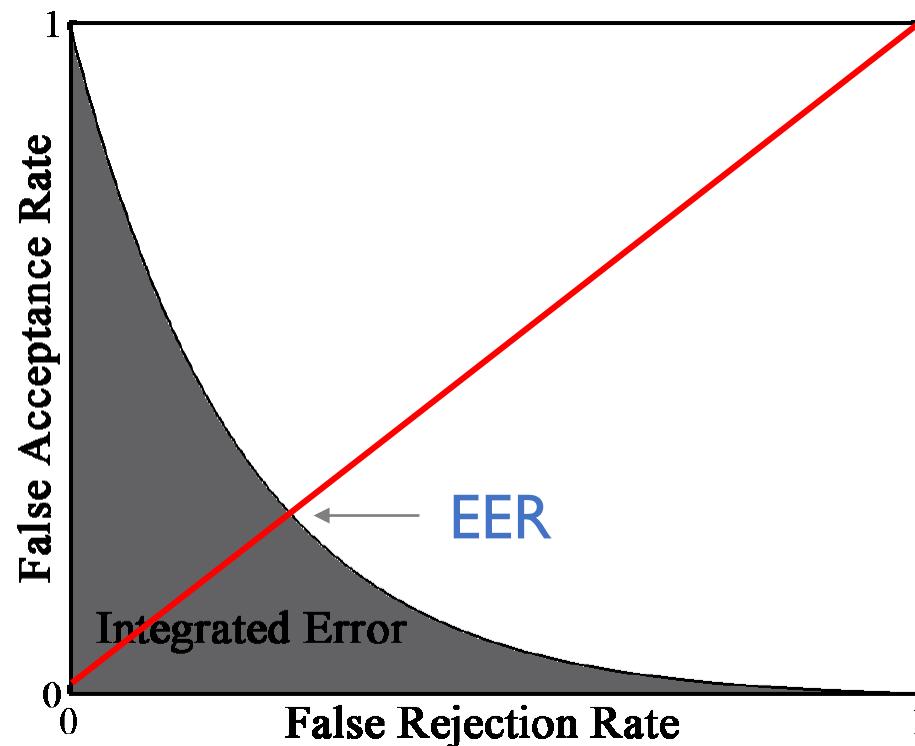
		Predicted class	
		Novel	Normal
Actual class	Novel	A	B
	Normal	C	D

- ✓ Performance measures when the cut-off (threshold) is set

Metric	Description
Detection Rate	$(\text{Identified as novel}) / (\text{Actually novel}) = A / (A+B)$
False Rejection Rate (FRR)	$(\text{Rejected as novel}) / (\text{Actually normal}) = C / (C+D)$
False Acceptance Rate (FAR)	$(\text{Accepted as normal}) / (\text{Actually novel}) = B / (A+B)$

Performance Measures

- To evaluate an intrinsic performance of novelty detection algorithms
 - ✓ Equal error rate (EER): Error rate where the FAR and FRR are the same
 - ✓ Integrated Error (IE): the area under the FRR-FAR curve
 - AUROC for classification: the higher the better
 - IE for novelty detection: the lower the better



AGENDA

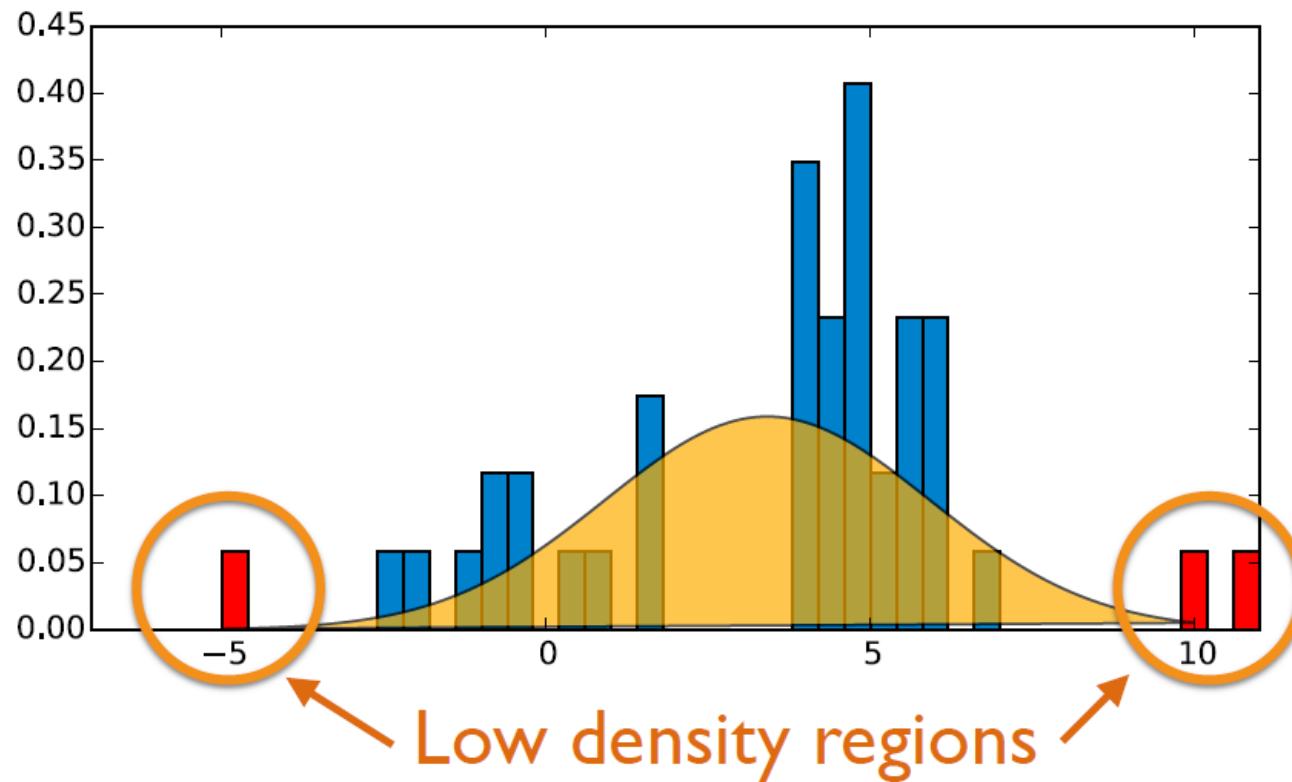
- 01 Novelty Detection: Overview
- 02 Density-based Novelty Detection
- 03 Distance/Reconstruction-based ND
- 04 Model-based Novelty Detection

Density-based Novelty Detection

Gramfort (2006)

- Purpose

- ✓ Estimate the data-driven density function
- ✓ If a new instance has a low probability according the trained density function, it will be identified as novel

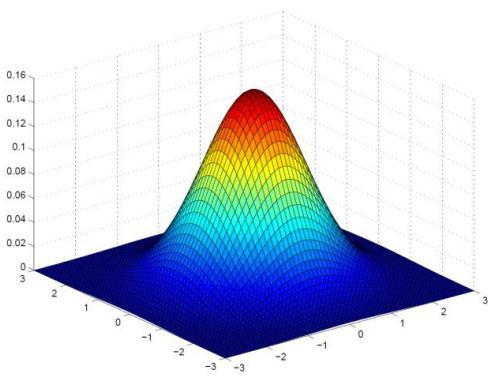


Density-based Novelty Detection

- Purpose

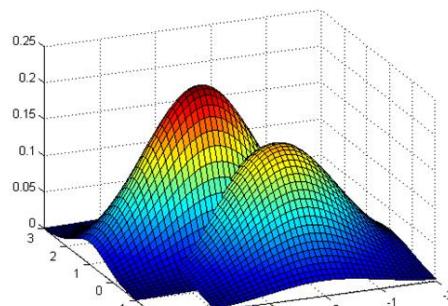
- ✓ Estimate the data-driven density function
- ✓ If a new instance has a low probability according the trained density function, it will be identified as novel

Gaussian Density Estimation



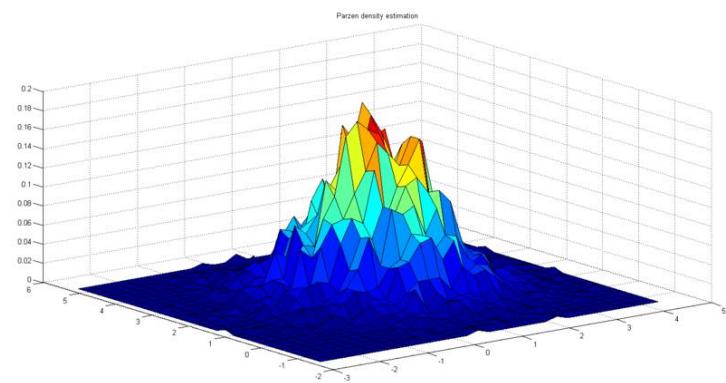
Number of modals
= 1

Mixture of Gaussian Density Estimation



| <
Number of modals
< Number of instances

Kernel Density Estimation

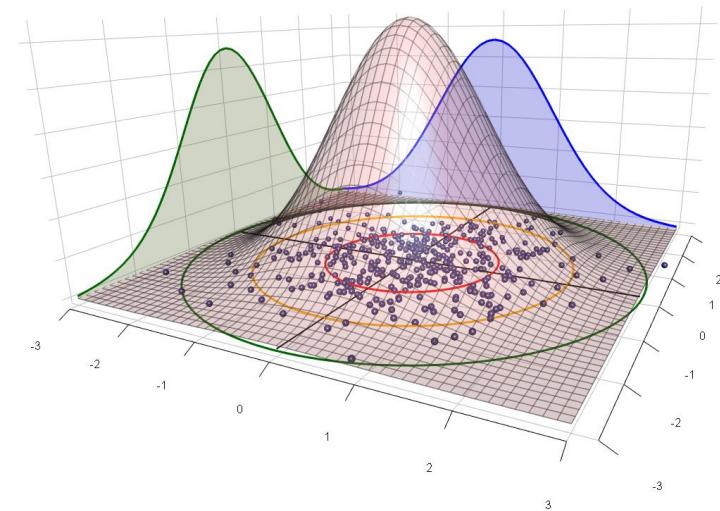
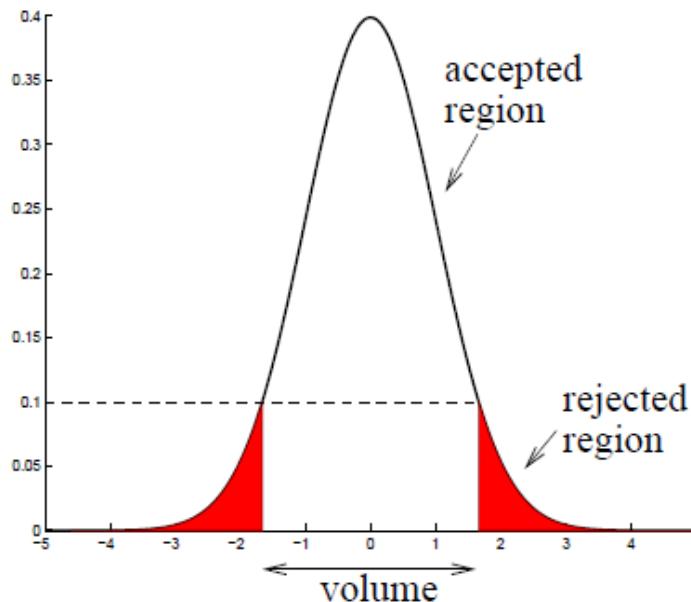


Number of modals
= Number of instances

Gaussian Density Estimation

- Gaussian Density Estimation

- ✓ Assume that the observed data are drawn from a Gaussian distribution



$$p(\mathbf{x}) = \frac{1}{(2\pi)^{d/2} |\Sigma|^{1/2}} \exp \left[\frac{1}{2} (\mathbf{x} - \boldsymbol{\mu})^T \Sigma^{-1} (\mathbf{x} - \boldsymbol{\mu}) \right]$$

$$\boldsymbol{\mu} = \frac{1}{n} \sum_{\mathbf{x}_i \in \mathbf{X}^+} \mathbf{x}_i \quad (\text{mean vector}), \quad \Sigma = \frac{1}{n} \sum_{\mathbf{x}_i \in \mathbf{X}^+} (\mathbf{x}_i - \boldsymbol{\mu})(\mathbf{x}_i - \boldsymbol{\mu})^T \quad (\text{covariance matrix})$$

Gaussian Density Estimation

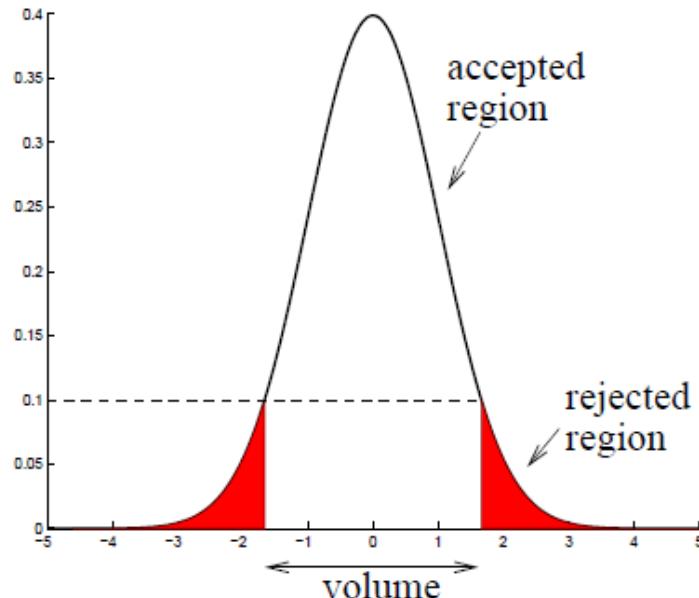
- Gaussian Density Estimation

- ✓ Advantages

- In insensitive to scaling of the data

$$p(\mathbf{x}) = \frac{1}{(2\pi)^{d/2} |\Sigma|^{1/2}} \exp\left[\frac{1}{2} (\mathbf{x} - \boldsymbol{\mu})^T \boldsymbol{\Sigma}^{-1} (\mathbf{x} - \boldsymbol{\mu})\right]$$

- Possible to compute analytically the optimal threshold



Gaussian Density Estimation

- Gaussian Density Estimation

- ✓ Parameter estimation: μ and σ^2

- ✓ For one-dimensional data,

$$L = \prod_{i=1}^N P(x_i | \mu, \sigma^2) = \prod_{i=1}^N \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x_i - \mu)^2}{2\sigma^2}\right)$$

$$\log L = -\frac{1}{2} \sum_{i=1}^N \frac{(x_i - \mu)^2}{\sigma^2} - \frac{N}{2} \log(2\pi\sigma^2)$$

Gaussian Density Estimation

- Gaussian Density Estimation

✓ Maximum likelihood estimation, let's set $\gamma = 1/\sigma^2$

$$\log L = -\frac{1}{2} \sum_{i=1}^N \gamma(x_i - \mu)^2 - \frac{N}{2} \log(2\pi) + \frac{N}{2} \log(\gamma)$$

$$\frac{\partial \log L}{\partial \mu} = \gamma \sum_{i=1}^N (x_i - \mu) = 0 \rightarrow \mu = \frac{1}{N} \sum_{i=1}^N x_i$$

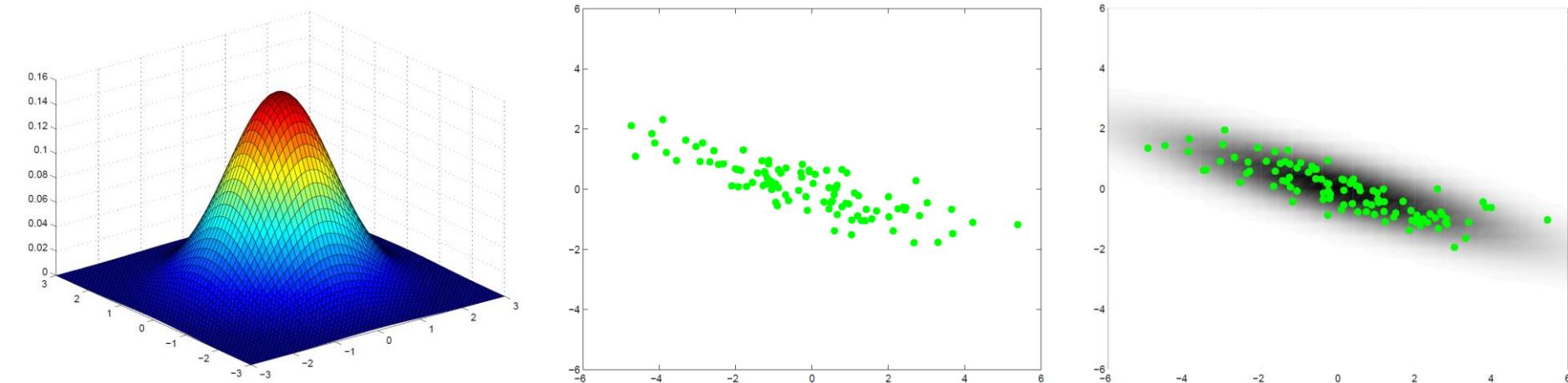
$$\frac{\partial \log L}{\partial \gamma} = -\frac{1}{2} \sum_{i=1}^N (x_i - \mu)^2 + \frac{N}{2\gamma} = 0 \rightarrow \sigma^2 = \frac{1}{N} \sum_{i=1}^N (x_i - \mu)^2$$

Gaussian Density Estimation

- Gaussian Density Estimation

✓ In general,

$$\boldsymbol{\mu} = \frac{1}{N} \sum_{i=1}^N \mathbf{x}_i, \quad \boldsymbol{\Sigma} = \frac{1}{N} \sum_{i=1}^N (\mathbf{x}_i - \boldsymbol{\mu})(\mathbf{x}_i - \boldsymbol{\mu})^T$$



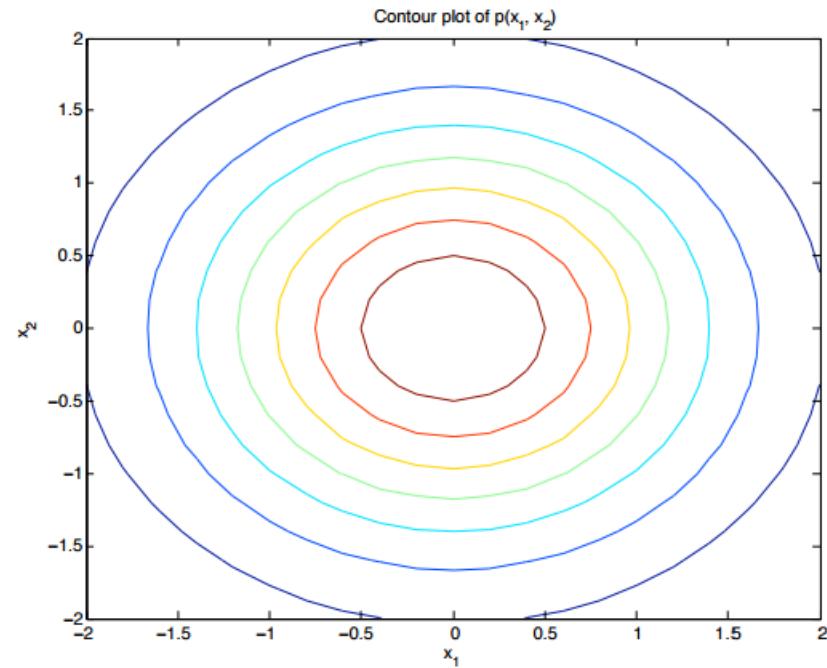
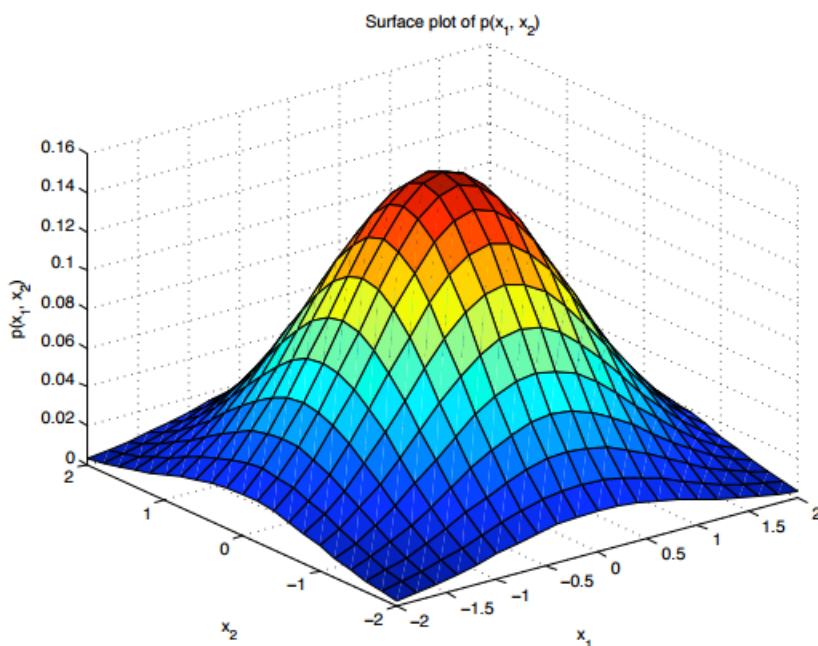
Gaussian Density Estimation

- Gaussian Density Estimation

- ✓ The shape of Gaussian distribution according to the Covariance matrix type

Spherical

$$\Sigma = \sigma^2 \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix}$$



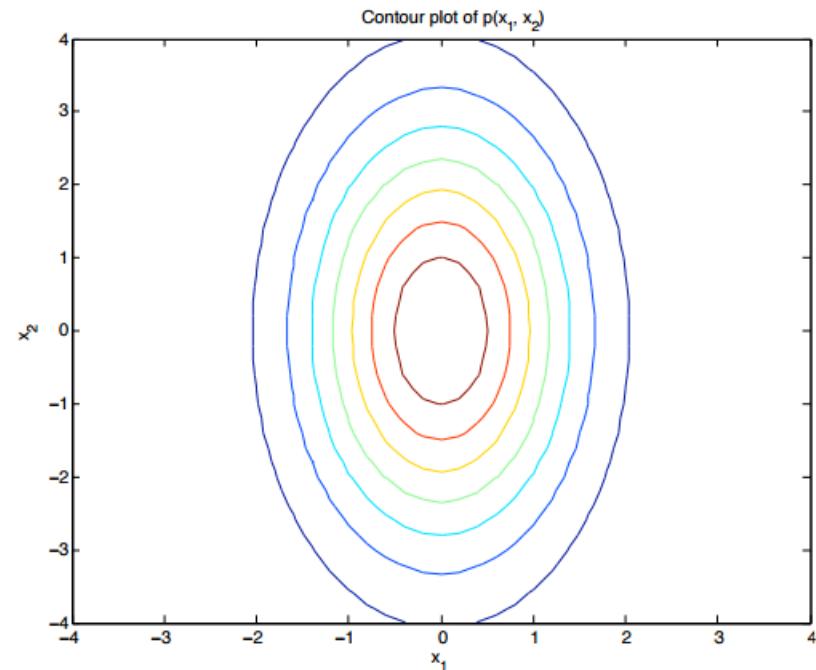
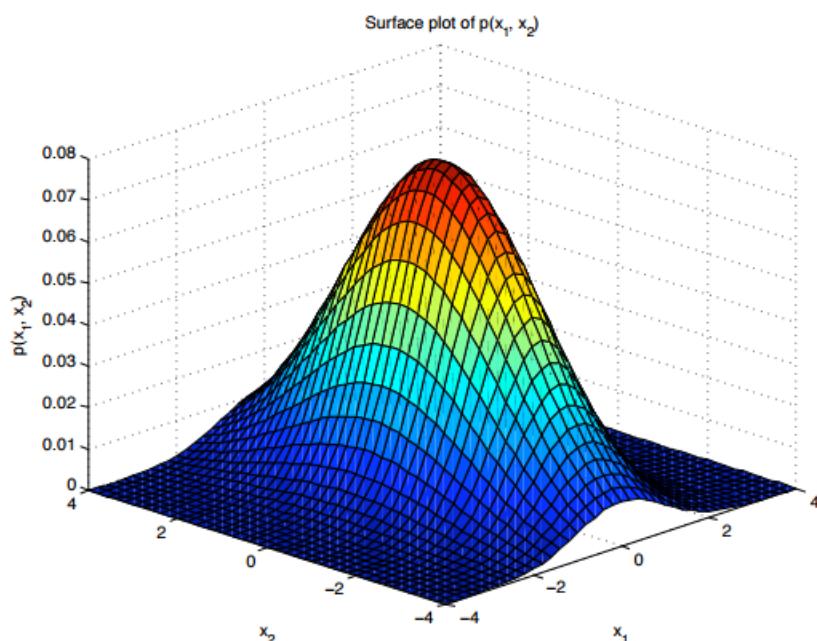
(a) Spherical Gaussian (diagonal covariance, equal variances)

Gaussian Density Estimation

- Gaussian Density Estimation
 - ✓ The shape of Gaussian distribution according to the Covariance matrix type

Diagonal

$$\Sigma = \begin{bmatrix} \sigma_1^2 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & \sigma_d^2 \end{bmatrix}$$



