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INTRODUCTION TO COMPUTER VISION

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Example: Image classification

input	desired output	
	apple	 apple
	pear	 pear
	tomato	 tomato
	cow	 cow
	dog	 dog
	horse	 horse

Training data:

Example 2: Spam filter



Dear Sir.

First, I must solicit your confidence in this transaction, this is by virtue of its nature as being utterly confidential and top secret. ...



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MAILINGS, SIMPLY REPLY TO THIS
MESSAGE AND PUT "REMOVE" IN THE
SUBJECT.

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Ok, I know this is blatantly OT but I'm beginning to go insane. Had an old Dell Dimension XPS sitting in the corner and decided to put it to use, I know it was working pre being stuck in the corner, but when I plugged it in, hit the power nothing happened.

The basic *supervised learning* framework

$$y = f(x)$$

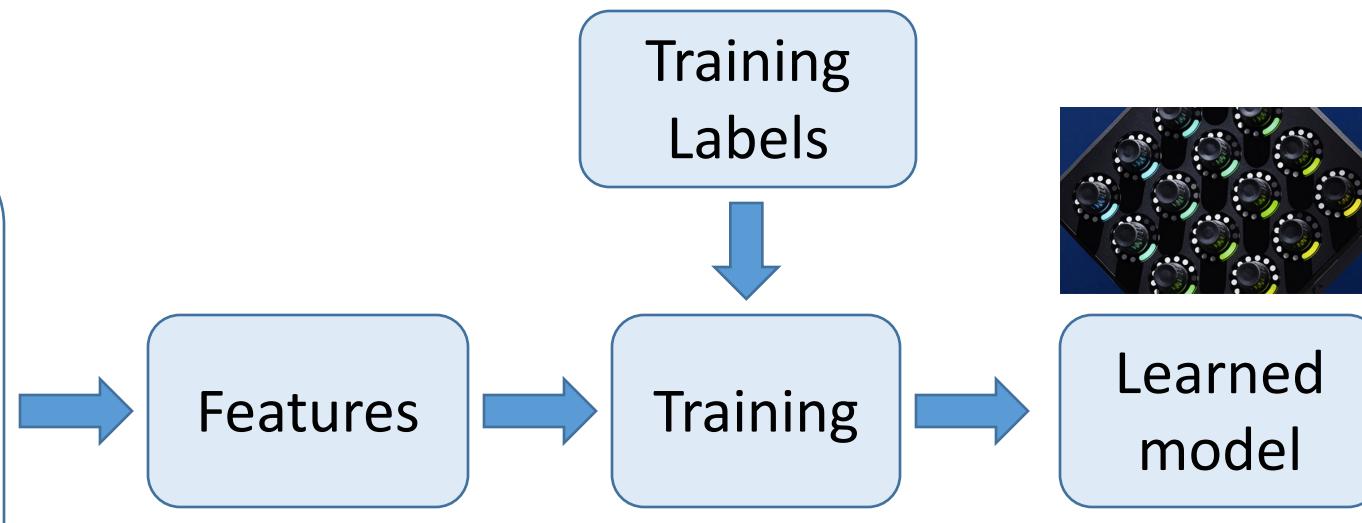
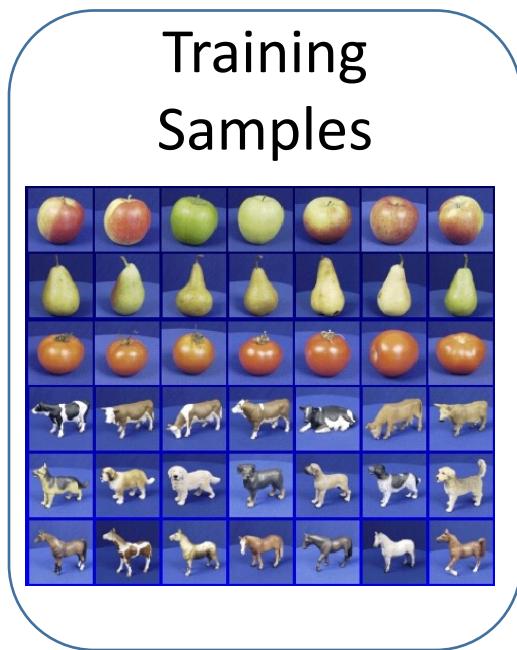
A diagram illustrating the supervised learning framework. At the top is the equation $y = f(x)$. Below it, three red arrows point upwards from the words "output", "classification function", and "input" to their respective components in the equation. The word "output" points to the variable y , "classification function" points to the function symbol f , and "input" points to the variable x .

output classification function input

- **Learning:** given a *training set* of labeled examples $\{(x_1, y_1), \dots, (x_N, y_N)\}$, estimate the parameters of the prediction function f
- **Inference:** apply f to a never before seen *test example* x and output the predicted value $y = f(x)$

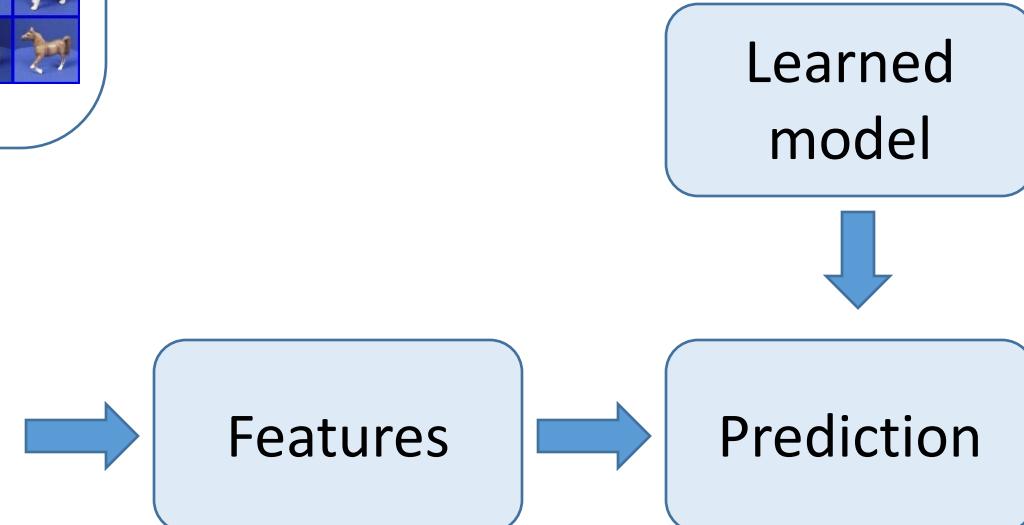
Learning and inference pipeline

Learning



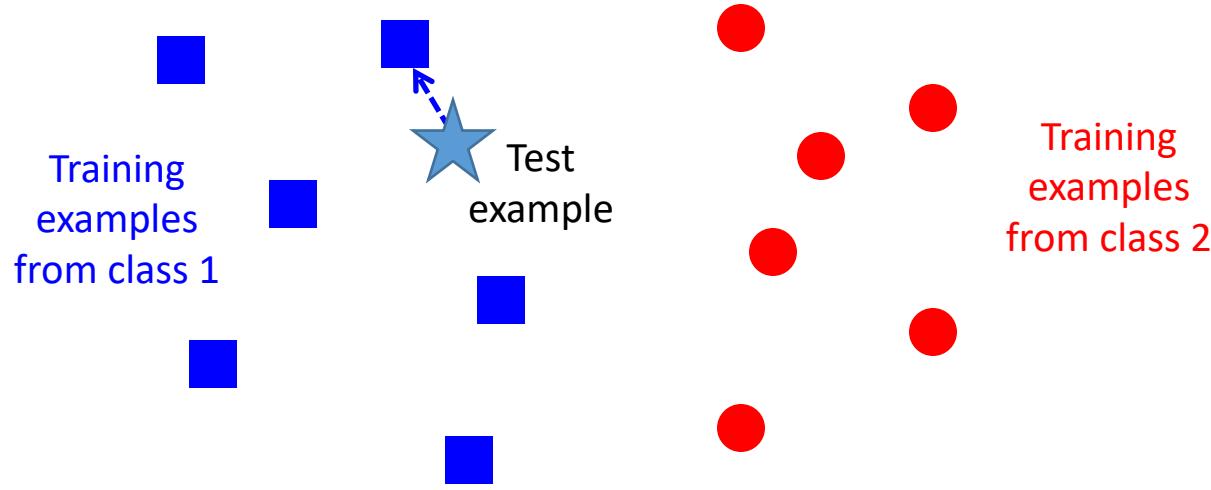
Inference

Test Sample



Learned model

Nearest neighbor classifier

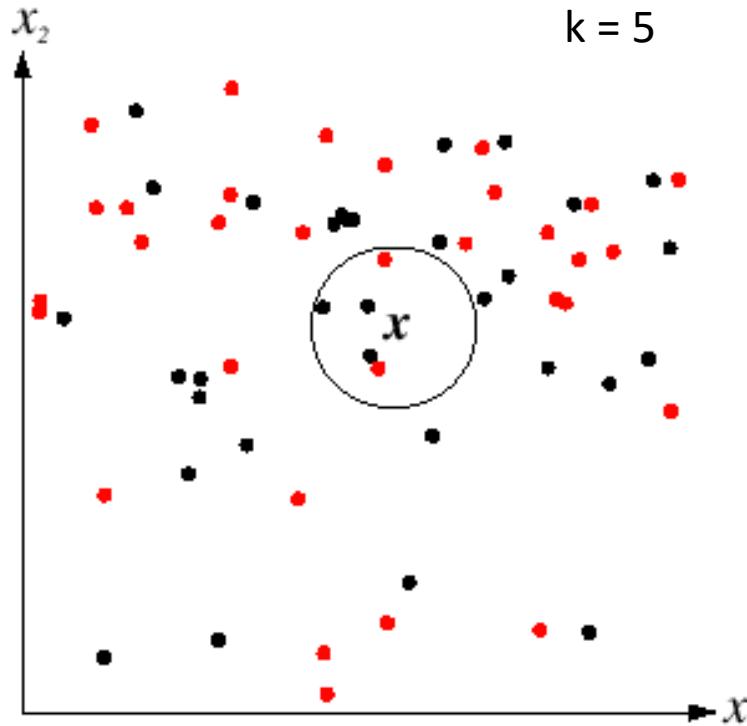


$f(x)$ = label of the training example nearest to x

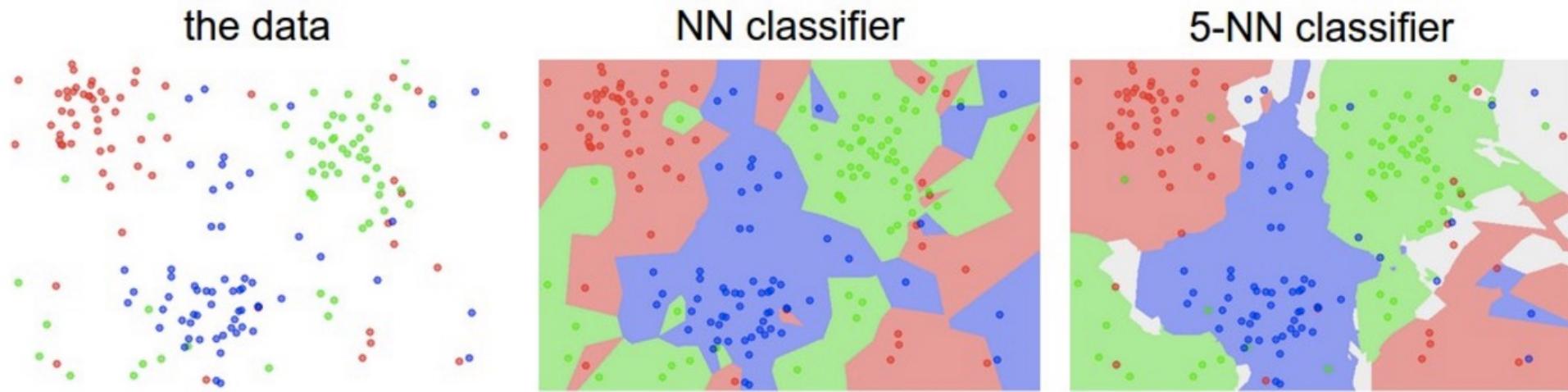
- All we need is a distance function for our inputs
- No training required!

