

10417/10617

Intermediate Deep Learning:

Fall2019

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<https://deeplearning-cmu-10417.github.io/>

Lectures 1,2

Evaluation

- 39% on 3 assignments, each worth 13%
- 31% on 2 exams (15% midterm exam, 16% final exam)
- 30% on Final Project (9% mid-way report, 21% final report)

Evaluation

Tentative Assignment Dates-- check Piazza for updates:

- Assignment 1: Out: Sep 16 -- Due: Sep 30
- Assignment 2: Out: Oct 9 -- Due: Oct 23
- Assignment 3: Out: Oct 30 -- Due: Nov 13

Tentative Exam Dates:

- Exam 1: Oct 8
- Exam 2: Nov 21

Tentative Project Report Dates:

- Midway 3-page project report: Due Oct 30
- Final 8-page project report: Due Dec 4

Evaluation

- 5 grace days for all assignments.
- No more than 3 grace days per assignment. After 3 late days, you will get 0.

- No grace days for projects
- Unused grace days from homeworks CANNOT be applied to the project.
- Late project reports will not be accepted.

Project

- The idea of the final project is to give you some experience trying to do a piece of original research in machine learning and coherently writing up your result.
- What is expected: A simple but original idea that you describe clearly, relate to existing methods, implement and test on some real-world problem.
- To do this you will need to write some basic code, run it on some data, make some figures, read a few background papers, collect some references, and write an 8-page report describing your model, algorithm, and results.

Text Books

- **Ian Goodfellow, Yoshua Bengio, Aaron Courville (2016)**
Deep Learning Book (available online)
- **Christopher M. Bishop (2006)**
[Pattern Recognition and Machine Learning](#), Springer.
- Kevin Murphy (2013)
Machine Learning: A Probabilistic Perspective
- Trevor Hastie, Robert Tibshirani, Jerome Friedman (2009)
[The Elements of Statistical Learning](#) (available online)
- David MacKay (2003)
[Information Theory, Inference, and Learning Algorithms](#)
- Most of the figures and material will come from these books.

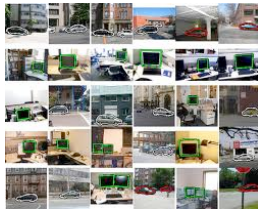
Online Resources

- I will be using a number of online resources, including
- Joan Bruna's Deep Learning Course
<http://joanbruna.github.io/stat212b/>
- Hugo Larochelle Neural Network Course
http://info.usherbrooke.ca/hlarochelle/neural_networks/description.html
- Deep Learning Summer School in Montreal
<https://sites.google.com/site/deeplearningsummerschool2016/home>
- I will be adding more resources, check the webpage.

Mining for Structure

Massive increase in both computational power and the amount of data available from web, video cameras, laboratory measurements.

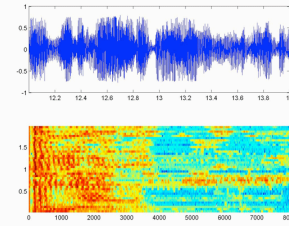
Images & Video



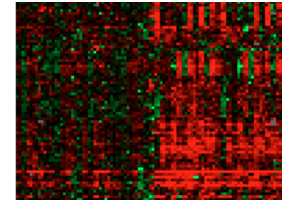
Text & Language



Speech & Audio



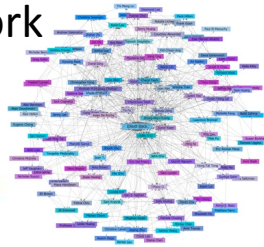
Gene Expression



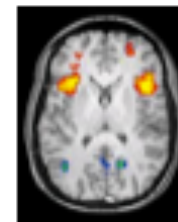
Product Recommendation



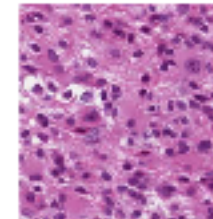
Relational Data/ Social Network



fMRI



Tumor region



- Develop statistical models that can discover underlying structure, cause, or statistical correlation from data.
- Multiple application domains.

Mining for Structure

Massive increase in both computational power and the amount of data available from web, video cameras, laboratory measurements.

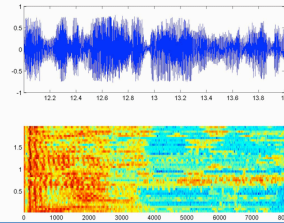
Images & Video



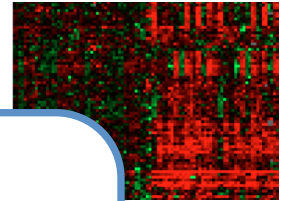
Text & Language



Speech & Audio



Gene Expression

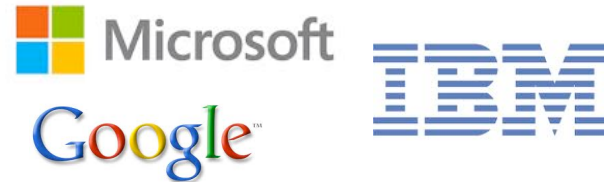


Deep Learning Models that support inferences and discover structure at multiple levels.

- Develop statistical models that can discover underlying structure, cause, or statistical correlation from data.
- Multiple application domains.

Impact of Deep Learning

- Speech Recognition



- Computer Vision



- Recommender Systems



- Language Understanding

- Drug Discovery and Medical Image Analysis



Understanding Images:



TAGS:

strangers, coworkers, conventioners,
attendants, patrons

Nearest Neighbor Sentence:

people taking pictures of a crazy person

Model Samples

- a group of people in a crowded area .
- a group of people are walking and talking .
- a group of people, standing around and talking .
- a group of people that are in the outside .

Caption Generation



LZ
a car is parked in
the middle of nowhere .



a wooden table and chairs
arranged in a room .



there is a cat sitting on a shelf .



a ferry boat on a marina
with a group of people .



a little boy with a bunch
of friends on the street .

Caption Generation



the two birds are trying
to be seen in the water .
(can't count)



a giraffe is standing next
to a fence in a field .
(hallucination)



a parked car while
driving down the road .
(contradiction)

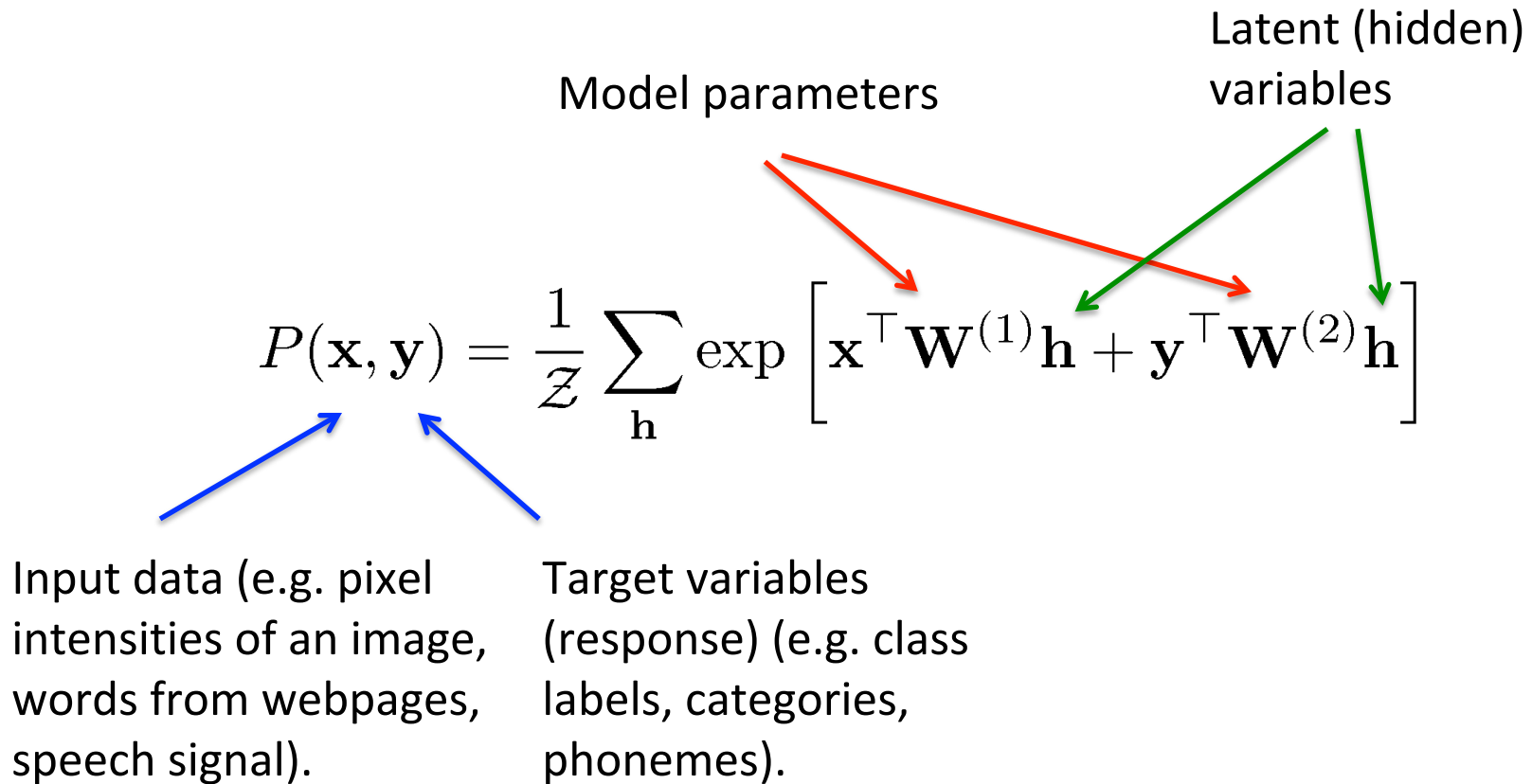


the handlebars are trying
to ride a bike rack .
(nonsensical)



a woman and a bottle of wine
in a garden . (gender)

Example: Boltzmann Machine



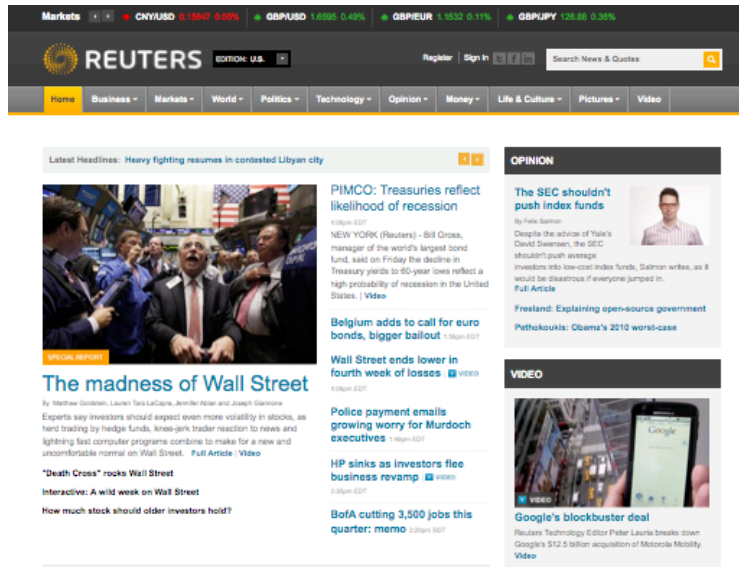
Markov Random Fields, Undirected Graphical Models.

Finding Structure in Data

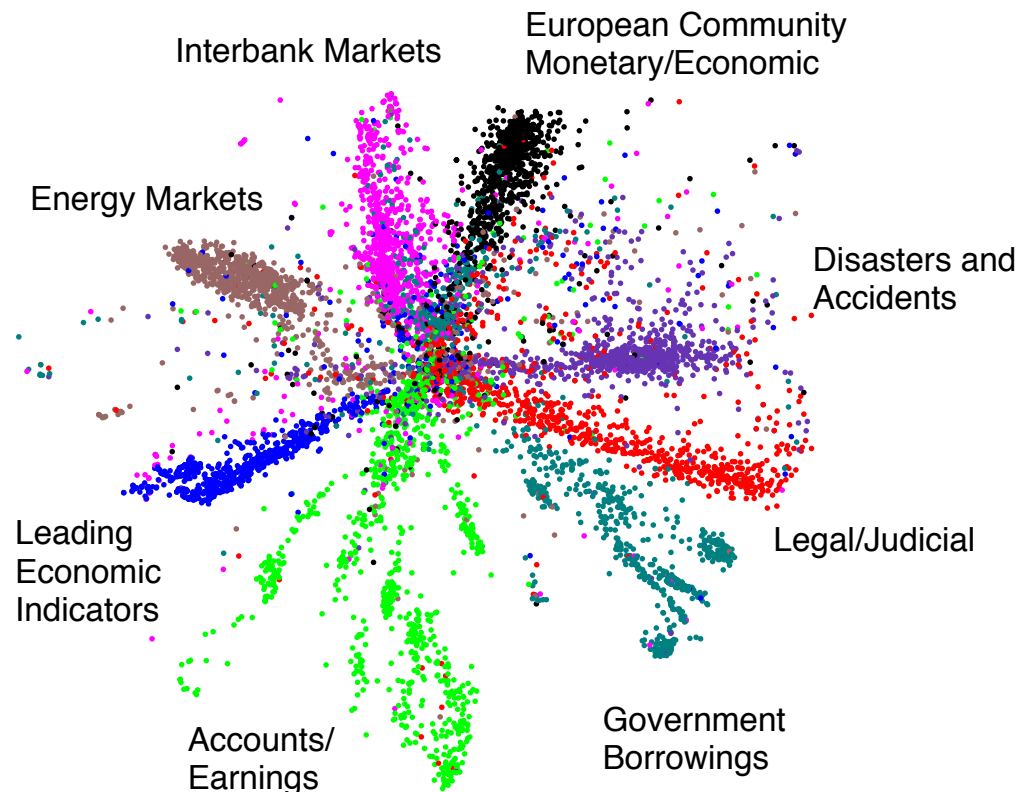
$$P(\mathbf{x}) = \frac{1}{Z} \sum_{\mathbf{h}} \exp [\mathbf{x}^T \mathbf{W} \mathbf{h}]$$

Vector of word counts
on a webpage

Latent variables:
hidden topics



804,414 newswire stories



Natural Language Understanding

In a series of conflicts from 1803-15 known as the Napoleonic Wars, various European powers formed five coalitions against the First French Empire. Like the wars sparked by the French Revolution (1789), these further revolutionized the formation, organization and training of European armies and led to an unprecedented militarization, mainly due to mass conscription. Under the leadership of Napoleon, French power rose quickly as the Grande Armée conquered most of Europe, and collapsed rapidly

XL Generation:

after the French conquest of Italy. This victory marked the beginning of the Second

Reference:

after the disastrous invasion of Russia in 1812. Napoleon's empire ultimately suffered complete military defeat in the 1813 – 14 campaigns, resulting in the restoration of the Bourbon monarchy in France. Although Napoleon made a spectacular return in 1815, known as the Hundred Days, his defeat at the Battle of Waterloo, the pursuit of his army and himself, his abdication and banishment to the Island of Saint Helena concluded the Napoleonic Wars.