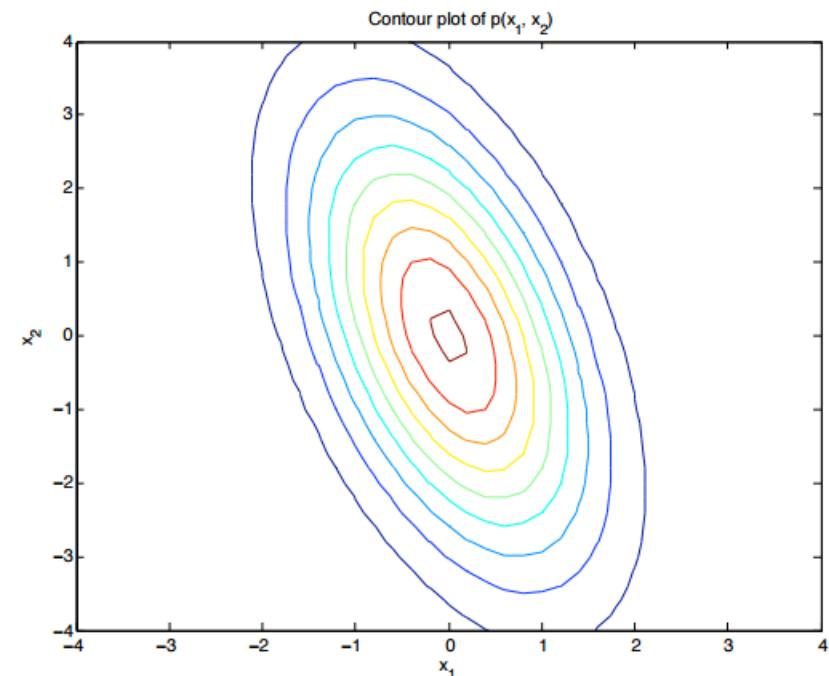
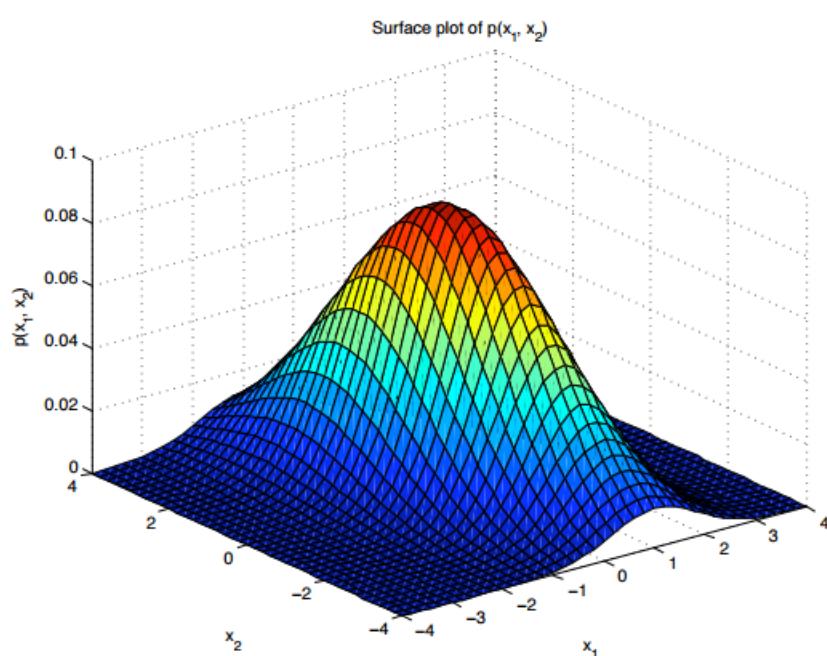
(b) Gaussian with diagonal covariance matrix

Gaussian Density Estimation

- Gaussian Density Estimation

- ✓ The shape of Gaussian distribution according to the Covariance matrix type

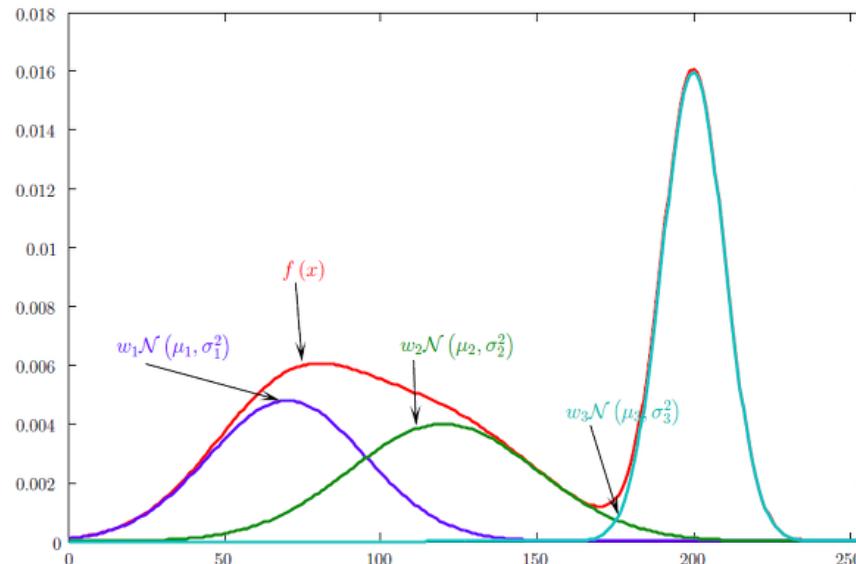
Full $\Sigma = \begin{bmatrix} \sigma_{11} & \cdots & \sigma_{1d} \\ \vdots & \ddots & \vdots \\ \sigma_{d1} & \cdots & \sigma_{dd} \end{bmatrix}$



(c) Gaussian with full covariance matrix

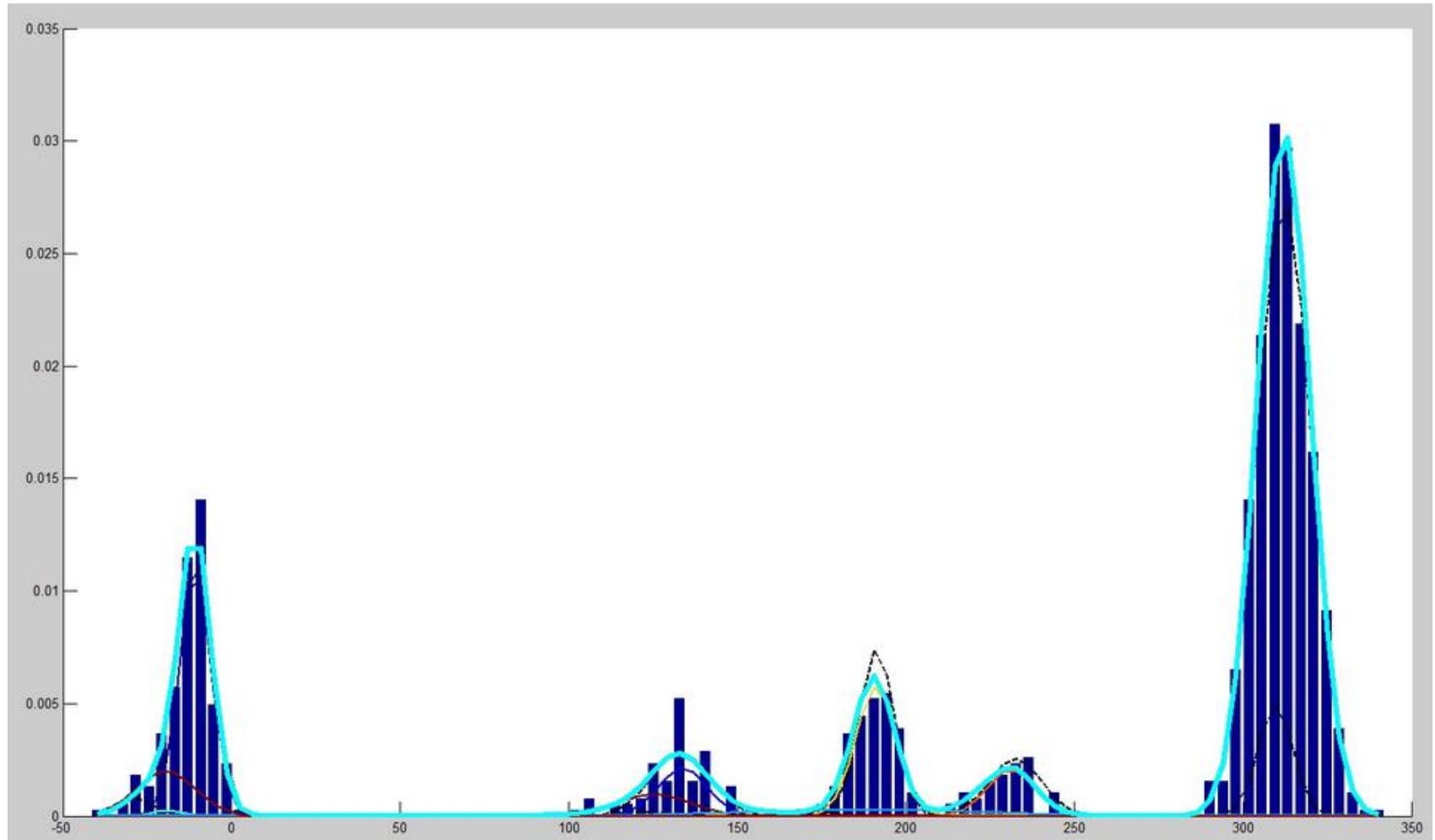
Mixture of Gaussian Density Estimation

- Mixture of Gaussian (MoG) Density Estimation
 - ✓ Gaussian Density Estimation
 - assumes a very strong model of the data: unimodal and convex
 - ✓ MoG
 - an extension of Gaussian that allows multi-modal distribution
 - a linear combination of normal distributions
 - Has a smaller bias than the single Gaussian distribution, but requires far more data for training



Mixture of Gaussian Density Estimation

- MoG example



Mixture of Gaussian Density Estimation

- Components of MoG
 - ✓ Probability of an instance belonging to the normal class

$$p(\mathbf{x}|\lambda) = \sum_{m=1}^M w_m g(\mathbf{x}|\boldsymbol{\mu}_m, \boldsymbol{\Sigma}_m)$$

- ✓ Distribution of each Gaussian model

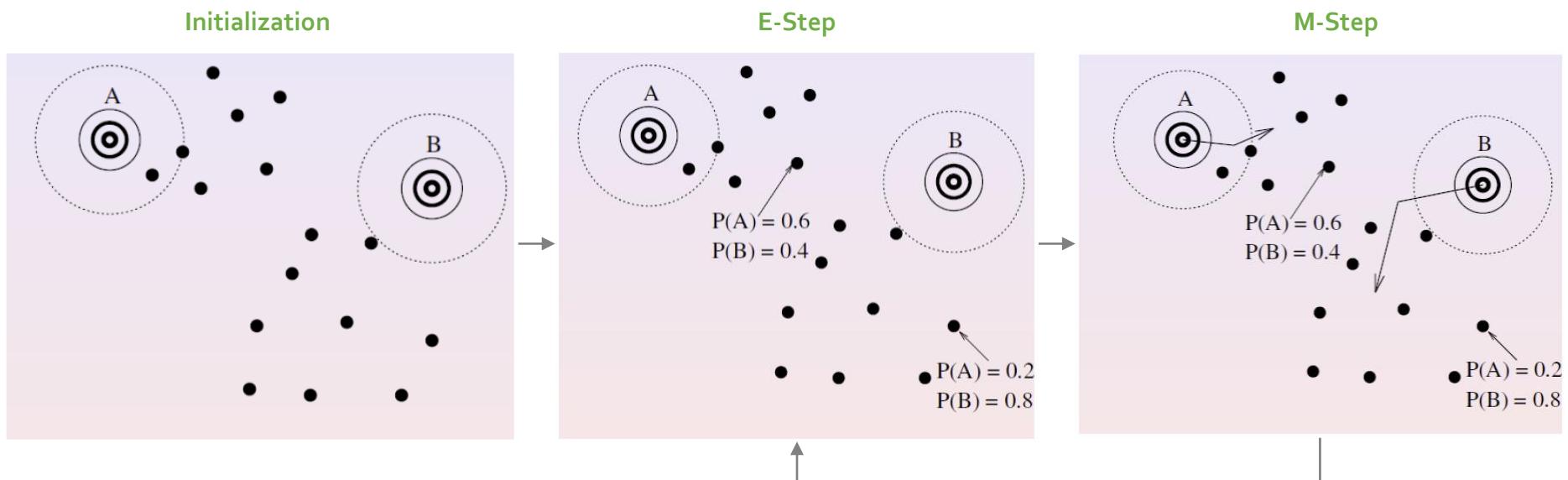
$$g(\mathbf{x}|\boldsymbol{\mu}_m, \boldsymbol{\Sigma}_m) = \frac{1}{(2\pi)^{d/2} |\boldsymbol{\Sigma}_m|^{1/2}} \exp \left[\frac{1}{2} (\mathbf{x} - \boldsymbol{\mu}_m)^T \boldsymbol{\Sigma}_m^{-1} (\mathbf{x} - \boldsymbol{\mu}_m) \right]$$

$$\lambda = \{w_m, \boldsymbol{\mu}_m, \boldsymbol{\Sigma}_m\}, \quad m = 1, \dots, M$$

Mixture of Gaussian Density Estimation

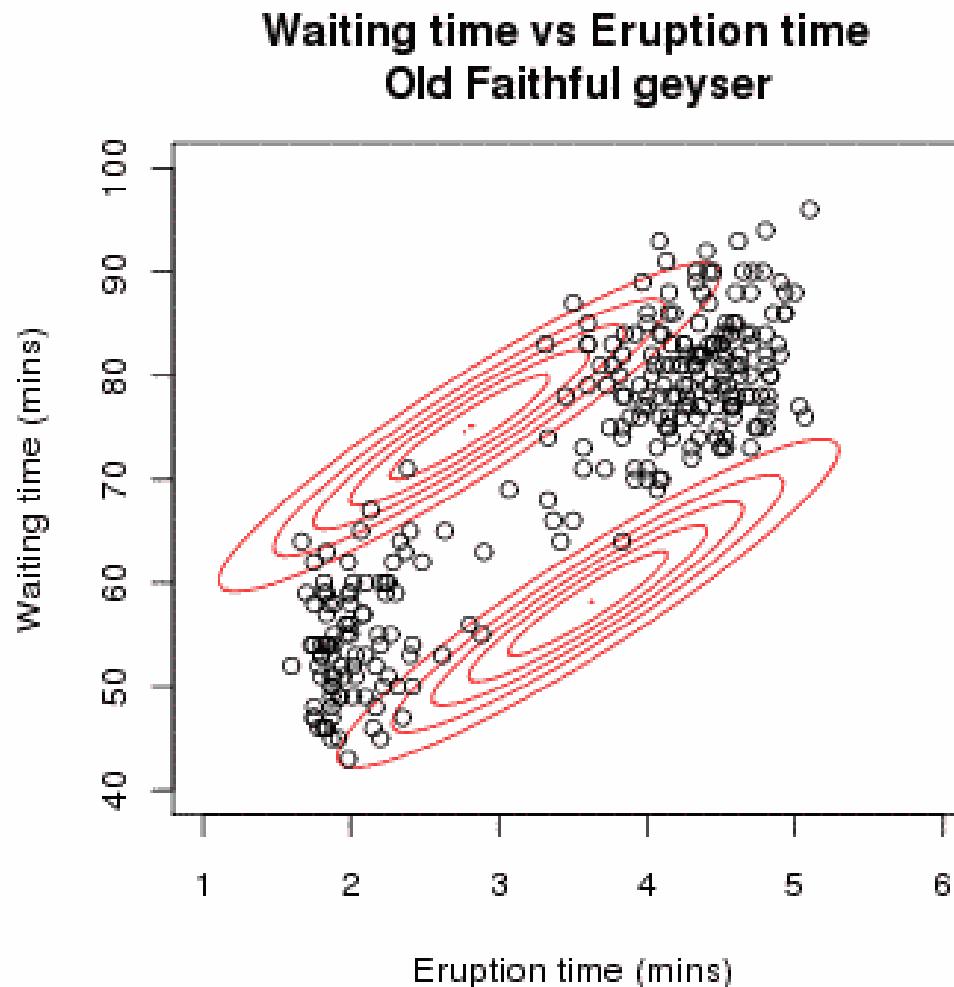
- Expectation-Maximization Algorithm

- ✓ E-Step: Given the current estimate of the parameters, compute the conditional probabilities
- ✓ M-Step: Update the parameters to maximize the expected likelihood found in the E-Step



Mixture of Gaussian Density Estimation

- Expectation-Maximization Algorithm: Illustrative example



Mixture of Gaussian Density Estimation

- EM algorithm for MoG

✓ Expectation

$$p(m|\mathbf{x}_i, \lambda) = \frac{w_m g(\mathbf{x}_i | \boldsymbol{\mu}_m, \boldsymbol{\Sigma}_m)}{\sum_{k=1}^M w_k g(\mathbf{x}_i | \boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k)}$$

✓ Maximization

- Mixture weight

$$w_m^{(new)} = \frac{1}{N} \sum_{i=1}^N p(m|\mathbf{x}_i, \lambda)$$

- Means and variances

$$\boldsymbol{\mu}_m^{(new)} = \frac{\sum_{i=1}^N p(m|\mathbf{x}_i, \lambda) \mathbf{x}_i}{\sum_{i=1}^N p(m|\mathbf{x}_i, \lambda)}, \quad \sigma_m^{2(new)} = \frac{\sum_{i=1}^N p(m|\mathbf{x}_i, \lambda) \mathbf{x}_i^2}{\sum_{i=1}^N p(m|\mathbf{x}_i, \lambda)} - \boldsymbol{\mu}_m^{2(new)}$$

Mixture of Gaussian Density Estimation

- The shape of MoG according to the covariance matrix

Spherical

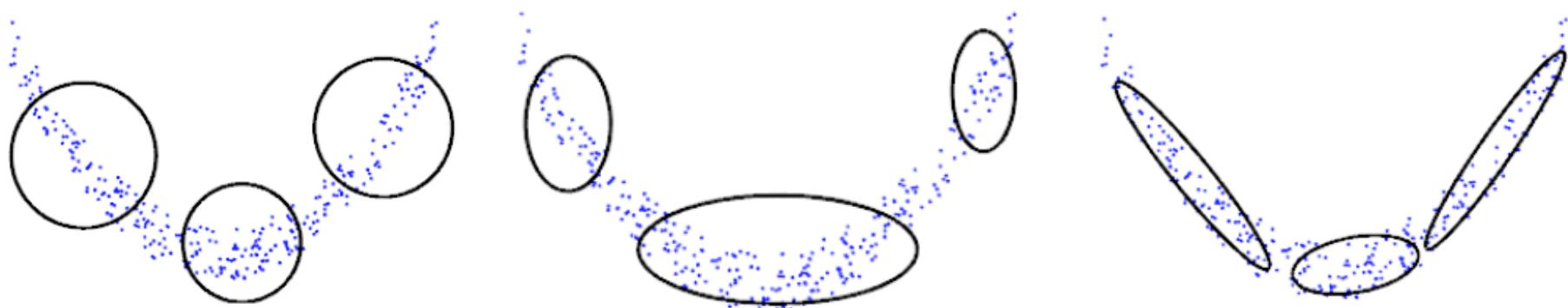
$$\Sigma = \sigma^2 \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix}$$

Diagonal

$$\Sigma = \begin{bmatrix} \sigma_1^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_d^2 \end{bmatrix}$$

Full

$$\Sigma = \begin{bmatrix} \sigma_{11} & \cdots & \sigma_{1d} \\ \vdots & \ddots & \vdots \\ \sigma_{d1} & \cdots & \sigma_{dd} \end{bmatrix}$$



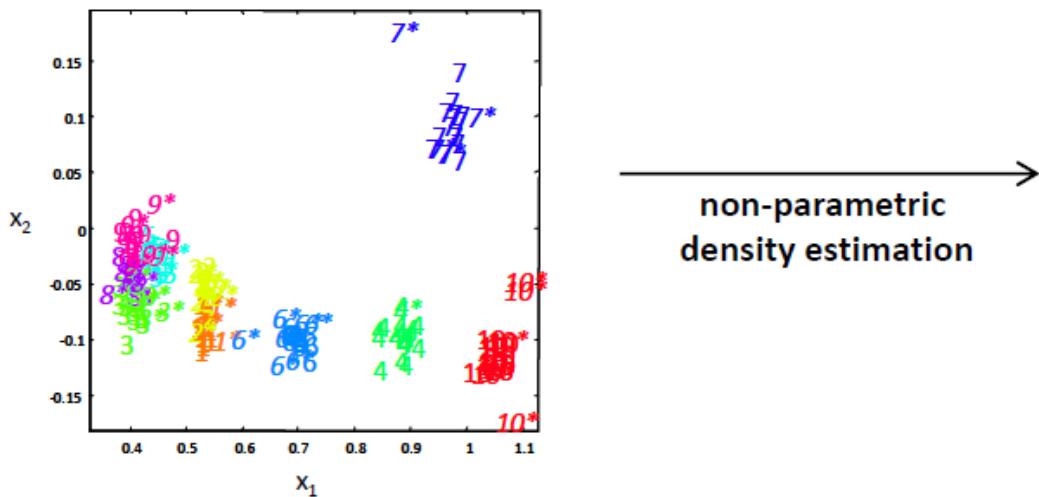
- Less precise
- Very efficient to compute

- More precise
- Efficient to compute

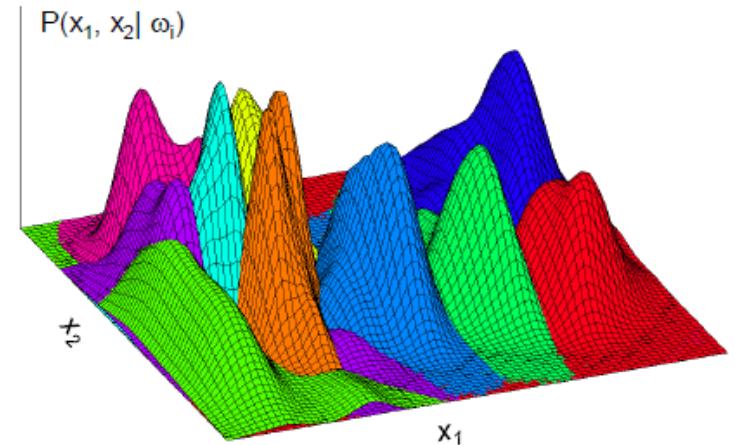
- Very precise
- Less efficient to compute

Kernel-density Estimation

- Kernel-density Estimation
 - ✓ Attempts to estimate the density directly from the data **without assuming a particular form** for the underlying distribution

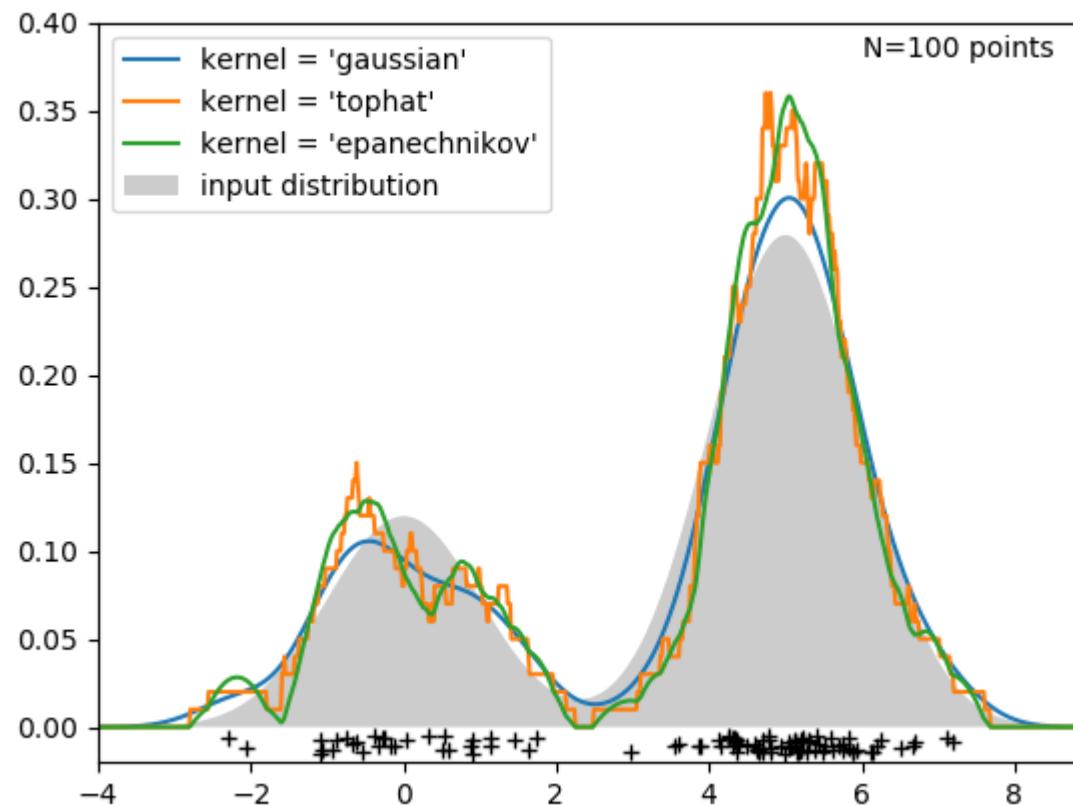


non-parametric
density estimation



Kernel-density Estimation

- Kernel-density Estimation: 1-D example



Kernel-density Estimation

- Kernel-density Estimation

- ✓ The probability that a vector x , drawn from a distribution $p(x)$, will fall in a given region R of the sample space

$$P = \int_R p(x')dx'$$

- ✓ Suppose that N vectors $\{x^1, x^2, \dots, x^n\}$ are drawn from the distribution; the probability that k of these N vectors fall in R is given by

$$P(k) = \binom{N}{k} P^k (1 - P)^{N-k}$$

- ✓ It can be shown that (from the binomial distribution) the mean and variance of the ratio k/N are

$$E\left[\frac{k}{N}\right] = P, \quad Var\left[\frac{k}{N}\right] = \frac{P(1 - P)}{N}$$

Kernel-density Estimation

- Kernel-density Estimation

- ✓ As $N \rightarrow \infty$, the distribution becomes sharper (the variance gets smaller), so we can expect that a good estimate of the probability P can be obtained from the mean fraction of the points that fall within R

$$P \cong \frac{k}{N}$$

- ✓ If we assume that R is so small that $p(x)$ does not vary appreciably within it, then

$$P = \int_R p(x')dx' \cong p(x)V$$

- ✓ where V is the volume enclosed by region R

- ✓ Merging the two previous results

$$P = \int_R p(x')dx' \cong p(x)V = \frac{k}{N}, \quad p(x) = \frac{k}{NV}$$

Kernel-density Estimation

- Kernel-density Estimation

$$p(x) = \frac{k}{NV}, \quad \text{where} \begin{cases} V: \text{volume surrounding } x \\ N: \text{the total number of examples} \\ k: \text{the number of examples inside } V \end{cases}$$