K-nearest neighbor classifier

- For a new point, find the k closest points from training data
- Vote for class label with labels of the k points

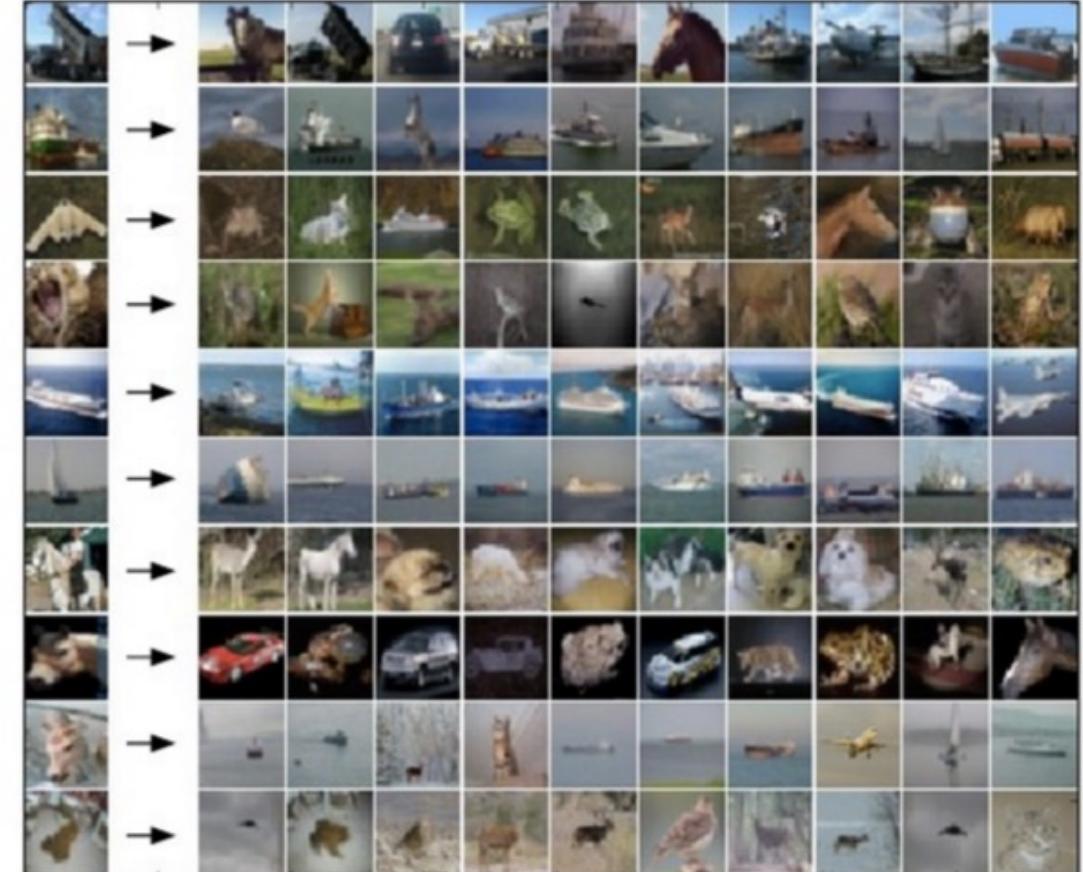
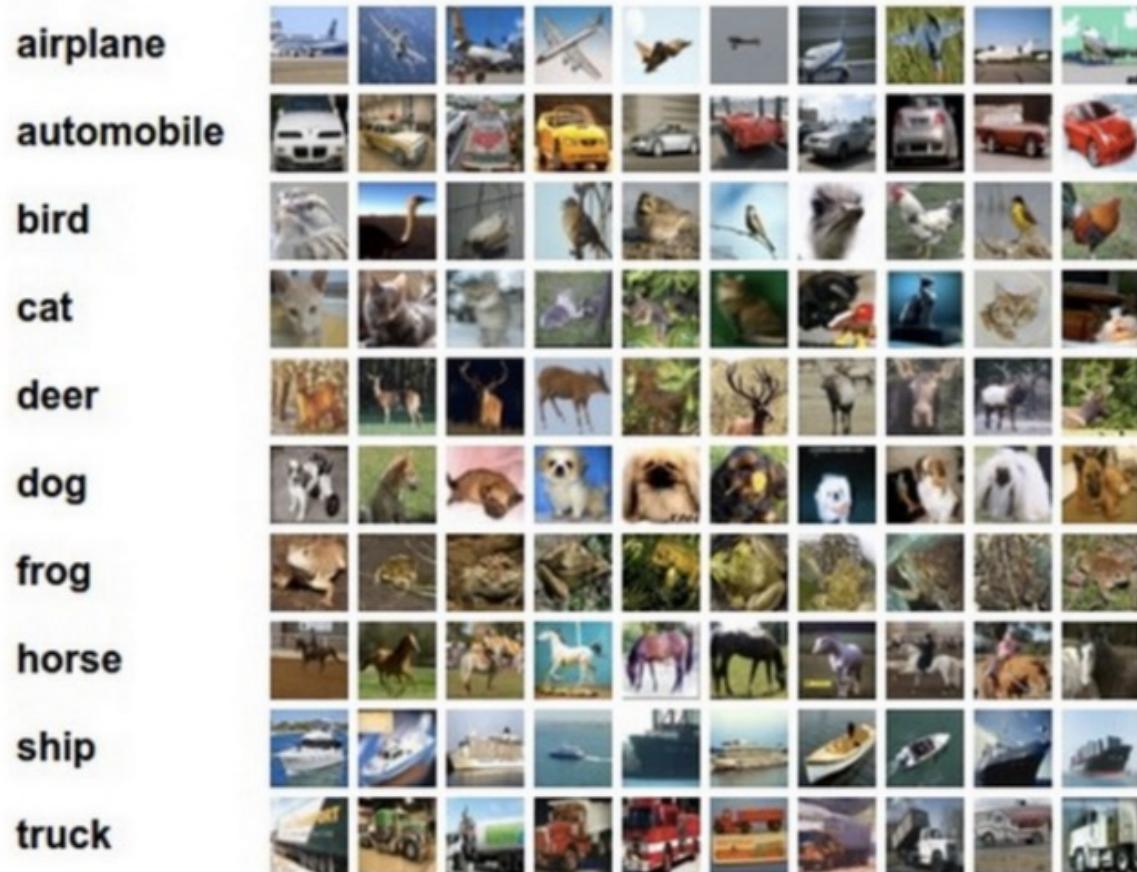


K-nearest neighbor classifier



- Which classifier is more robust to *outliers*?

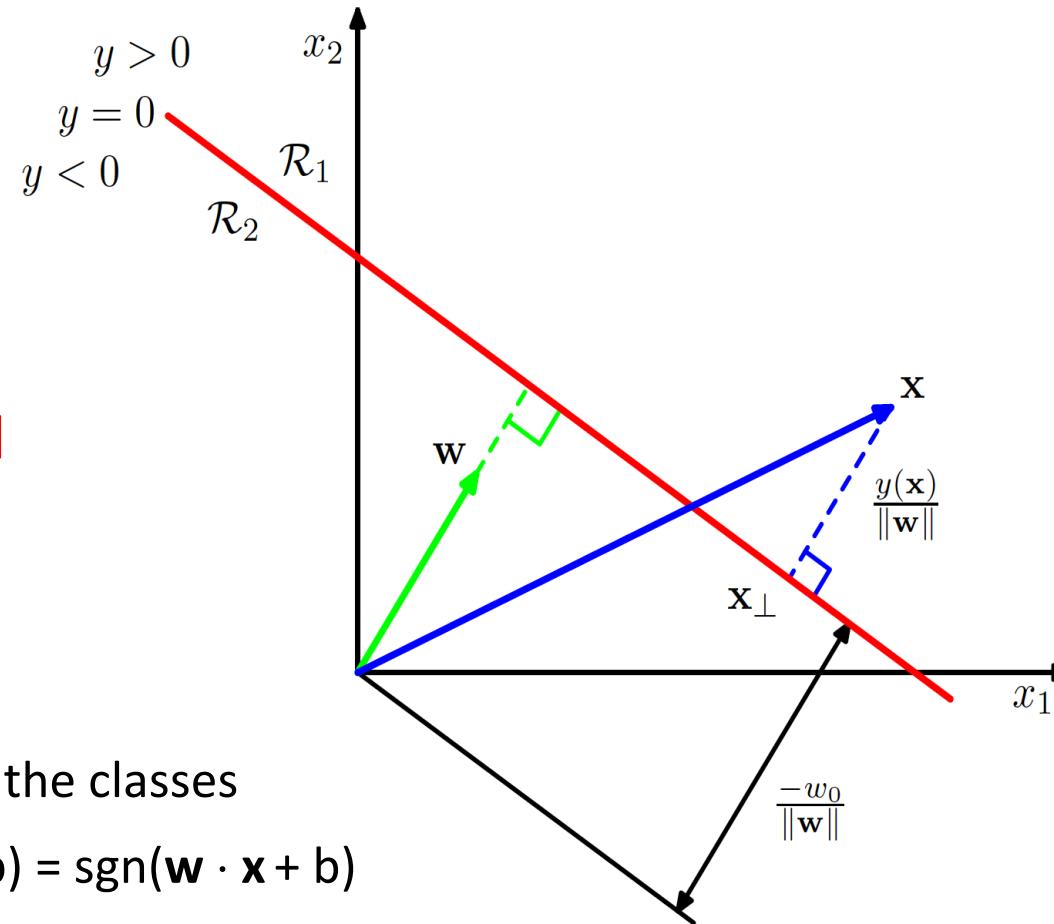
K-nearest neighbor classifier



Left: Example images from the [CIFAR-10 dataset](#). Right: first column shows a few test images and next to each we show the top 10 nearest neighbors in the training set according to pixel-wise difference.