== Danube campaign ==

From 1803-06 the Third Coalition fought the First French Empire and its client states (see table at right). Although several naval battles determined control of the seas, the outcome of the war was decided on the continent, predominantly in two major land operations in the Danube valley: the Ulm campaign in the upper Danube and the Vienna campaign, in the middle Danube valley. Political conflicts in Vienna delayed Austria's entry into the Third Coalition until 1805. After hostilities of the War of the Second Coalition ended in 1801, Archduke <unk> emperor's <unk> advantage of the subsequent years of peace to develop a military restructuring plan. He carefully put this plan into effect beginning in 1803 – 04, but implementation was incomplete in 1805 when Karl Mack, Lieutenant Field Marshal and Quartermaster-General of the Army, implemented his own restructuring. Mack bypassed Charles' methodical approach. Occurring in the field, Mack's plan also undermined the overall command and organizational structure. Regardless, Mack sent an enthusiastic report to Vienna on the military's readiness. Furthermore, after misreading Napoleon's maneuvers in Württemberg, Mack also reported to Vienna on the weakness of French dispositions. His reports convinced the war party advising the emperor, Francis II, to enter the conflict against France, despite Charles' own advice to the contrary. Responding to the report and rampant anti-French fever in Vienna, Francis dismissed Charles from his

XL Generation:

after the French conquest of Italy. This victory marked the beginning of the Second Coalition. Napoleon's rapid advance caused Austria – Russia, Britain and Russia to make peace negotiations. The Russian army under Prince Mikhail Mikhailovich Chaffee, commander of the Imperial Russian Army in Switzerland, was able to drive off the Austrians in the Battle of Stockach (1805) and to take Pressburg (modern Ö3 Austria) from the Austrians. At an early stage the Austro-Hungarian fleet had been damaged in a storm off Cape Matapan; this allowed the Allies to launch a full-scale invasion of Italy in February 1805. The Battle of Austerlitz was the decisive French victory against Napoleon and the largest naval battle in history, involving more modern-day European navies. The French military situation worsened as Napoleon faced several threats related to his newly formed Army of Europe, particularly Russia itself, which was now on the verge of collapse. The Russian general and friend of Napoleon, Alexander, had been dissatisfied with the conduct of the Austrians; he was still in conflict with Emperor Napoleon, the French Republic's king, who had declared war on Austria during the summer of 1804. With the war over, Napoleon decided to launch a second invasion of Italy in October 1805.

Napoleon decided to launch a second invasion of Italy in October 1805.

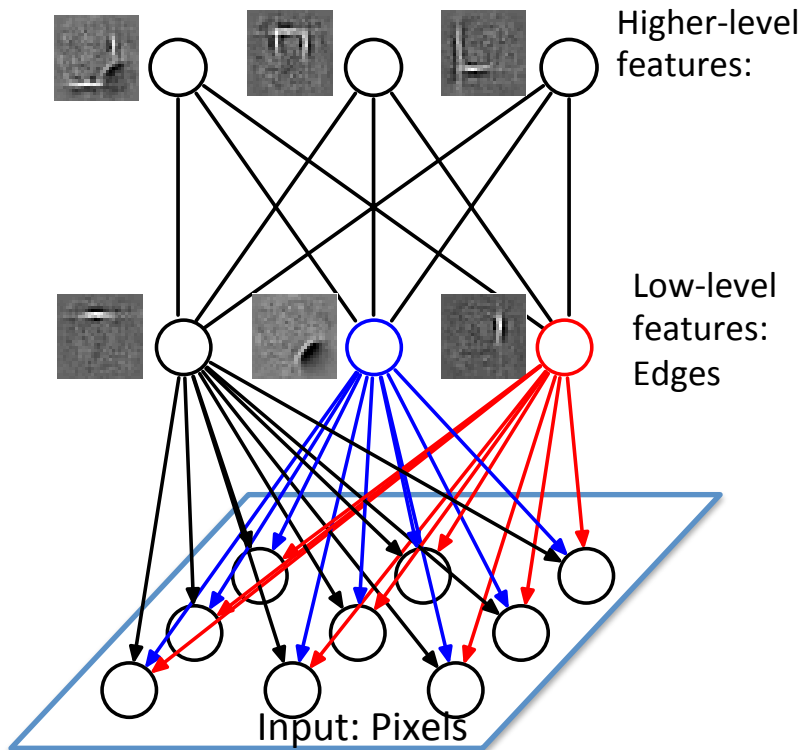
= = Prelude = =

In July 1805, the French 1st Army entered southern Italy. The army, under the command of Marshal Marmont, were reinforced by a few battalions of infantry under Claude General Auguste de Marmont at the town of Philippsburg and another battalion at Belluno. On **17 September 1805**, the army marched from Belluno towards Krems. By **29 September**, they had reached Belluno and conducted its advance against a small Austrian force. By **31 September**, the whole force had been reinforced by a brigade from the Army of Tyrol under the command of Pierre Augereau. The Austrians were now under the command of Marshal Jean Victor Marie Moreau, a member of the Directory. Moreau had taken command of the Austrian invasion force in the spring of 1805. His command included the VI Corps commanded by Jean Baptiste Drouet de Ney and the VI Corps commanded by Generals Jean Victor Marie Moreau and Joseph Souham. Ney's corps consisted of the III. Corps and VI. Corps, which consisted of the III Corps and VI. Corps, located in the Austrian Netherlands, was commanded by Friedrich Joseph, Count Baillet de Latour. Moreau's army consisted of six divisions and several associated brigades.

Important Breakthroughs

- **Deep Belief Networks, 2006 (Unsupervised)**

Hinton, G. E., Osindero, S. and Teh, Y., A fast learning algorithm for deep belief nets, Neural Computation, 2006.



Theoretical Breakthrough:

- Adding additional layers improves variational lower-bound.

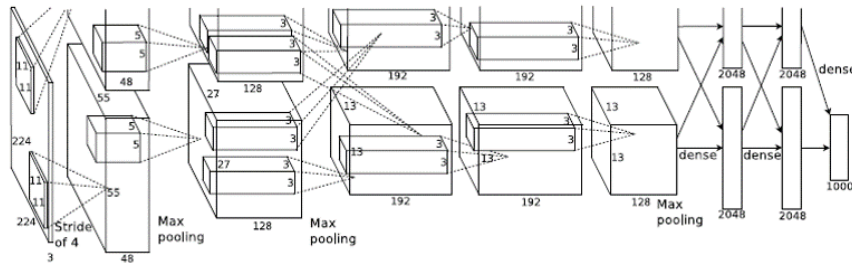
Efficient Learning and Inference with multiple layers:

- Efficient greedy layer-by-layer learning algorithm.
- Inferring the states of the hidden variables in the top most layer is easy.

Important Breakthroughs

- Deep Convolutional Nets for Vision (Supervised)

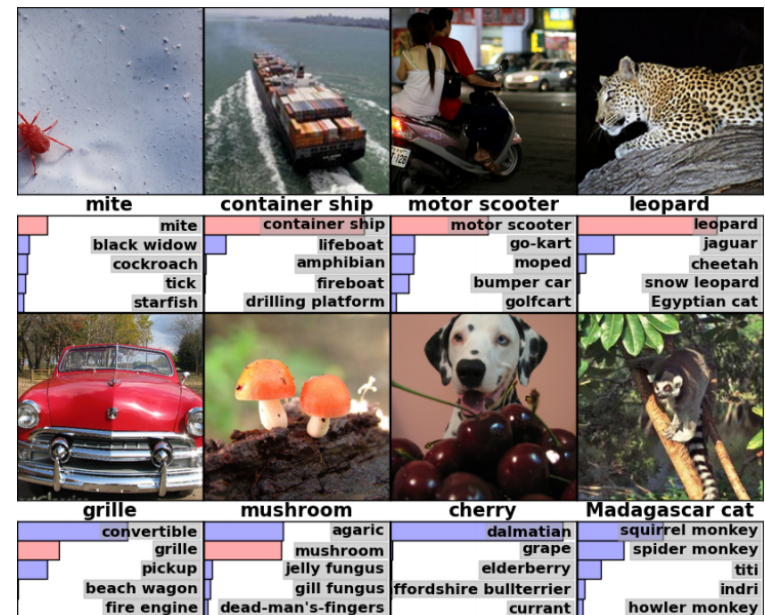
Krizhevsky, A., Sutskever, I. and Hinton, G. E., ImageNet Classification with Deep Convolutional Neural Networks, NIPS, 2012.



IMAGENET

1.2 million training images

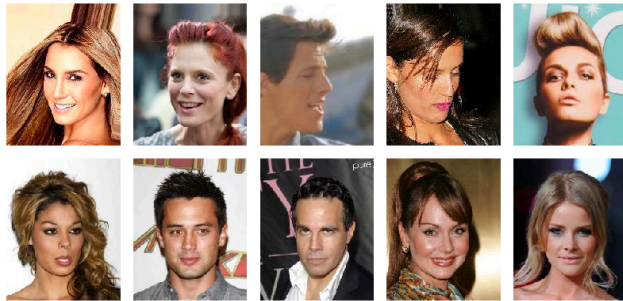
1000 classes



- Deep Nets for Speech (Supervised)

Hinton et. al. Deep Neural Networks for Acoustic Modeling in Speech Recognition: The Shared Views of Four Research Groups, IEEE Signal Processing Magazine. 2012.

Statistical Generative Models



Training
Data(CelebA)



Model Samples (Karras et.al.,
2018)

4 years of progression on Faces



2014



2015



2016



2017

Brundage et al.,
2017

Statistical Generative Models

- Conditional generative model $P(\text{zebra images} | \text{horse images})$



► Style Transfer



Input Image



Monet



Van Gogh

Statistical Generative Models

- Conditional generative model $P(\text{zebra images} | \text{horse images})$



► Failure Case



Statistical Generative Models

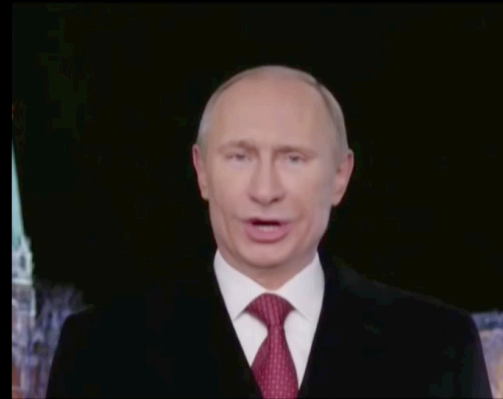
Source
actor



Target
actor



Real-time Reenactment



Real-time
reenactment

Reenactment Result

Course Organization

- Introduction / Background:
 - Linear Algebra, Distributions, Rules of probability.
 - Regression, Classification.
 - Feedforward neural nets, backpropagation algorithm.
 - Introduction to popular optimization and regularization techniques for deep nets.
 - Convolutional models with applications to computer vision.

Course Organization

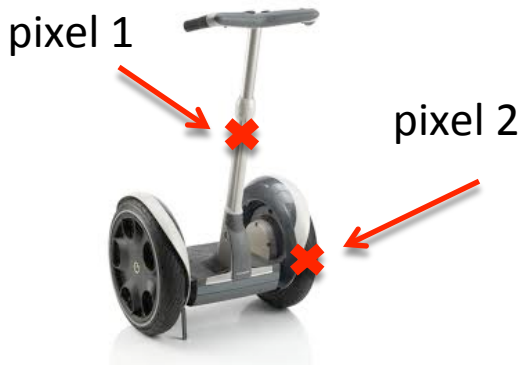
- Deep Learning Essentials:
 - Graphical Models: Directed and Undirected.
 - Autoencoders and its extensions.
 - Energy-based models, RBMs.
 - Deep Generative Models: Deep Belief Networks, Deep Boltzmann Machines, Helmholtz Machines,
 - Variational Autoencoders, Importance-weighted Autoencoders, Wake-Sleep Algorithm.
 - Generative Adversarial Networks (GANs), Generative Moment Matching Nets, Neural Autoregressive Density Estimator (NADE).

Course Organization

- Additional Topics

- More on Regularization and Optimization in Deep Nets.
- Sequence Modeling: Recurrent Neural Networks.
- Sequence-to-Sequence Architectures, Attention models.
- Deep Reinforcement Learning.