- ✓ Estimation becomes more accurate as we increase the number of sample points N and shrink the volume V
- ✓ In practice, the total number of examples is fixed so that we have to find a compromise for V
 - Large enough to include enough examples within R
 - Small enough to support the assumption that $p(x)$ is constant within R
- ✓ Fix V and determine k from the data: Kernel-density estimation
- ✓ Fix k and determine V from the data: k -nearest neighbor density estimation

Parzen Window Density Estimation

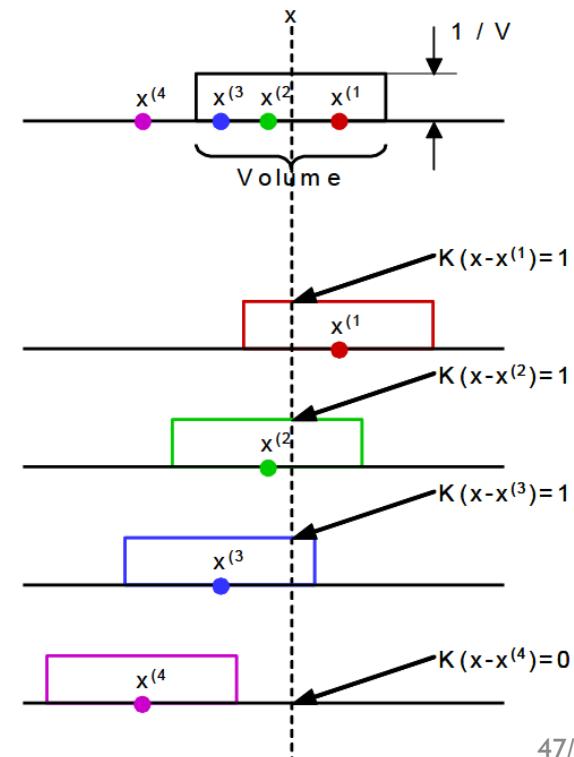
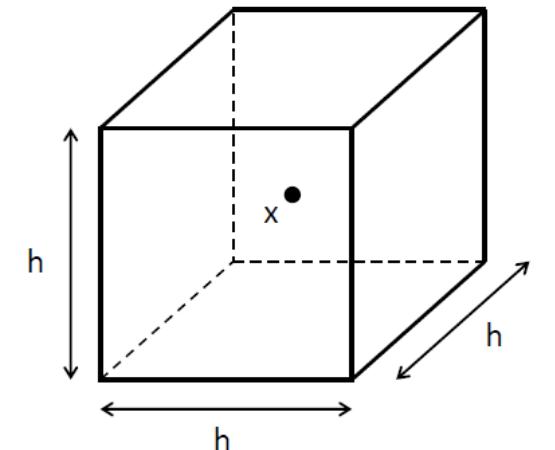
- Parzen Window Density Estimation

- ✓ Assume that the region R that encloses the k examples is a hypercube with sides of length h centered at x
 - Its volume is given by $V = h^d$, d : N. dimensions

- ✓ Define a kernel function $K(u)$

$$K(u) = \begin{cases} 1 & |u_j| < \frac{1}{2} \forall j = 1, \dots, d \\ 0 & \text{otherwise} \end{cases}$$

$$k = \sum_{i=1}^N K\left(\frac{\mathbf{x}^i - \mathbf{x}}{h}\right) \quad p(x) = \frac{1}{Nh^d} \sum_{i=1}^N K\left(\frac{\mathbf{x}^i - \mathbf{x}}{h}\right)$$

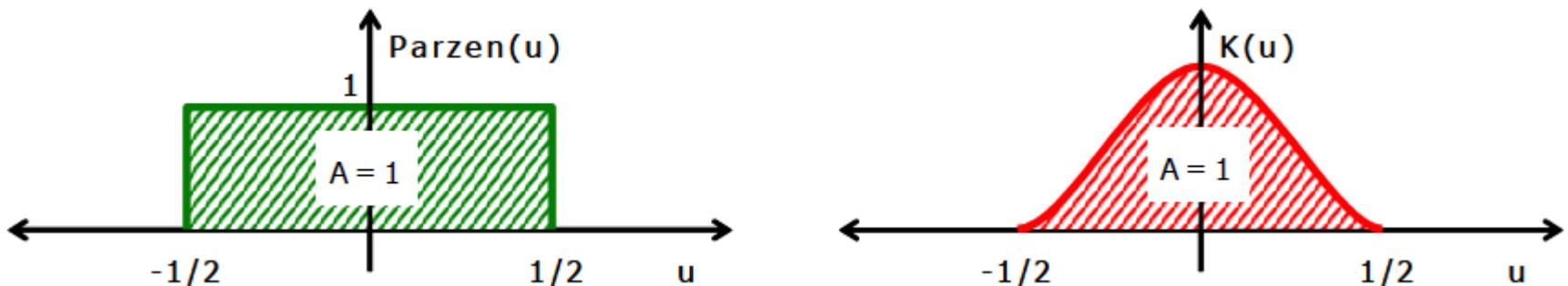


Parzen Window Density Estimation

- Drawbacks of $K(u)$
 - ✓ Yields density estimate that have discontinuities
 - ✓ Weights equally all points \mathbf{x}^i , regardless of their distance to the estimation point \mathbf{x}
- Smooth kernel function

$$P = \int_R K(x) dx = 1$$

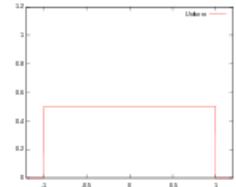
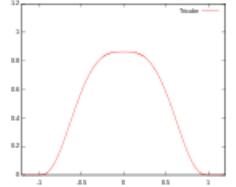
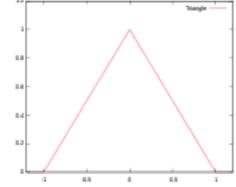
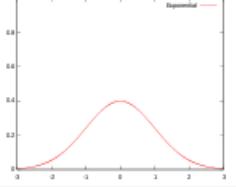
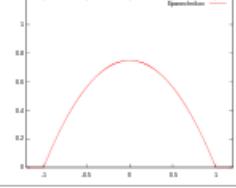
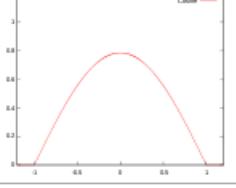
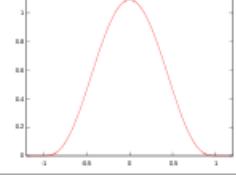
- ✓ Commonly use a radially symmetric and unimodal pdf, such as Gaussian



$$p(\mathbf{x}) = \frac{1}{N} \sum_{i=1}^N K\left(\frac{\mathbf{x}^i - \mathbf{x}}{h}\right)$$

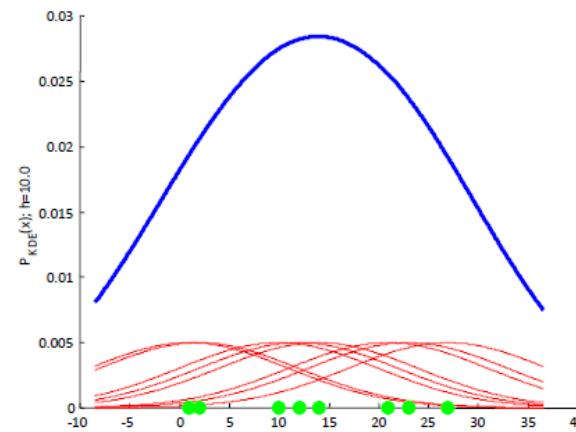
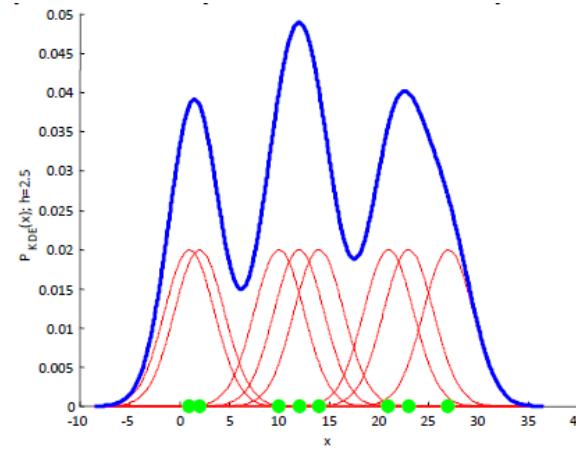
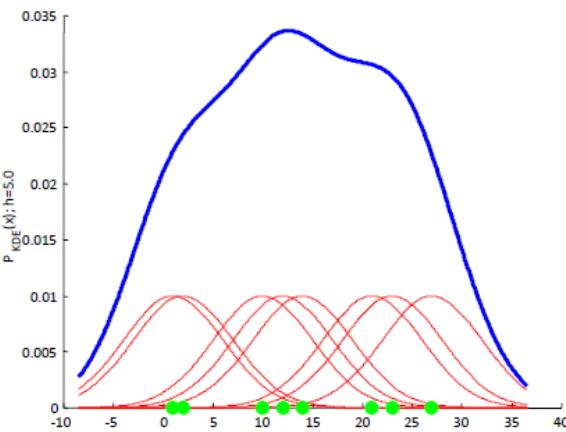
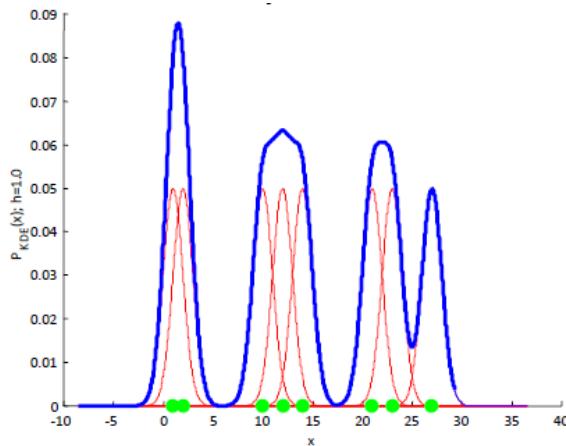
Parzen Window Density Estimation

- Example of smooth kernels

Uniform	$K(u) = \frac{1}{2} \mathbf{1}_{\{ u \leq 1\}}$	 A step function plot labeled "Uniform". The x-axis ranges from -1 to 1, and the y-axis ranges from 0 to 1.2. The function is constant at 0.5 for u ≤ 1 and drops to 0 outside this range.	Tricube	$K(u) = \frac{70}{81}(1 - u ^3)^3 \mathbf{1}_{\{ u \leq 1\}}$	 A smooth bell-shaped curve labeled "Tricube". The x-axis ranges from -1 to 1, and the y-axis ranges from 0 to 1.2. The curve is zero at u > 1 and reaches a maximum value of approximately 0.7 at u=0.
Triangular	$K(u) = (1 - u) \mathbf{1}_{\{ u \leq 1\}}$	 A triangular plot labeled "Triangular". The x-axis ranges from -1 to 1, and the y-axis ranges from 0 to 1.2. The function is zero at u > 1 and reaches a maximum value of 1 at u=0.	Gaussian	$K(u) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}u^2}$	 A smooth bell-shaped curve labeled "Gaussian". The x-axis ranges from -3 to 3, and the y-axis ranges from 0 to 1.2. The curve is centered at 0 with a standard deviation of approximately 1.5.
Epanechnikov	$K(u) = \frac{3}{4}(1 - u^2) \mathbf{1}_{\{ u \leq 1\}}$	 A smooth bell-shaped curve labeled "Epanechnikov". The x-axis ranges from -1 to 1, and the y-axis ranges from 0 to 1.2. The curve is zero at u > 1 and reaches a maximum value of 0.75 at u=0.	Cosine	$K(u) = \frac{\pi}{4} \cos\left(\frac{\pi}{2}u\right) \mathbf{1}_{\{ u \leq 1\}}$	 A smooth bell-shaped curve labeled "Cosine". The x-axis ranges from -1 to 1, and the y-axis ranges from 0 to 1.2. The curve is zero at u > 1 and reaches a maximum value of 0.75 at u=0.
Quartic (biweight)	$K(u) = \frac{15}{16}(1 - u^2)^2 \mathbf{1}_{\{ u \leq 1\}}$	 A smooth bell-shaped curve labeled "Quartic". The x-axis ranges from -1 to 1, and the y-axis ranges from 0 to 1.2. The curve is zero at u > 1 and reaches a maximum value of 0.9375 at u=0.	Logistic	$K(u) = \frac{1}{e^u + 2 + e^{-u}}$	 A smooth bell-shaped curve labeled "Logistic". The x-axis ranges from -3 to 3, and the y-axis ranges from 0 to 1.2. The curve is centered at 0 with a standard deviation of approximately 2.2.
Triweight	$K(u) = \frac{35}{32}(1 - u^2)^3 \mathbf{1}_{\{ u \leq 1\}}$	 A smooth bell-shaped curve labeled "Triweight". The x-axis ranges from -1 to 1, and the y-axis ranges from 0 to 1.2. The curve is zero at u > 1 and reaches a maximum value of 1.09375 at u=0.	Silverman kernel^[4]	$K(u) = \frac{1}{2} e^{-\frac{ u }{\sqrt{2}}} \cdot \sin\left(\frac{ u }{\sqrt{2}} + \frac{\pi}{4}\right)$	 A smooth bell-shaped curve labeled "Silverman kernel". The x-axis ranges from -3 to 3, and the y-axis ranges from 0 to 1.2. The curve is centered at 0 with a standard deviation of approximately 2.2.

Parzen Window Density Estimation

- Smoothing parameter (bandwidth) h
 - ✓ A large h will over-smooth the density distribution
 - ✓ A small h will result in a spiky density distribution

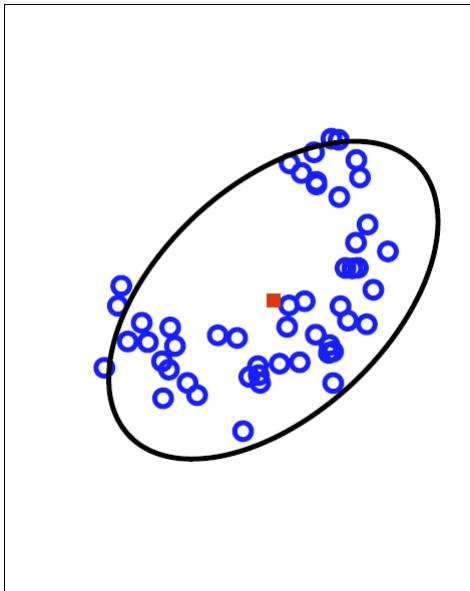


Parzen Window Density Estimation

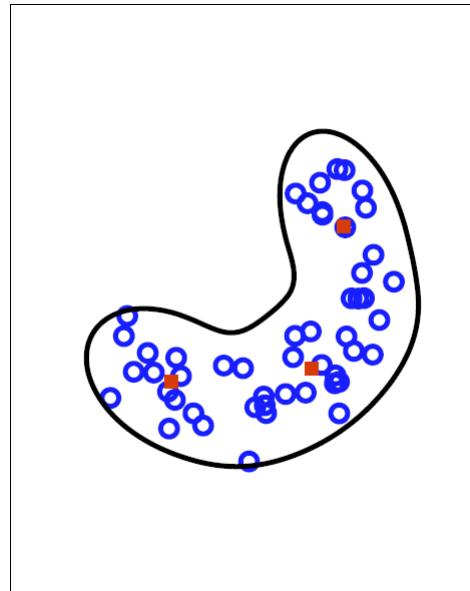
- Kernel Density Estimation

- ✓ The smoothing parameter h can be optimized through EM algorithm

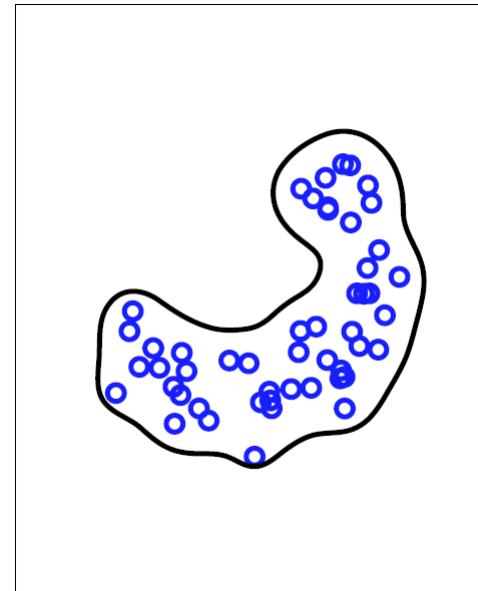
Gaussian density estimation



Mixture of Gaussian

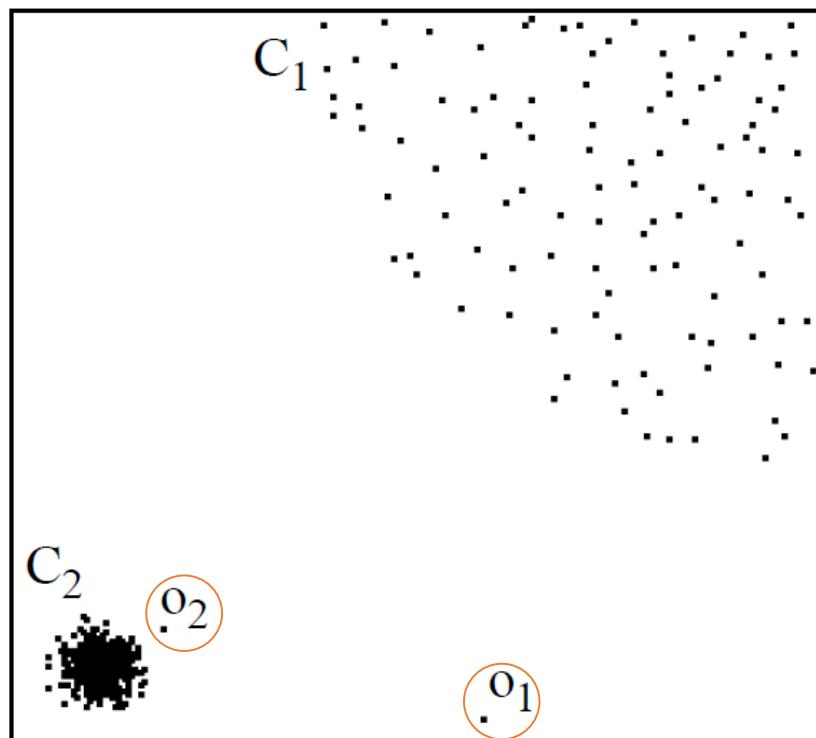


Parzen window with Gaussian Kernel



Local Outlier Factors (LOF)

- Motivation
 - ✓ Compute the novelty score of an instance by considering local density around it



Local Outlier Factors (LOF)

- Local Outlier Factors (LOF)

✓ **Definition I:** k-distance of an object p

- For any positive integer k, the k-distance of object p, denoted as k-distance(p), is defined as the distance $d(p,o)$ between p and an object o in D such that
- for at least k objects o' in $D \setminus \{p\}$ it holds that $d(p, o') \leq d(p, o)$
- for at most $k-1$ objects o' in $D \setminus \{p\}$ it holds that $d(p, o') < d(p, o)$
- Simply it is the distance to the k-th nearest neighbor considering ties.

1st	2nd	3rd	4th	5th	6th	7th	3-distance
1	2	3	3	3	4	5	3
1	2	2	2	3	4	5	2
1	1	1	1	2	3	4	1

Local Outlier Factors (LOF)

- Local Outlier Factors (LOF)

✓ **Definition 2:** k-distance neighborhood of an object p

- Given the k-distance of p, the k-distance neighborhood of p contains every object whose distance from p is not greater than the k-distance

$$N_k(p) = \{q \in D \setminus \{p\} \mid d(p, q) \leq k - \text{distance}(p)\}$$

- Example

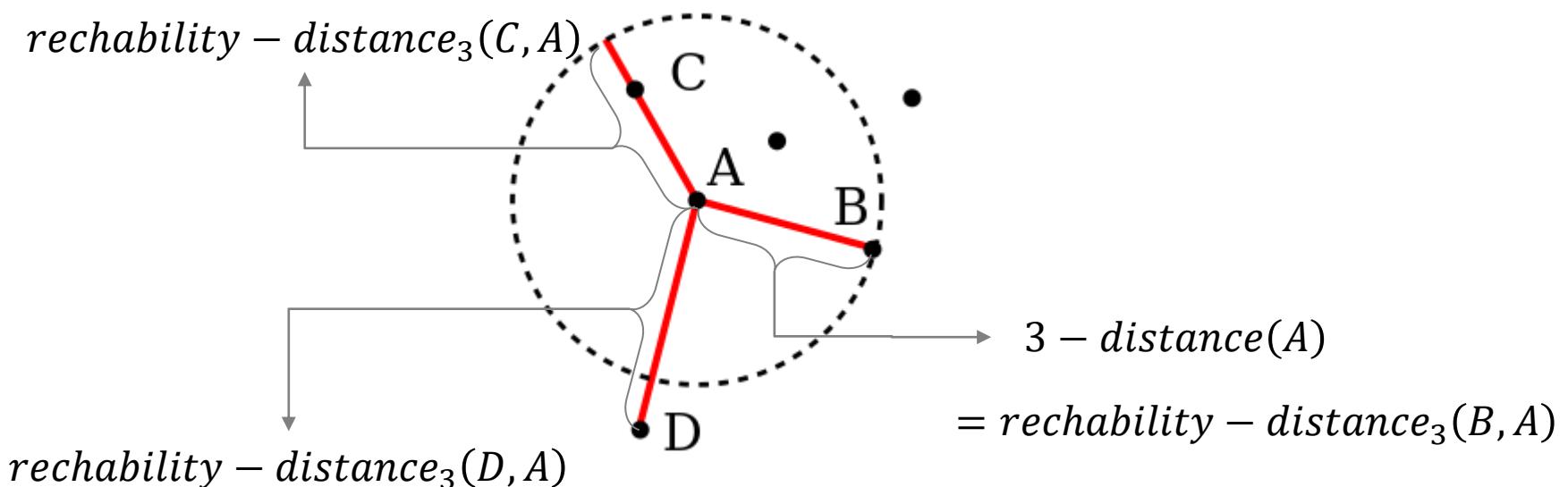
1st	2nd	3rd	4th	5th	6th	7th	$k - \text{distance}(3)$	$N_3(p)$
1	2	3	3	3	4	5	3	5
1	2	2	2	3	4	5	2	4
1	1	1	1	2	3	4	1	4

Local Outlier Factors (LOF)

- Local Outlier Factors (LOF)

- ✓ **Definition 3:** reachability distance

- $\text{reachability-distance}_k(p, o) = \max\{k - \text{distance}(o), d(p, o)\}$
 - Examples



Local Outlier Factors (LOF)

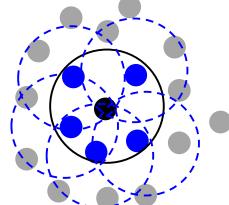
- Local Outlier Factors (LOF)

✓ Definition 4: local reachability density of an object p

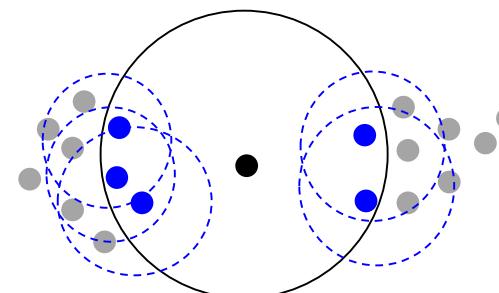
$$lrd_k(p) = \frac{|N_k(p)|}{\sum_{o \in N_k(p)} \text{reachability} - \text{distance}_k(p, o)}$$

- Case 1: p is located in the middle of a denser area: the denominator of $lrd_k(p)$ becomes small, which results in a large $lrd_k(p)$
- Case 2: p is located in a spare area between two dense data clusters: the denominator of $lrd_k(p)$ becomes large, which results in a small $lrd_k(p)$

Case 1



Case 2



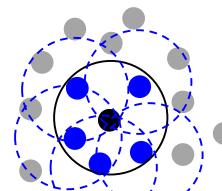
Local Outlier Factors (LOF)

- Local Outlier Factors (LOF)

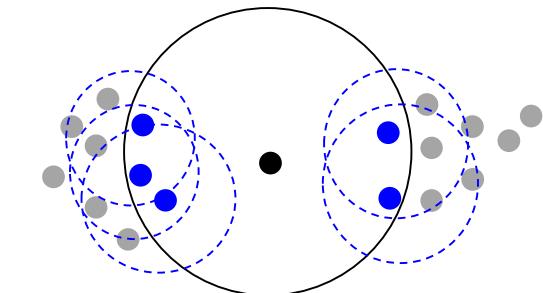
✓ Definition 5: local outlier factor of an object p

$$LOF_k(p) = \frac{\sum_{o \in N_k(p)} \frac{lrd_k(o)}{lrd_k(p)}}{|N_k(p)|} = \frac{1}{lrd_k(p)} \frac{\sum_{o \in N_k(p)} lrd_k(o)}{|N_k(p)|}$$