Linear classifier

The Classification
Boundary marked in Red
(Decision Hyperplane)



- Find a *linear function* to separate the classes

$$f(\mathbf{x}) = \text{sgn}(w_1x_1 + w_2x_2 + \dots + w_Dx_D + b) = \text{sgn}(\mathbf{w} \cdot \mathbf{x} + b)$$

Logistic Regression

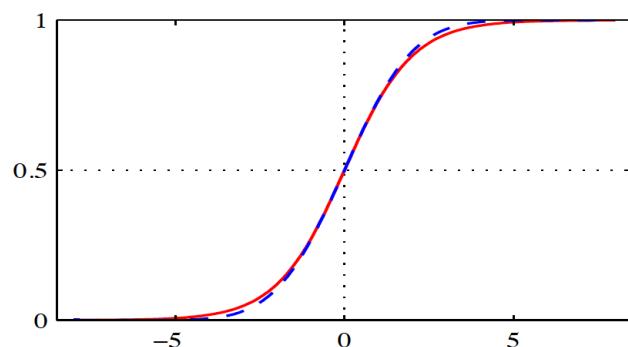
- Definition of **Logistic Sigmoid** function $\sigma(a)$:

$$\sigma(a) = \frac{1}{1 + \exp(-a)}$$

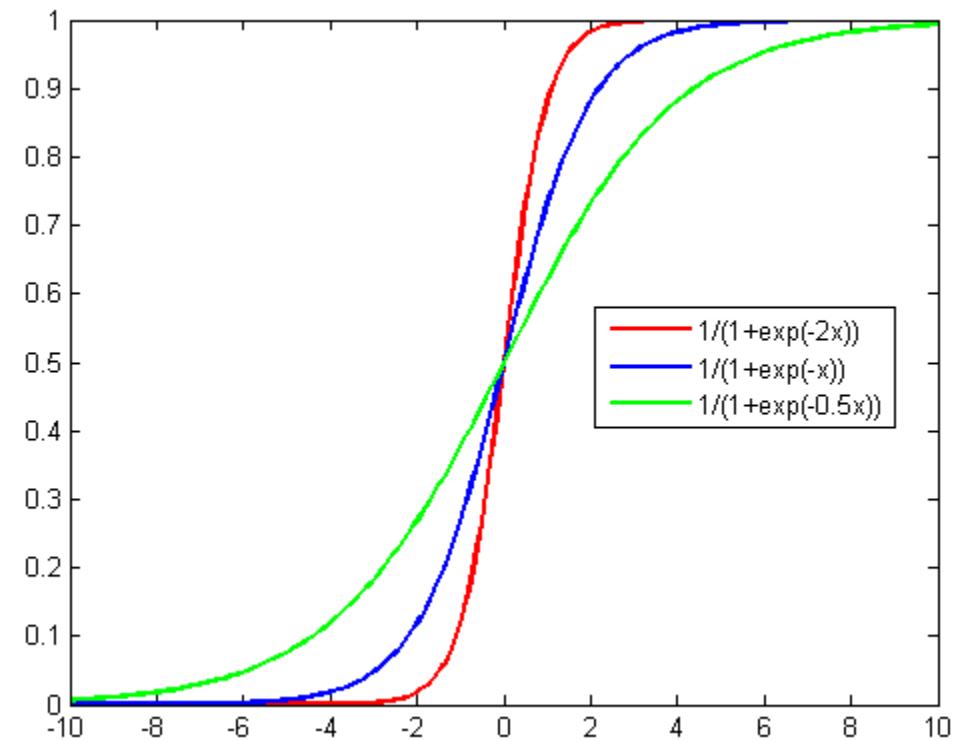
- Properties of Logistic Sigmoid function $\sigma(a)$:

$$\sigma(-a) = 1 - \sigma(a)$$

$$\frac{d\sigma}{da} = \sigma(1 - \sigma)$$



Plot of the logistic sigmoid function $\sigma(a)$ (Red Line)



A Continuously Differentiable
Approximation of the 0-1 loss

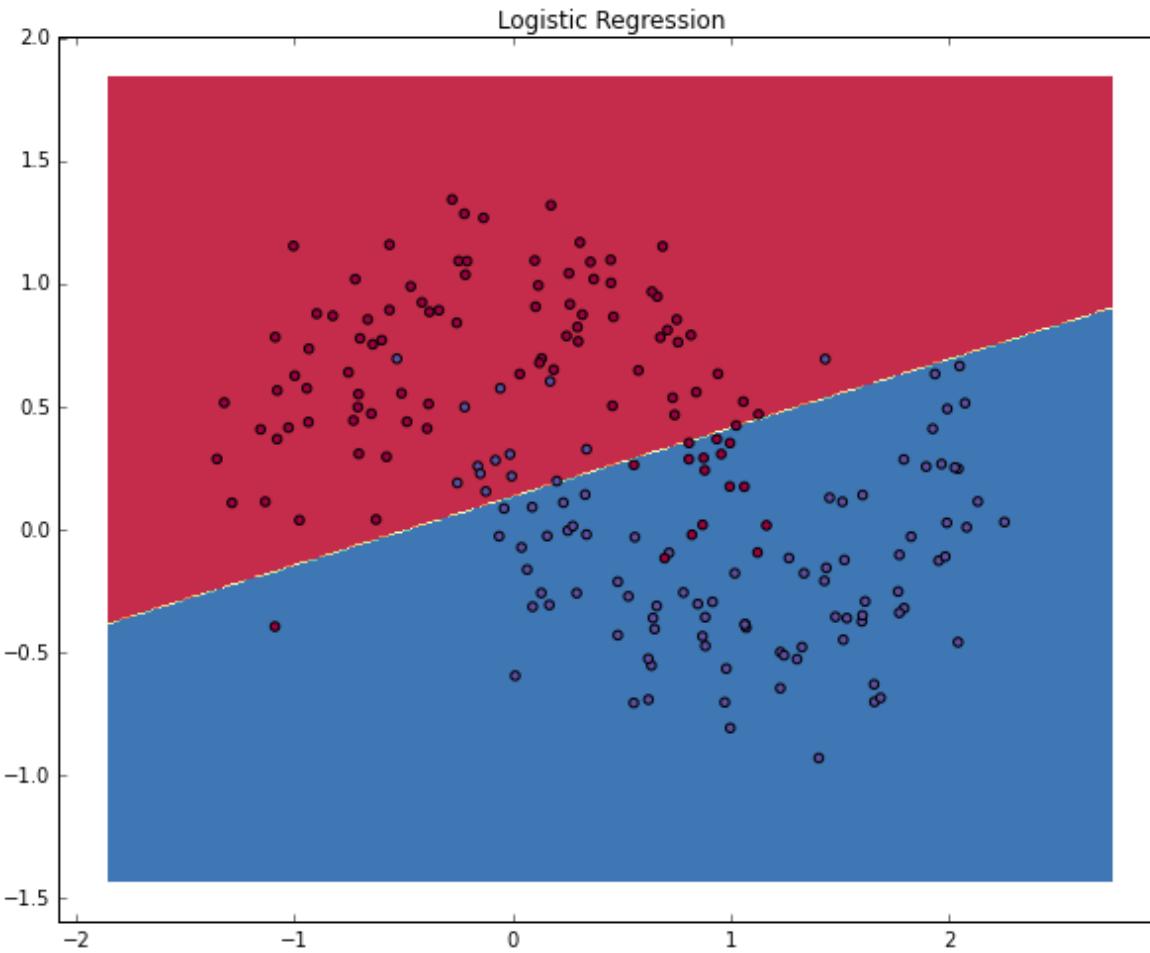
Logistic Regression

- In two-class problem, the posterior probability of class \mathcal{C}_1 can be written as a logistic sigmoid acting on a linear function of the feature vector ϕ so that

$$p(\mathcal{C}_1|\phi) = y(\phi) = \sigma(\mathbf{w}^T \phi).$$

- $\sigma(\cdot)$ is the logistic sigmoid function.
- $p(\mathcal{C}_2|\phi) = 1 - p(\mathcal{C}_1|\phi)$
- In statistics, the model is known as **logistic regression**.
- The model is for **classification**, not for regression.
- In logistic regression, we estimate the parameter \mathbf{w} directly.

Logistic Regression



Linear Decision
Boundary! Why?

Logistic Regression

- For a training data set $\{\phi_n, t_n\}$ where $t_n \in \{0, 1\}$ and $n = 1, 2, \dots, N$, the likelihood function is

$$p(\mathbf{t}|\mathbf{w}) = \prod_{n=1}^N y_n^{t_n} (1 - y_n)^{1-t_n} \quad (3)$$

- Definitions of t_n , \mathbf{t} and y_n

$$t_n = \begin{cases} 1 & \text{if } n \in \mathcal{C}_1 \\ 0 & \text{if } n \in \mathcal{C}_2 \end{cases}$$

$$\mathbf{t} = (t_1, t_2, \dots, t_N)^T$$

$$y_n = p(\mathcal{C}_1 | \phi_n) = \sigma(\mathbf{w}^T \phi_n)$$

Logistic Regression

- The error function is the negative logarithm of the likelihood, namely, **Cross-entropy** error function:

$$E(\mathbf{w}) = -\ln p(\mathbf{t}|\mathbf{w}) = \sum_{n=1}^N \{ t_n \ln y_n + (1 - t_n) \ln(1 - y_n) \}$$

The gradient of cross entropy function with respect to \mathbf{w} is

$$\nabla E(\mathbf{w}) = \sum_{n=1}^N (y_n - t_n) \phi_n$$

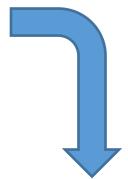
NN vs. linear classifiers

- NN pros:
 - + Simple to implement
 - + Decision boundaries not necessarily linear
 - + Works for any number of classes
 - + *Nonparametric* method
- NN cons:
 - Need good distance function
 - Slow at test time
- Linear pros:
 - + Low-dimensional *parametric* representation
 - + Very fast at test time
- Linear cons:
 - Works for two classes
 - How to train the linear function?
 - What if data is not linearly separable?