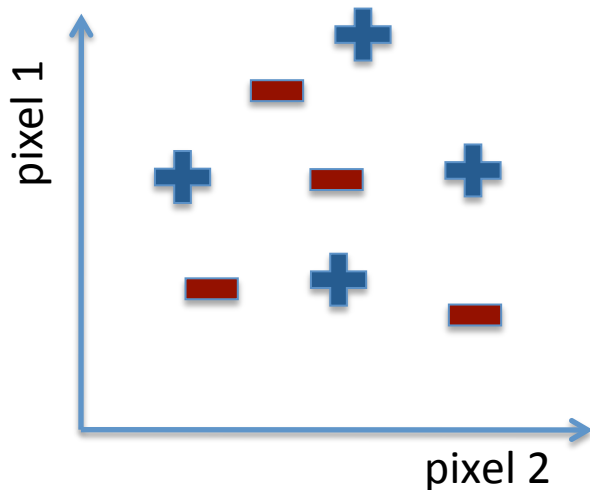
Learning Feature Representations



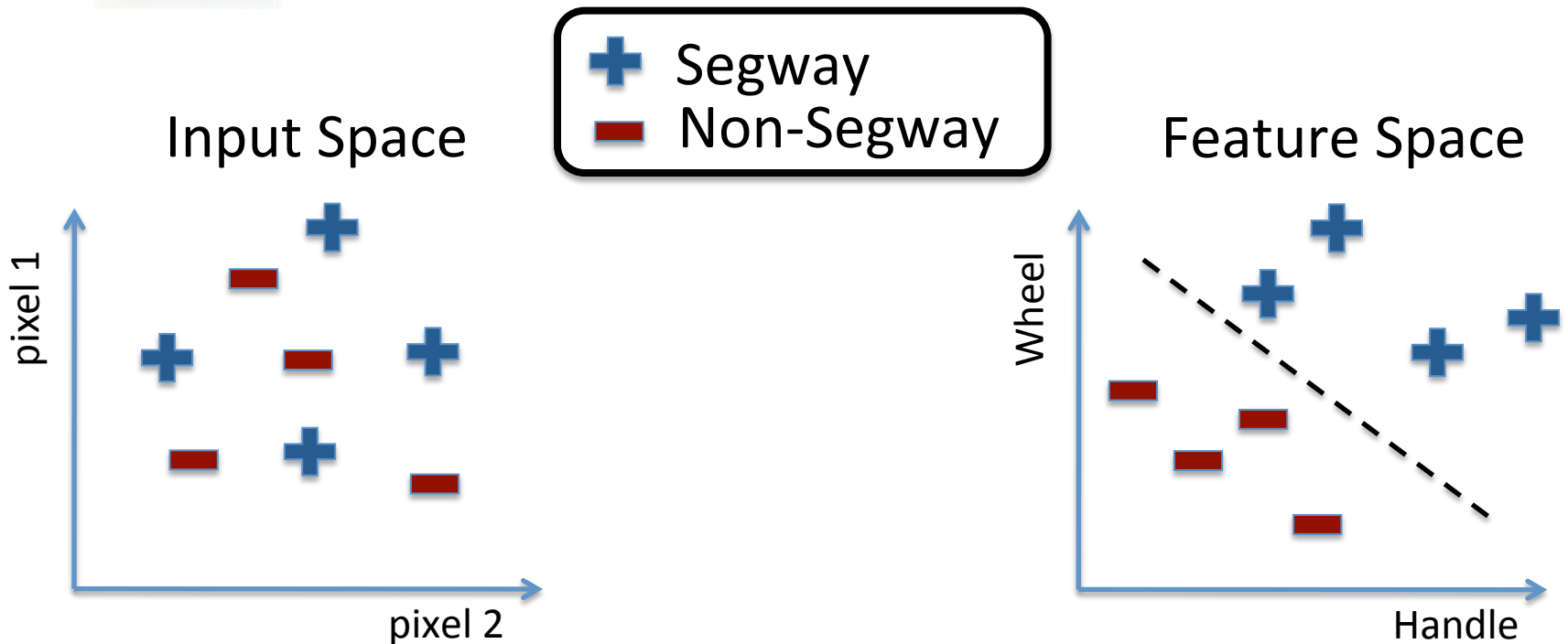
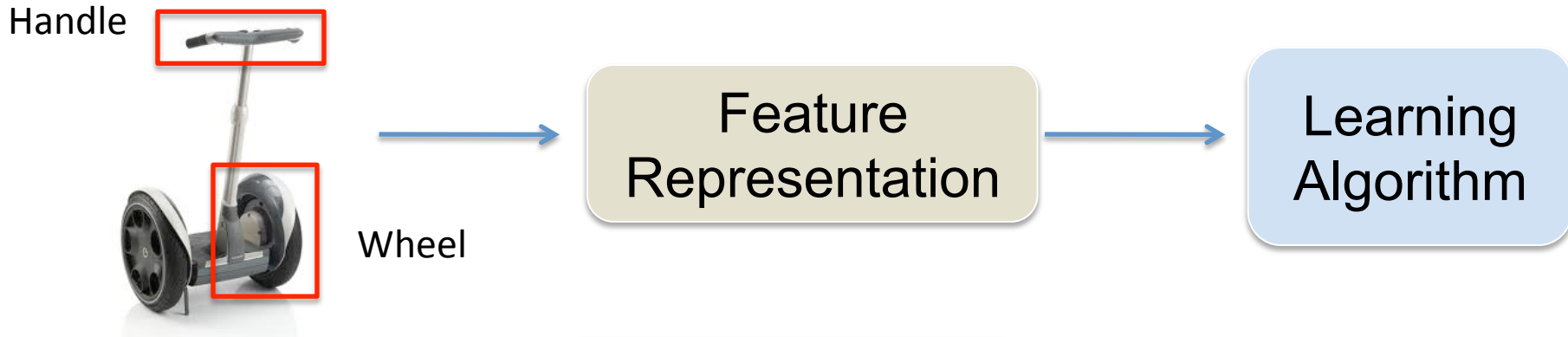
Learning
Algorithm

Input Space

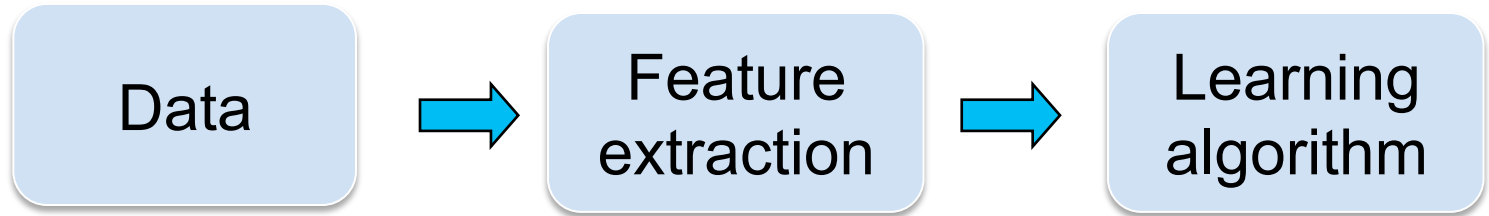
+ Segway
- Non-Segway



Learning Feature Representations



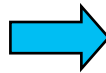
Traditional Approaches



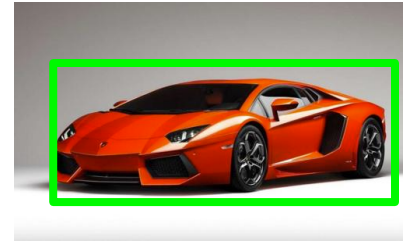
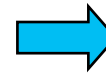
Object
detection



Image

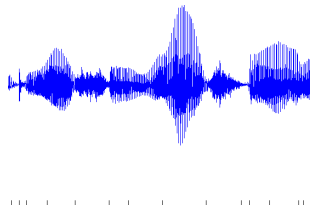


vision features

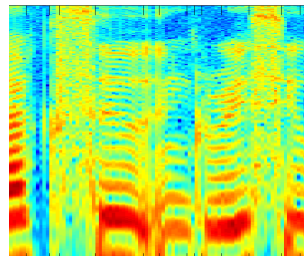
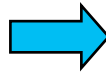


Recognition

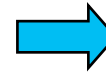
Audio
classification



Audio

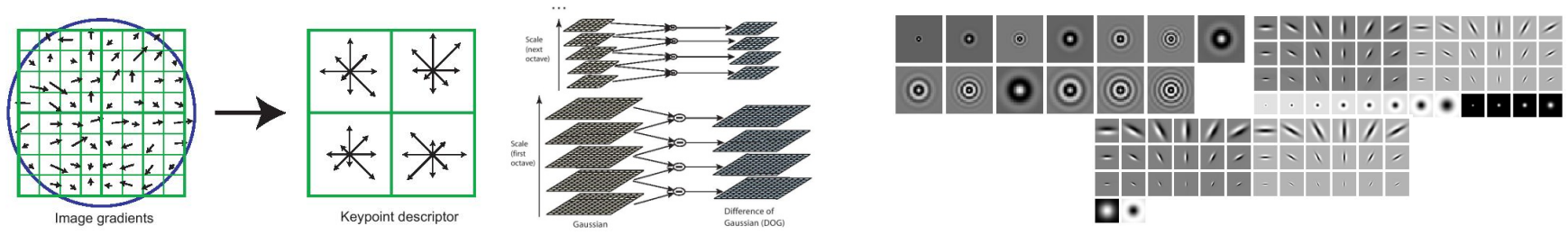


audio features



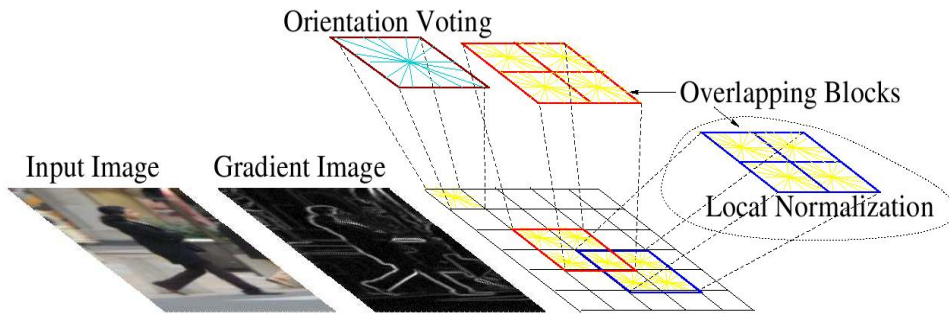
Speaker
identification

Computer Vision Features

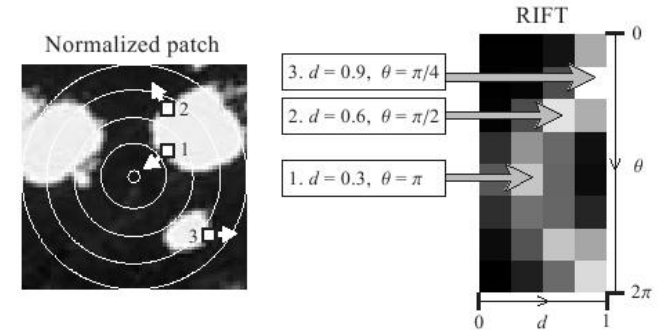


SIFT

Textons

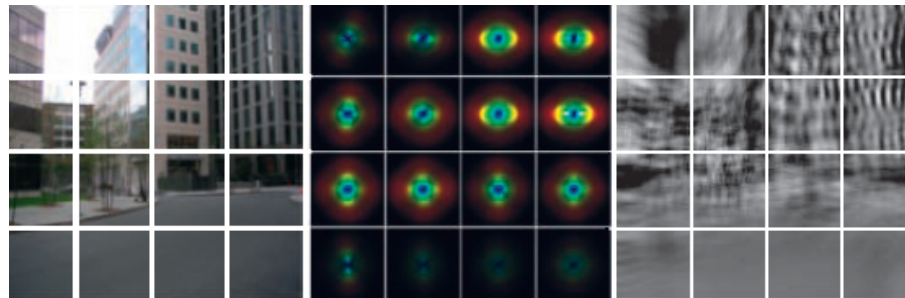


HoG

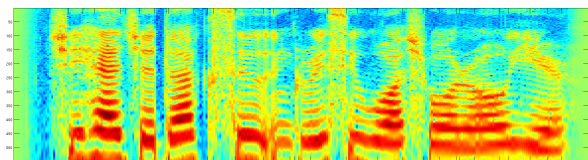
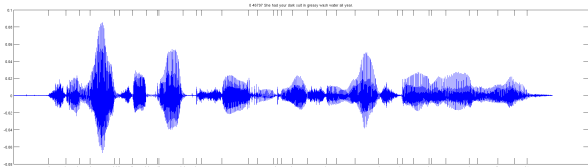


RIFT

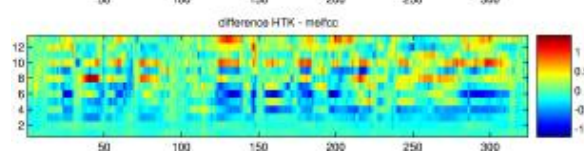
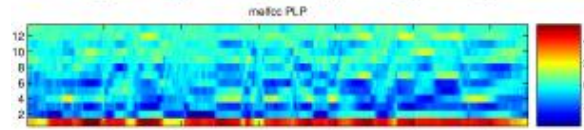
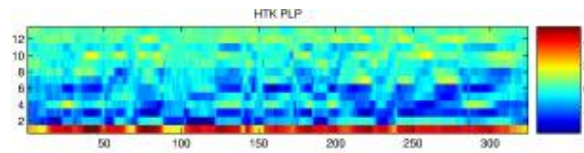
GIST



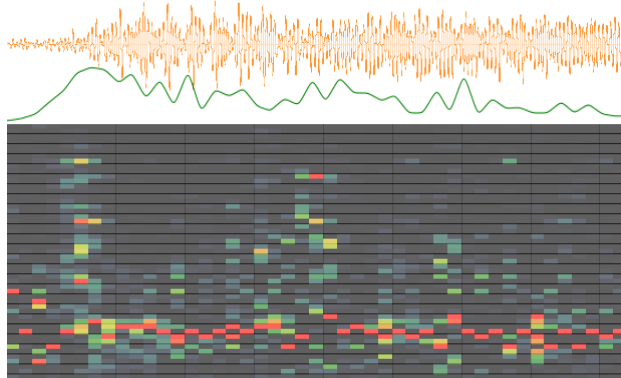
Audio Features



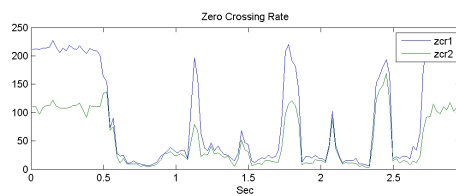
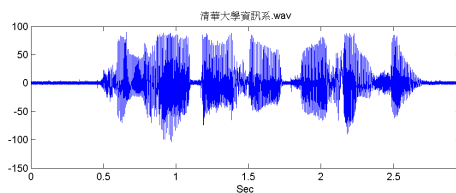
Spectrogram