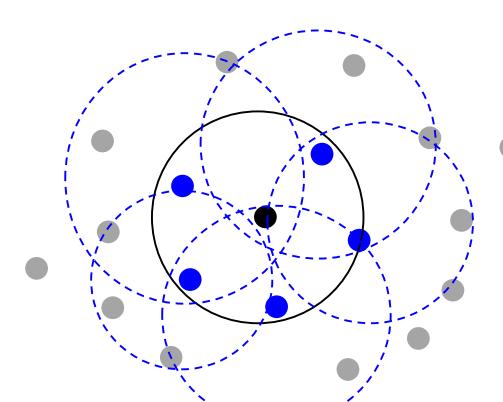
Case 1



Case 2



Case 3



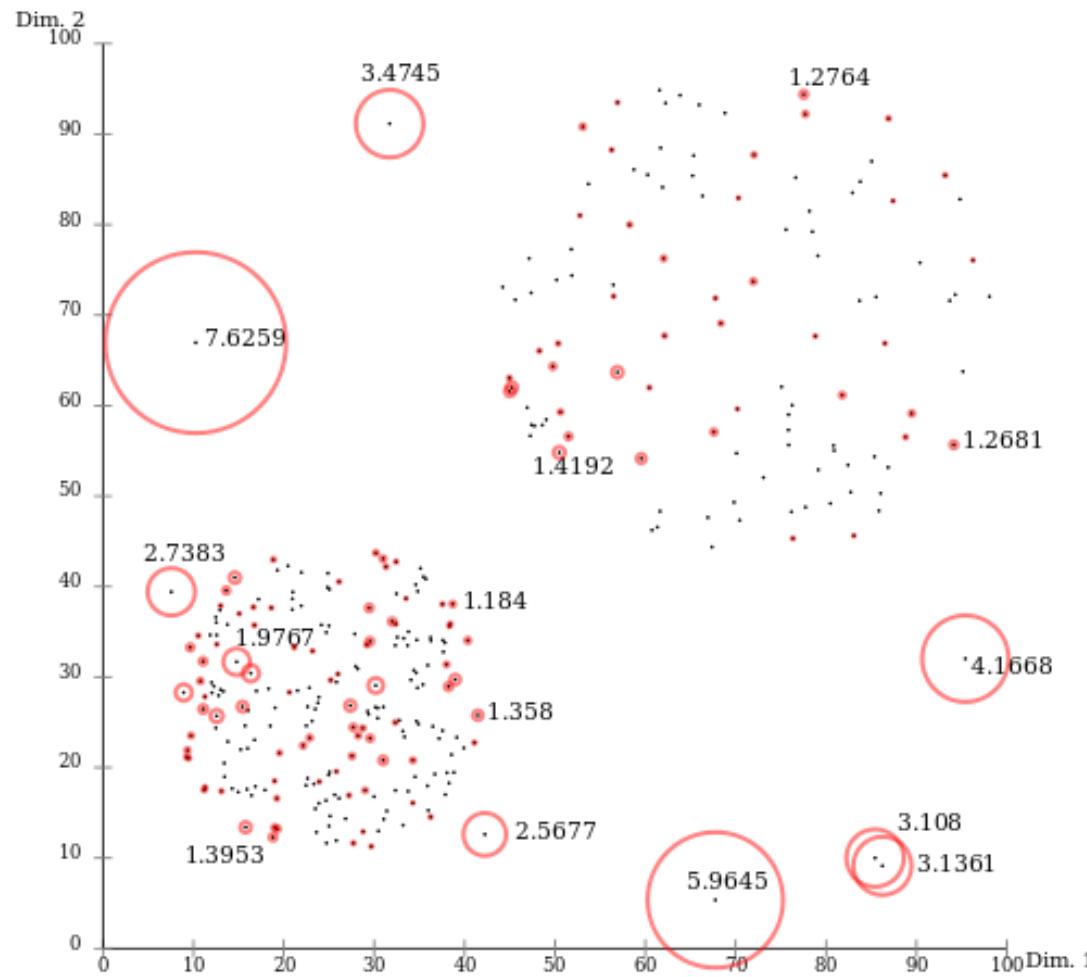
● : p ● : o ○ : k -distance of p ○ : k -distance of o

Case	$lrd_k(p)$	$lrd_k(o)$	$LOF_k(p)$
Case 1	Large	Large	Small
Case 2	Small	Large	Large
Case 3	Small	Small	Small

Local Outlier Factors (LOF)

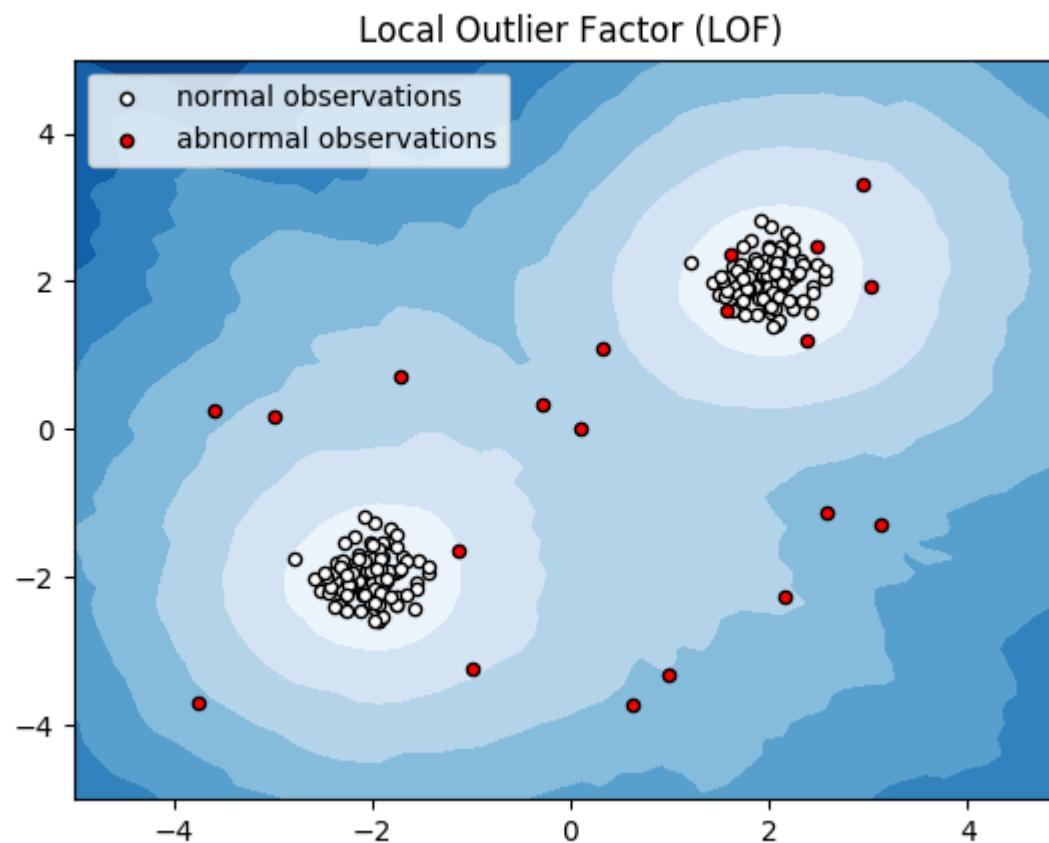
- Local Outlier Factors (LOF)

✓ For each point, compute the density of its local neighborhood



Local Outlier Factors (LOF)

- Local Outlier Factors (LOF)
 - ✓ LOF contour plot



AGENDA

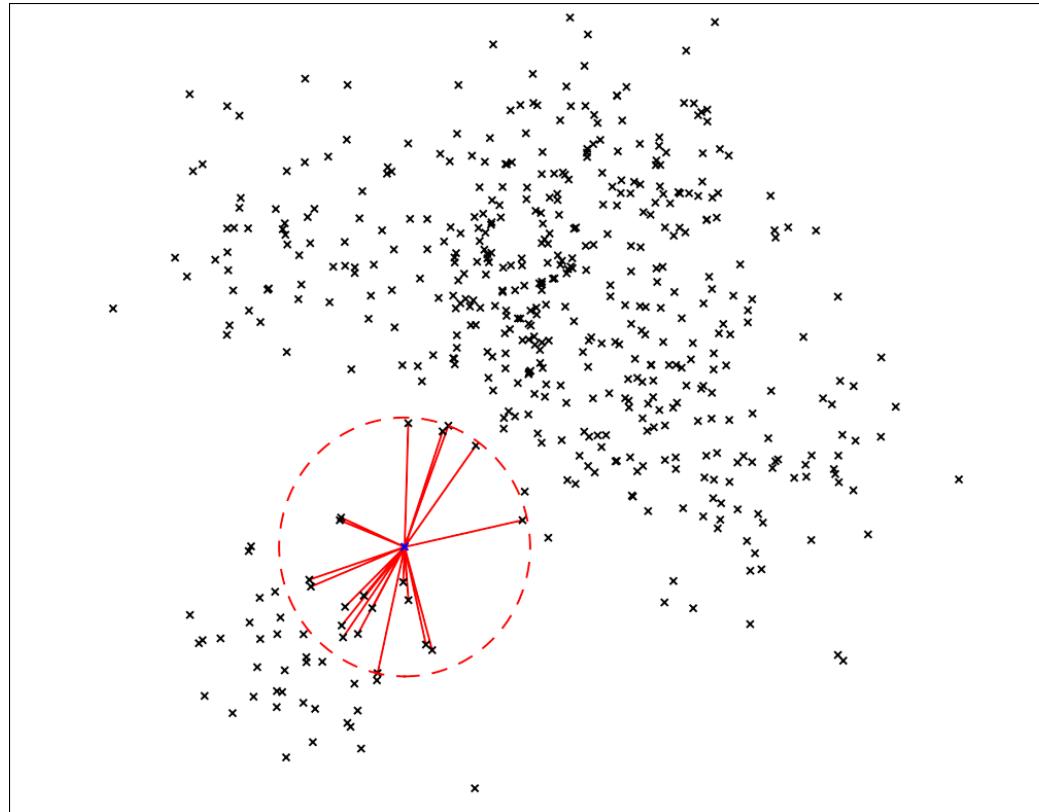
- 01 Novelty Detection: Overview
- 02 Density-based Novelty Detection
- 03 Distance/Reconstruction-based ND
- 04 Model-based Novelty Detection

k-Nearest Neighbor-based Novelty Detection

Harmeling et al. (2006)

- k-Nearest Neighbor-based Approach

- ✓ Novelty score of an instance is computed based on the distance information to k nearest neighbors
- ✓ Does not assume any prior probability distribution for the normal class



k-Nearest Neighbor-based Novelty Detection

- Various distance information used for novelty score

- ✓ Maximum distance to the k-th nearest neighbor

$$d_{max}^k = \kappa(\mathbf{x}) = \|\mathbf{x} - z_k(\mathbf{x})\|$$

- ✓ Average distance to the k-nearest neighbors

$$d_{avg}^k = \gamma(\mathbf{x}) = \frac{1}{k} \sum_{j=1}^k \|\mathbf{x} - z_j(\mathbf{x})\|$$

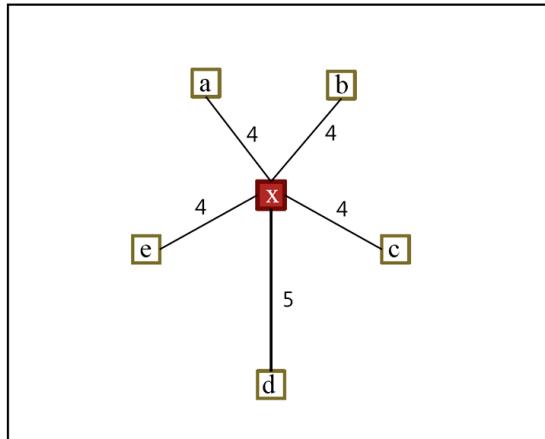
- ✓ Distance to the mean of the k-nearest neighbors

$$d_{mean}^k = \delta(\mathbf{x}) = \left\| \mathbf{x} - \frac{1}{k} \sum_{j=1}^k z_j(\mathbf{x}) \right\|$$

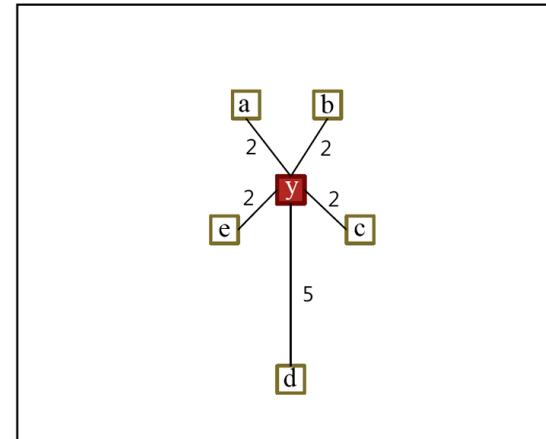
k-Nearest Neighbor-based Novelty Detection

Kang and Cho (2009)

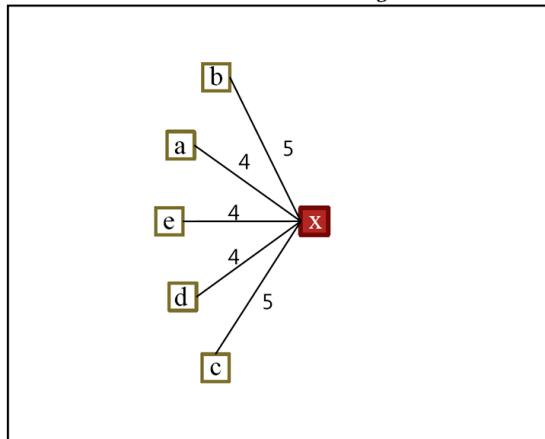
- Various distance information used for novelty score
 - ✓ Comparison among the maximum, average, and mean distance



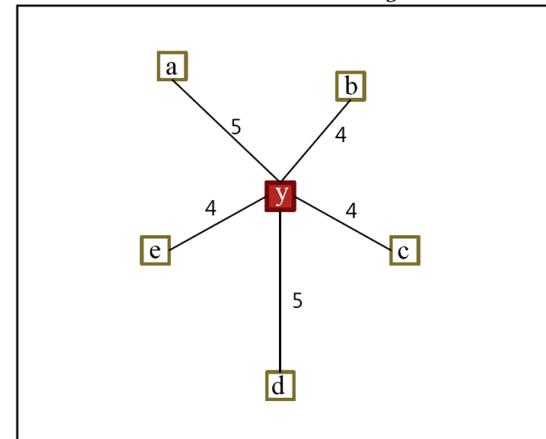
$$(a) d_{max}^5 = 5.0, d_{avg}^5 = 4.2.$$



$$(b) d_{max}^5 = 5.0, d_{avg}^5 = 2.6.$$



$$(c) d_{avg}^5 = 4.4, d_{mean}^5 = 3.3.$$



$$(d) d_{avg}^5 = 4.4, d_{mean}^5 = 2.1.$$

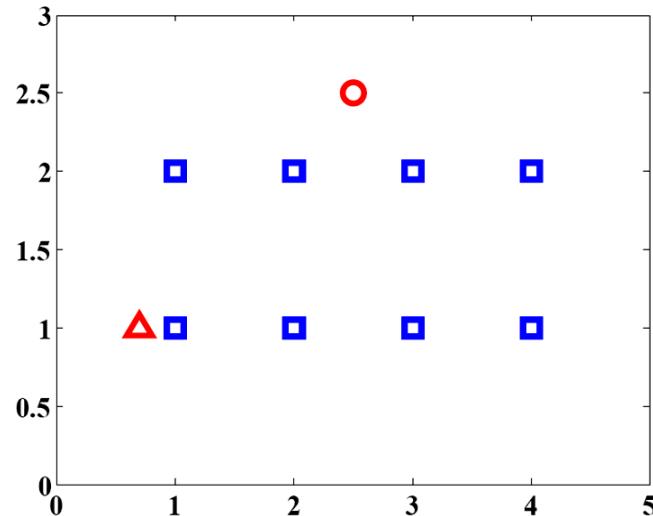
k-Nearest Neighbor-based Novelty Detection

Kang and Cho (2009)

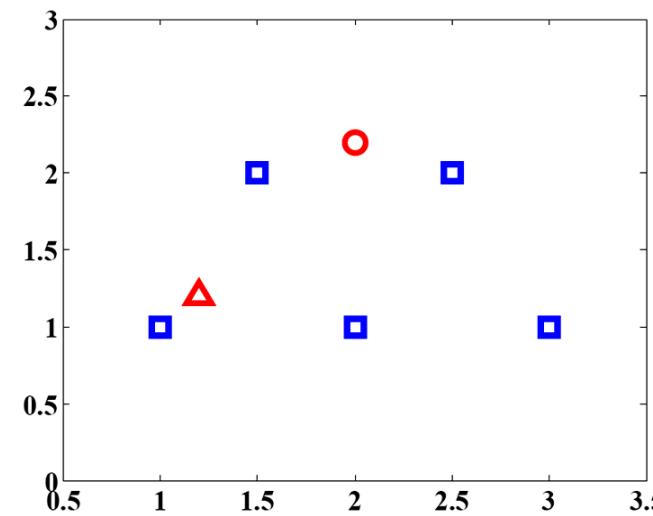
- Counter example of the previous novelty scores

✓ Which one should be identified as novel?

A



B



		d^k_{\max}	d^k_{avg}	d^k_{mean}
A (k=4)	Circle	1.58	1.14	0.50
	Triangle	1.64	1.07	0.94
B (k=5)	Circle	1.56	1.08	0.80
	Triangle	1.86	1.09	0.88

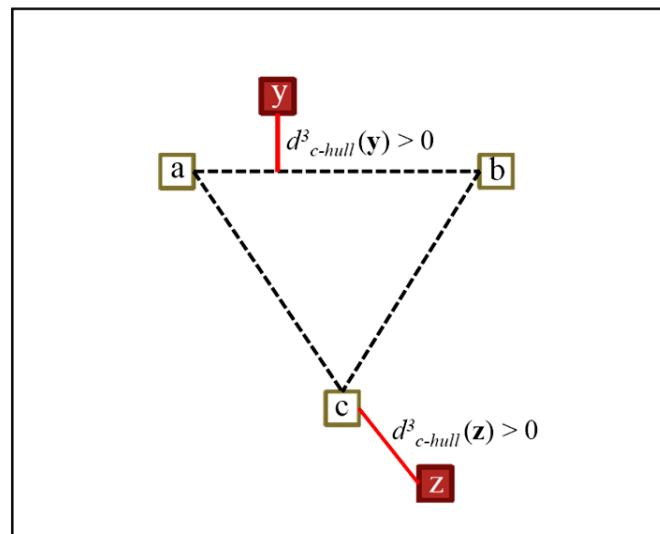
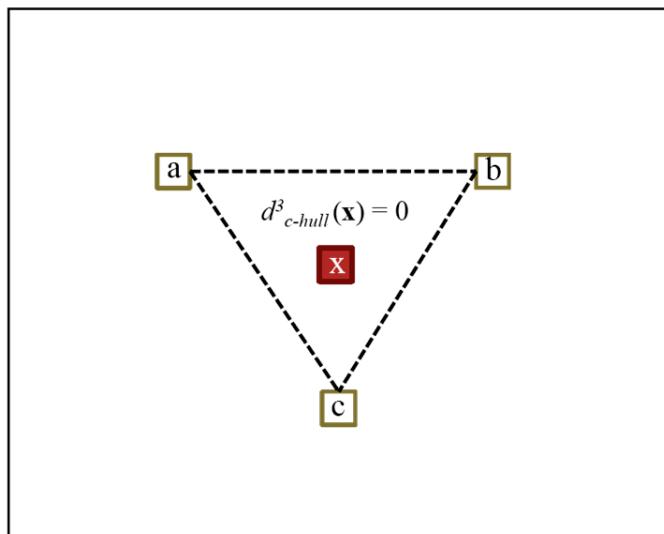
k-Nearest Neighbor-based Novelty Detection

- Consider additional factor

✓ whether the new instance is located inside the convex hull of its neighbors

$$\min_{\mathbf{w}} \left(d_{c-hull}^k(\mathbf{x}) \right)^2 = \left\| \mathbf{x}_{new} - \sum_{j=1}^k \mathbf{w}_i z_j(\mathbf{x}) \right\|^2$$

$$s.t. \quad \sum_{i=1}^k \mathbf{w}_i = 1, \quad \mathbf{w}_i \geq 0, \quad \forall i.$$



k-Nearest Neighbor-based Novelty Detection

- Combine the average distance and convex distance

- ✓ Average distance to the k-nearest neighbors

$$d_{avg}^k = \frac{1}{k} \sum_{j=1}^k \|\mathbf{x} - z_j(\mathbf{x})\|$$

- ✓ Convex distance to its k-nearest neighbors

$$d_{c-hull}^k = \left\| \mathbf{x} - \sum_{j=1}^k \mathbf{w}_i z_j(\mathbf{x}) \right\|$$

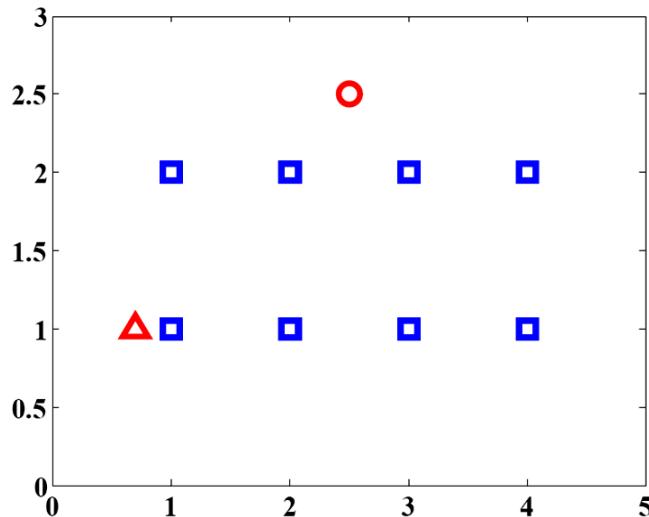
- ✓ Put the penalty term using the convex distance for those instances located outside the convex hull of its k-nearest neighbors

$$d_{hybrid}^k = d_{avg}^k \times \left(\frac{2}{1 + \exp(-d_{c-hull}^k)} \right)$$

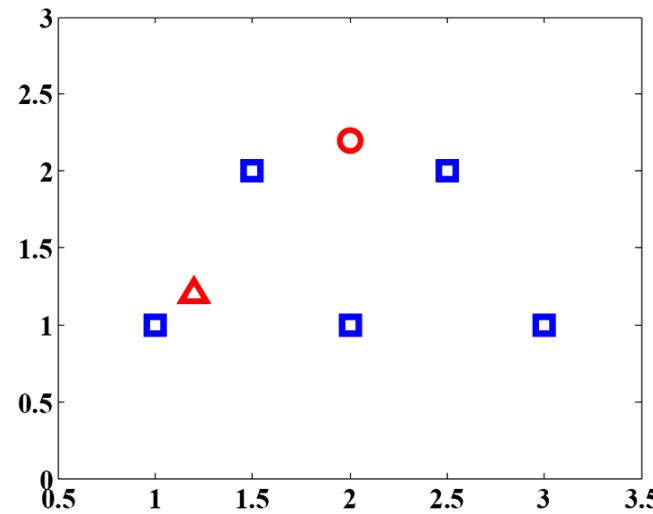
k-Nearest Neighbor-based Novelty Detection

- Counter example revisited

A

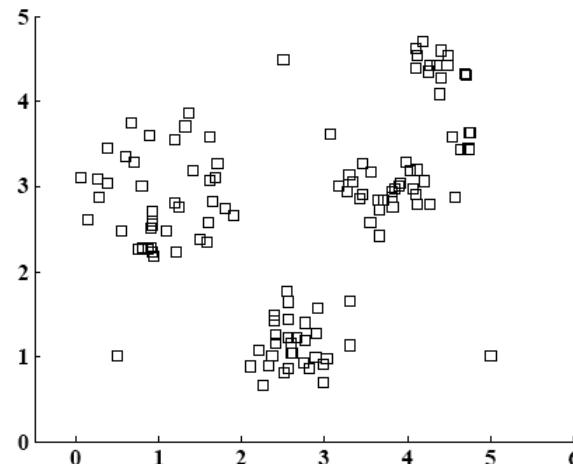


B

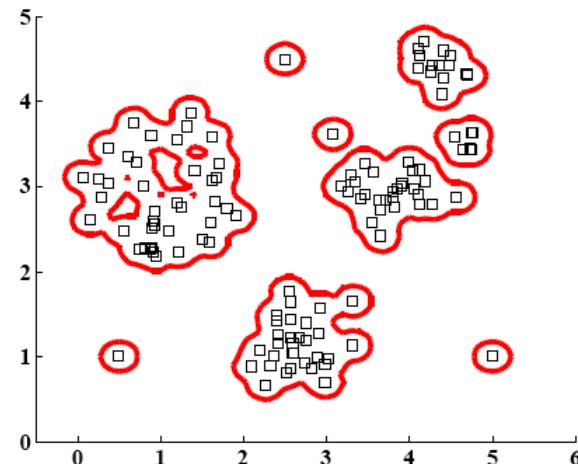


		d^k_{\max}	d^k_{avg}	d^k_{mean}	d^k_{hybrid}
A (k=4)	Circle	1.58	1.14	0.50	1.42
	Triangle	1.64	1.07	0.94	1.18
B (k=5)	Circle	1.56	1.08	0.80	1.18
	Triangle	1.86	1.09	0.88	1.09

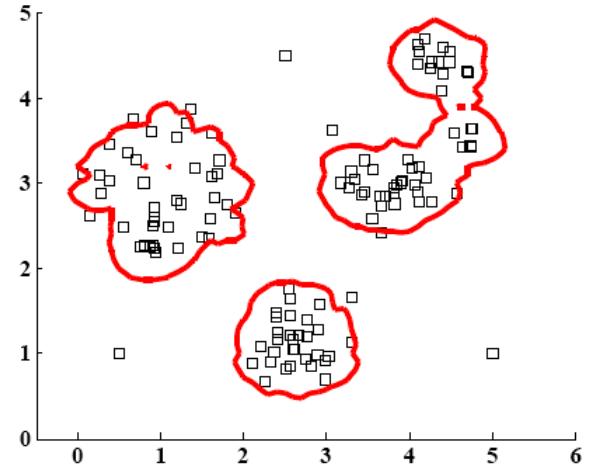
k-Nearest Neighbor-based Novelty Detection