Softmax Regression

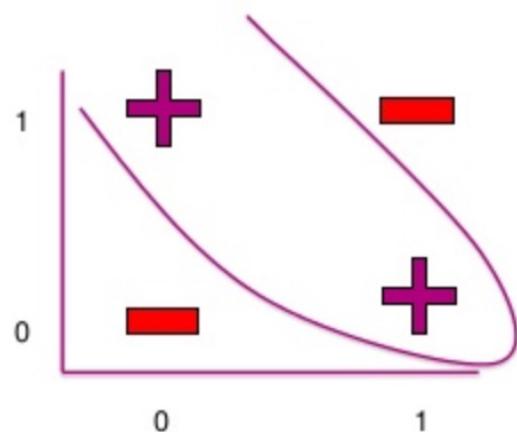
- The Multi-Class version of Logistic Regression (popular in deep learning)
(Reference: <http://ufldl.stanford.edu/tutorial/supervised/SoftmaxRegression/>)

$$h_{\theta}(x) = \frac{1}{1 + \exp(-\theta^T x)},$$



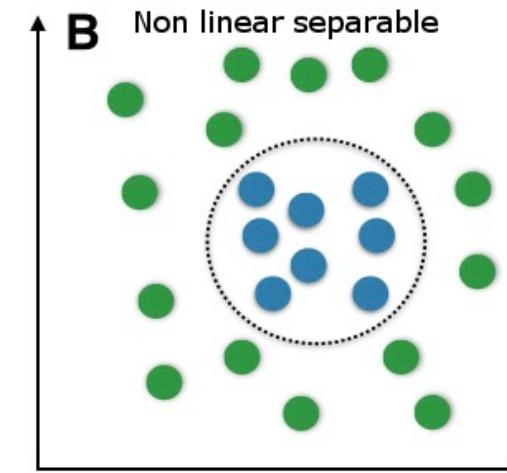
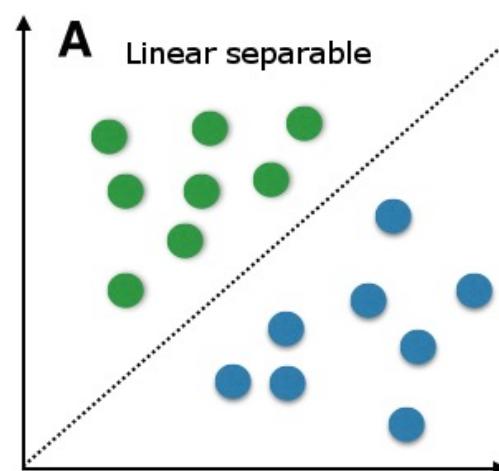
$$h_{\theta}(x) = \begin{bmatrix} P(y = 1|x; \theta) \\ P(y = 2|x; \theta) \\ \vdots \\ P(y = K|x; \theta) \end{bmatrix} = \frac{1}{\sum_{j=1}^K \exp(\theta^{(j)\top} x)} \begin{bmatrix} \exp(\theta^{(1)\top} x) \\ \exp(\theta^{(2)\top} x) \\ \vdots \\ \exp(\theta^{(K)\top} x) \end{bmatrix}$$

Limitation of Linear Classifiers



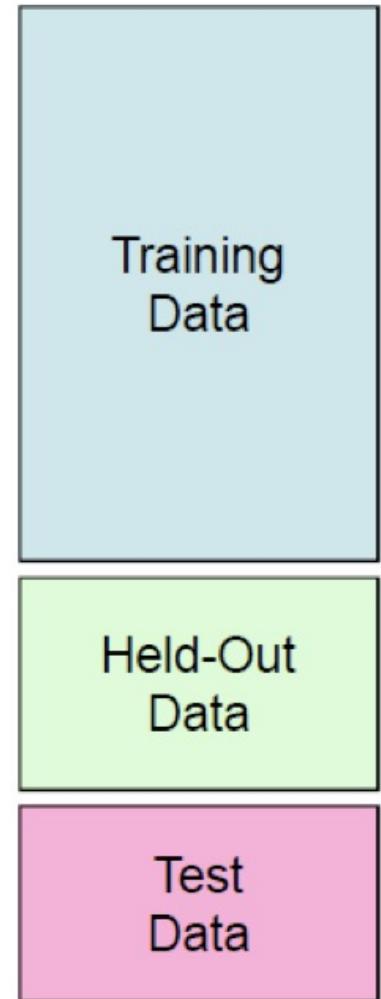
XOR

Need non-linear features



Experimentation cycle

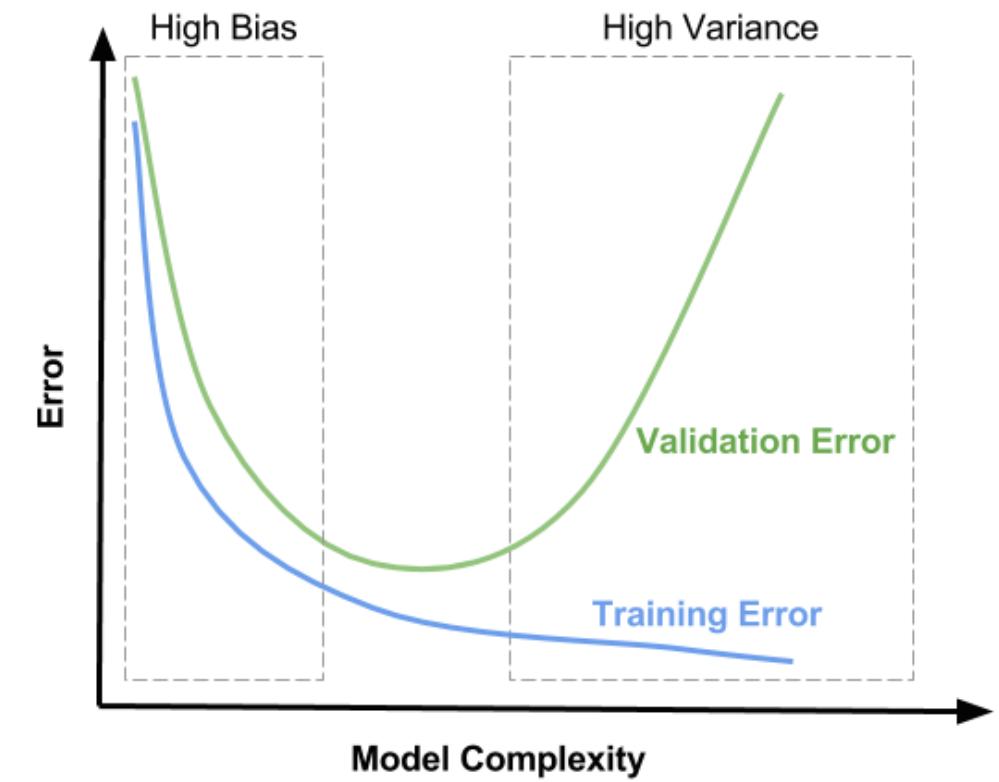
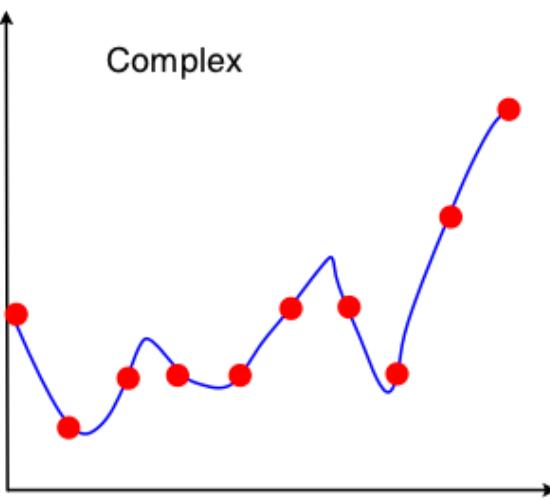
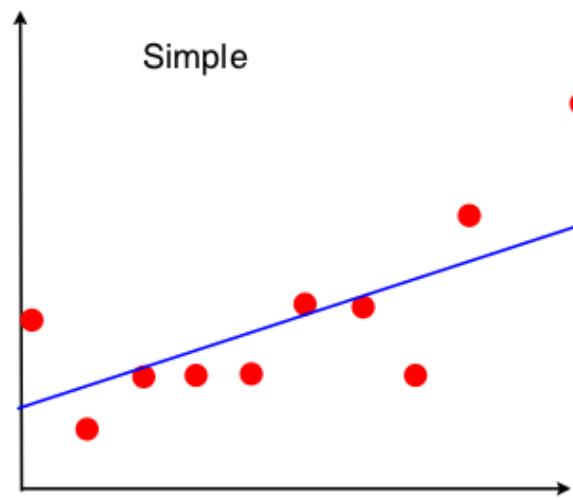
- Learn *parameters* on the *training set*
- Tune *hyperparameters* (implementation choices) on the *held out validation set*
- Evaluate performance on the *test set*
- Do not peek at the test set!
- *Generalization* and *overfitting*
 - Want classifier that does well on never before seen data
 - Overfitting: good performance on the training/validation set, poor performance on test set



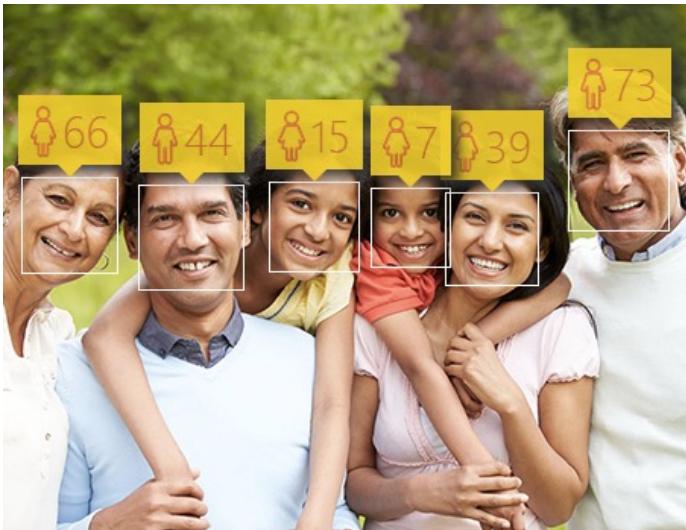
Bias-Variance Tradeoff

- The bias–variance tradeoff is the fundamental dilemma of minimizing between two sources of errors that prevent ML algorithms from generalizing beyond their training set:
 - The bias is error from **erroneous assumptions** in the learning algorithm. High bias can cause an algorithm to miss the relevant relations between features and target outputs (e.g., **model is too simple** -> **underfitting**).
 - The variance is error **from sensitivity to small fluctuations** in the training set. High variance can cause an algorithm to model the random noise in the training data, rather than the intended outputs (e.g., **model is too complicated** -> **overfitting**).