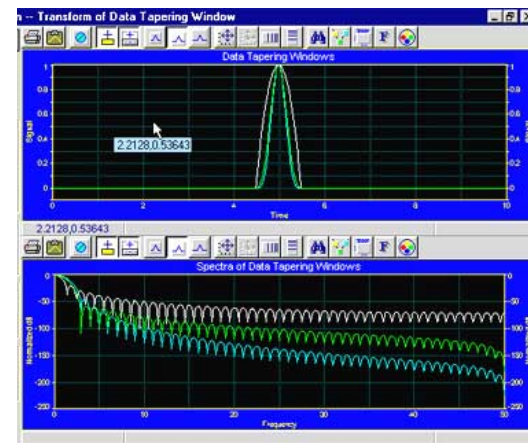
MFCC



Flux

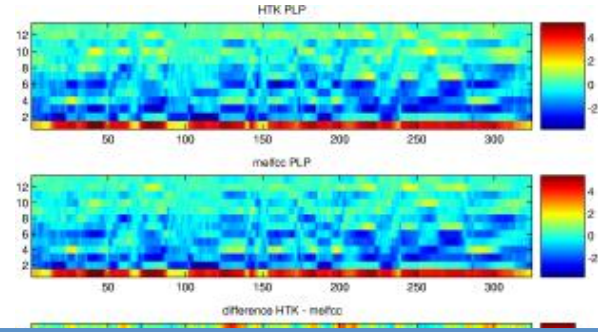
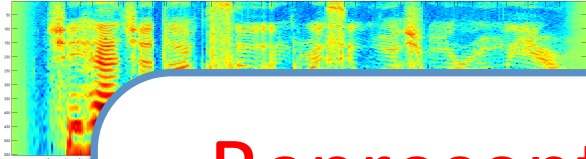
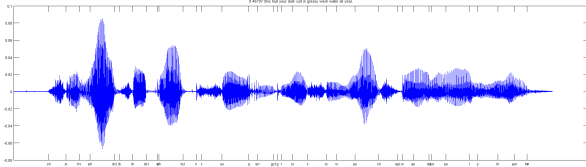


ZCR

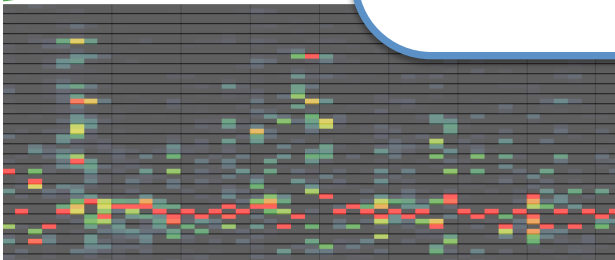
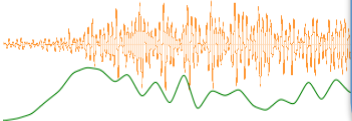


Rolloff

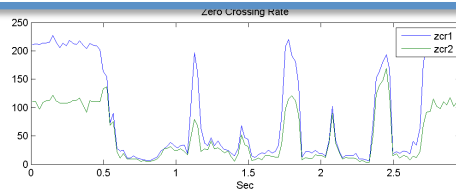
Audio Features



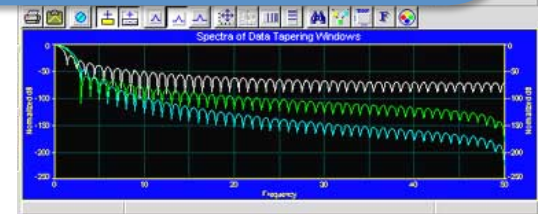
Representation Learning:
Can we automatically learn
these representations?



Flux



ZCR



Rolloff

Types of Learning

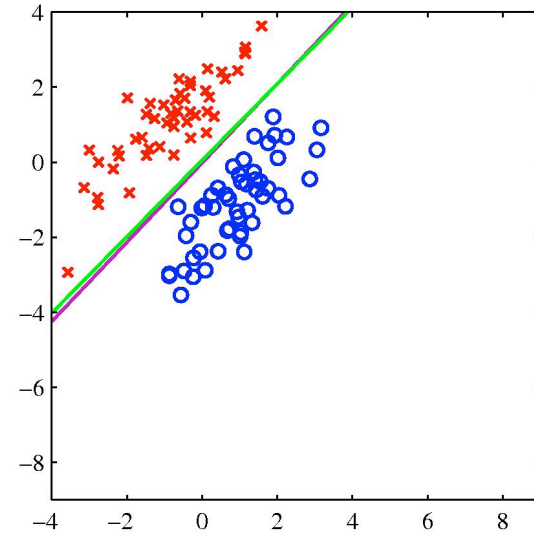
Consider observing a series of input vectors:

$$\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, \mathbf{x}_4, \dots$$

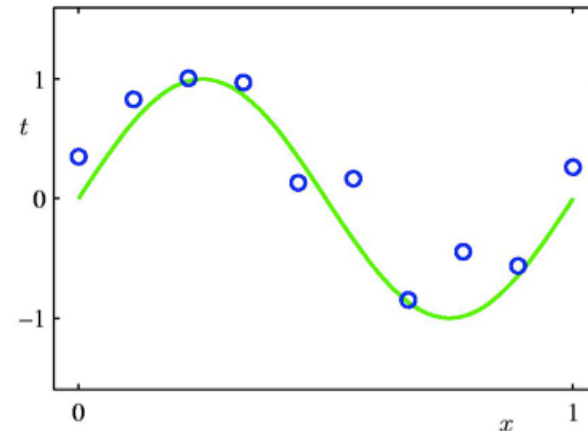
- **Supervised Learning:** We are also given **target outputs (labels, responses)**: y_1, y_2, \dots , and the goal is to predict correct output given a new input.
- **Unsupervised Learning:** The goal is to build a statistical model of \mathbf{x} , which can be used for making predictions, decisions.
- **Reinforcement Learning:** the model (agent) produces a set of actions: a_1, a_2, \dots that affect the state of the world, and received rewards r_1, r_2, \dots . The goal is to learn actions that maximize the reward.
- **Semi-supervised Learning:** We are given only a limited amount of labels, but lots of unlabeled data.

Supervised Learning

Classification: target outputs y_i are discrete class labels. The goal is to correctly classify new inputs.



Regression: target outputs y_i are continuous. The goal is to predict the output given new inputs.



Handwritten Digit Classification

0 0 0 1 1 1 1 1 1 2

2 2 2 2 2 2 2 3 3 3

3 4 4 4 4 4 5 5 5 5

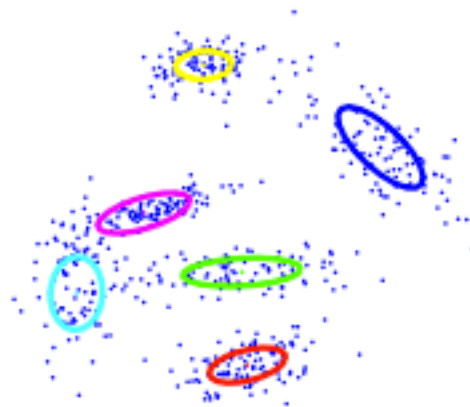
6 6 7 7 7 7 7 8 8 8

8 8 8 8 8 9 9 9 9

Unsupervised Learning

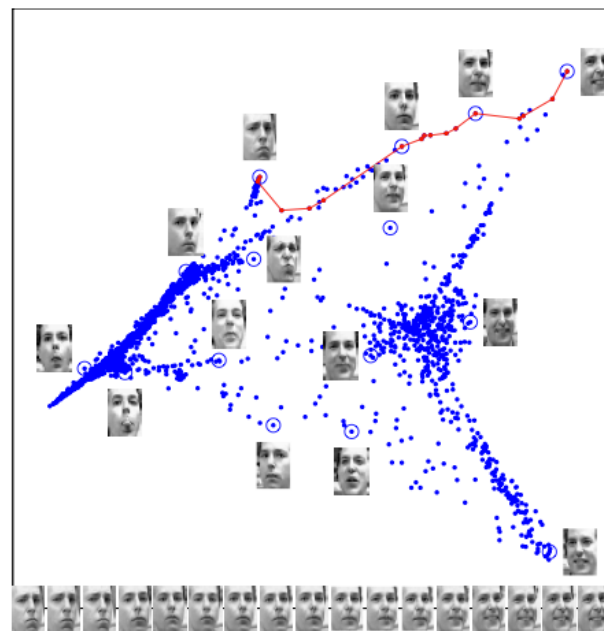
The goal is to construct statistical model that finds useful representation of data:

- Clustering
- Dimensionality reduction
- Modeling the data density
- Finding hidden causes (useful explanation) of the data

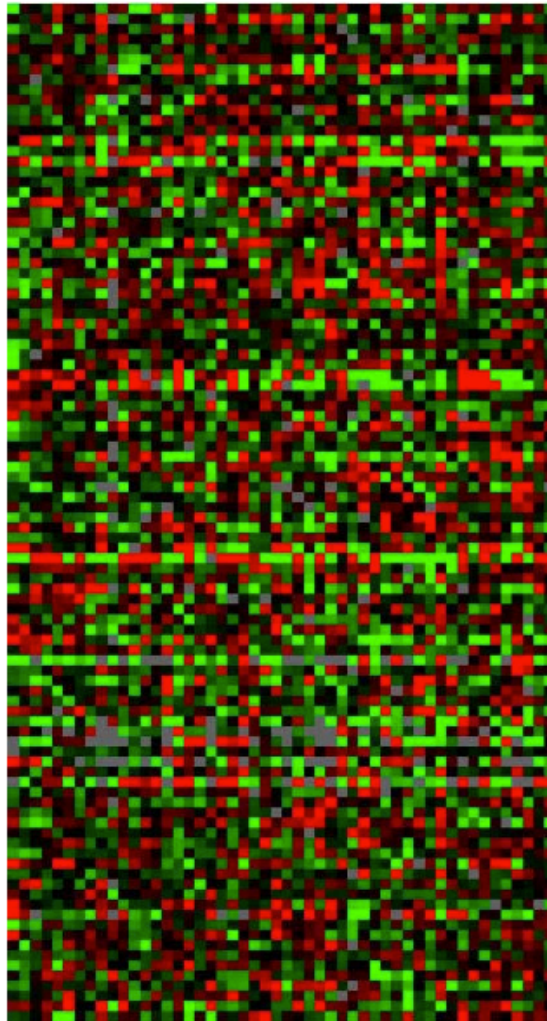


Unsupervised Learning can be used for:

- Structure discovery
- Anomaly detection / Outlier detection
- Data compression, Data visualization
- Used to aid classification/regression tasks



DNA Microarray Data



SIDW299104
SIDW980102
SID73161
GNAL
H.sapiensmFR
SID25294
RAGTTPASE
SID237172
ESTs
SIDW377402
HumanmRNA
SIDW469884
ESTs
SIDW71915
MYB3PROTO
ESTsChr 1
SID27491
DNAPOLYME
SID275912
SIDW31489
SID167117
SIDW470459
SIDW487261
Homosapiens
SIDW375698
Chr
MITOCHOND
SID47115
ESTsChr 9
SIDW995019
SID488017
SID325167
ESTsChr 3
SID127504
SID289414
PTFRFC
SIDW298203
SIDW310141
SIDW376588
ESTsChr31
SID1142911
SID377419
SID297117
SIDW201620
SIDW279054
SIDW10534
HLAclassII
SIDW203454
SID229012
SIDW205719
SIDW376776
HYPOTHETI
WASWskuzt
SIDW221854
ESTsChr 15
SIDW376394
SID290096
ESTsChr 5
SIDW488221
SID46536
SIDW207915
ESTsChr 2
SIDW202906
SID200394
ESTsChr 15
SID208483
SID485148
SID297905
ESTs
SIDW486740
SMALLNUC
ESTs
SIDW96511
SIDW201797
SID262979
ESTs
SID43609
SIDW416621
ERLUMEN
TIER 11321
SIDW428642
SID381079
SIDW286052
SIDW417270
SIDW362471
ESTsChr 15
SIDW201925
SID208265
SIDW208182
SID381508
SID377153
SIDW965039
ESTsChr 10
SIDW205160
SID395097
SID315990
SIDW125388
SID321922
SID21184
SID42384

Expression matrix of 6830 genes (rows) and 64 samples (columns) for the human tumor data.

The display is a heat map ranging from bright green (under expressed) to bright red (over expressed).

Questions we may ask:

- Which samples are similar to other samples in terms of their expression levels across genes.
- Which genes are similar to each other in terms of their expression levels across samples.

BLCA1
BLCA2
BLCA3
BLCA4
BLCA5
BLCA6
BLCA7
BLCA8
BLCA9
BLCA10
BLCA11
BLCA12
BLCA13
BLCA14
BLCA15
BLCA16
BLCA17
BLCA18
BLCA19
BLCA20
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BLCA94
BLCA95
BLCA96
BLCA97
BLCA98
BLCA99
BLCA100

Linear Least Squares

- Given a vector of d -dimensional inputs $\mathbf{x} = (x_1, x_2, \dots, x_d)^T$, we want to predict the target (response) using the linear model:

$$y(x, \mathbf{w}) = w_0 + w_1x_1 + w_2x_2 + \dots + w_dx_d = w_0 + \sum_{j=1}^d w_jx_j.$$

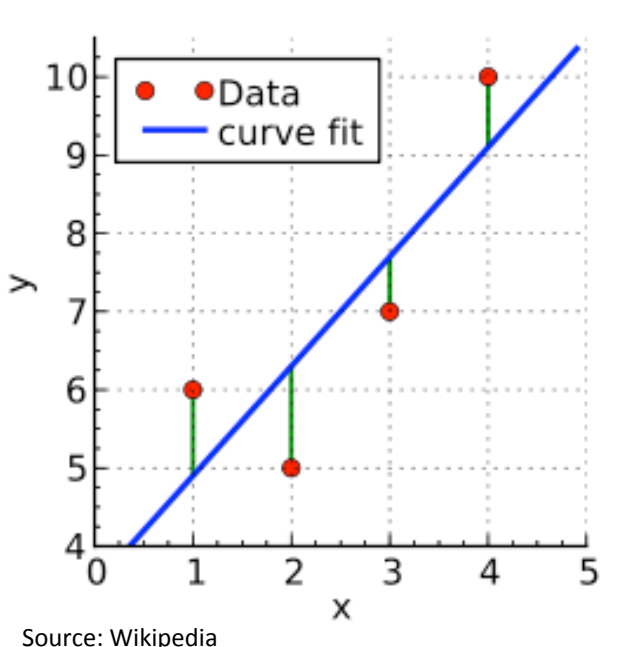
- The term w_0 is the intercept, or often called bias term. It will be convenient to include the constant variable 1 in \mathbf{x} and write:

$$y(\mathbf{x}, \mathbf{w}) = \mathbf{x}^T \mathbf{w}.$$

- Observe a **training set** consisting of N observations $\mathbf{X} = (\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_N)^T$, together with the corresponding target values $\mathbf{t} = (t_1, t_2, \dots, t_N)^T$.
- Note that \mathbf{X} is an $N \times (d + 1)$ matrix.

Linear Least Squares

One option is to minimize **the sum of the squares of the errors** between the predictions $y(\mathbf{x}_n, \mathbf{w})$ for each data point \mathbf{x}_n and the corresponding real-valued targets t_n .