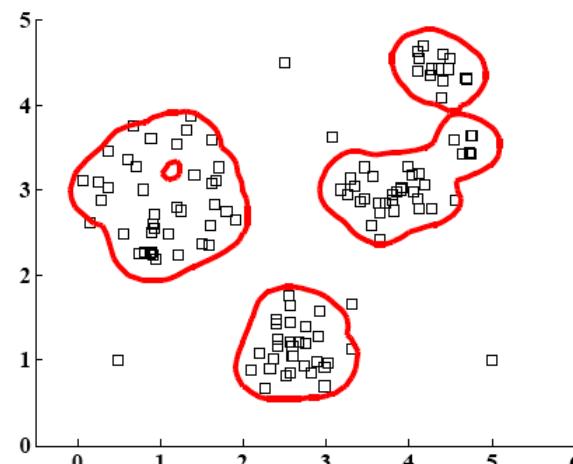
(a) Normal instances



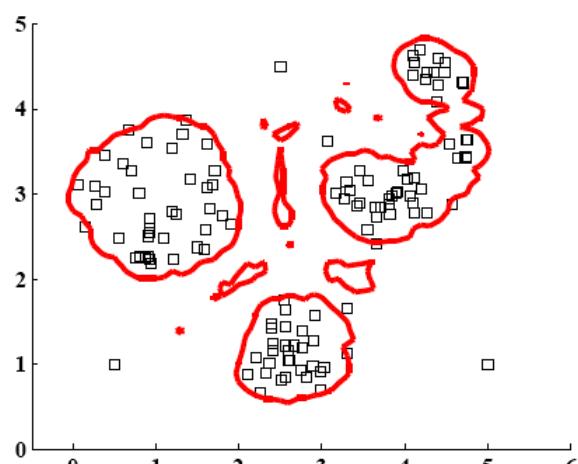
(b) 1-*NN*



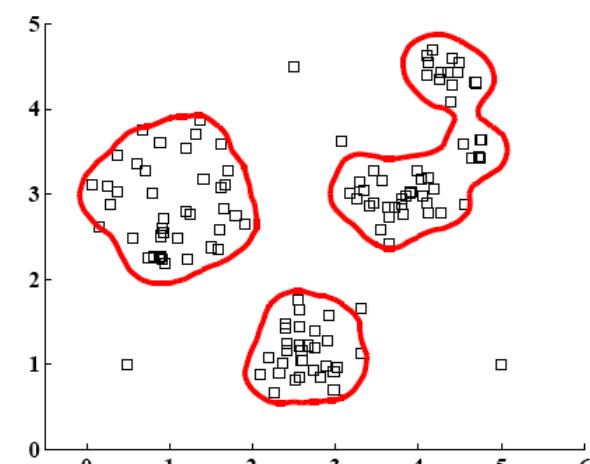
(c) d_{max}^5



(d) d_{avg}^5



(e) d_{mean}^5



(f) d_{hybrid}^5

k-Nearest Neighbor-based Novelty Detection

- Experiment
- ✓ Datasets

No.	Name	Source	Class	Dim.	TrN _n	TsN _n	TsN _o
1	Banana	Rätsch	-1	2	216	2,708	271
2	Titanic	Rätsch	-1	3	100	1,390	139
3	Liver	UCI	healthy	6	73	72	7
4	Ecoli	UCI	cp	7	72	71	7
5	Yeast	UCI	0	8	232	231	23
6	Pima	UCI	0	8	250	250	25
7	Diabetes	Rätsch	-1	8	304	196	20
8	Glass	UCI	1	9	35	35	4
9	Breast	Rätsch	-1	9	142	54	5
10	Flare	Rätsch	-1	9	300	178	18
11	Heart	Rätsch	-1	13	94	56	6
12	Image	Rätsch	-1	18	554	436	44
13	Twonorm	Rätsch	-1	20	198	3,499	350
14	German	Rätsch	-1	20	489	211	21
15	Waveform	Rätsch	-1	21	268	3,085	308
16	Parkinsons	UCI	parkinsons	22	74	73	7
17	Ionosphere	UCI	0	33	113	112	11
18	Spectf	UCI	0	44	28	27	3
19	Sonar	UCI	mine	60	56	55	6
20	Ozone	UCI	non-ozone	72	29	28	3
21	Arrhythmia	UCI	normal	258	119	118	12

k-Nearest Neighbor-based Novelty Detection

- Performance (in terms of the Integrated Error)

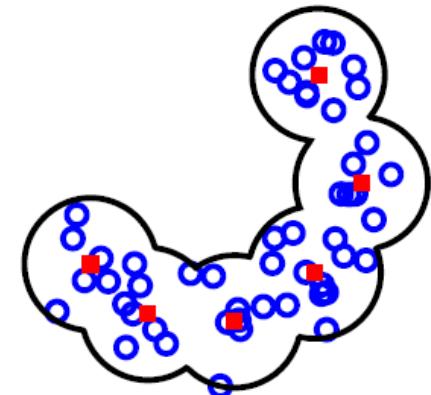
Data	Dim.	TrN _n	Gauss	MoG	Parzen	1-SVM	KMC	KCC	HC	PCA	d_{max}^k	d_{avg}^k	d_{mean}^k	1-NN	MST-CD	d_{hybrid}^k
Titanic	3	100	19.12	19.12	18.50	17.27	21.12	21.26	22.80	22.48	3.64	3.53	10.00	8.73	1.33*	1.33*
Liver	6	73	44.41	45.04	41.11	38.82	41.90	43.41	40.91	40.68	40.00	38.85	38.96	39.81	39.14	38.18
Ecoli	7	72	3.61	2.58	3.14	2.35	2.45	3.38	3.88	20.12	2.22	2.13	2.84	3.94	2.67	2.11
Glass	9	35	18.82	18.29	22.25	17.43	18.61	22.61	24.42	22.21	13.86	12.25	12.36	18.93	11.54	11.39
Breast	9	142	35.83	31.51	32.04	29.64	34.68	40.68	32.80	31.24	29.58	28.84	29.53	34.62	33.18	26.99*
Banana	2	216	54.91	8.56	7.96	8.30	16.93	12.53	7.65	42.55	8.51	8.08	9.87	10.57	11.67	7.89
Yeast	8	232	31.55	28.98	27.99	26.58	28.78	33.25	27.32	31.47	25.81	24.54	25.87	27.79	26.50	23.40
Pima	8	250	29.86	33.55	26.04	27.50	29.60	32.69	28.46	33.28	24.82	24.57	27.68	28.17	27.72	24.45
Diabetes	8	304	30.61	34.68	27.35	26.60	28.80	35.31	26.45	31.32	23.70	23.29	25.68	26.66	28.21	23.64
Flare	9	300	23.19	23.19	24.82	15.40	29.67	26.65	25.57	26.76	10.49	9.74	17.09	5.62	5.47	6.14
Spectf	44	28	28.33	16.42	21.11	14.75	15.00	28.02	16.36	26.30	14.20	13.40	12.96	17.16	13.33	11.67*
Sonar	60	56	41.59	37.27	34.32	33.80	41.55	40.06	40.07	42.32	39.65	34.67	32.12	33.73	31.30	32.62
Ozone	72	29	23.99	14.64	13.15	12.50	13.51	19.11	16.49	34.46	11.07	10.71	9.76	14.11	12.86	10.30
Arrhythmia	258	119	28.01	40.25	28.03	25.79	25.38	28.62	27.42	28.17	26.10	26.01	25.93	26.16	24.57	23.93
Heart	13	94	21.13	19.05	20.58	18.61	19.84	20.79	18.22	20.21	15.23	14.75	15.72	23.08	23.24	14.30
Image	18	554	13.11	13.61	11.79	10.38	23.22	30.13	31.21	15.87	13.80	11.99	10.32	10.53	9.19*	11.04
Twonorm	20	198	9.83	11.80	11.62	9.48	8.82	12.38	6.13*	9.62	9.62	10.02	10.79	12.87	12.62	10.11
German	20	489	38.16	36.99	37.24	35.72	39.23	42.79	40.56	37.73	34.72	33.95	34.59	37.88	36.35	33.77
Waveform	21	268	42.14	30.25	26.33	22.65*	27.56	31.26	25.44	43.07	23.75	24.58	27.69	29.05	27.09	25.24
Parkinsons	22	74	32.71	46.35	32.14	29.16	32.65	32.66	32.79	34.60	36.95	32.54	31.63	34.22	30.68	30.30
Ionosphere	33	113	4.44	4.93	4.16	2.80	3.54	4.40	4.39	3.68	2.70	2.76	2.75	4.00	2.70	2.72

Clustering-based Approach

- K-Means clustering-based novelty detection
 - ✓ Novelty score of an instance is computed based on the distance information to the nearest centroid
 - ✓ Does not assume any prior probability distribution for the normal class

$$\mathcal{X} = C_1 \cup C_2 \dots \cup C_K, \quad C_i \cap C_j = \emptyset, \quad i \neq j.$$

$$\arg \min_{\mathbf{C}} \sum_{i=1}^K \sum_{\mathbf{x}_j \in C_i} \|\mathbf{x}_j - \mathbf{c}_i\|^2$$

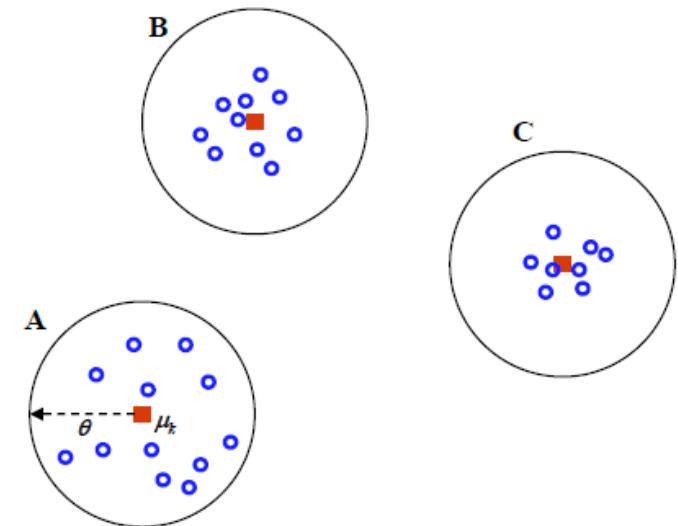
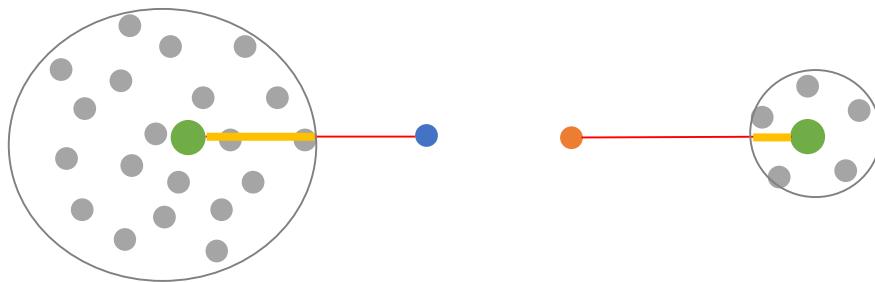


- ✓ EM algorithm for K-Means clustering

-
- 1: Select K points as the initial centroids.
 - 2: **repeat**
 - 3: Form K clusters by assigning all points to the closest centroid.
 - 4: Recompute the centroid of each cluster.
 - 5: **until** The centroids don't change

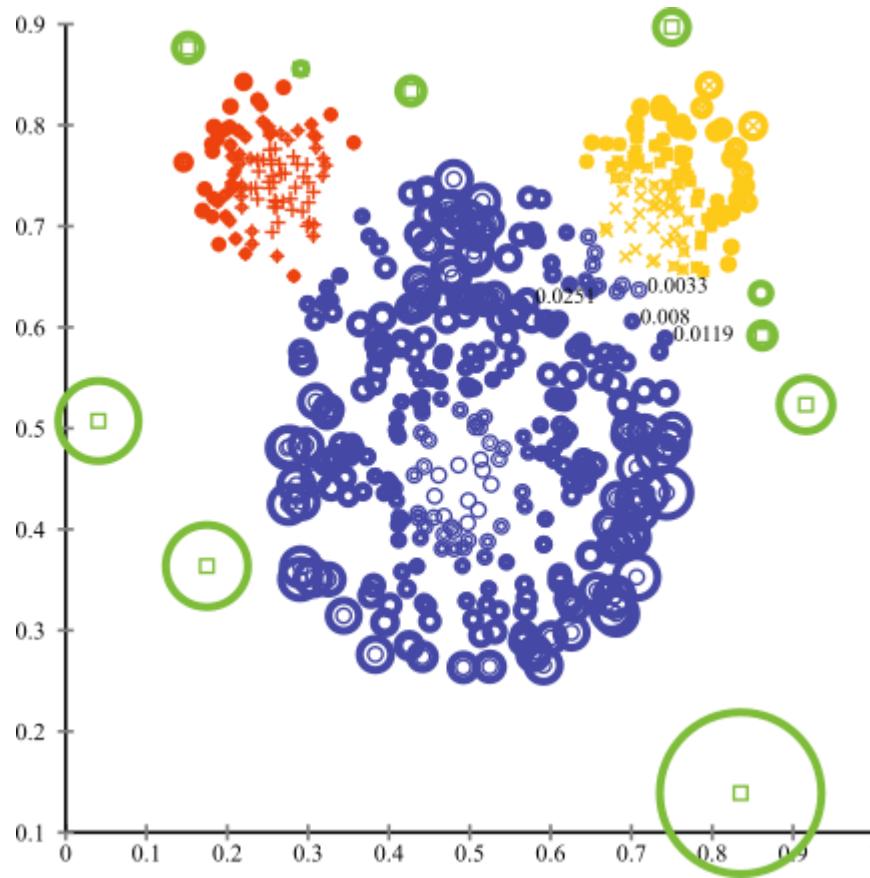
Clustering-based Approach

- Clustering-based Approach
 - ✓ Two novelty scores by KMC
 - Absolute distance to the nearest centroid
 - Relative distance to the nearest centroid



Clustering-based Approach

- KMC-based novelty score: Example



Principal Component Analysis-based Novelty Detection

- PCA revisited
 - ✓ Purpose: maximize the variance after projection

$$\max \mathbf{w}^T \mathbf{S} \mathbf{w}$$

$$s.t. \quad \mathbf{w}^T \mathbf{w} = 1$$

- ✓ Solution

$$L = \mathbf{w}^T \mathbf{S} \mathbf{w} - \lambda(\mathbf{w}^T \mathbf{w} - 1)$$

$$\frac{\partial L}{\partial \mathbf{w}} = 0 \Rightarrow \mathbf{S} \mathbf{w} - \lambda \mathbf{w} = 0 \Rightarrow (\mathbf{S} - \lambda \mathbf{I}) \mathbf{w} = 0$$

Principal Component Analysis-based Novelty Detection

- PCA as a novelty detector
 - ✓ Novelty score: the amount of reconstruction loss from the projected space into the original space

	Projection →										Reconstruction →									
\mathbf{X}	$\mathbf{w}^T \mathbf{X}$										$\mathbf{w} \mathbf{w}^T \mathbf{X}$									
	(d by n)										(1 by d) (d by n)									
x_1	0.69	-1.31	0.39	0.09	1.29	0.49	0.19	-0.81	-0.31	-0.71	$w^T \mathbf{X}$									
x_2	0.49	-1.21	0.99	0.29	1.09	0.79	-0.31	-0.81	-0.31	-1.01										
z_1	0.83	-1.78	0.99	0.27	1.68	0.91	-0.10	-1.14	-0.44	-1.22	$w^T \mathbf{X}$									
x'_1	0.56	-1.21	0.67	0.19	1.14	0.62	-0.07	-0.78	-0.30	-0.83	$ww^T \mathbf{X}$									
x'_2	0.61	-1.31	0.73	0.20	1.23	0.67	-0.07	-0.84	-0.32	-0.90										



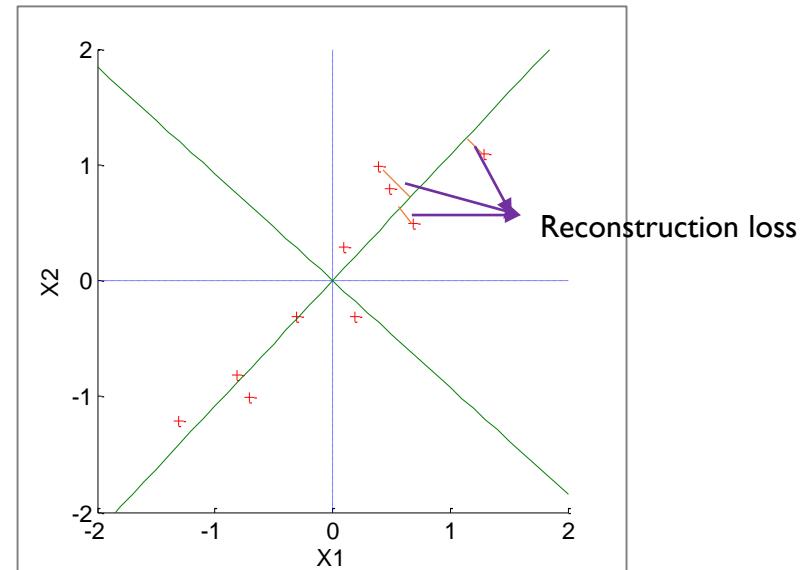
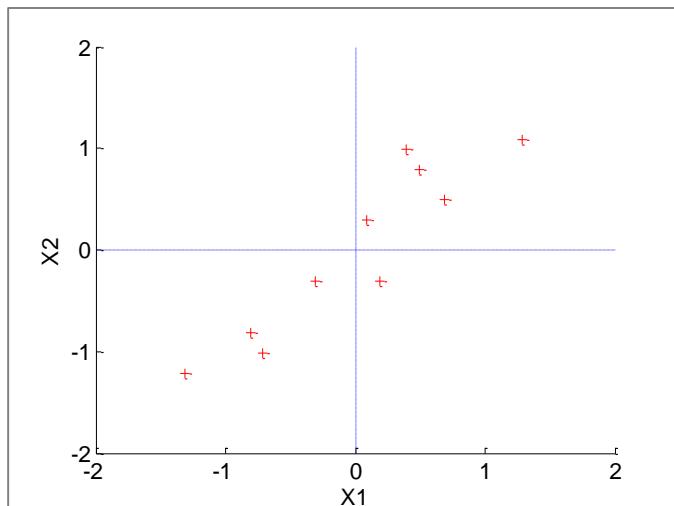
Principal Component Analysis-based Novelty Detection

- PCA as a novelty detector
 - ✓ Compute the reconstruction loss

$$\text{error}(\mathbf{x}) = \|\mathbf{x} - \mathbf{w}\mathbf{w}^T\mathbf{x}\|^2 = (\mathbf{x} - \mathbf{w}\mathbf{w}^T\mathbf{x})^T(\mathbf{x} - \mathbf{w}\mathbf{w}^T\mathbf{x})$$

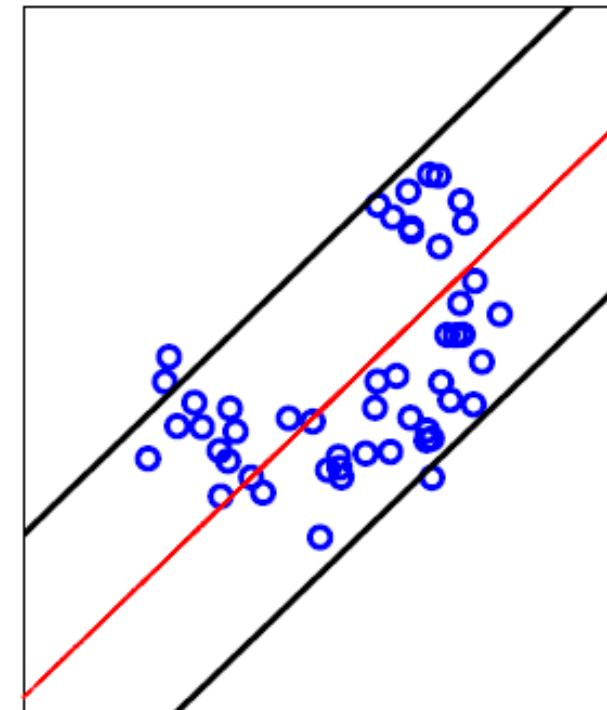
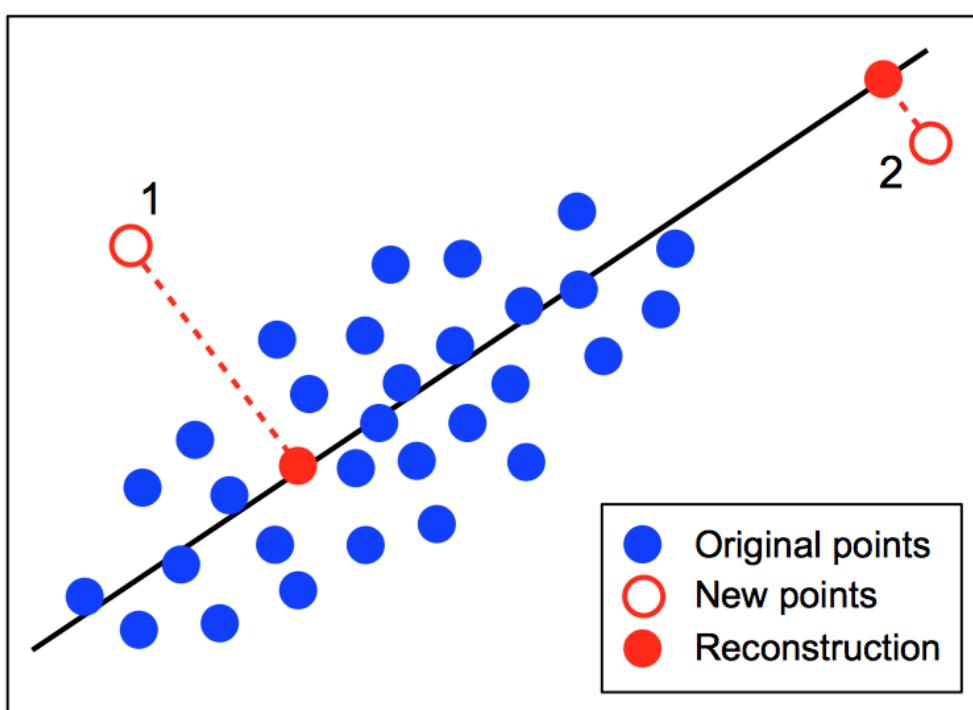
$$= \mathbf{x}^T\mathbf{x} - \mathbf{x}^T\mathbf{w}\mathbf{w}^T\mathbf{x} - \mathbf{x}^T\mathbf{w}\mathbf{w}^T\mathbf{x} + \mathbf{x}^T\mathbf{w}\mathbf{w}^T\mathbf{w}\mathbf{w}^T\mathbf{x}$$

$$= \mathbf{x}^T\mathbf{x} - \mathbf{x}^T\mathbf{w}\mathbf{w}^T\mathbf{x} = \|\mathbf{x}\|^2 - \|\mathbf{w}^T\mathbf{x}\|^2$$



Principal Component Analysis-based Novelty Detection

- PCA as a novelty detector
 - ✓ Graphical interpretation



<https://stats.stackexchange.com/questions/259806/anomaly-detection-using-pca-reconstruction-error>

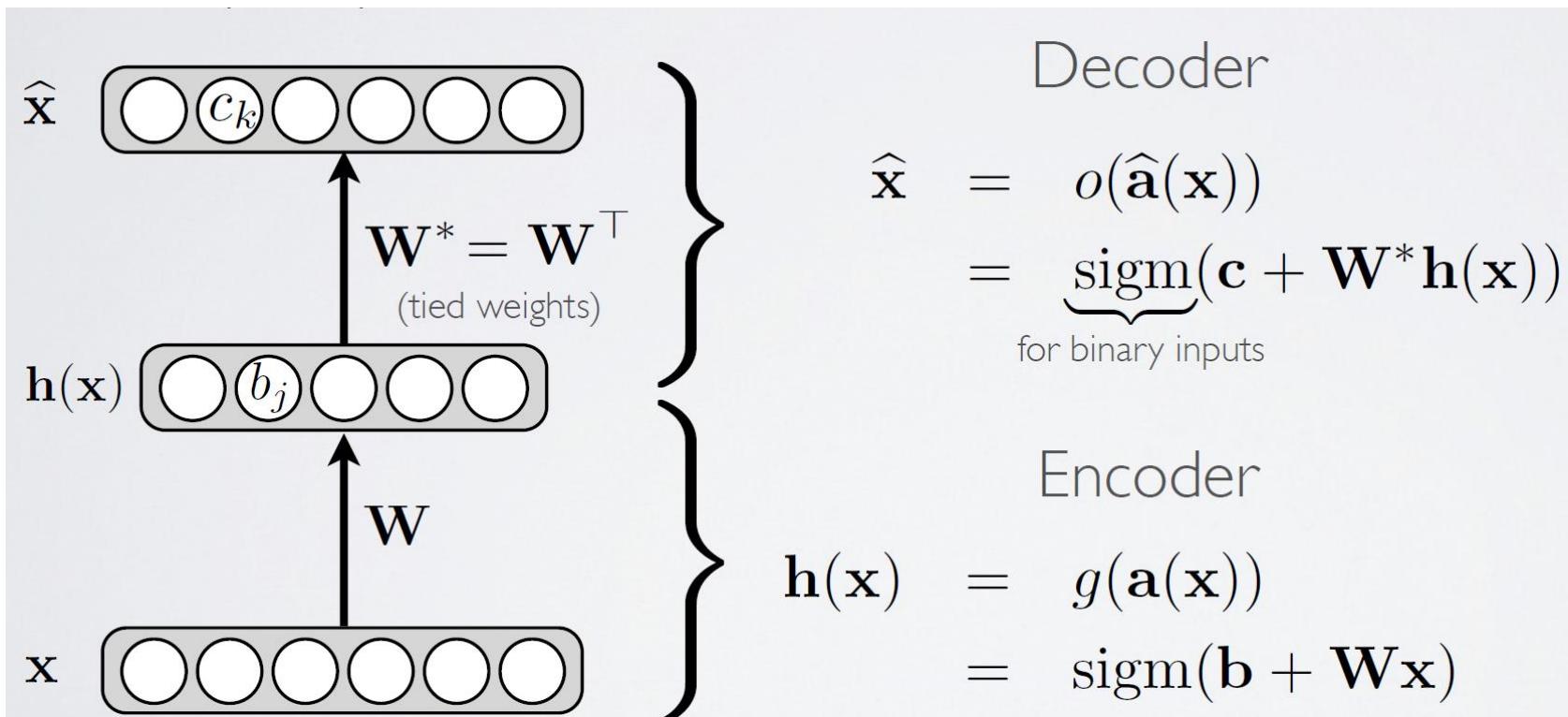
AGENDA

- 01 Novelty Detection: Overview
- 02 Density-based Novelty Detection
- 03 Distance/Reconstruction-based ND
- 04 Model-based Novelty Detection