Bias-Variance Tradeoff



Beyond classification: Regression

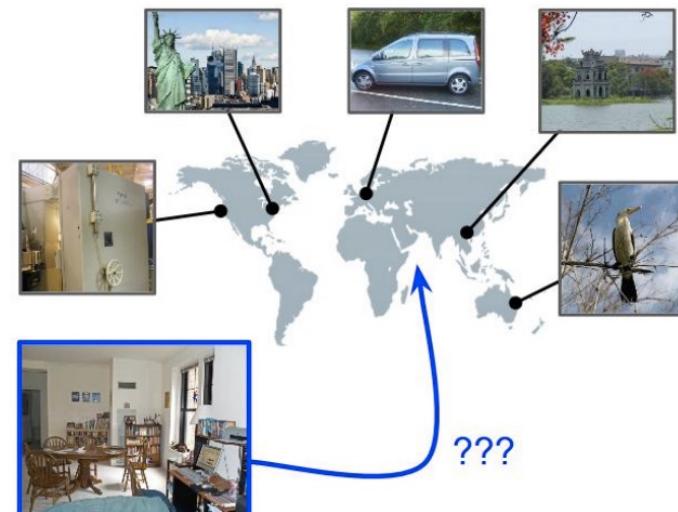


Age estimation

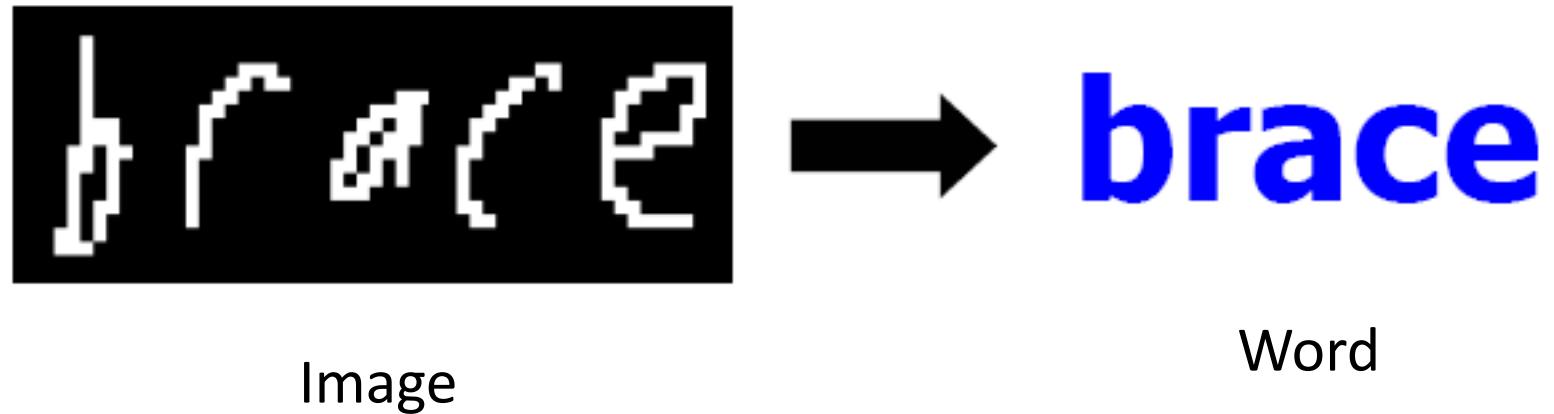


When was that made?

IM2GPS



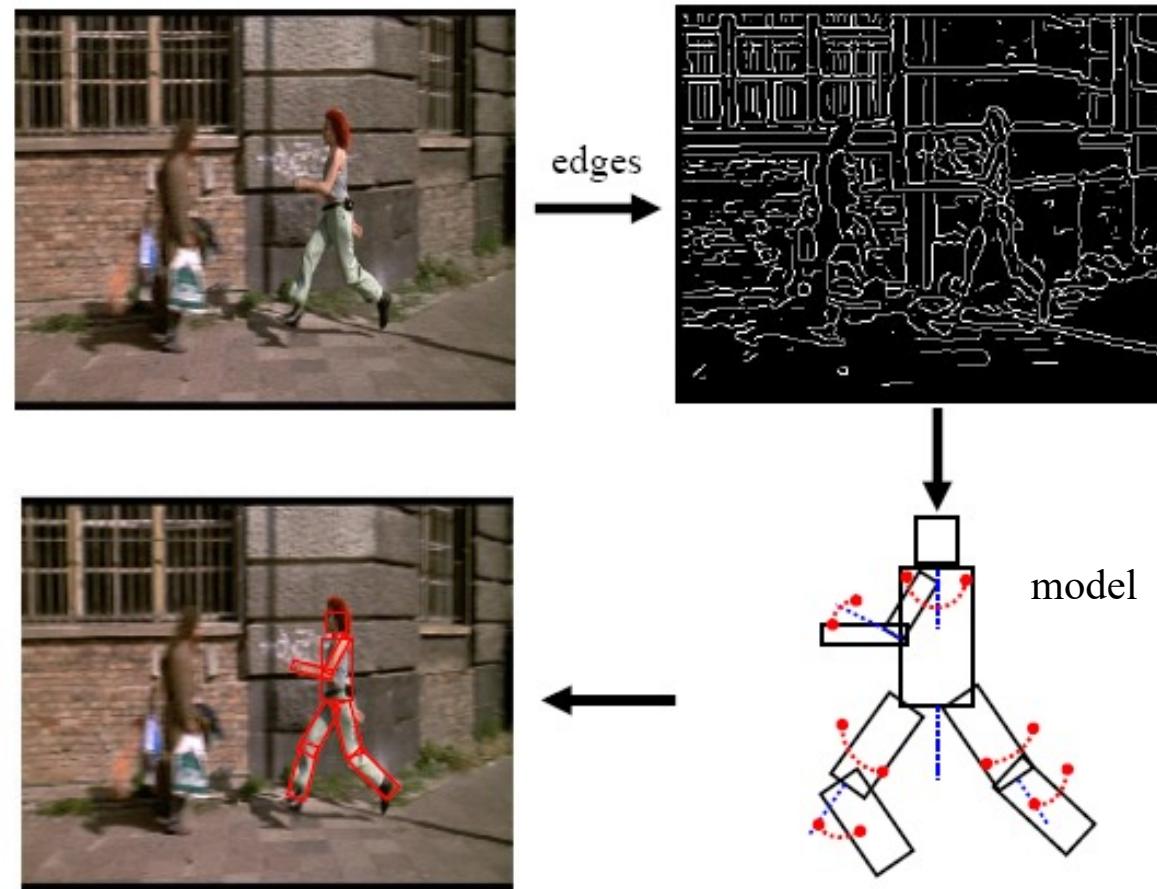
Beyond classification: Structured prediction



Source: B. Taskar

Structured Prediction

- Many image-based inference tasks can loosely be thought of as “structured prediction”



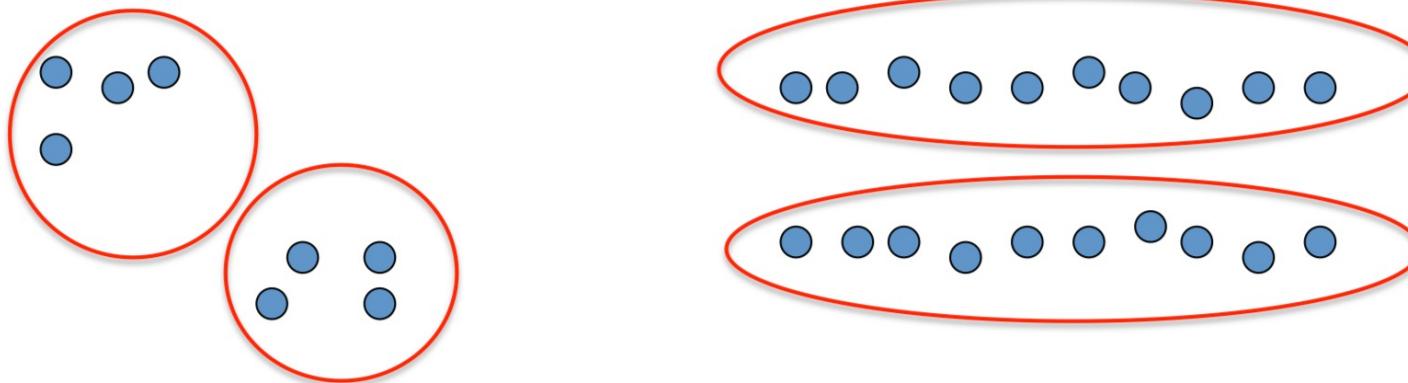
Source: D. Ramanan

Unsupervised Learning

- Idea: Given only *unlabeled* data as input, learn some sort of structure
- The objective is often more vague or subjective than in supervised learning
- This is more of an exploratory/descriptive data analysis

Clustering

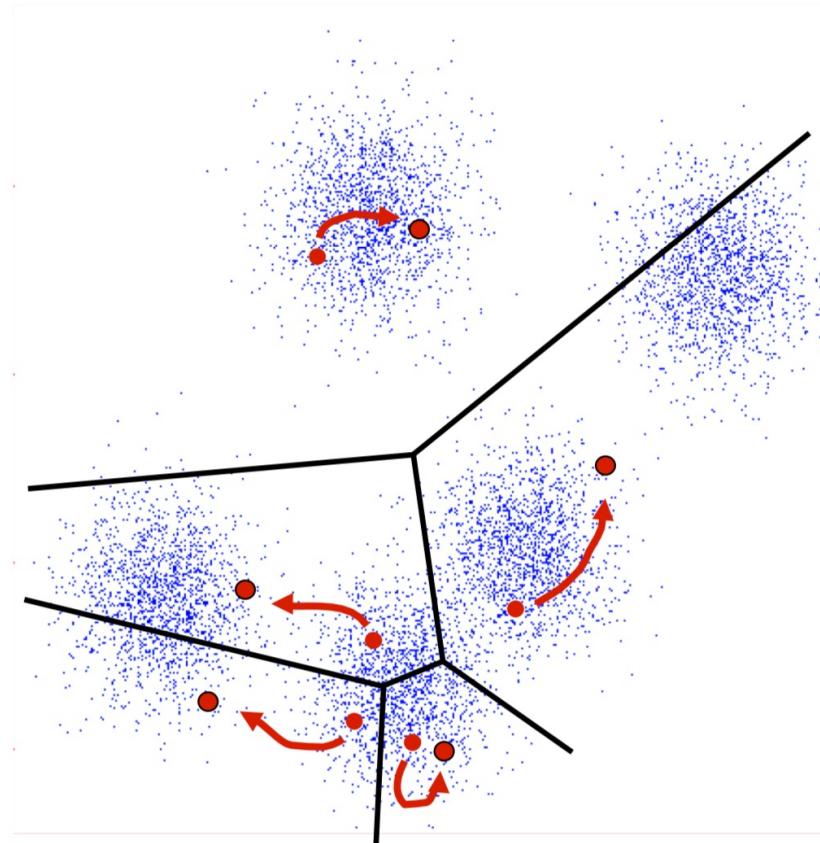
- Basic idea: group together similar instances
- Example: 2D point patterns