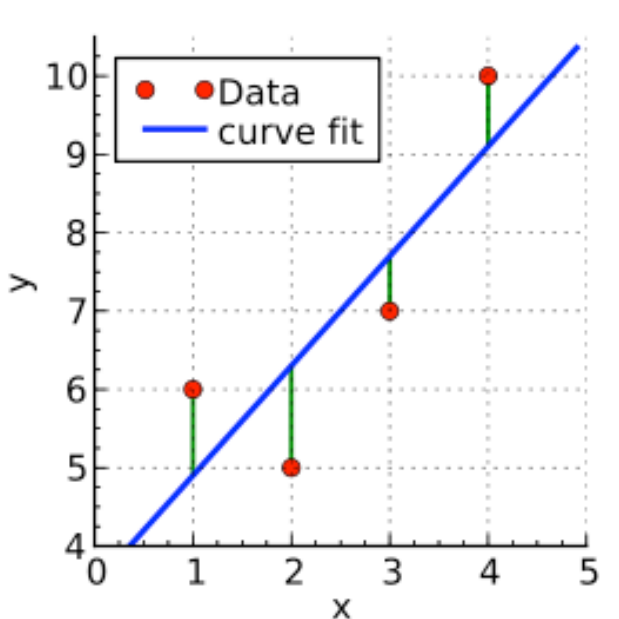


Loss function: sum-of-squared error function:

$$\begin{aligned} E(\mathbf{w}) &= \frac{1}{2} \sum_{n=1}^N (\mathbf{x}_n^T \mathbf{w} - t_n)^2 \\ &= \frac{1}{2} (\mathbf{X}\mathbf{w} - \mathbf{t})^T (\mathbf{X}\mathbf{w} - \mathbf{t}). \end{aligned}$$

Linear Least Squares

If $\mathbf{X}^T \mathbf{X}$ is nonsingular, then the unique solution is given by:



Source: Wikipedia

$$\mathbf{w}^* = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{t}$$

optimal weights

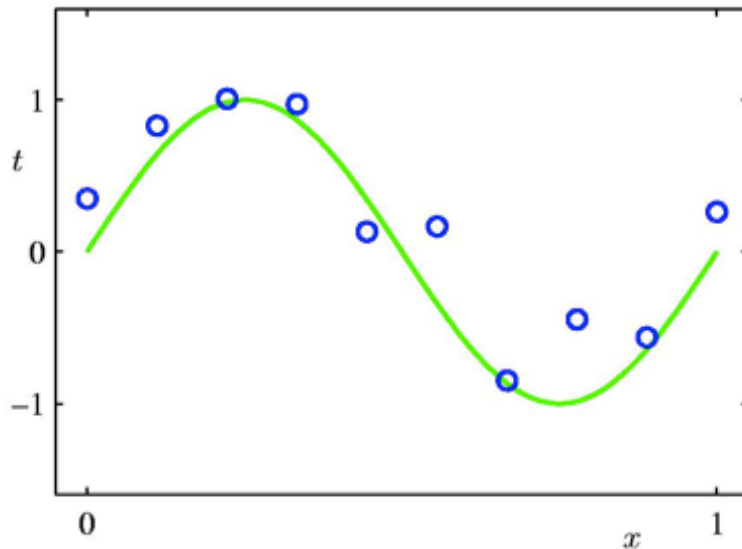
vector of target values

the design matrix has one input vector per row

- At an arbitrary input \mathbf{x}_0 , the prediction is $y(\mathbf{x}_0, \mathbf{w}) = \mathbf{x}_0^T \mathbf{w}^*$.
- The entire model is characterized by $d+1$ parameters \mathbf{w}^* .

Example: Polynomial Curve Fitting

Consider observing a **training set** consisting of N 1-dimensional observations: $\mathbf{x} = (x_1, x_2, \dots, x_N)^T$, together with corresponding real-valued targets: $\mathbf{t} = (t_1, t_2, \dots, t_N)^T$.



- The green plot is the true function $\sin(2\pi x)$.
- The training data was generated by taking x_n spaced uniformly between $[0, 1]$.
- The target set (blue circles) was obtained by first computing the corresponding values of the sin function, and then adding a small Gaussian noise.

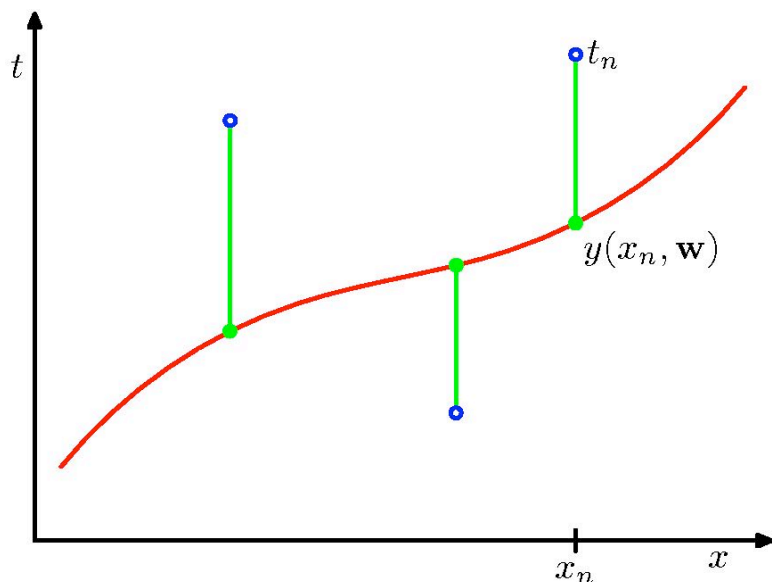
Goal: Fit the data using a polynomial function of the form:

$$y(x, \mathbf{w}) = w_0 + w_1x + w_2x^2 + \dots + w_Mx^M = \sum_{j=0}^M w_jx^j.$$

Note: the polynomial function is a nonlinear function of x , but it is a linear function of the coefficients $\mathbf{w} \rightarrow$ **Linear Models**.

Example: Polynomial Curve Fitting

- As for the least squares example: we can minimize the sum of the squares of the errors between the predictions $y(x_n, \mathbf{w})$ for each data point x_n and the corresponding target values t_n .

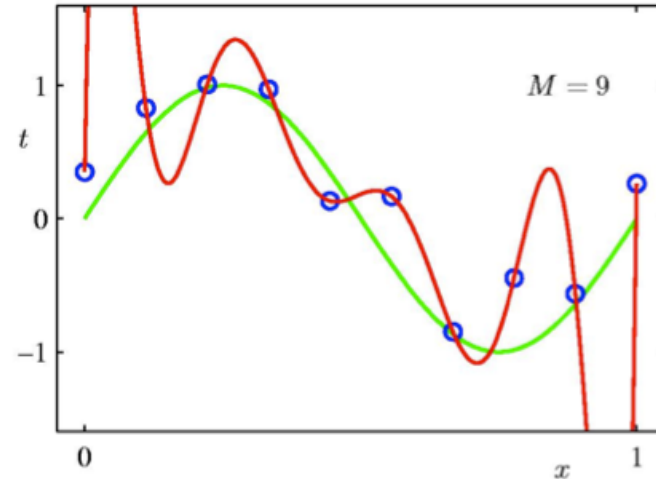
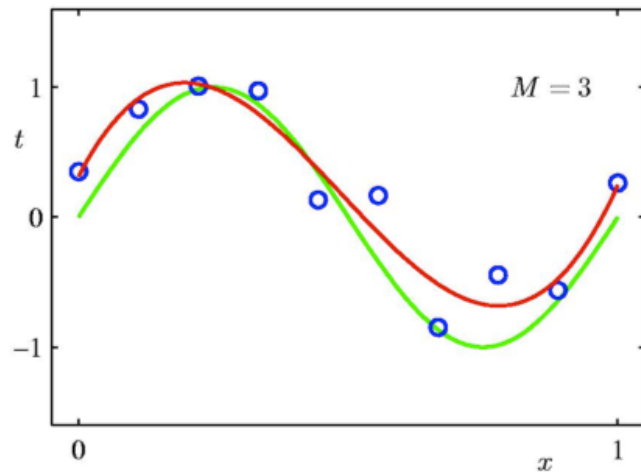
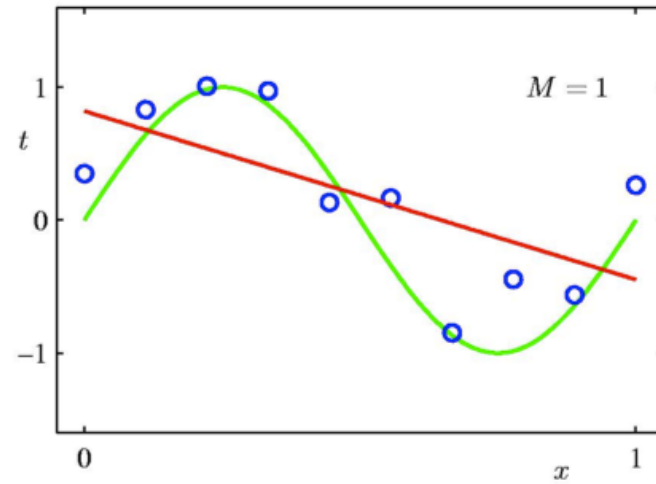
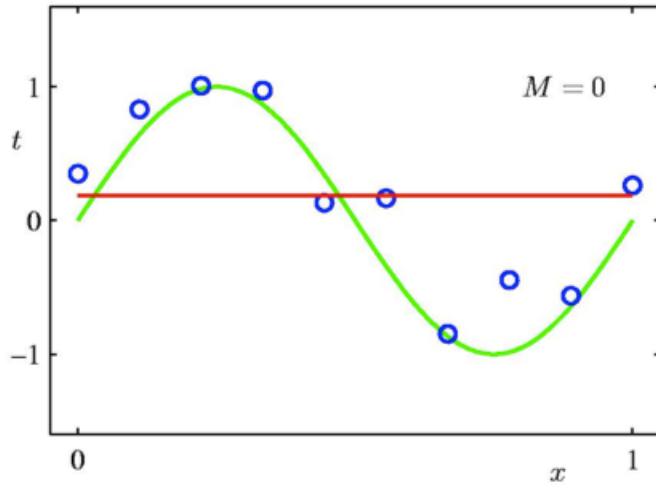


Loss function: sum-of-squared error function:

$$E(\mathbf{w}) = \frac{1}{2} \sum_{i=1}^N (y(x_n, \mathbf{w}) - t_n)^2.$$

- Similar to the linear least squares: Minimizing sum-of-squared error function has a unique solution \mathbf{w}^* .
- The model is characterized by $M+1$ parameters \mathbf{w}^* .
- How do we choose M ? → **Model Selection.**

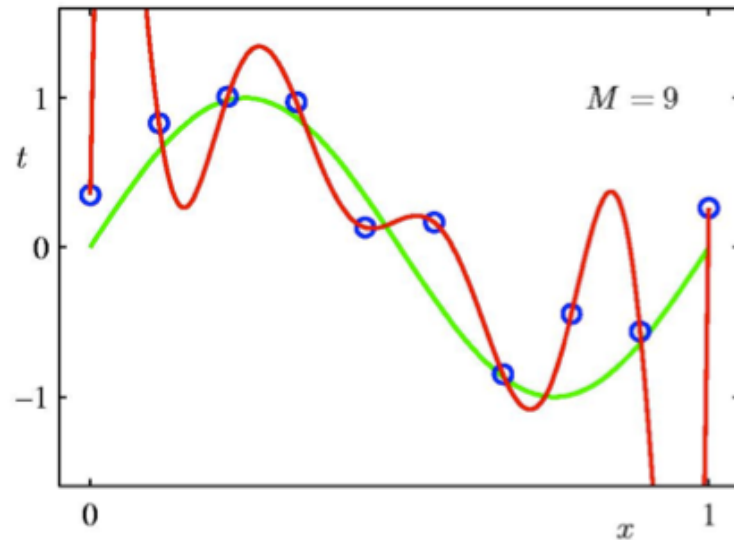
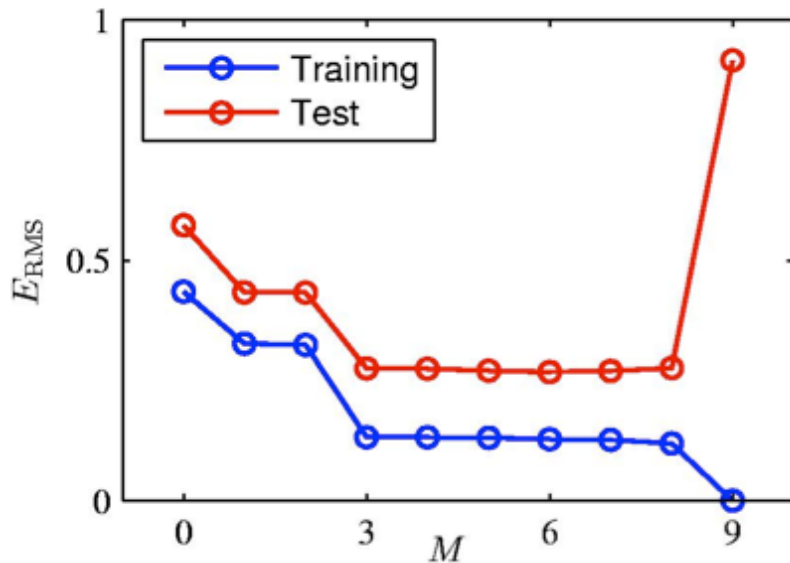
Some Fits to the Data



For $M=9$, we have fitted the training data perfectly.

Overfitting

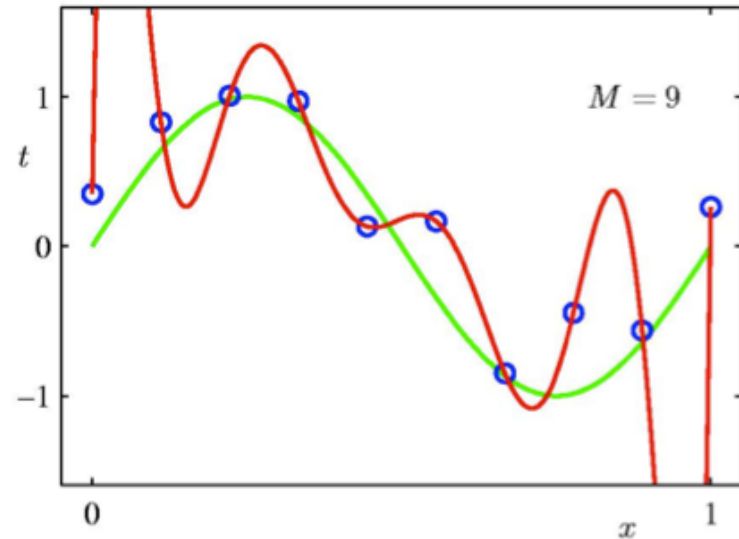
- Consider a separate **test set** containing 100 new data points generated using the same procedure that was used to generate the training data.