Auto-Encoder for Novelty Detection

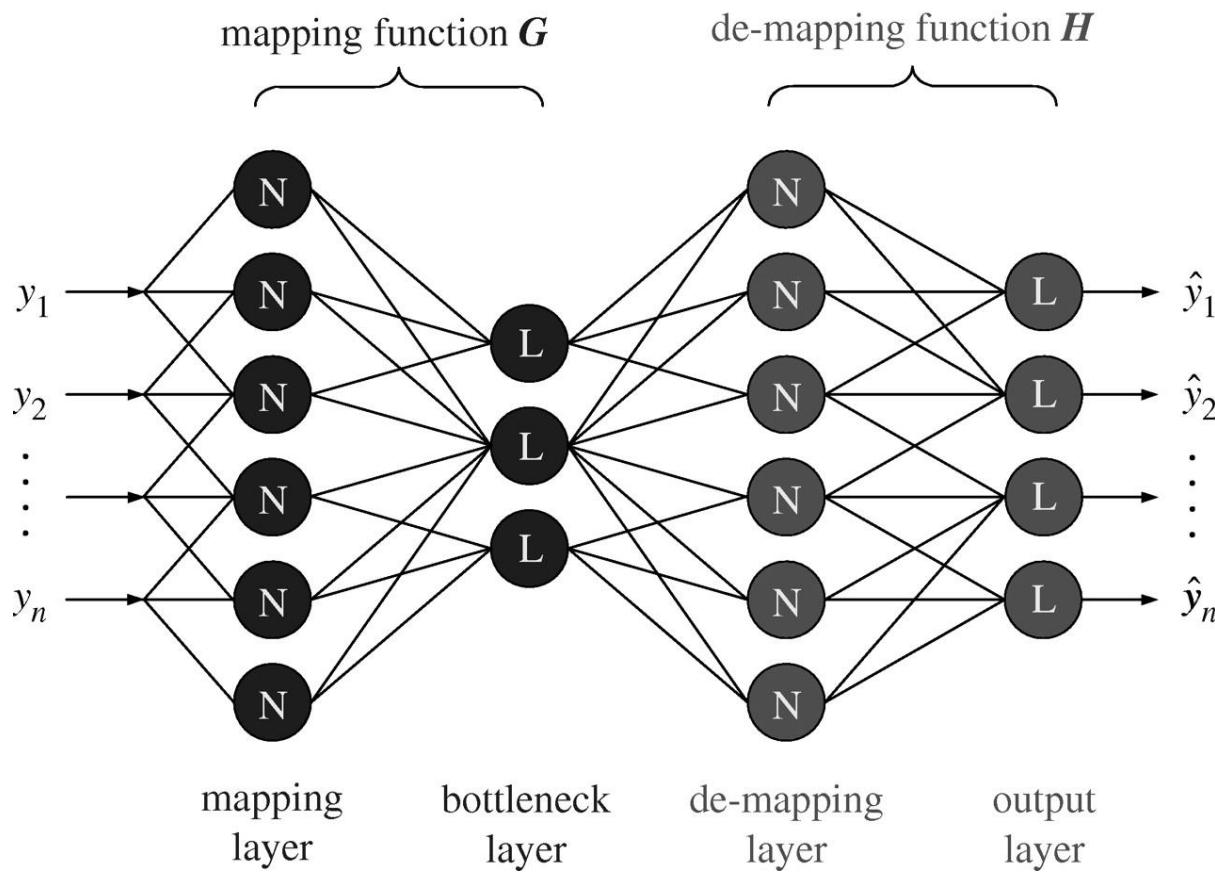
- Auto-Encoder (Auto-Associative Neural Network)
 - ✓ Feed-forward neural network trained to **reproduce** its input at the output layer

- Loss function:
$$l(f(\mathbf{x})) = \frac{1}{2} \sum_k (\hat{x}_k - x_k)^2$$



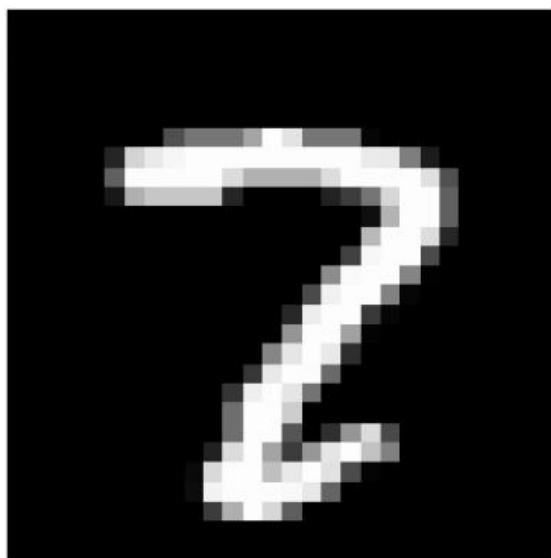
Auto-Encoder for Novelty Detection

- Auto Encoder (Auto-Associative Neural Network)
 - ✓ Feed-forward neural network trained to **reproduce** its input at the output layer
 - ✓ Overcomplete and Undercomplete hidden layers for AE

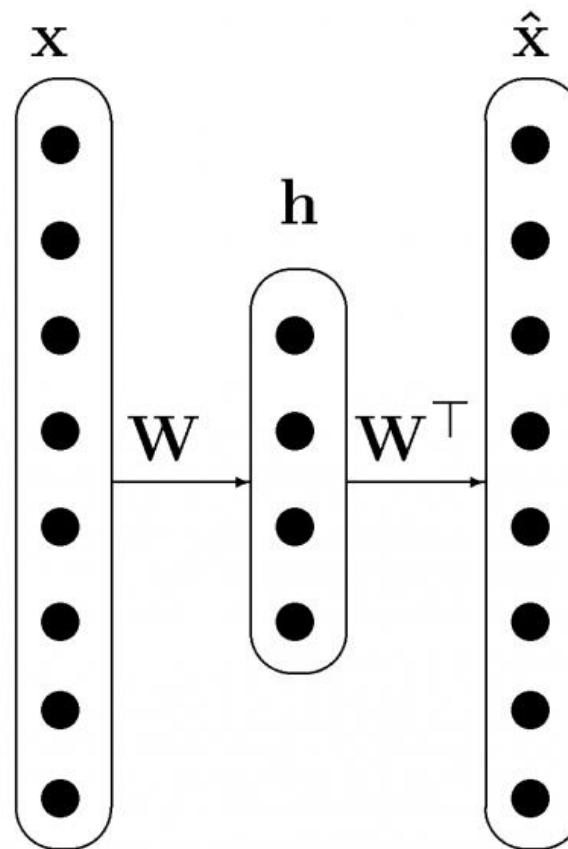


Auto-Encoder for Novelty Detection

- Auto Encoder (Auto-Associative Neural Network)
 - ✓ Example



(a) Input



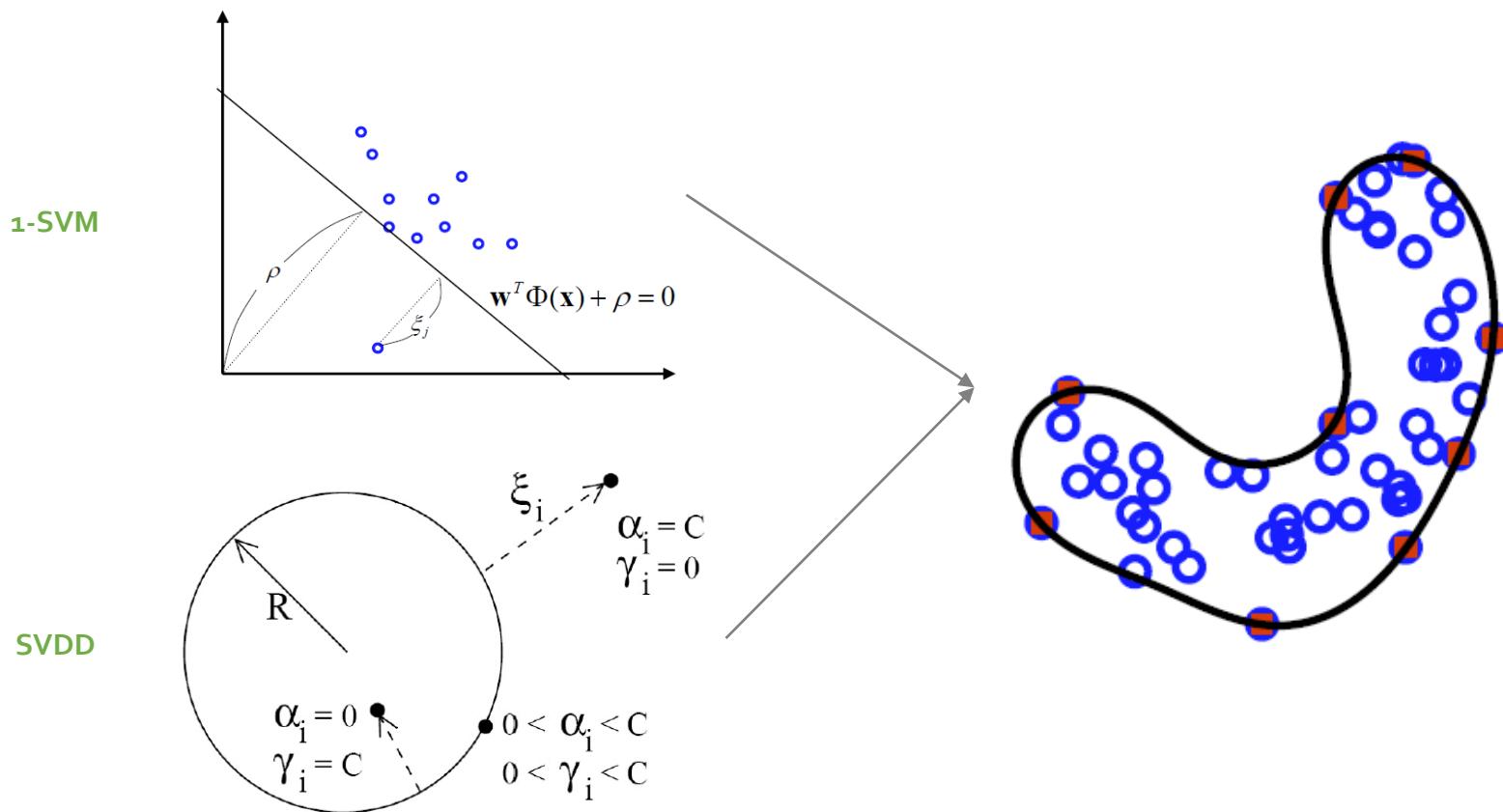
(b) Neural Encoding



(c) Reconstruction

Support Vector-based Novelty Detection

- Support vector-based novelty detection
 - ✓ Define boundaries of normal regions directly by finding function that separates the normal and abnormal observations



One-Class Support Vector Machine

Scholkopf et al. (2001)

- One-class support vector machine (1-SVM)

- ✓ Map the data into the feature space corresponding to the kernel and to separate them from the origin with maximum margin

- Optimization problem

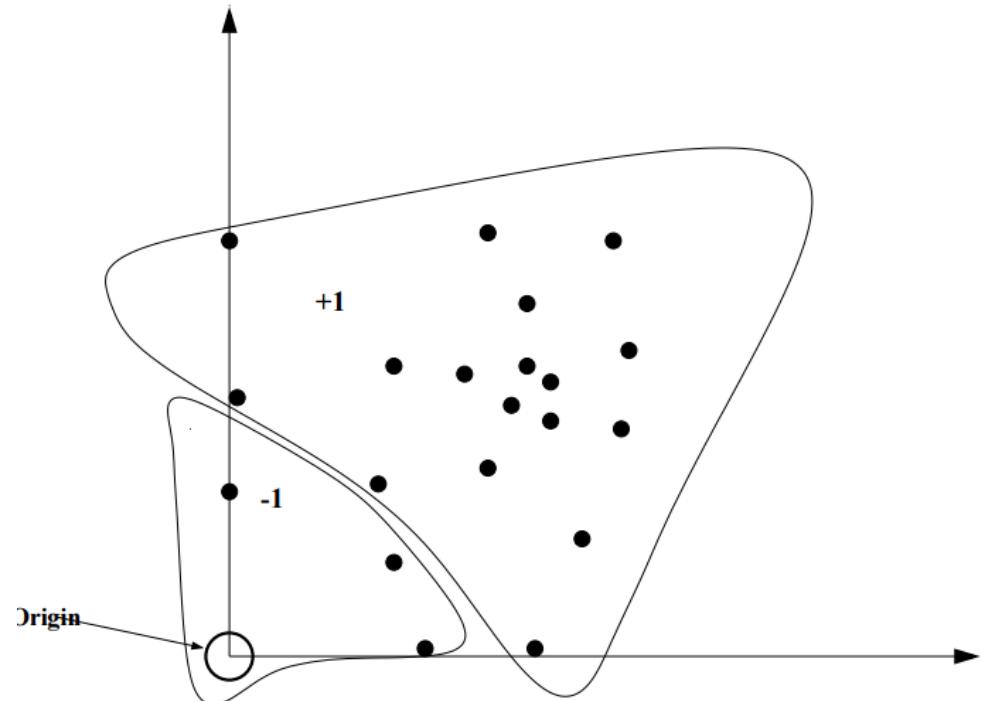
$$\min_{\mathbf{w}} \frac{1}{2} \|\mathbf{w}\|^2 + \frac{1}{\nu l} \sum_{i=1}^l \xi_i - \rho$$

$$s.t. \quad \mathbf{w} \cdot \Phi(\mathbf{x}_i) \geq \rho - \xi_i$$

$$i = 1, 2, \dots, l, \quad \xi_i \geq 0$$

- Decision function

$$f(\mathbf{x}_i) = \text{sign}(\mathbf{w} \cdot \Phi(\mathbf{x}_i) - \rho)$$



One-Class Support Vector Machine

- One-class support vector machine (1-SVM)

- ✓ Primal Lagrangian problem (Minimize)

$$L = \frac{1}{2} \|\mathbf{w}\|^2 + \frac{1}{\nu l} \sum_{i=1}^l \xi_i - \rho - \sum_{i=1}^l \alpha_i (\mathbf{w} \cdot \Phi(\mathbf{x}_i) - \rho + \xi_i) - \sum_{i=1}^l \beta_i \xi_i$$

- ✓ KKT condition

$$\frac{\partial L}{\partial \mathbf{w}} = \mathbf{w} - \sum_{i=1}^l \alpha_i \Phi(\mathbf{x}_i) = 0 \quad \Rightarrow \quad \mathbf{w} = \sum_{i=1}^l \alpha_i \Phi(\mathbf{x}_i)$$

$$\frac{\partial L}{\partial \xi_i} = \frac{1}{\nu l} - \alpha_i - \beta_i = 0 \quad \Rightarrow \quad \alpha_i = \frac{1}{\nu l} - \beta_i$$

$$\frac{\partial L}{\partial \rho} = -1 + \sum_{i=1}^l \alpha_i = 0 \quad \Rightarrow \quad \sum_{i=1}^l \alpha_i = 1$$

One-Class Support Vector Machine

- One-class support vector machine (1-SVM)

✓ Dual Lagrangian problem (Maximize)

$$L = \frac{1}{2} \sum_{i=1}^l \sum_{j=1}^l \alpha_i \alpha_j \Phi(\mathbf{x}_i) \Phi(\mathbf{x}_j) + \frac{1}{\nu l} \sum_{i=1}^l \xi_i - \rho$$

$$- \sum_{i=1}^l \sum_{j=1}^l \alpha_i \alpha_j \Phi(\mathbf{x}_i) \Phi(\mathbf{x}_j) + \rho \sum_{i=1}^l \alpha_i - \sum_{i=1}^l \alpha_i \xi_i - \sum_{i=1}^l \beta_i \xi_i$$

✓ We should solve

$$\min L = \frac{1}{2} \sum_{i=1}^l \sum_{j=1}^l \alpha_i \alpha_j \Phi(\mathbf{x}_i) \Phi(\mathbf{x}_j)$$

$$s.t. \quad \sum_{i=1}^l \alpha_i = 1, \quad 0 \leq \alpha_i \leq \frac{1}{\nu l}$$

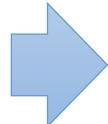
One-Class Support Vector Machine

- One-class support vector machine (1-SVM)

✓ Employ Kernel Trick for a non-linear mapping

$$\min L = \frac{1}{2} \sum_{i=1}^l \sum_{j=1}^l \alpha_i \alpha_j \Phi(\mathbf{x}_i) \Phi(\mathbf{x}_j)$$

$$s.t. \quad \sum_{i=1}^l \alpha_i = 1, \quad 0 \leq \alpha_i \leq \frac{1}{\nu l}$$



$$\min L = \frac{1}{2} \sum_{i=1}^l \sum_{j=1}^l \alpha_i \alpha_j K(\mathbf{x}_i, \mathbf{x}_j)$$

$$s.t. \quad \sum_{i=1}^l \alpha_i = 1, \quad 0 \leq \alpha_i \leq \frac{1}{\nu l}$$

Some possible kernels $K(\cdot, \cdot)$:

$$K(x, x_i) = x_i^T x \text{ (linear SVM)}$$

$$K(x, x_i) = (x_i^T x + \tau)^d \text{ (polynomial SVM of degree } d\text{)}$$

$$K(x, x_i) = \exp(-\|x - x_i\|_2^2 / \sigma^2) \text{ (RBF kernel)}$$

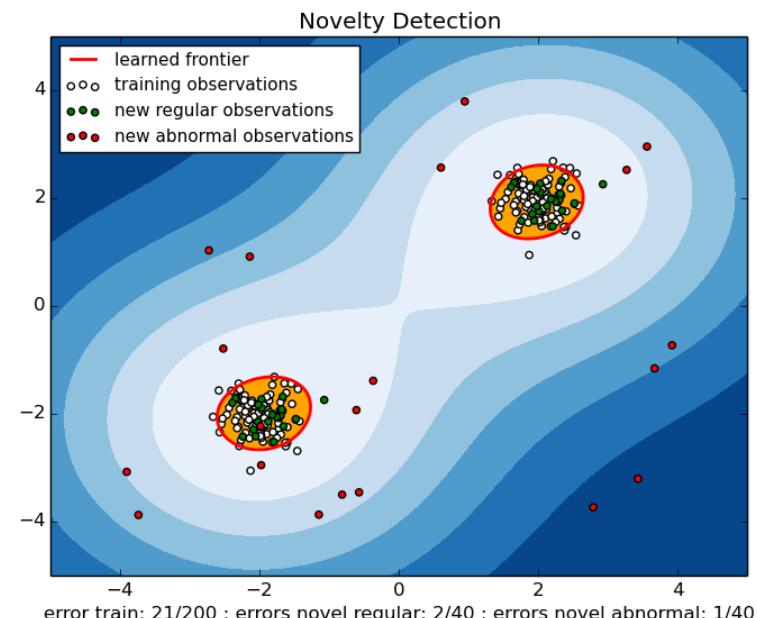
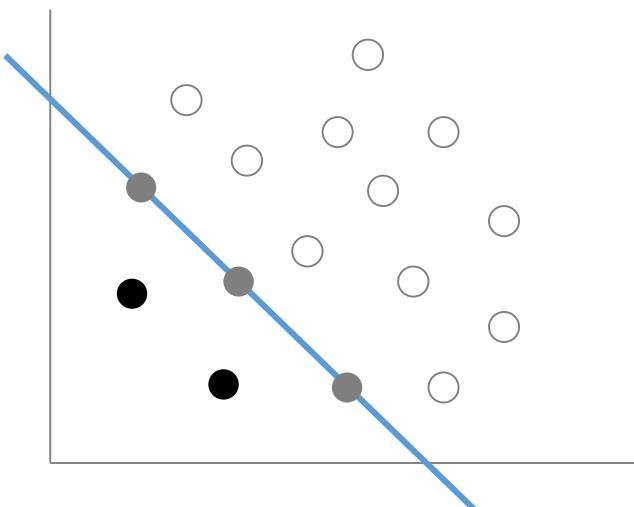
$$K(x, x_i) = \tanh(\kappa x_i^T x + \theta) \text{ (MLP kernel)}$$

One-Class Support Vector Machine

- One-class support vector machine (1-SVM)

- ✓ Location of a point w.r.t. α_i

- ▪ Case 1: $\alpha_i = 0 \Rightarrow$ a non-support vector
- ▪ Case 2: $\alpha_i = \frac{1}{\nu l} \Rightarrow \beta_i = 0 \Rightarrow \xi_i > 0 \Rightarrow$ Support vector (outsider the hyperplane)
- ▪ Case 3: $0 < \alpha_i < \frac{1}{\nu l} \Rightarrow \beta_i > 0 \Rightarrow \xi_i = 0 \Rightarrow$ Support vector (on the hyperplane)



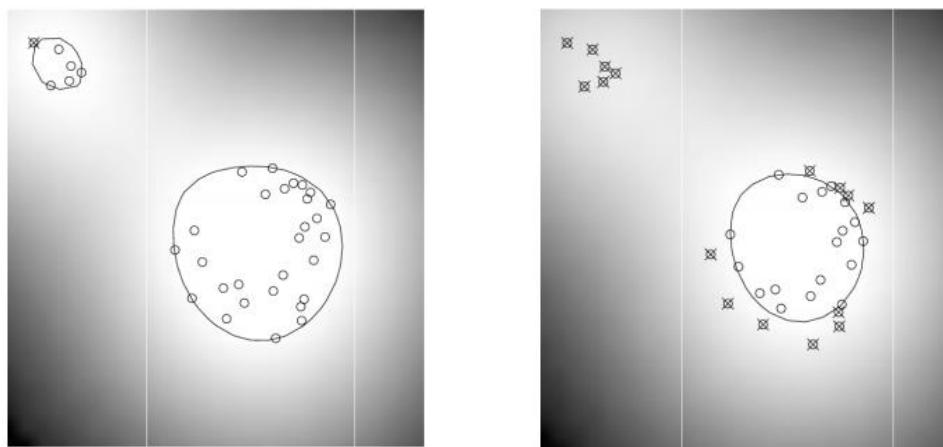
One-Class Support Vector Machine

- One-class support vector machine (1-SVM)

- ✓ The role of ν

- The maximum possible value of $\alpha_i = \frac{1}{\nu l}$
 - At least νl support vectors exist
 - At most νl support vectors can be located outside the hyperplane
 - Thus, ν is the **lower bound for the fraction of support vectors** and the **upper bound for the fraction of errors**

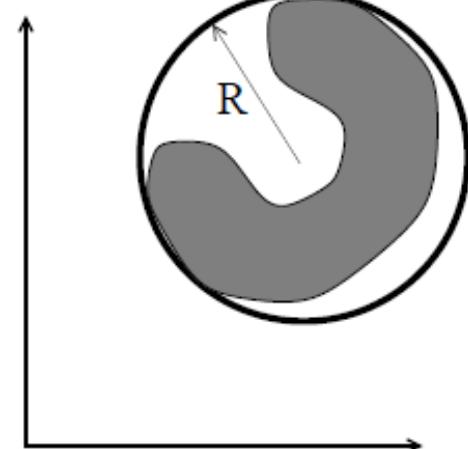
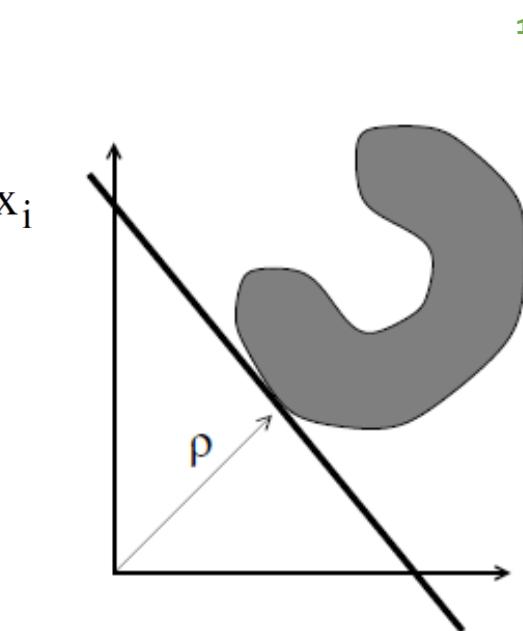
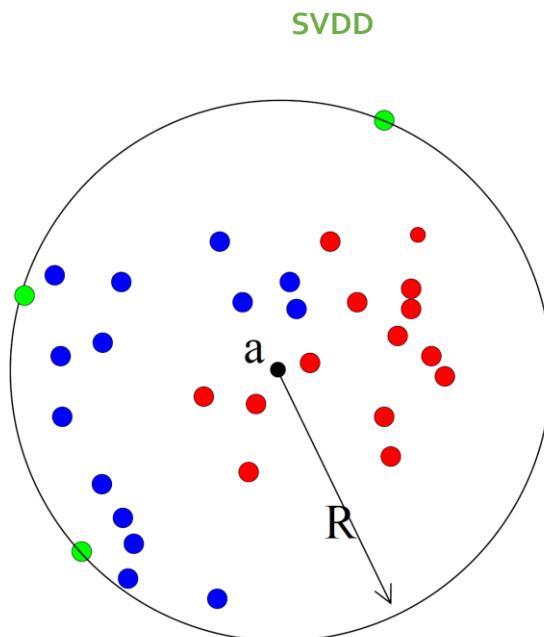
- ✓ The higher the ν , the more complex decision boundary is generated