- What could “similar” mean?
 - One option: small Euclidean distance (squared)
$$\text{dist}(\vec{x}, \vec{y}) = \|\vec{x} - \vec{y}\|_2^2$$
 - Clustering results are crucially dependent on the measure of similarity (or distance) between “points” to be clustered

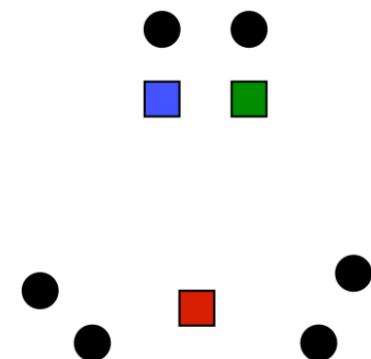
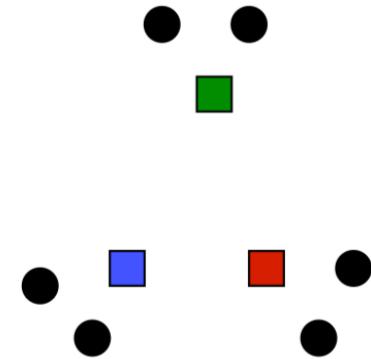
K-Means

- An iterative clustering algorithm
 - **Initialize:** Pick K random points as cluster centers
 - **Alternate:**
 1. Assign data points to closest cluster center
 2. Change the cluster center to the average of its assigned points
 - Stop when no points' assignments change

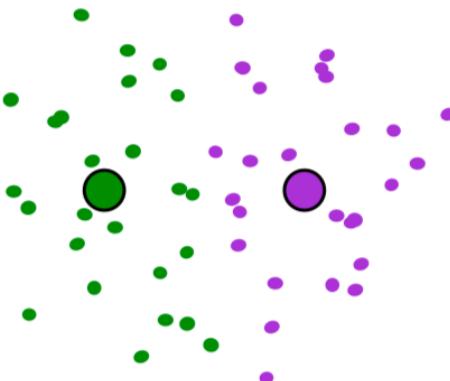


K-Means is Fragile

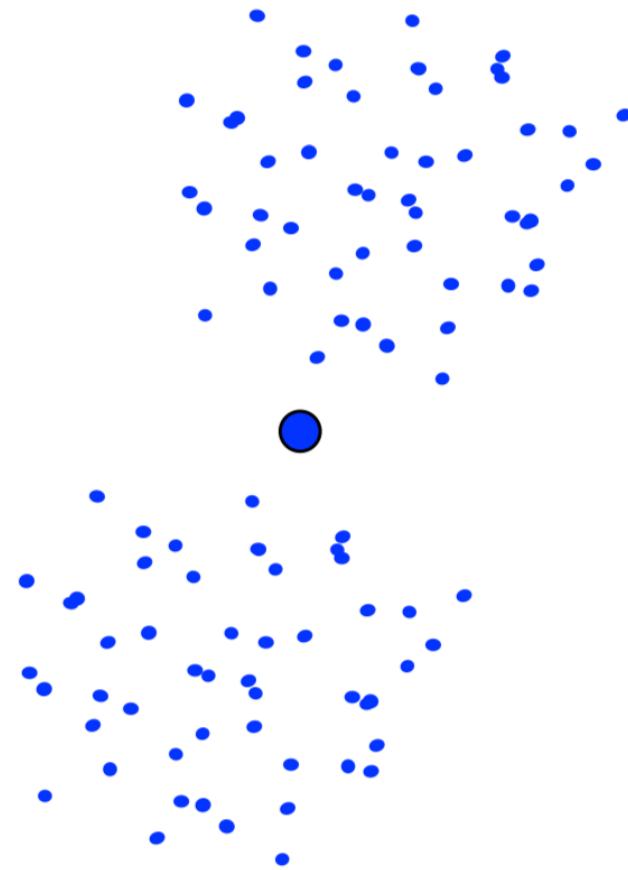
- K-means **algorithm** is a heuristic
 - Requires initial means
 - It does matter what you pick!
 - What can go wrong?
 - Various schemes for preventing this kind of thing: variance-based split / merge, initialization heuristics



Stuck at Poor Local Minimum

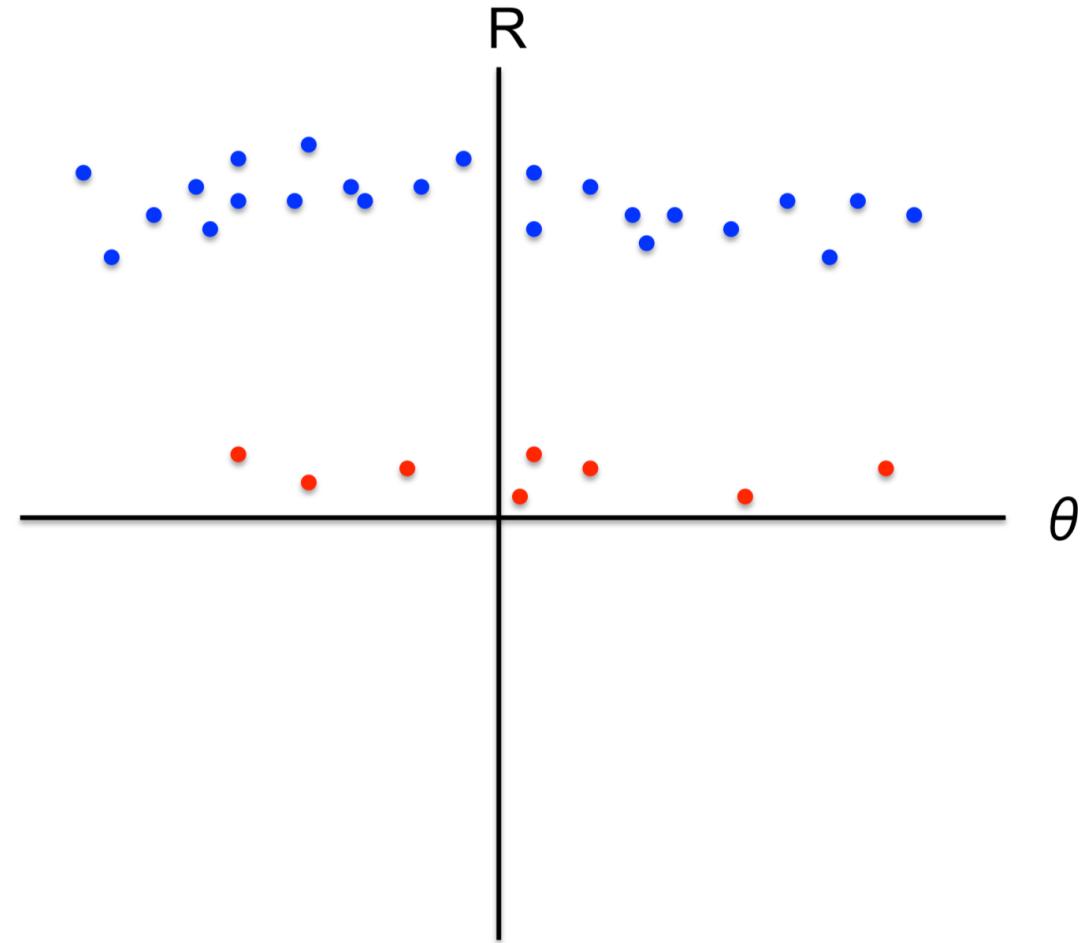
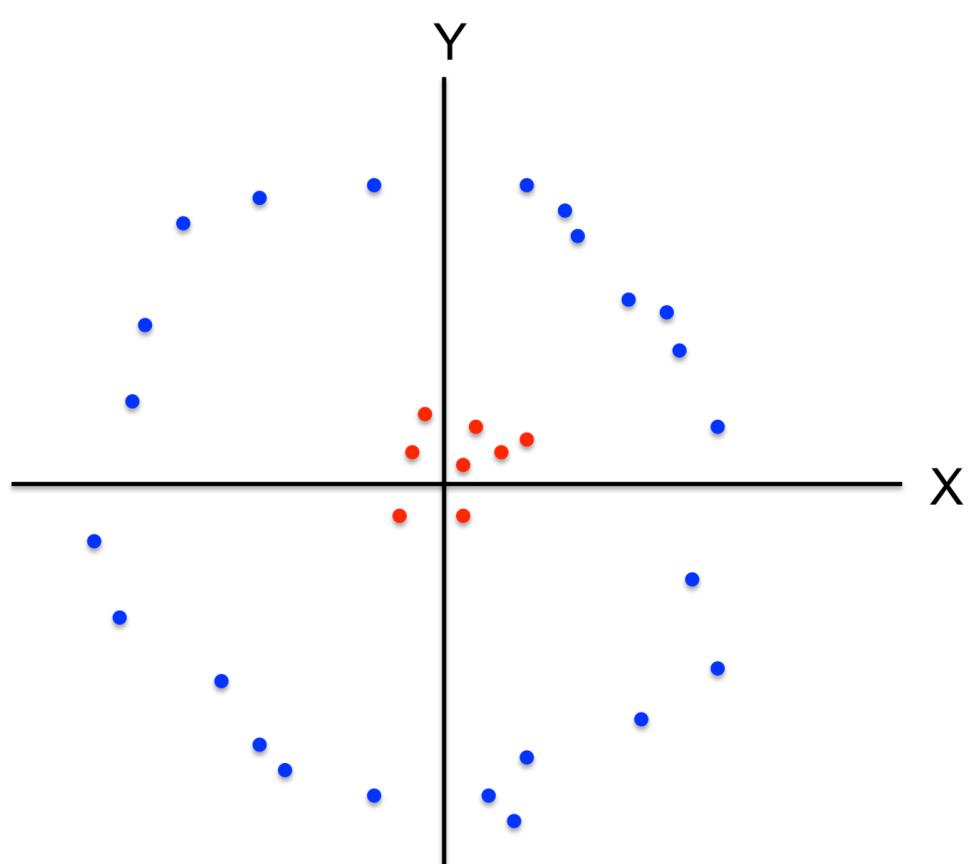