- For $M=9$, the training error is zero \rightarrow The polynomial contains 10 degrees of freedom corresponding to 10 parameters \mathbf{w} , and so can be fitted exactly to the 10 data points.
- However, the test error has become very large. Why?

Overfitting

	$M = 0$	$M = 1$	$M = 3$	$M = 9$
w_0^*	0.19	0.82	0.31	0.35
w_1^*		-1.27	7.99	232.37
w_2^*			-25.43	-5321.83
w_3^*			17.37	48568.31
w_4^*				-231639.30
w_5^*				640042.26
w_6^*				-1061800.52
w_7^*				1042400.18
w_8^*				-557682.99
w_9^*				125201.43

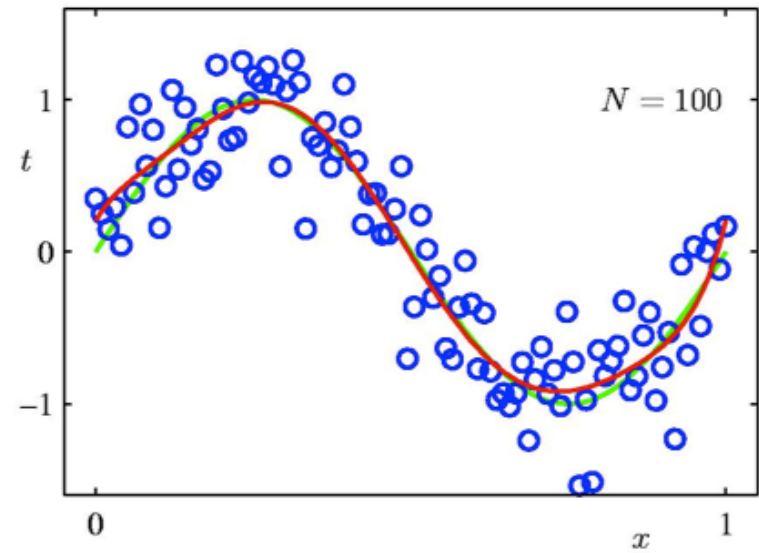
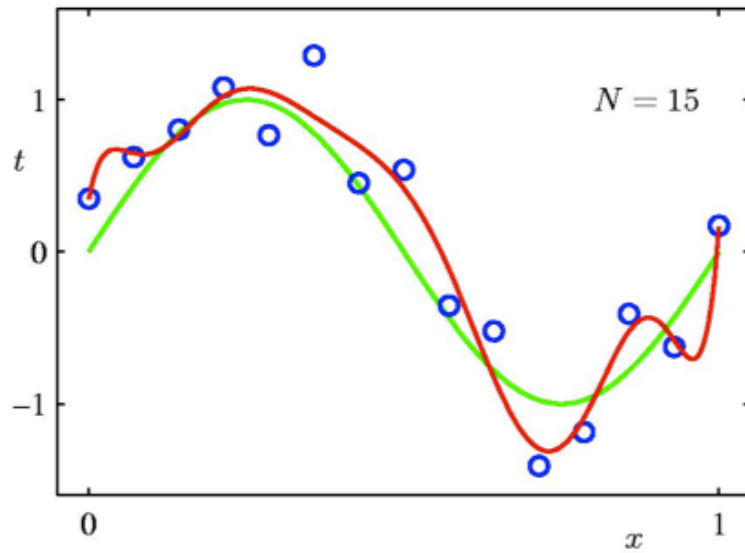


- As M increases, the magnitude of coefficients gets larger.
- For $M=9$, the coefficients have become finely tuned to the data.
- Between data points, the function exhibits large oscillations.

More flexible polynomials with larger M tune to the random noise on the target values.

Varying the Size of the Data

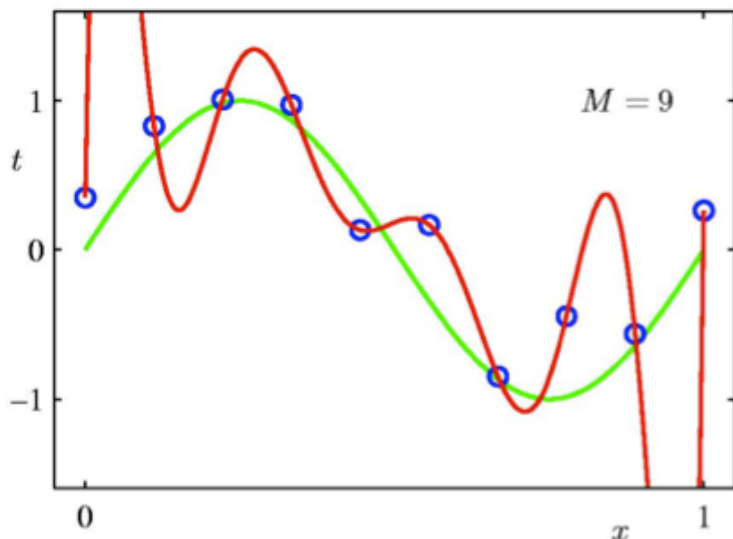
9th order polynomial



- For a given model complexity, the overfitting problem becomes less severe as the size of the dataset increases.
- However, the number of parameters is not necessarily the most appropriate measure of the model complexity.

Generalization

- The goal is achieve good **generalization** by making accurate predictions for new test data that is not known during learning.
- Choosing the values of parameters that minimize the loss function on the training data may not be the best option.
- We would like to model the true regularities in the data and ignore the noise in the data:
 - It is hard to know which regularities are real and which are accidental due to the particular training examples we happen to pick.



- **Intuition:** We expect the model to generalize if it explains the data well given the complexity of the model.
- If the model has as many degrees of freedom as the data, it can fit the data perfectly. But this is not very informative.
- Some theory on how to control model complexity to optimize generalization.

A Simple Way to Penalize Complexity

One technique for controlling over-fitting phenomenon is **regularization**, which amounts to adding a penalty term to the error function.

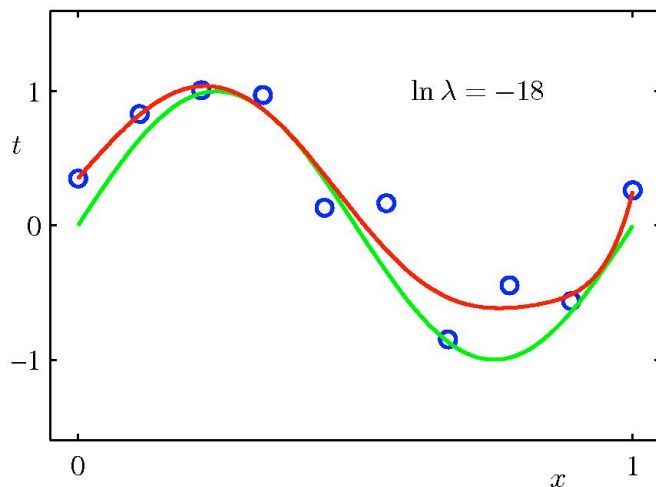
penalized error function

target value

regularization parameter

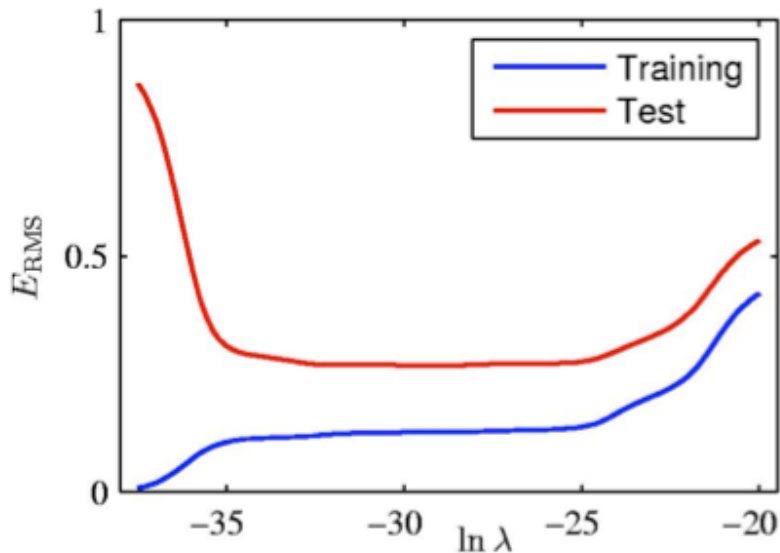
$$\tilde{E}(\mathbf{w}) = \frac{1}{2} \sum_{n=1}^N \{y(x_n, \mathbf{w}) - t_n\}^2 + \frac{\lambda}{2} \|\mathbf{w}\|^2$$

where $\|\mathbf{w}\| = \mathbf{w}^T \mathbf{w} = w_1^2 + w_2^2 + \dots + w_M^2$ called the regularization term. Note that we do not penalize the bias term w_0 .



- The idea is to “shrink” estimated parameters towards zero (or towards the mean of some other weights).
- Shrinking to zero: penalize coefficients based on their size.
- For a penalty function which is the sum of the squares of the parameters, this is known as “**weight decay**”, or “**ridge regression**”.

Regularization



	$\ln \lambda = -\infty$	$\ln \lambda = -18$	$\ln \lambda = 0$
w_0^*	0.35	0.35	0.13
w_1^*	232.37	4.74	-0.05
w_2^*	-5321.83	-0.77	-0.06
w_3^*	48568.31	-31.97	-0.05
w_4^*	-231639.30	-3.89	-0.03
w_5^*	640042.26	55.28	-0.02
w_6^*	-1061800.52	41.32	-0.01
w_7^*	1042400.18	-45.95	-0.00
w_8^*	-557682.99	-91.53	0.00
w_9^*	125201.43	72.68	0.01

Graph of the root-mean-squared training and test errors vs. $\ln \lambda$ for the $M=9$ polynomial.

How to choose λ ?

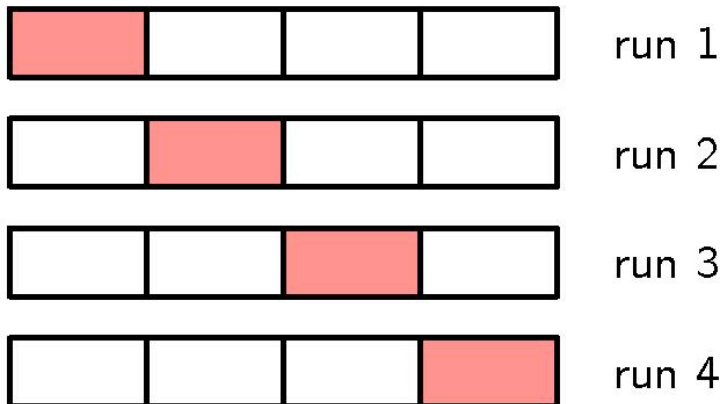
Cross Validation

If the data is plentiful, we can divide the dataset into three subsets:

- **Training Data:** used to fitting/learning the parameters of the model.
- **Validation Data:** not used for learning but for selecting the model, or choosing the amount of regularization that works best.
- **Test Data:** used to get performance of the final model.

For many applications, the supply of data for training and testing is limited. To build good models, we may want to use as much training data as possible. If the validation set is small, we get noisy estimate of the predictive performance.

S fold cross-validation



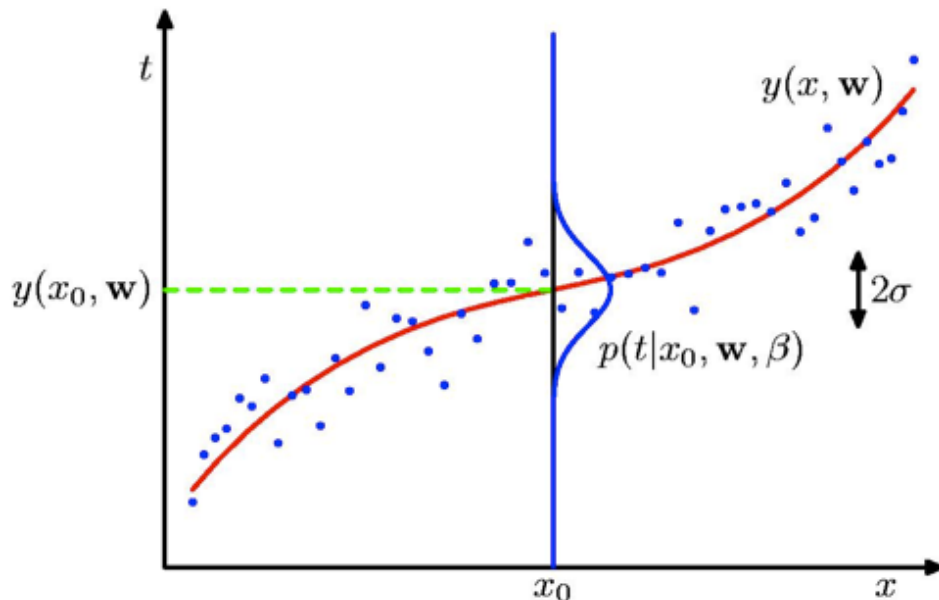
- The data is partitioned into S groups.
- Then S-1 of the groups are used for training the model, which is evaluated on the remaining group.
- Repeat procedure for all S possible choices of the held-out group.
- Performance from the S runs are averaged.

Probabilistic Perspective

- So far we saw that polynomial curve fitting can be expressed in terms of error minimization. We now view it from probabilistic perspective.
- Suppose that our model arose from a statistical model:

$$t = y(\mathbf{x}, \mathbf{w}) + \epsilon,$$

where ϵ is a random error having Gaussian distribution with zero mean, and is independent of \mathbf{x} .



Thus we have:

$$p(t|\mathbf{x}, \mathbf{w}, \beta) = \mathcal{N}(t|y(\mathbf{x}, \mathbf{w}), \beta^{-1}),$$

where β is a precision parameter, corresponding to the inverse variance.

I will use probability distribution and probability density interchangeably. It should be obvious from the context.

Sampling Assumption

- Assume that the training examples are drawn **independently** from the set of all possible examples, or from the same underlying distribution $p(\mathbf{x}, t)$.
- We also assume that the training examples are **identically distributed** \rightarrow i.i.d assumption.
- Assume that the test samples are drawn in exactly the same way -- i.i.d from the same distribution as the training data.
- These assumptions make it unlikely that some strong regularity in the training data will be absent in the test data.