Support Vector Data Description

Tax and Duin (2004)

- Support Vector Data Description (SVDD)
 - ✓ Find a hypersphere enclosing all the normal instances in a feature space



Support Vector Data Description

- Support Vector Data Description (SVDD)
 - ✓ Find a hypersphere enclosing all the normal instances in a feature space
 - Optimization function

$$\min_{R, \mathbf{a}, \xi_i} R^2 + C \sum_{i=1}^l \xi_i$$

$$s.t. \quad ||\Phi(\mathbf{x}_i) - \mathbf{a}||^2 \leq R^2 + \xi_i, \quad \xi_i \geq 0, \quad \forall i.$$

- Decision function

$$f(\mathbf{x}) = sign(R^2 - ||\Phi(\mathbf{x}_i) - \mathbf{a}||^2)$$

Support Vector Data Description

- Support Vector Data Description (SVDD)

- ✓ Find a hypersphere enclosing all the normal instances in a feature space

- Primal Lagrangian problem (Minimization)

$$L = R^2 + C \sum_{i=1}^l \xi_i - \sum_{i=1}^l \alpha_i \left(R^2 + \xi_i - (\Phi(\mathbf{x}_i) \cdot \Phi(\mathbf{x}_i) - 2 \cdot \mathbf{a} \cdot \Phi(\mathbf{x}_i) + \mathbf{a} \cdot \mathbf{a}) \right) - \sum_{i=1}^l \beta_i \xi_i$$
$$\alpha_i \geq 0, \quad \beta_i \geq 0$$

- KKT condition

$$\frac{\partial L}{\partial R} = 2R - 2R \sum_{i=1}^l \alpha_i = 0 \quad \Rightarrow \quad \sum_{i=1}^l \alpha_i = 1$$

$$\frac{\partial L}{\partial \mathbf{a}} = 2 \sum_{i=1}^l \alpha_i \cdot \Phi(\mathbf{x}_i) - 2\mathbf{a} \sum_{i=1}^l \alpha_i = 0 \quad \Rightarrow \quad \mathbf{a} = \sum_{i=1}^l \alpha_i \cdot \Phi(\mathbf{x}_i)$$

$$\frac{\partial L}{\partial \xi_i} = C - \alpha_i - \beta_i = 0 \quad \forall i$$

Support Vector Data Description

- Support Vector Data Description (SVDD)
 - ✓ Find a hypersphere enclosing all the normal instances in a feature space
 - Dual Lagrangian problem (Maximization)

$$L = R^2 + C \sum_{i=1}^l \xi_i - \sum_{i=1}^l \alpha_i \left(R^2 + \xi_i - (\Phi(\mathbf{x}_i) \cdot \Phi(\mathbf{x}_i) - 2 \cdot \mathbf{a} \cdot \Phi(\mathbf{x}_i) + \mathbf{a} \cdot \mathbf{a}) \right) - \sum_{i=1}^l \beta_i \xi_i$$



$$L = R^2 - R^2 \sum_{i=1}^l \alpha_i + \sum_{i=1}^l \xi_i (C - \alpha_i - \beta_i)$$

$$+ \sum_{i=1}^l \alpha_i \Phi(\mathbf{x}_i) \cdot \Phi(\mathbf{x}_i) - 2 \sum_{i=1}^l \sum_{j=1}^l \alpha_i \alpha_j \Phi(\mathbf{x}_i) \Phi(\mathbf{x}_j) + \sum_{i=1}^l \sum_{j=1}^l \alpha_i \alpha_j \Phi(\mathbf{x}_i) \Phi(\mathbf{x}_j)$$



$$L = \sum_{i=1}^l \alpha_i \Phi(\mathbf{x}_i) \cdot \Phi(\mathbf{x}_i) - \sum_{i=1}^l \sum_{j=1}^l \alpha_i \alpha_j \Phi(\mathbf{x}_i) \Phi(\mathbf{x}_j) \quad (0 \leq \alpha_i \leq C)$$

Support Vector Data Description

- Support Vector Data Description (SVDD)
 - ✓ Find a hypersphere enclosing all the normal instances in a feature space
 - Dual Lagrangian problem (Maximization)

$$L = \sum_{i=1}^l \alpha_i \Phi(\mathbf{x}_i) \cdot \Phi(\mathbf{x}_i) - \sum_{i=1}^l \sum_{j=1}^l \alpha_i \alpha_j \Phi(\mathbf{x}_i) \Phi(\mathbf{x}_j) \quad (0 \leq \alpha_i \leq C)$$

- Dual Lagrangian problem (Minimization)

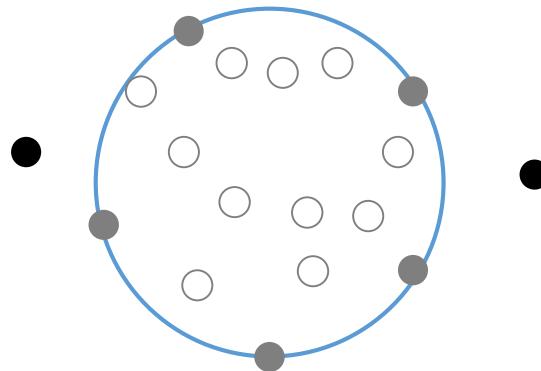
$$L = \sum_{i=1}^l \sum_{j=1}^l \alpha_i \alpha_j \Phi(\mathbf{x}_i) \Phi(\mathbf{x}_j) - \sum_{i=1}^l \alpha_i \Phi(\mathbf{x}_i) \cdot \Phi(\mathbf{x}_i) \quad (0 \leq \alpha_i \leq C)$$

Support Vector Data Description

- Support Vector Data Description (SVDD)

- ✓ Location of a point w.r.t. α_i

- ▪ Case 1: $\alpha_i = 0 \Rightarrow$ a non-support vector
 - ▪ Case 2: $\alpha_i = C \Rightarrow \beta_i = 0 \Rightarrow \xi_i > 0 \Rightarrow$ Support vector (outsider the hypersphere)
 - ▪ Case 3: $0 < \alpha_i < C \Rightarrow \beta_i > 0 \Rightarrow \xi_i = 0 \Rightarrow$ Support vector (on the hypersphere)



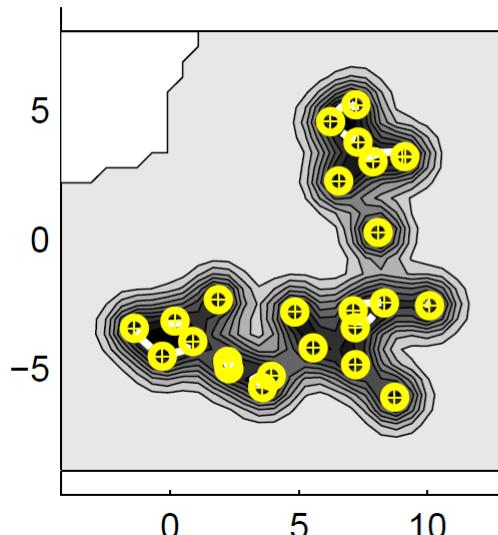
Support Vector Data Description

- Support Vector Data Description (SVDD)

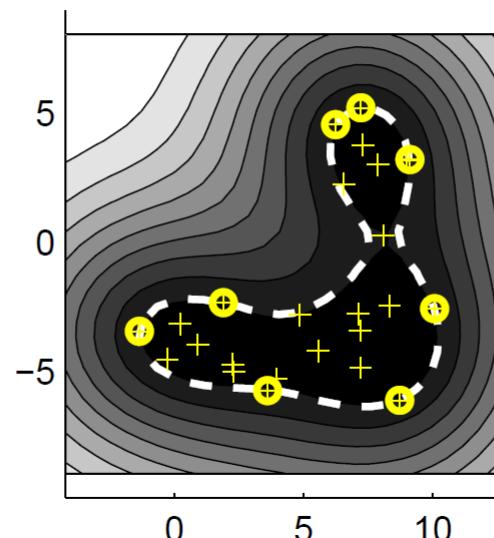
- ✓ SVDD with Gaussian (RBF) kernels

$$K(\mathbf{x}_i, \mathbf{x}_j) = \exp\left(\frac{-\|\mathbf{x}_i - \mathbf{x}_j\|^2}{s^2}\right)$$

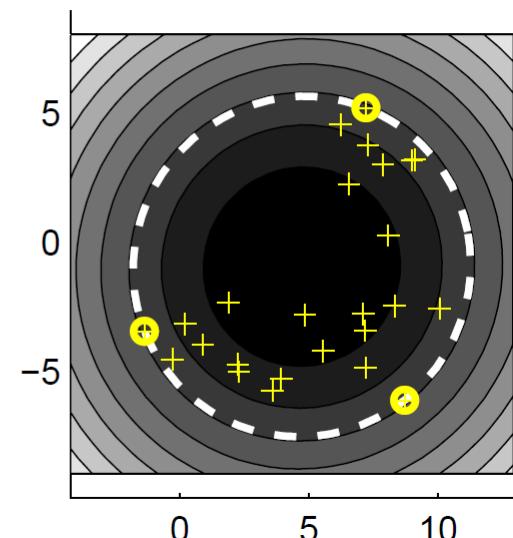
$s = 1.0$



$s = 5.0$

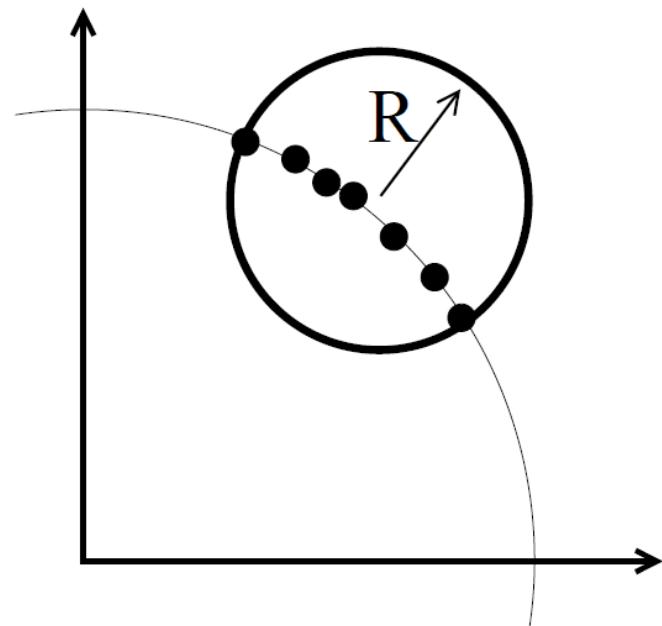
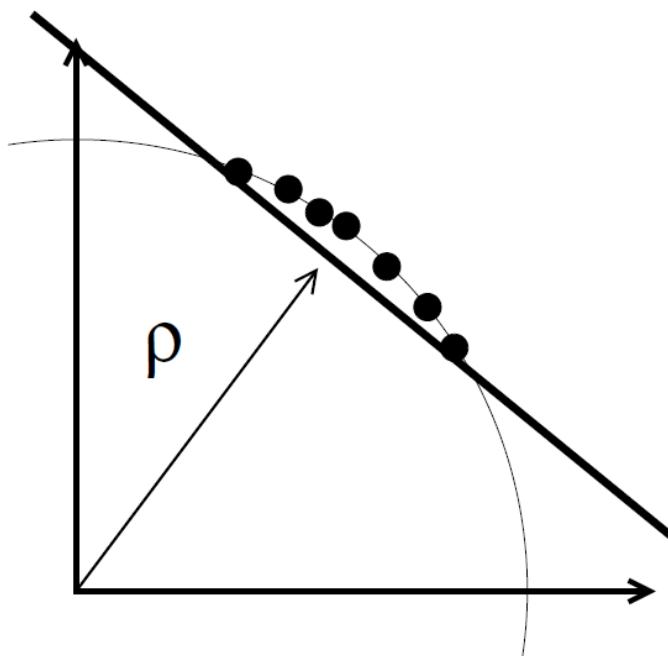


$s = 25.0$



Support Vector Data Description

- Support Vector Data Description (SVDD)
 - ✓ When all data is normalized to unit norm vector, SVDD and 1-SVM are equivalent

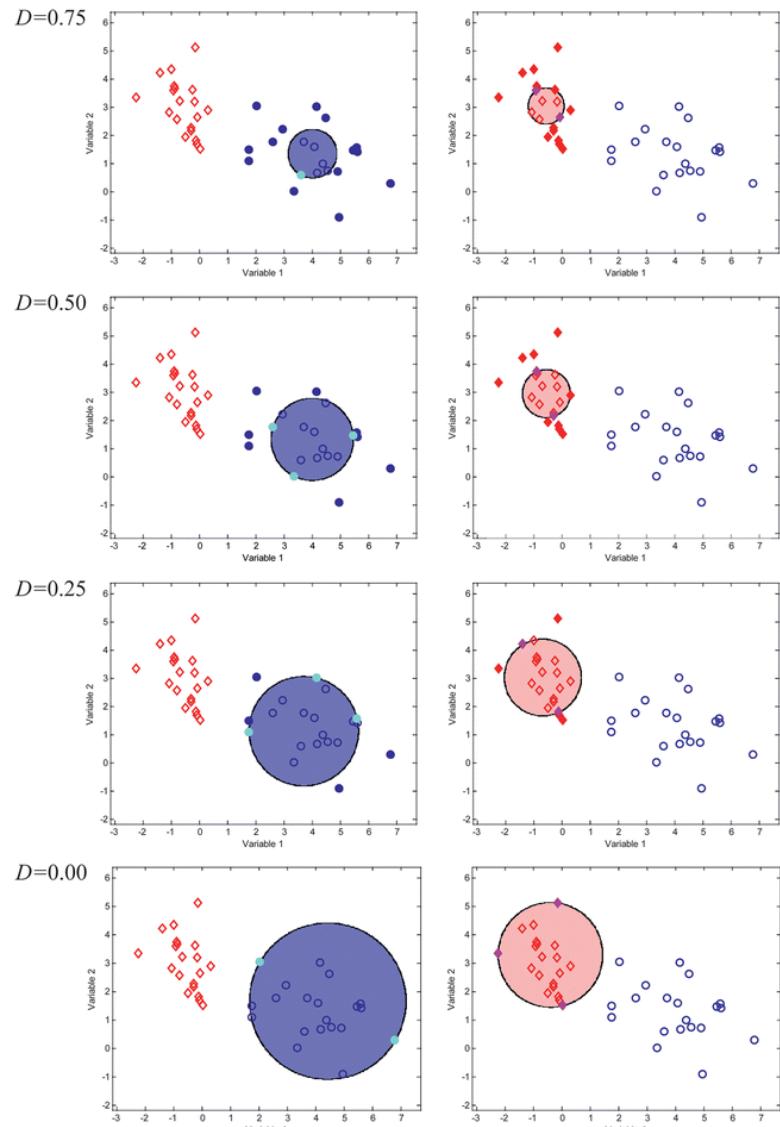


- For the detailed proof, please refer to Tax (2001) pp. 39-41.

Support Vector Data Description

- Support Vector Data Description (SVDD)

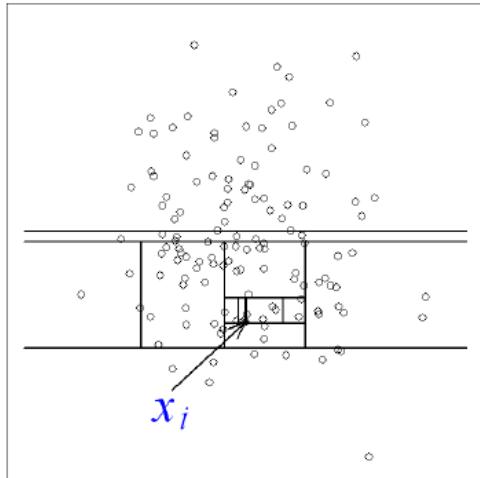
- ✓ As in 1-SVM, ν -SVDD can also be formulated
- ✓ D in the right figure is ν



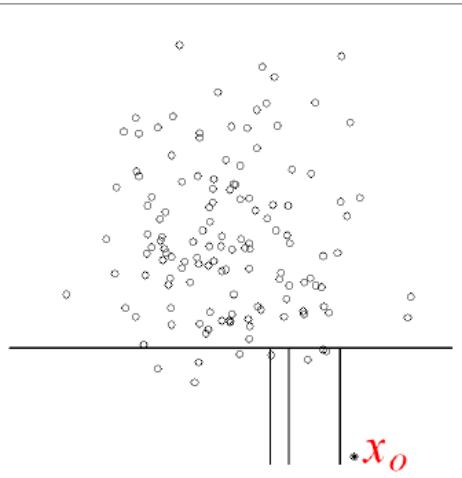
Isolation Forest

Liu et al. (2008, 2012)

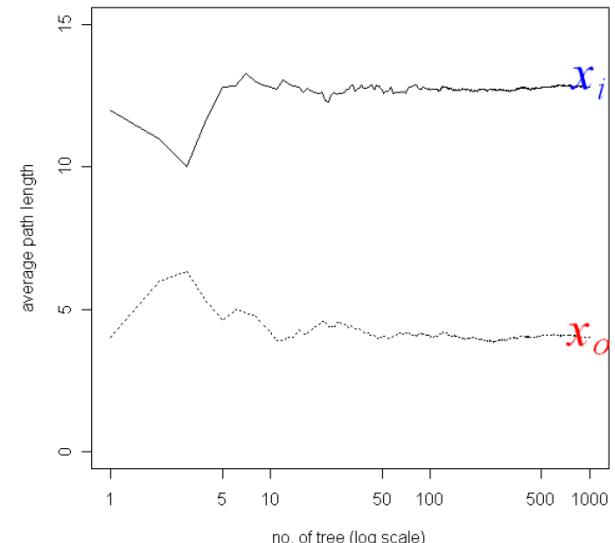
- Motivation: Few and Different
 - ✓ The minority consists of fewer instances
 - ✓ They have attribute-values, which are very different from those of normal instances
- A tree structure can be constructed effectively to **isolate** every single instances
 - ✓ Novel instances are isolated closer to the root of the tree
 - ✓ Normal instances are isolated at the deeper end of the tree



(a) Isolating x_i

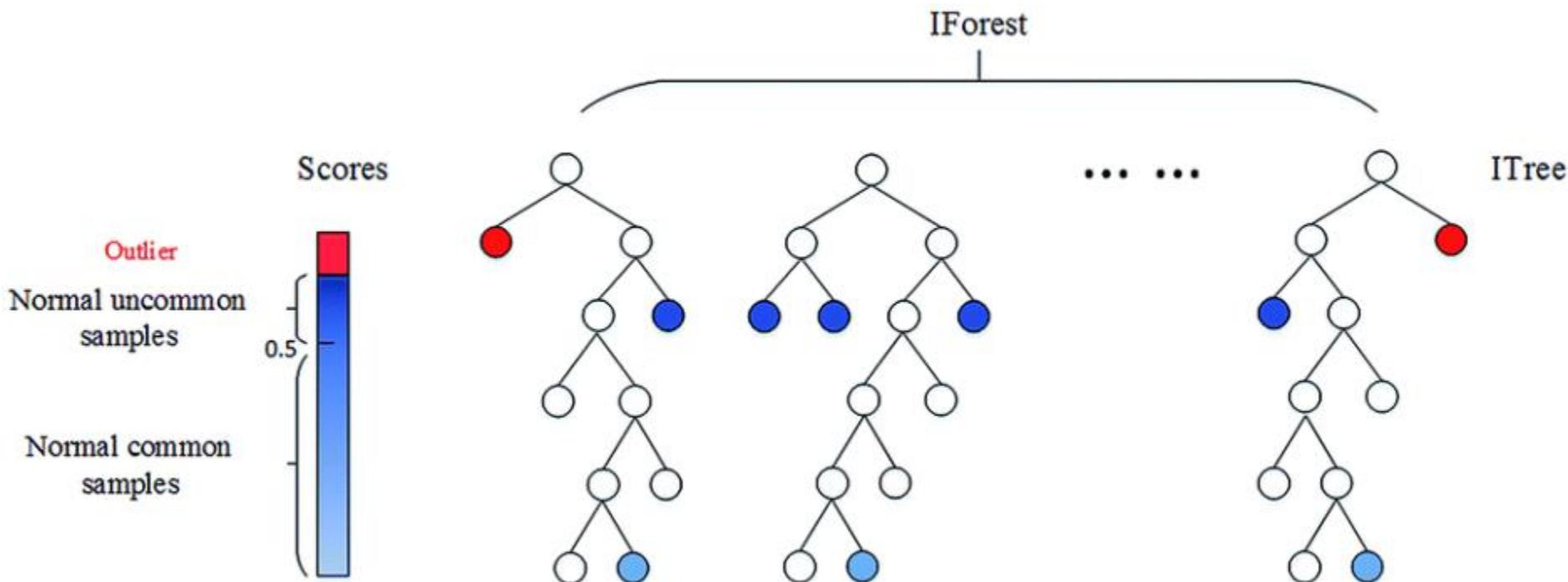


(b) Isolating x_o



Isolation Forest

- The isolation characteristics of tree forms the basis of the method to detect novel instances
 - ✓ The average path to the terminal node can be used as a novelty score of an instance



Isolation Forest

- Definition: Isolation Tree (iTree)
 - ✓ Given a sample of data X of n instances, the dataset X is recursively divided by randomly selected attribute q with a split value p , until either
 - The tree reaches a height limit
 - $|X| = 1$
 - All instances in X have the same value
- Definition: Path Length
 - ✓ The path length $h(x)$ of an instance x is measured by the number of edges x traverses an iTree from the root node to the terminal node in which the instance x is located
 - ✓ $h(x)$ is normalized by the average path length of $h(x)$ given n
 - $c(n) = 2H(n-1)-(2(n-1)/n)$ ($H(i) = \ln(i) + 0.5772156649$ (Euler's constant))

Isolation Forest

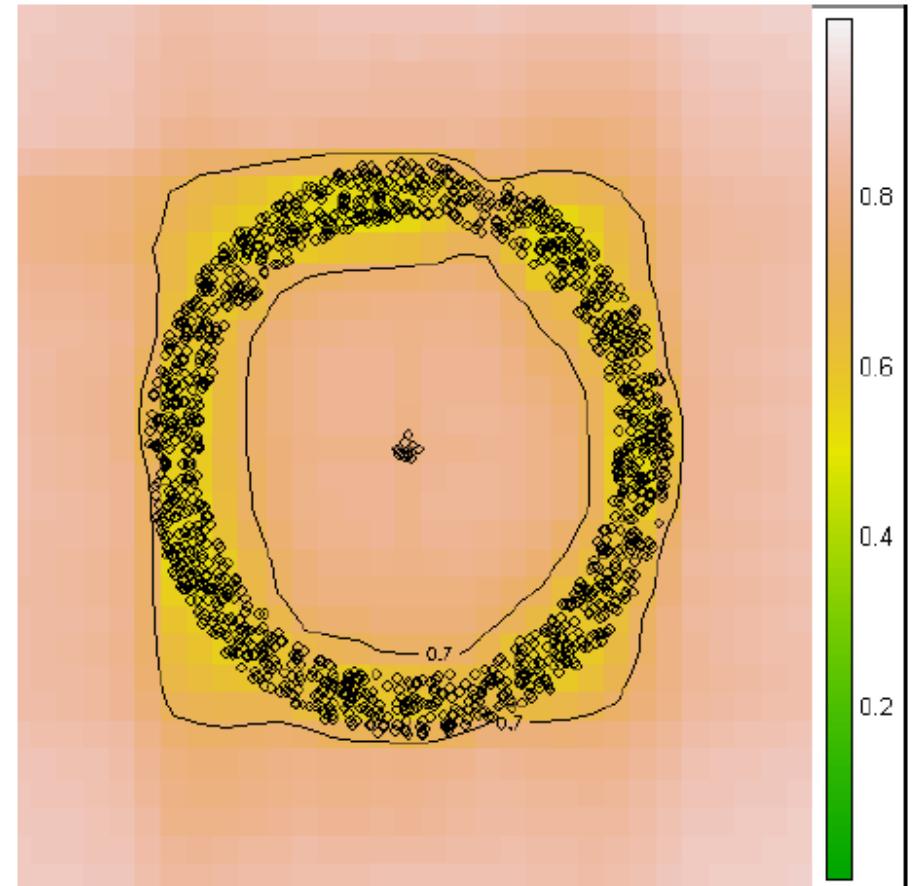
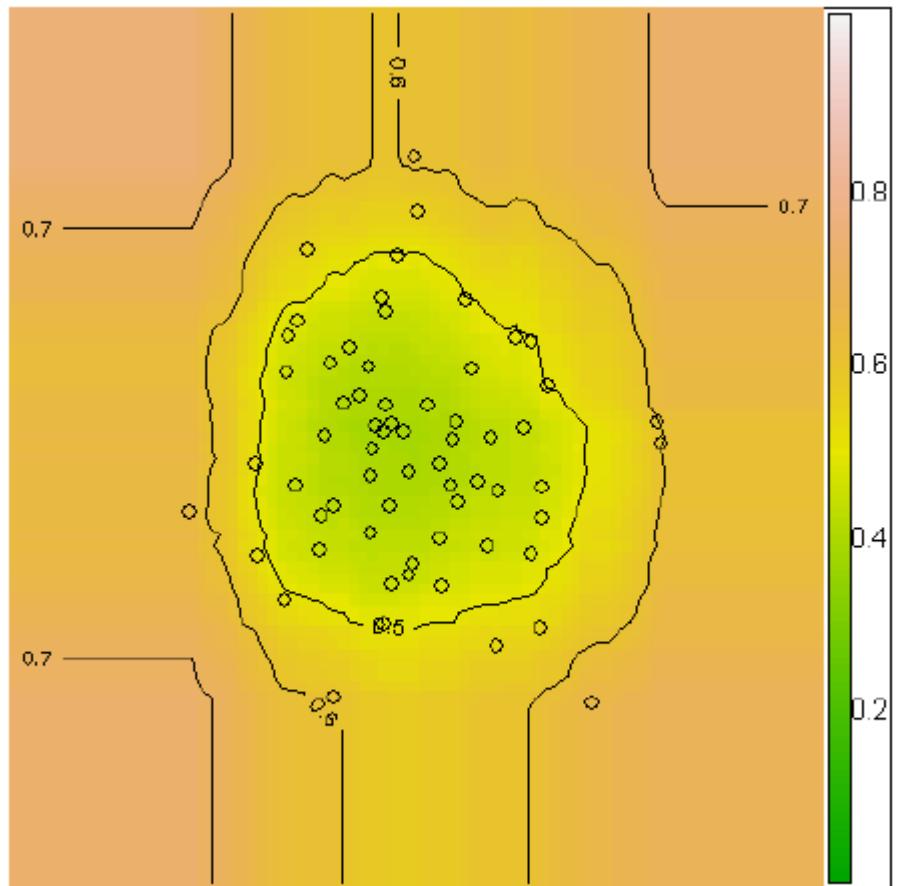
- Definition: Novelty score
 - ✓ The path length $h(x)$ of an instance x is measured by the number of edges x traverses an iTree from the root node to the terminal node in which the instance x is located
 - ✓ $h(x)$ is normalized by the average path length of $h(x)$ given n
 - $c(n) = 2H(n-1) - (2(n-1)/n)$ ($H(i) = \ln(i) + 0.5772156649$ (Euler's constant))
 - ✓ The novelty score s of an instance x is defined by

$$s(x, n) = 2^{-\frac{E(h(x))}{c(n)}}$$

- When $E(h(x)) \rightarrow c(n)$, $s \rightarrow 0.5$
- When $E(h(x)) \rightarrow 0$, $s \rightarrow 1$
- When $E(h(x)) \rightarrow n - 1$, $s \rightarrow 0$