Would be better to have
one cluster here

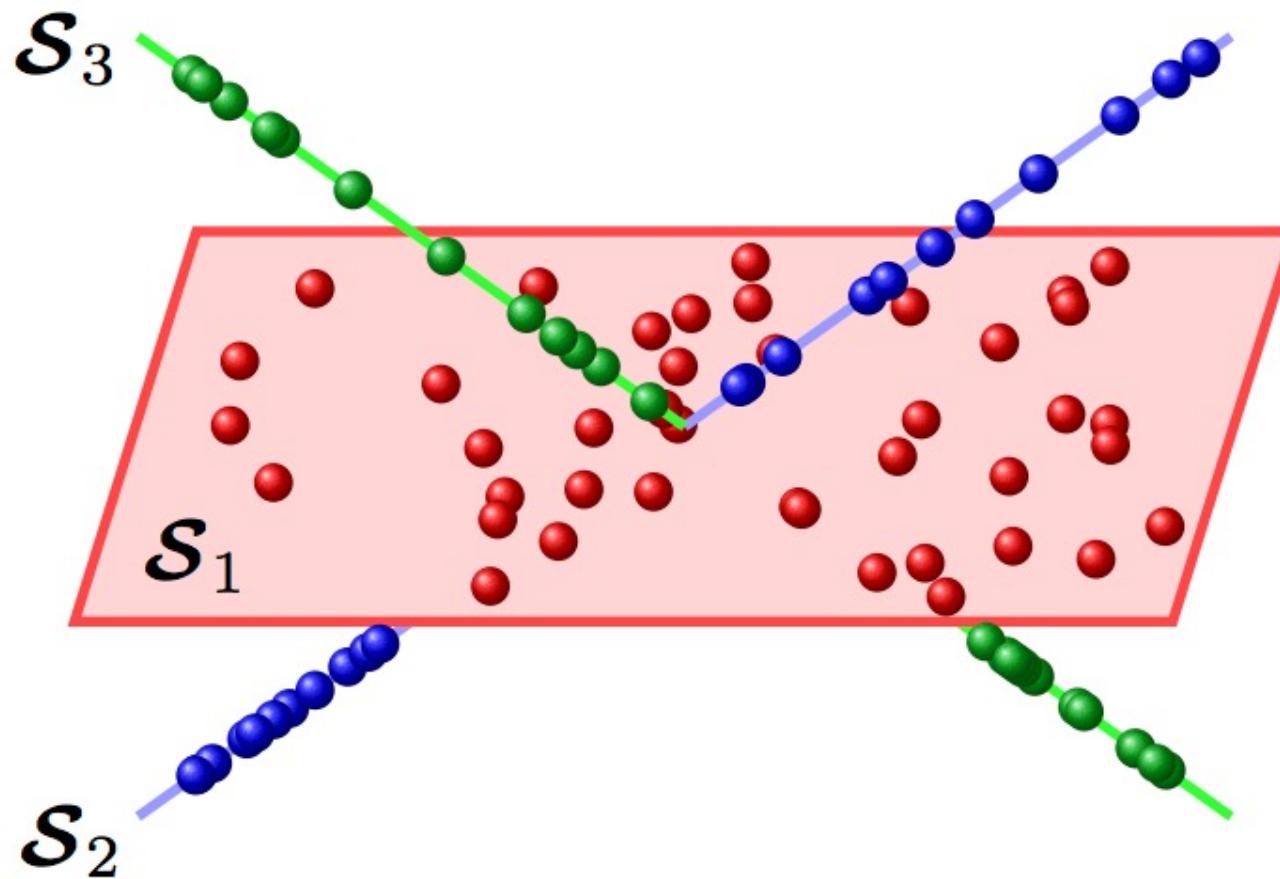


... and two clusters here

Euclidean Distance Might Not be Proper

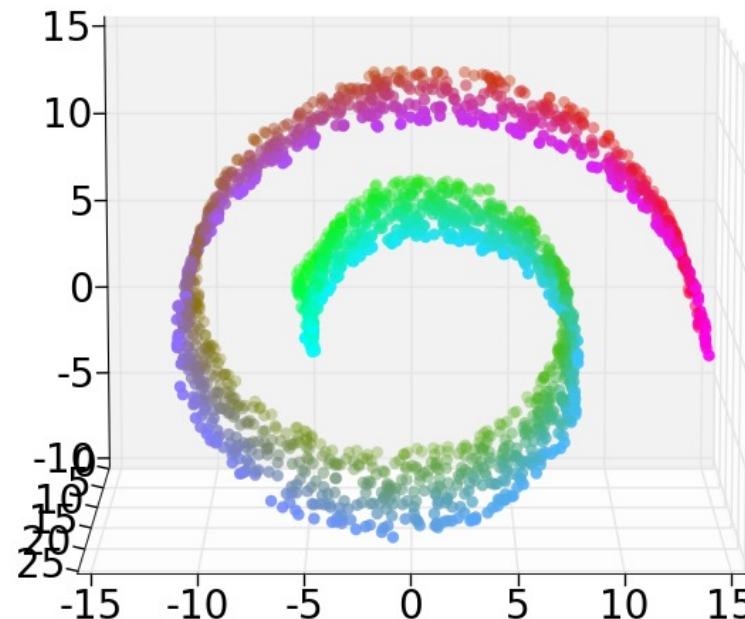


Do not underestimate clustering!!



Unsupervised Learning

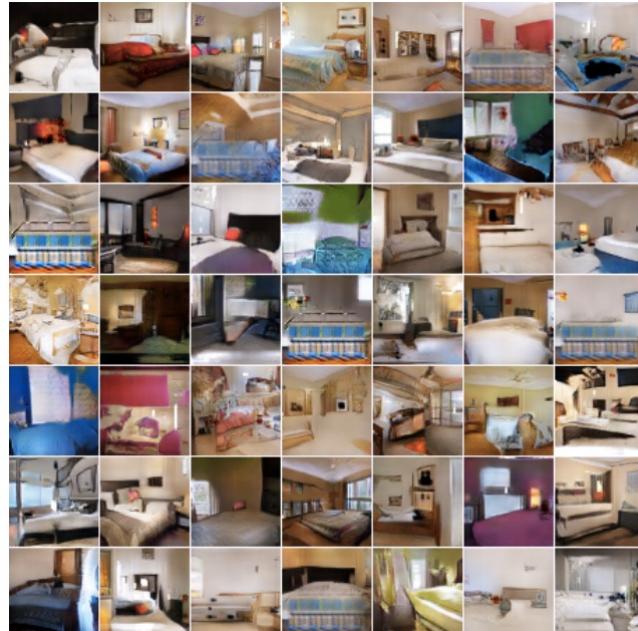
- **Dimensionality reduction, manifold learning**
 - Discover a lower-dimensional surface on which the data lives



Unsupervised Learning

- **Density estimation**
 - Produce samples from a data distribution that mimics the training set

“Bedroom”

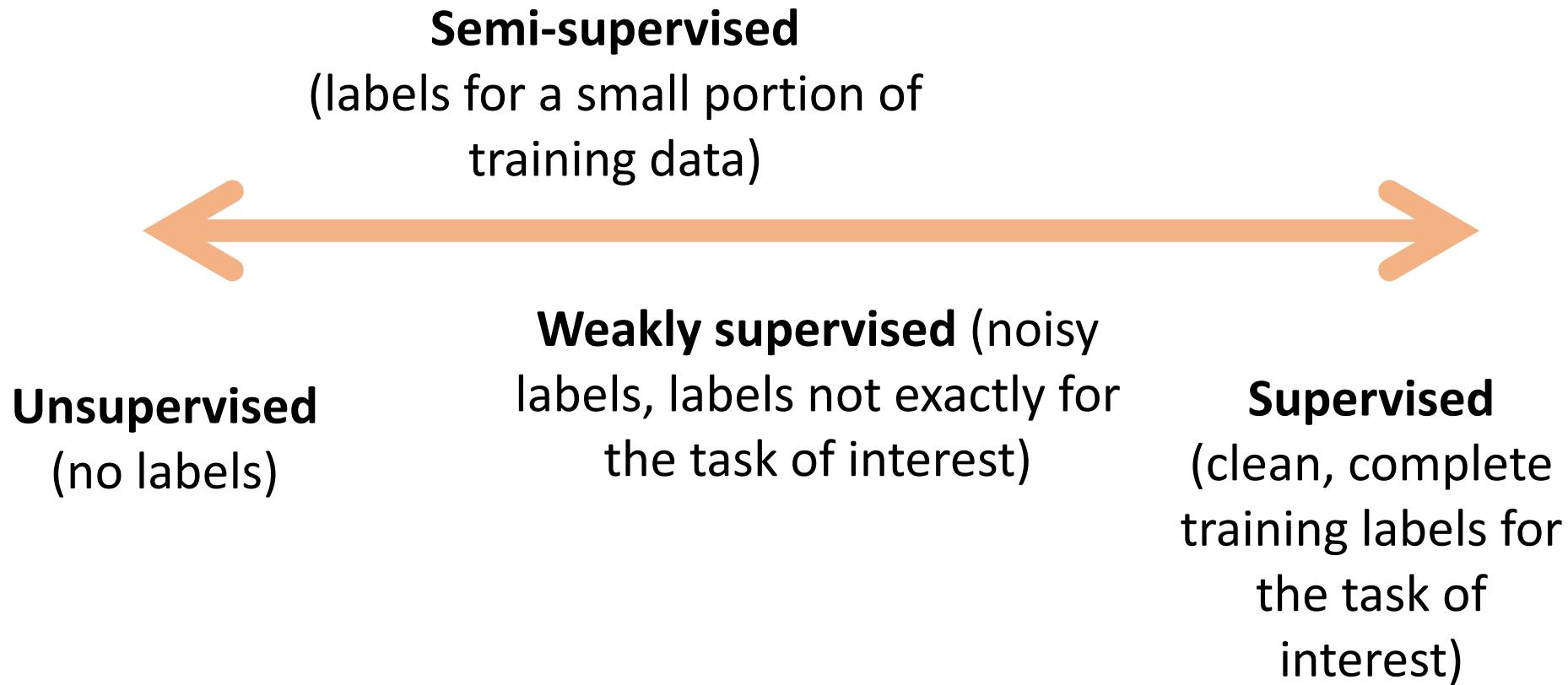


“Face”