Maximum Likelihood

If the data are assumed to be independently and identically distributed (*i.i.d assumption*), the likelihood function takes form:

$$p(\mathbf{t}|\mathbf{x}, \mathbf{w}, \beta) = \prod_{i=1}^N \mathcal{N}(t_n | y(\mathbf{x}_n, \mathbf{w}), \beta^{-1}).$$

It is often convenient to maximize the log of the likelihood function:

$$\ln p(\mathbf{t}|\mathbf{x}, \mathbf{w}, \beta) = -\frac{\beta}{2} \underbrace{\sum_{n=1}^N (y(\mathbf{x}_n, \mathbf{w}) - t_n)^2}_{\beta E(\mathbf{w})} + \frac{N}{2} \ln \beta - \frac{N}{2} \ln(2\pi).$$

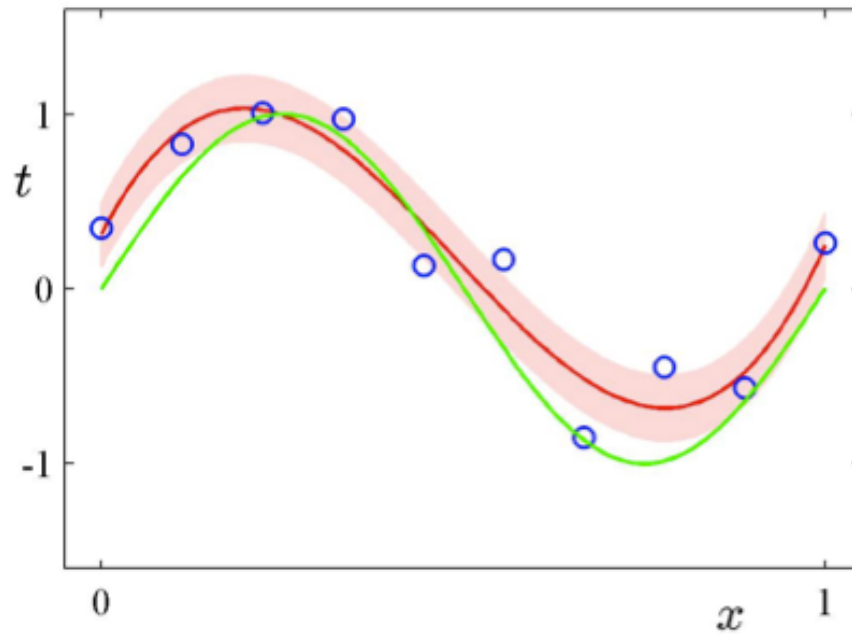
- Maximizing log-likelihood with respect to \mathbf{w} (under the assumption of a Gaussian noise) is equivalent to minimizing the *sum-of-squared error* function.
- Determine \mathbf{w}_{ML} by maximizing log-likelihood. Then maximizing w.r.t. β :

$$\frac{1}{\beta_{ML}} = \frac{1}{N} \sum_n (y(\mathbf{x}_n, \mathbf{w}_{ML}) - t_n)^2.$$

Predictive Distribution

Once we determined the parameters \mathbf{w} and β , we can make prediction for new values of \mathbf{x} :

$$p(t|\mathbf{x}, \mathbf{w}_{ML}, \beta_{ML}) = \mathcal{N}(t|y(\mathbf{x}, \mathbf{w}_{ML}), \beta_{ML}^{-1}).$$



Statistical Decision Theory

- We now develop a small amount of theory that provides a framework for developing many of the models we consider.
- Suppose we have a real-valued input vector \mathbf{x} and a corresponding target (output) value t with joint probability distribution: $p(\mathbf{x}, t)$.
- Our goal is predict target t given a new value for \mathbf{x} :
 - for regression: t is a real-valued continuous target.
 - for classification: t a categorical variable representing class labels.

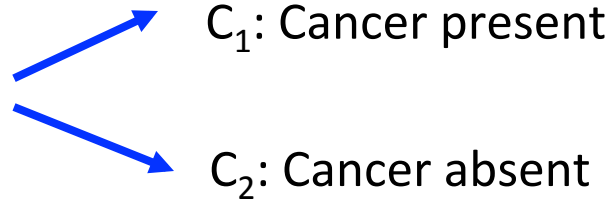
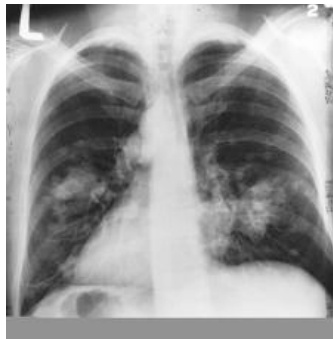
The joint probability distribution $p(\mathbf{x}, t)$ provides a complete summary of uncertainties associated with these random variables.

Determining $p(\mathbf{x}, t)$ from training data is known as the **inference problem**.

Example: Classification

Medical diagnosis: Based on the X-ray image, we would like determine whether the patient has cancer or not.

- The input vector \mathbf{x} is the set of pixel intensities, and the output variable t will represent the presence of cancer, class C_1 , or absence of cancer, class C_2 .



\mathbf{x} -- set of pixel intensities

- Choose t to be binary: $t=0$ correspond to class C_1 , and $t=1$ corresponds to C_2 .

Inference Problem: Determine the joint distribution $p(\mathbf{x}, C_k)$ or equivalently $p(\mathbf{x}, t)$. However, in the end, we must **make a decision** of whether to give treatment to the patient or not.

Example: Classification

Informally: Given a new X-ray image, our goal is to decide which of the two classes that image should be assigned to.

- We could compute conditional probabilities of the two classes, given the input image:

posterior probability of C_k given observed data.

probability of observed data given C_k

prior probability for class C_k

$$p(C_k|\mathbf{x}) = \frac{p(\mathbf{x}, C_k)}{\sum_{k=1}^K p(\mathbf{x}, C_k)} = \frac{p(\mathbf{x}|C_k)p(C_k)}{p(\mathbf{x})}$$

Bayes' Rule

- If our goal to minimize the probability of assigning \mathbf{x} to the wrong class, then we should choose the class having the highest posterior probability.

Expected Loss

- **Loss Function**: overall measure of loss incurred by taking any of the available decisions.
- Suppose that for \mathbf{x} , the true class is C_k , but we assign \mathbf{x} to class j
→ incur loss of L_{kj} (k,j element of a loss matrix).

Consider medical diagnosis example: example of a loss matrix:

		Decision	
		cancer	normal
Truth	cancer	0	1000
	normal	1	0

Expected Loss:

$$\mathbb{E}[L] = \sum_k \sum_j \int_{\mathcal{R}_j} L_{kj} p(\mathbf{x}, C_k) d\mathbf{x}$$

Goal is to choose decision regions \mathcal{R}_j as to minimize expected loss.

Regression

Let $\mathbf{x} \in \mathbb{R}^d$ denote a real-valued input vector, and $t \in \mathbb{R}$ denote a real-valued random target (output) variable with joint the distribution $p(\mathbf{x}, t)$.

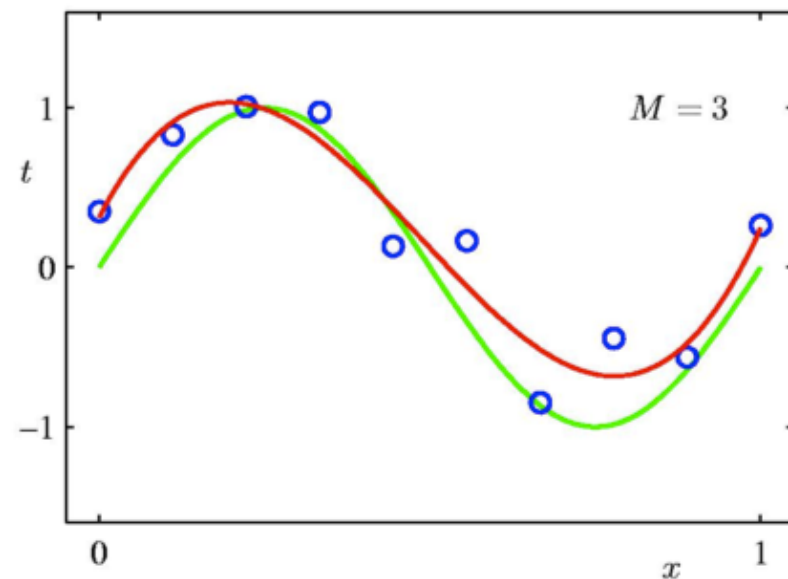
- The decision step consists of finding an estimate $y(\mathbf{x})$ of t for each input \mathbf{x} .
- To quantify what it means to do well or poorly on a task, we need to define a loss (error) function: $L(t, y(\mathbf{x}))$.

- The average, or expected, loss is given by:

$$\mathbb{E}[L] = \int \int L(t, y(\mathbf{x})) p(\mathbf{x}, t) d\mathbf{x} dt.$$

- If we use squared loss, we obtain:

$$\mathbb{E}[L] = \int \int (t - y(\mathbf{x}))^2 p(\mathbf{x}, t) d\mathbf{x} dt.$$



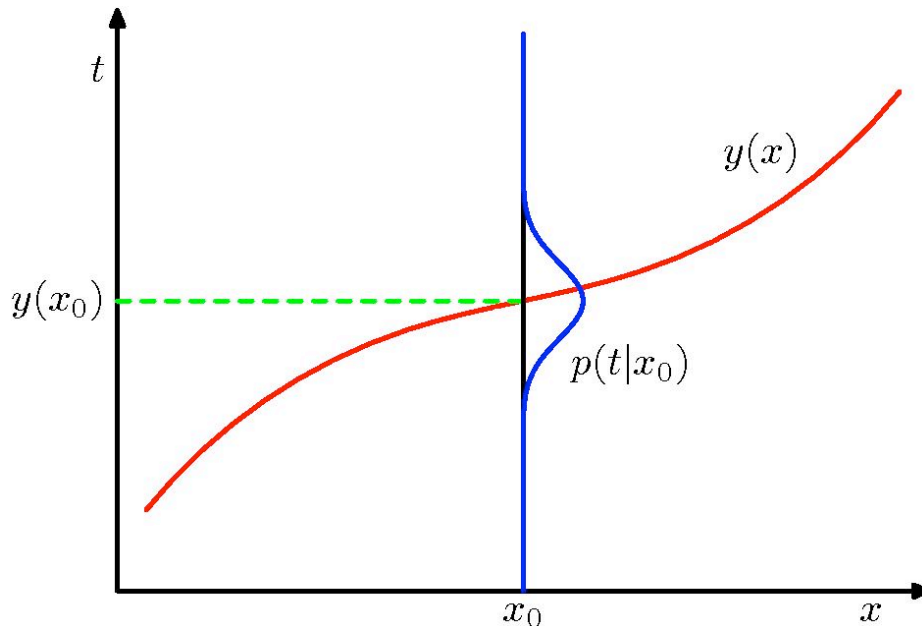
Squared Loss Function

- If we use squared loss, we obtain:

$$\mathbb{E}[L] = \int \int (t - y(\mathbf{x}))^2 p(\mathbf{x}, t) d\mathbf{x} dt.$$

- Our goal is to choose $y(x)$ so as to minimize the expected squared loss.
- The optimal solution (if we assume a completely flexible function) is the conditional average:

$$y(\mathbf{x}) = \int t p(t|\mathbf{x}) dt = \mathbb{E}[t|\mathbf{x}].$$



The regression function $y(\mathbf{x})$ that minimizes the expected squared loss is given by the mean of the conditional distribution $p(t|\mathbf{x})$.

Squared Loss Function

- If we use squared loss, we obtain:

$$\begin{aligned}(y(\mathbf{x}) - t)^2 &= (y(\mathbf{x}) - \mathbb{E}[t|\mathbf{x}] + \mathbb{E}[t|\mathbf{x}] - t)^2 \\ &= (y(\mathbf{x}) - \mathbb{E}[t|\mathbf{x}])^2 + 2(y(\mathbf{x}) - \mathbb{E}[t|\mathbf{x}])(\mathbb{E}[t|\mathbf{x}] - t) + (\mathbb{E}[t|\mathbf{x}] - t)^2.\end{aligned}$$

- Plugging into expected loss:

$$\mathbb{E}[L] = \underbrace{\int \{y(\mathbf{x}) - \mathbb{E}[t|\mathbf{x}]\}^2 p(\mathbf{x}) d\mathbf{x}}_{\text{expected loss is minimized}} + \underbrace{\int \text{var} [t|\mathbf{x}] p(\mathbf{x}) d\mathbf{x}}_{\text{intrinsic variability of the target values.}}$$

expected loss is minimized
when $y(\mathbf{x}) = \mathbb{E}[t|\mathbf{x}]$.

intrinsic variability of the
target values.

Because it is independent noise, it represents an irreducible minimum value of expected loss.

Other Loss Function

- Simple generalization of the squared loss, called the *Minkowski* loss:

$$\mathbb{E}[L] = \int \int (t - y(\mathbf{x}))^q p(\mathbf{x}, t) d\mathbf{x} dt.$$

- The minimum of $\mathbb{E}[L]$ is given by:
 - the conditional mean for $q=2$,
 - the conditional median when $q=1$, and
 - the conditional mode for $q \rightarrow 0$.

Discriminative vs. Generative

- **Generative Approach:**

Model the joint density: $p(\mathbf{x}, t) = p(\mathbf{x}|t)p(t)$,
or joint distribution: $p(\mathbf{x}, C_k) = p(\mathbf{x}|C_k)p(C_k)$.

Infer conditional
density:
$$p(t|\mathbf{x}) = \frac{p(\mathbf{x}|t)p(t)}{p(\mathbf{x})}.$$

- **Discriminative Approach:**

Model conditional density $p(t|\mathbf{x})$ directly.

Linear Basis Function Models

- Remember, the simplest linear model for regression:

$$y(\mathbf{x}, \mathbf{w}) = w_0 + w_1x_1 + w_2x_2 + \dots + w_dx_d = w_0 + \sum_{j=1}^d w_jx_j,$$

where $\mathbf{x} = (x_1, x_2, \dots, x_d)^T$ is a d-dimensional input vector (covariates).

Key property: linear function of the parameters w_0, w_1, \dots, w_d .

- However, it is also a linear function of the input variables.