Isolation Forest

- Novelty score contour



Isolation Forest

- Training Isolation Forest

- ✓ Randomly sample datasets
- ✓ Construct iTree
- ✓ Compute the path length

Algorithm 1 : $iForest(X, t, \psi)$

Inputs: X - input data, t - number of trees, ψ - subsampling size

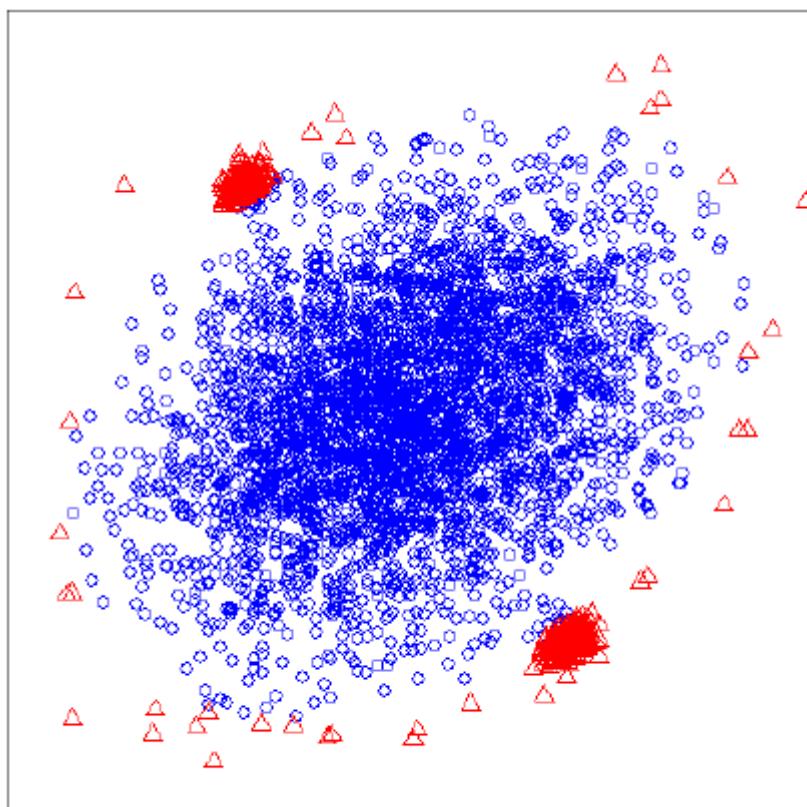
Output: a set of t $iTrees$

```
1: Initialize  $Forest$ 
2: for  $i = 1$  to  $t$  do
3:    $X' \leftarrow sample(X, \psi)$ 
4:    $Forest \leftarrow Forest \cup iTree(X')$ 
5: end for
6: return  $Forest$ 
```

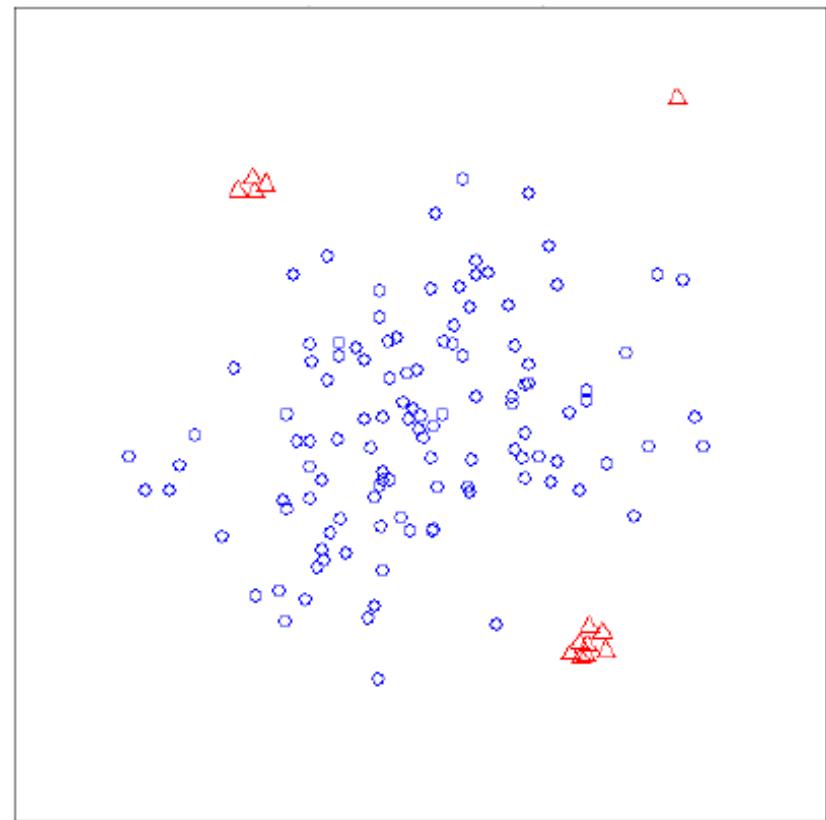
Isolation Forest

- Training Isolation Forest

- ✓ Randomly sample datasets: 256 is generally enough



(a) Original sample
(4096 instances)



(b) Sub-sample
(128 instances)

Isolation Forest

- Training Isolation Forest

- ✓ Construct iTree

Algorithm 2 : $iTree(X')$

Inputs: X' - input data

Output: an $iTree$

```
1: if  $X'$  cannot be divided then
2:   return  $exNode\{Size \leftarrow |X'|\}$ 
3: else
4:   let  $Q$  be a list of attributes in  $X'$ 
5:   randomly select an attribute  $q \in Q$ 
6:   randomly select a split point  $p$  between the  $max$  and  $min$  values of attribute
     $q$  in  $X'$ 
7:    $X_l \leftarrow filter(X', q < p)$ 
8:    $X_r \leftarrow filter(X', q \geq p)$ 
9:   return  $inNode\{Left \leftarrow iTree(X_l),$ 
10:       $Right \leftarrow iTree(X_r),$ 
11:       $SplitAtt \leftarrow q,$ 
12:       $SplitValue \leftarrow p\}$ 
13: end if
```

Isolation Forest

- Training Isolation Forest

✓ Compute the path length

Algorithm 3 : $\text{PathLength}(x, T, hlim, e)$

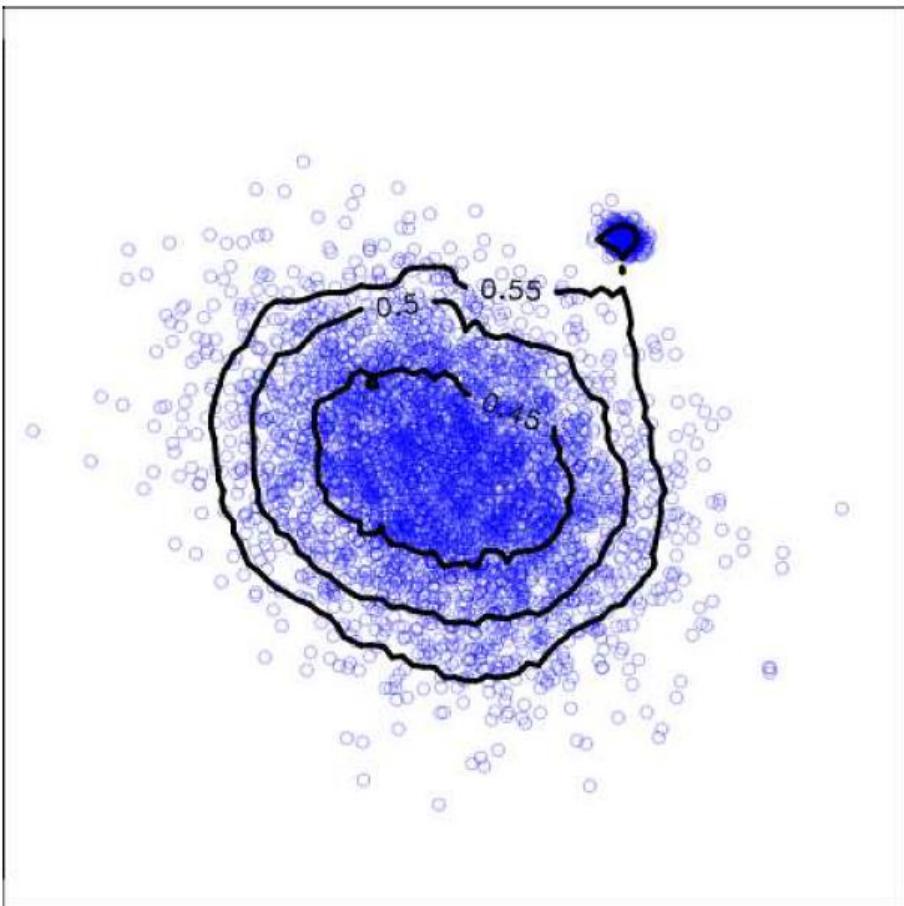
Inputs : x - an instance, T - an i Tree, $hlim$ - height limit, e - current path length;
to be initialized to zero when first called

Output: path length of x

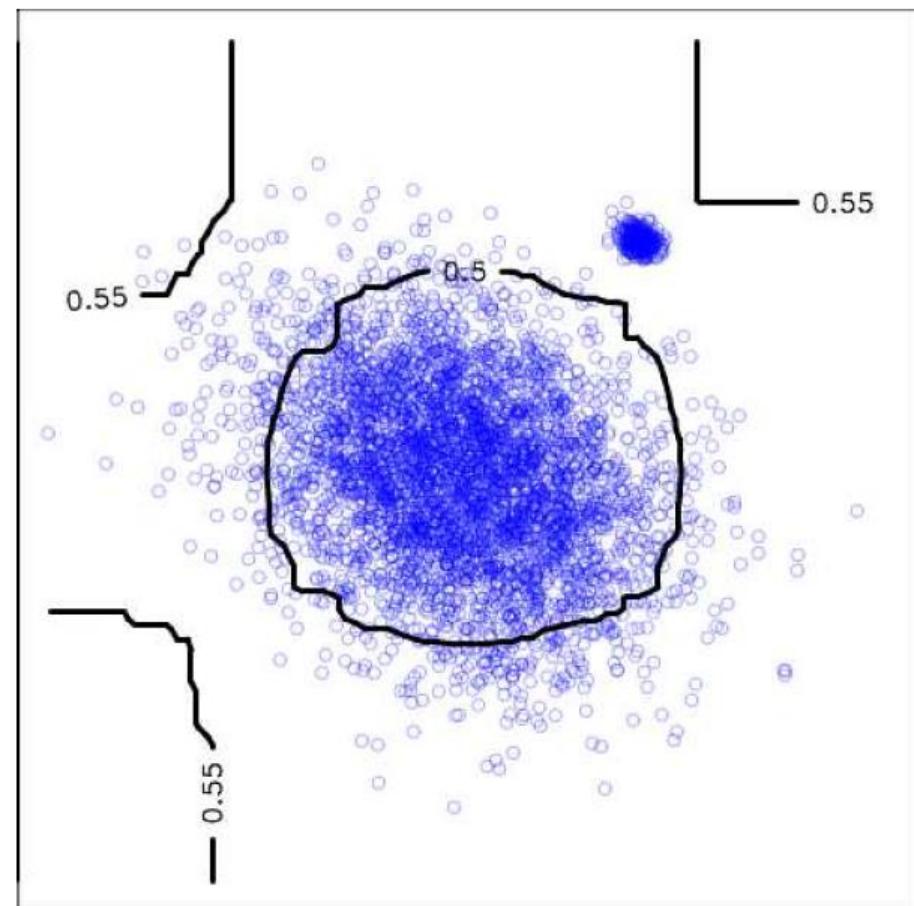
```
1: if  $T$  is an external node or  $e \geq hlim$  then
2:   return  $e + c(T.\text{size})$   $\{c(\cdot)\}$  is defined in Equation 1}
3: end if
4:  $a \leftarrow T.\text{splitAtt}$ 
5: if  $x_a < T.\text{splitValue}$  then
6:   return  $\text{PathLength}(x, T.\text{left}, hlim, e + 1)$ 
7: else  $\{x_a \geq T.\text{splitValue}\}$ 
8:   return  $\text{PathLength}(x, T.\text{right}, hlim, e + 1)$ 
9: end if
```

Isolation Forest

- Effect of the height limit



(a) $hlim = 6,$



(b) $hlim = 1,$

Isolation Forest

- Empirical evaluation

✓ Datasets

	n	d	anomaly class
Http (KDDCUP99)	567497	3	attack (0.4%)
			class 4 (0.9%)
ForestCover	286048	10	vs. class 2
Mulcross	262144	4	2 clusters (10%)
Smtp (KDDCUP99)	95156	3	attack (0.03%)
Shuttle	49097	9	classes 2,3,5,6,7 (7%)
Mammography	11183	6	class 1 (2%)
Annthyroid	6832	6	classes 1, 2 (7%)
Satellite	6435	36	3 smallest classes (32%)
Pima	768	8	pos (35%)
Breastw	683	9	malignant (35%)
Arrhythmia	452	274	classes 03,04,05,07, 08,09,14,15 (15%)
Ionosphere	351	32	bad (36%)
hbk	75	4	14 points (19%)
wood	20	6	6 instances (30%)

Isolation Forest

- Empirical evaluation
 - ✓ Performance (in terms of AUROC)

	AUC				
	<i>i</i> Forest	ORCA	SVM	LOF	RF
Http (KDDCUP99)	1.00	0.36	0.90	*	**
ForestCover	0.87	0.83	0.90	0.57	**
Mulcross	0.96	0.33	0.59	0.59	**
Smtp (KDDCUP99)	0.89	0.80	0.78	0.32	**
Shuttle	1.00	0.60	0.79	0.55	**
Mammography	0.84	0.77	0.65	0.67	**
Annthyroid	0.84	0.68	0.63	0.72	**
Satellite	0.73	0.65	0.61	0.52	**
Pima	0.67	0.71	0.55	0.49	0.65
Breastw	0.98	0.98	0.66	0.37	0.97
Arrhythmia	0.81	0.78	0.71	0.73	0.60
Ionosphere	0.83	0.92	0.71	0.89	0.85

(a) AUC performance

Isolation Forest

- Empirical evaluation

- ✓ Performance (in terms of computational complexity)

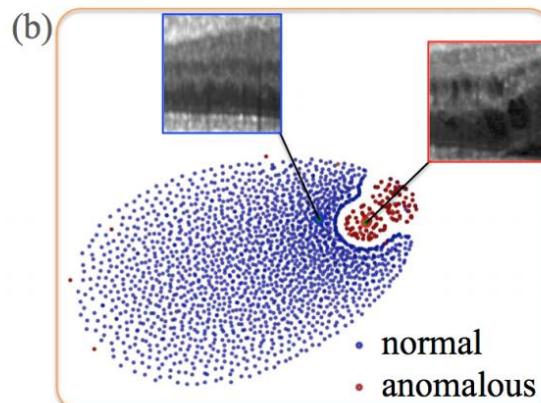
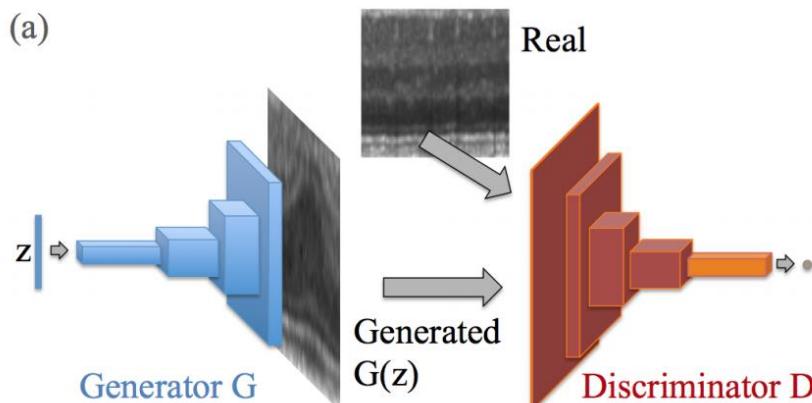
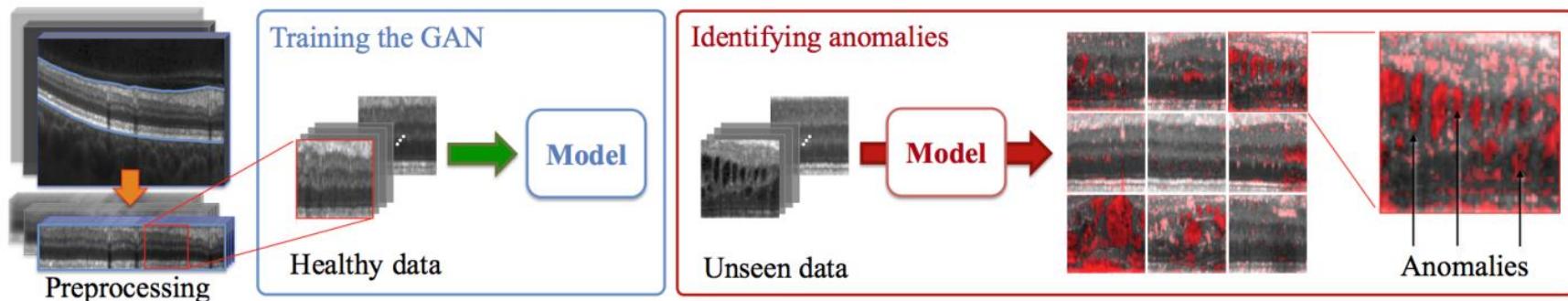
	Time (seconds)							
	iForest			ORCA	SVM	LOF	RF	
	Train	Eval.	Total					
Http	0.25	15.33	15.58	9487.47	35872.09	*	**	
ForestCover	0.76	15.57	16.33	6995.17	9737.81	224380.19	**	
Mulcross	0.26	12.26	12.52	2512.20	7342.54	156044.13	**	
Smtp	0.14	2.58	2.72	267.45	986.84	24280.65	**	
Shuttle	0.30	2.83	3.13	156.66	332.09	7489.74	**	
Mammography	0.16	0.50	0.66	4.49	10.8	14647.00	**	
Annthyroid	0.15	0.36	0.51	2.32	4.18	72.02	**	
Satellite	0.46	1.17	1.63	8.51	8.97	217.39	**	
Pima	0.17	0.11	0.28	0.06	0.06	1.14	4.98	
Breastw	0.17	0.11	0.28	0.04	0.07	1.77	3.10	
Arrhythmia	2.12	0.86	2.98	0.49	0.15	6.35	2.32	
Ionosphere	0.33	0.15	0.48	0.04	0.04	0.64	0.83	

(b) Actual processing time

AnoGAN

- AnoGAN

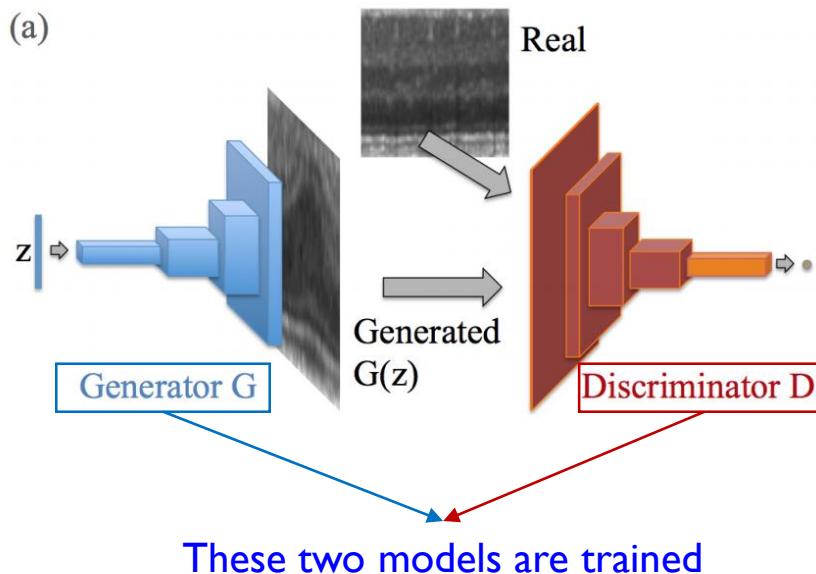
- ✓ Schlegl, T., Seeböck, P., Waldstein, S. M., Schmidt-Erfurth, U., & Langs, G. (2017, June). Unsupervised anomaly detection with generative adversarial networks to guide marker discovery. In *International Conference on Information Processing in Medical Imaging* (pp. 146-157). Springer, Cham.



AnoGAN

- AnoGAN

- ✓ Training: Train a GAN with normal data (medical images in the original paper)
 - Train the parameters of Generator G and Discriminator D

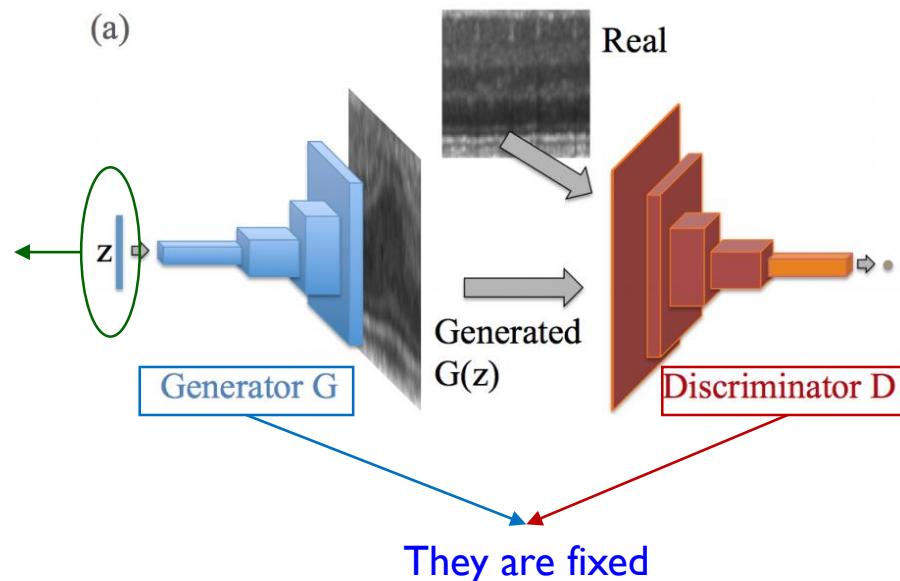


AnoGAN

- AnoGAN

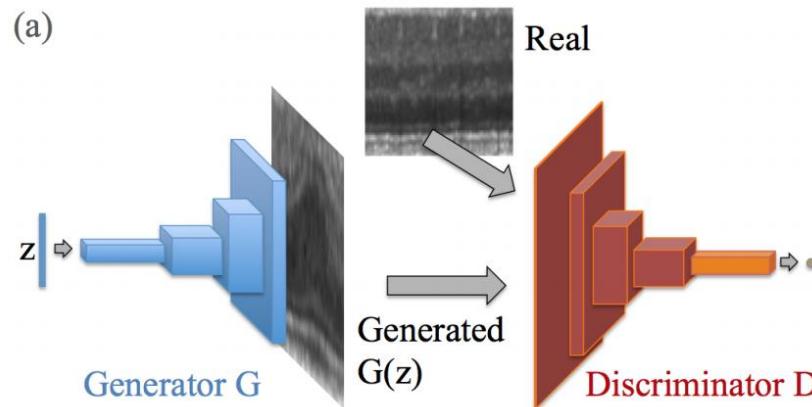
- ✓ Test: Update the latent vector z to generate a similar image of the given image and to fool the discriminator
 - Train the latent vector
 - Parameters of Generator G and Discriminator D are fixed in this step

This latent vector is updated to generate a fake image as similar as possible to the test image



AnoGAN

- AnoGAN



✓ Two types of loss functions are used

- Generation loss: $L_R(z_\gamma) = \sum |x - G(z_\gamma)|$
- Discrimination loss: $L_D(z_\gamma) = \sum |f(x) - f(G(z_\gamma))|$

✓ Total loss: $L(z_\gamma) = (1 - \lambda) \cdot L_R(z_\gamma) + \lambda \cdot L_D(z_\gamma)$



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References

Other materials

- Pages 28-33 & 36: http://research.cs.tamu.edu/prism/lectures/pr/pr_I7.pdf
- Figures in Auto-encoder section: https://dl.dropboxusercontent.com/u/19557502/6_01_definition.pdf
- Gramfort, A. (2016). Anomaly/Novelty detection with scikit-learn: <https://www.slideshare.net/agramfort/anomaly-novelty-detection-with-scikitlearn>