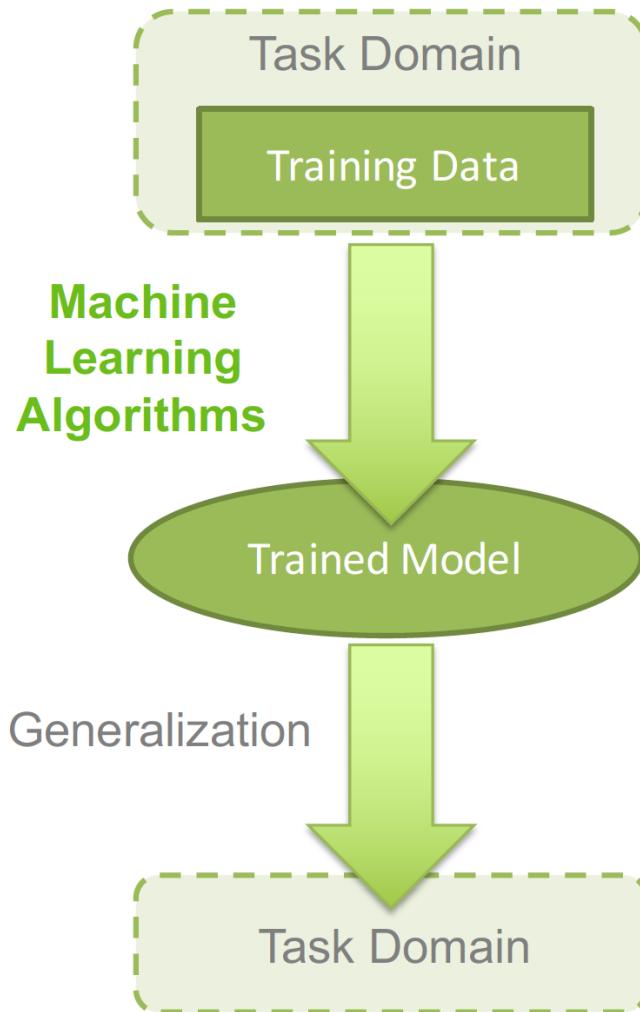
Generative adversarial networks

Continuum of supervision



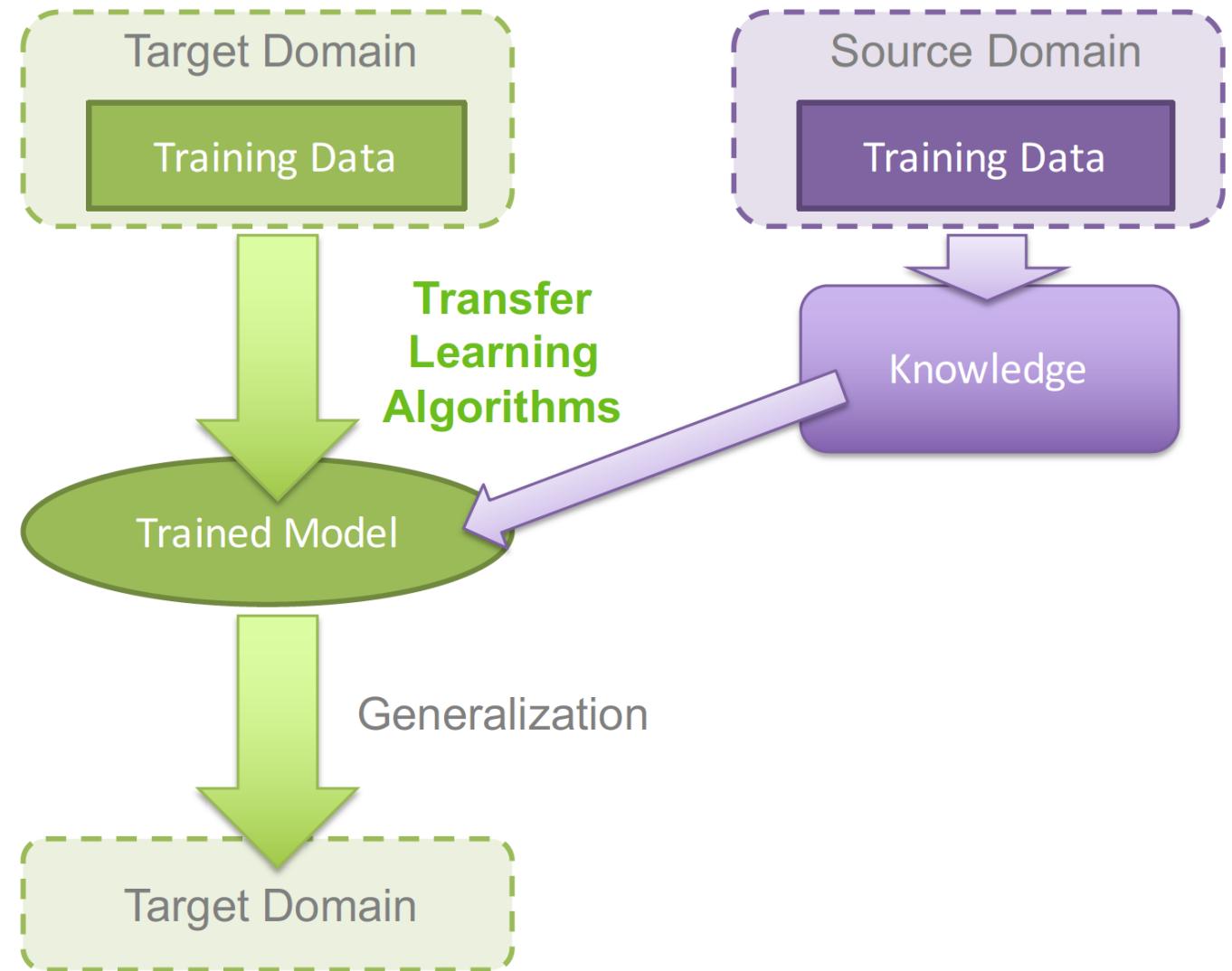
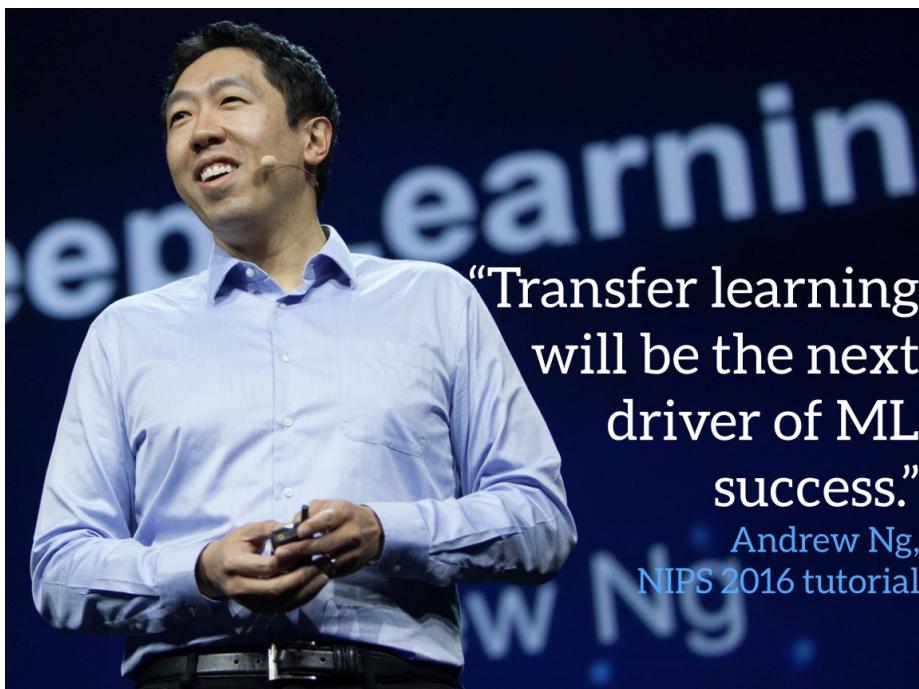
Machine Learning for Single Task

- Elements of machine learning on single task
 - The problem (**task/domain**)
 - Training data
 - Learning algorithms
 - Trained model
 - Applying model on unseen data (**generalization**)

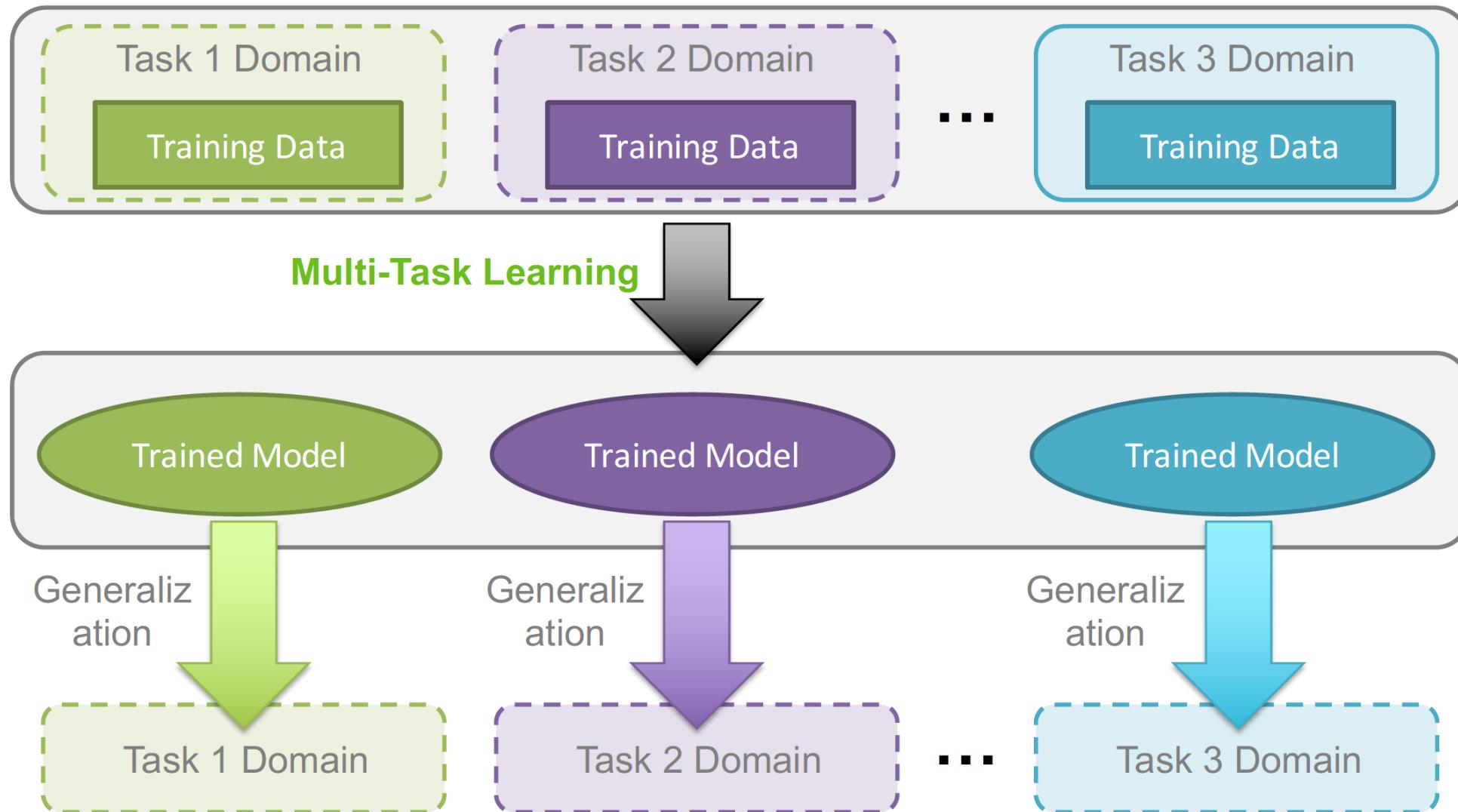


Transfer Learning

Improve Learning New Task
by Learned Task



Multi-Task Learning





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