Instead consider:

$$y(\mathbf{x}, \mathbf{w}) = w_0\phi_0(\mathbf{x}) + w_1\phi_1(\mathbf{x}) + \dots + w_{M-1}\phi_{M-1}(\mathbf{x}) = \sum_{j=0}^{M-1} w_j\phi_j(\mathbf{x}),$$

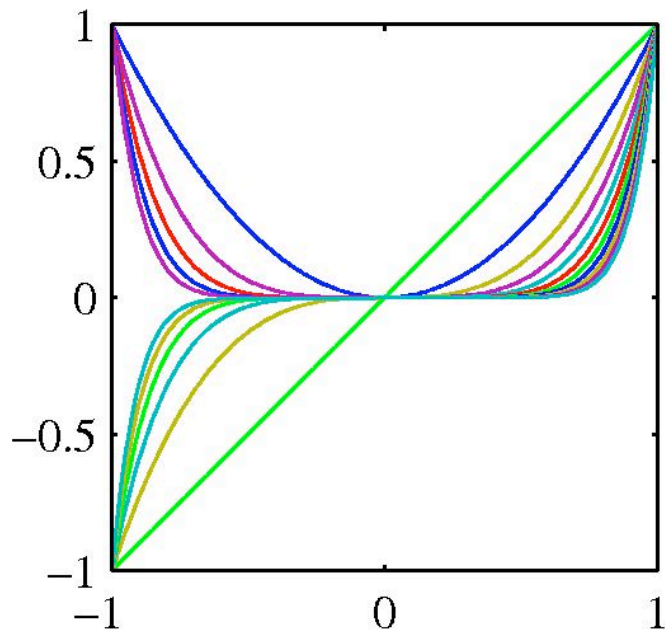
where $\phi_j(\mathbf{x})$ are known as basis functions.

- Typically $\phi_0(\mathbf{x}) = 1$ so that w_0 acts as a bias (or intercept).
- In the simplest case, we use linear bases functions: $\phi_j(\mathbf{x}) = x_j$.
- Using nonlinear basis allows the functions $y(\mathbf{x}, \mathbf{w})$ to be nonlinear functions of the input space.

Linear Basis Function Models

Polynomial basis functions:

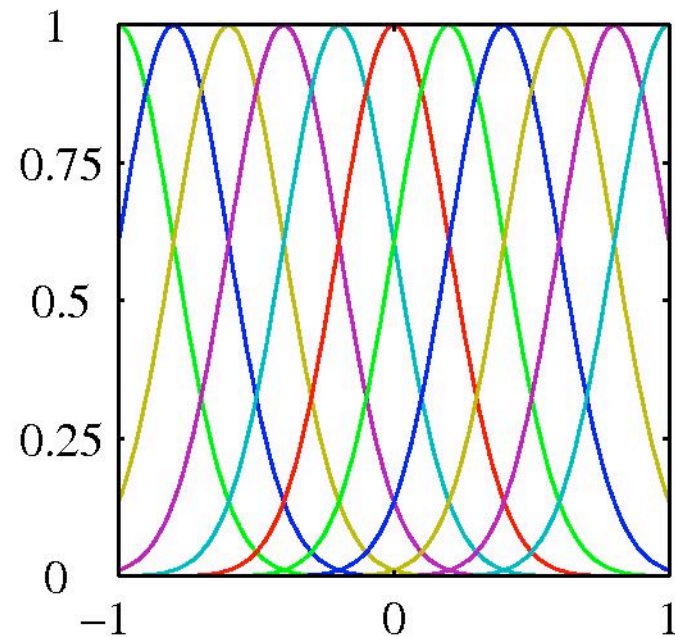
$$\phi_j(x) = x^j.$$



Basis functions are global: small changes in \mathbf{x} affect all basis functions.

Gaussian basis functions:

$$\phi_j(x) = \exp\left(-\frac{(x - \mu_j)^2}{2s^2}\right).$$

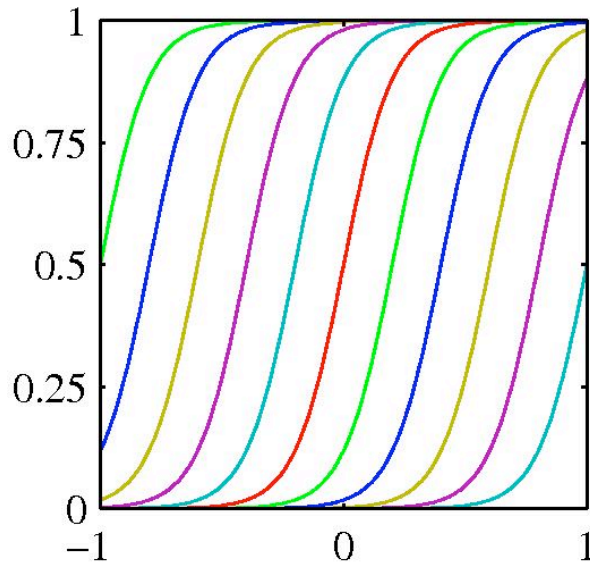


Basis functions are local: small changes in \mathbf{x} only affect nearby basis functions.
 μ_j and s control location and scale (width).

Linear Basis Function Models

Sigmoidal basis functions

$$\phi_j(x) = \sigma\left(\frac{x - \mu_j}{s}\right), \text{ where } \sigma(a) = \frac{1}{1 + \exp(-a)}.$$

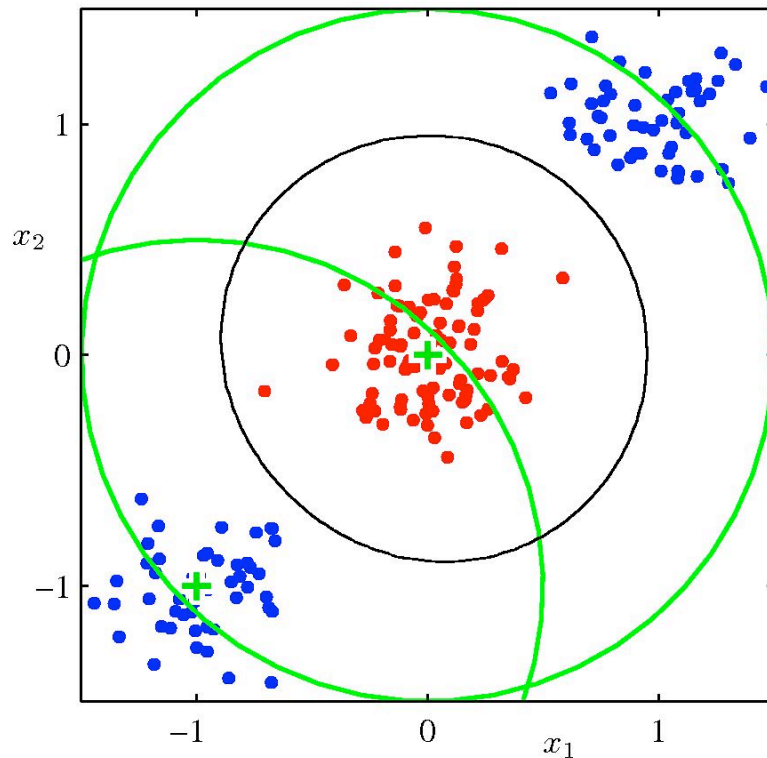


Basis functions are local: small changes in \mathbf{x} only affect nearby basis functions. μ_j and s control location and scale (slope).

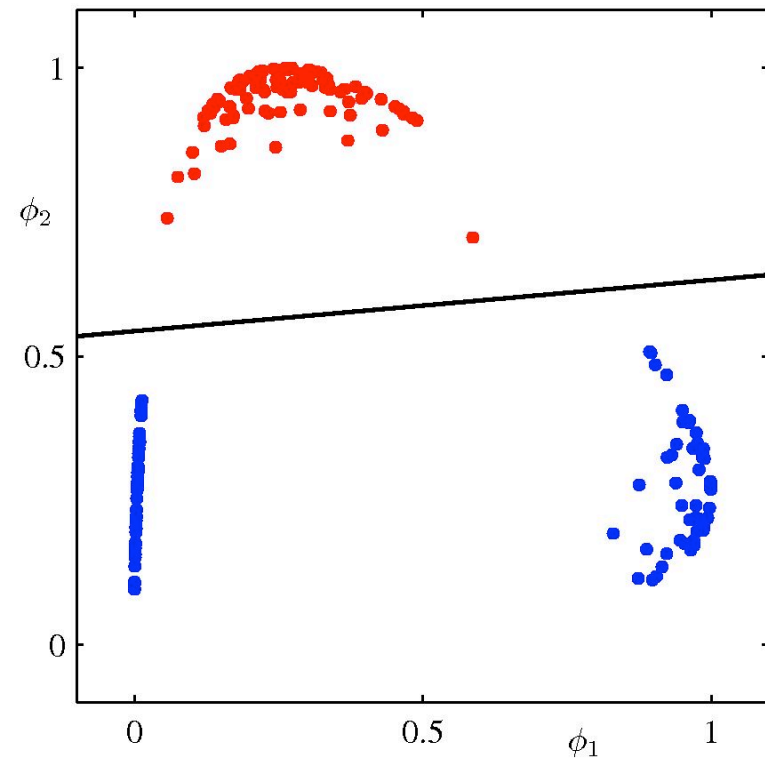
- Decision boundaries will be linear in the feature space ϕ , but would correspond to nonlinear boundaries in the original input space x .
- Classes that are linearly separable in the feature space $\phi(\mathbf{x})$ need not be linearly separable in the original input space.

Linear Basis Function Models

Original input space



Corresponding feature space using two Gaussian basis functions



- We define two Gaussian basis functions with centers shown by green the crosses, and with contours shown by the green circles.
- Linear decision boundary (right) is obtained using logistic regression, and corresponds to nonlinear decision boundary in the input space (left, black curve).

Maximum Likelihood

- As before, assume observations arise from a deterministic function with an additive Gaussian noise:

$$t = y(\mathbf{x}, \mathbf{w}) + \epsilon,$$

which we can write as:

$$p(t|\mathbf{x}, \mathbf{w}, \beta) = \mathcal{N}(t|y(\mathbf{x}, \mathbf{w}), \beta^{-1}).$$

- Given observed inputs $\mathbf{X} = \{\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_N\}$, and corresponding target values $\mathbf{t} = [t_1, t_2, \dots, t_N]^T$, under i.i.d assumption, we can write down the likelihood function:

$$p(\mathbf{t}|\mathbf{X}, \mathbf{w}, \beta) = \prod_{i=1}^N \mathcal{N}(t_n | \mathbf{w}^T \phi(\mathbf{x}_n), \beta),$$

where $\phi(\mathbf{x}) = (\phi_0(\mathbf{x}), \phi_1(\mathbf{x}), \dots, \phi_{M-1}(\mathbf{x}))^T$.

Maximum Likelihood

Taking the logarithm, we obtain:

$$\begin{aligned}\ln p(\mathbf{t}|\mathbf{X}, \mathbf{w}, \beta) &= \sum_{i=1}^N \ln \mathcal{N}(t_n | \mathbf{w}^T \boldsymbol{\phi}(\mathbf{x}_n), \beta) \\ &= -\frac{\beta}{2} \underbrace{\sum_{n=1}^N (t_n - \mathbf{w}^T \boldsymbol{\phi}(\mathbf{x}_n))^2}_{\text{sum-of-squares error function}} + \frac{N}{2} \ln \beta - \frac{N}{2} \ln(2\pi).\end{aligned}$$

Differentiating and setting to zero yields:

$$\nabla_{\mathbf{w}} \ln p(\mathbf{t}|\mathbf{w}, \beta) = \beta \sum_{n=1}^N \{t_n - \mathbf{w}^T \boldsymbol{\phi}(\mathbf{x}_n)\} \boldsymbol{\phi}(\mathbf{x}_n)^T = \mathbf{0}.$$

Maximum Likelihood

Differentiating and setting to zero yields:

$$\nabla_{\mathbf{w}} \ln p(\mathbf{t}|\mathbf{w}, \beta) = \beta \sum_{n=1}^N \{t_n - \mathbf{w}^T \boldsymbol{\phi}(\mathbf{x}_n)\} \boldsymbol{\phi}(\mathbf{x}_n)^T = \mathbf{0}.$$

Solving for \mathbf{w} , we get:

$$\mathbf{w}_{\text{ML}} = \left(\boldsymbol{\Phi}^T \boldsymbol{\Phi} \right)^{-1} \boldsymbol{\Phi}^T \mathbf{t}$$

The Moore-Penrose pseudo-inverse, $\boldsymbol{\Phi}^\dagger$.

where $\boldsymbol{\Phi}$ is known as the **design matrix**:

$$\boldsymbol{\Phi} = \begin{pmatrix} \phi_0(\mathbf{x}_1) & \phi_1(\mathbf{x}_1) & \cdots & \phi_{M-1}(\mathbf{x}_1) \\ \phi_0(\mathbf{x}_2) & \phi_1(\mathbf{x}_2) & \cdots & \phi_{M-1}(\mathbf{x}_2) \\ \vdots & \vdots & \ddots & \vdots \\ \phi_0(\mathbf{x}_N) & \phi_1(\mathbf{x}_N) & \cdots & \phi_{M-1}(\mathbf{x}_N) \end{pmatrix}.$$

Sequential Learning

- The training data examples are presented one at a time, and the model parameters are updated after each such presentation (online learning):

$$\mathbf{w}^{(t+1)} = \mathbf{w}^{(t)} - \eta \nabla E_n$$

weights after seeing training case $t+1$

learning rate

vector of derivatives of the squared error w.r.t. the weights on the training case presented at time t .

- For the case of sum-of-squares error function, we obtain:

$$\mathbf{w}^{(t+1)} = \mathbf{w}^{(t)} - \eta \left(t_n - \mathbf{w}^{(t)T} \phi(\mathbf{x}_n) \right) \phi(\mathbf{x}_n).$$

- **Stochastic gradient descent:** The training examples are picked at random (dominant technique when learning with very large datasets).
- Care must be taken when choosing learning rate to ensure convergence.

Regularized Least Squares

- Let us consider the following error function:

$$E_D(\mathbf{w}) + \lambda E_W(\mathbf{w})$$

Data term + Regularization term

λ is called the regularization coefficient.

- Using sum-of-squares error function with a quadratic penalization term, we obtain:

$$\frac{1}{2} \sum_{n=1}^N \{t_n - \mathbf{w}^T \phi(\mathbf{x}_n)\}^2 + \frac{\lambda}{2} \mathbf{w}^T \mathbf{w}$$

which is minimized by setting:

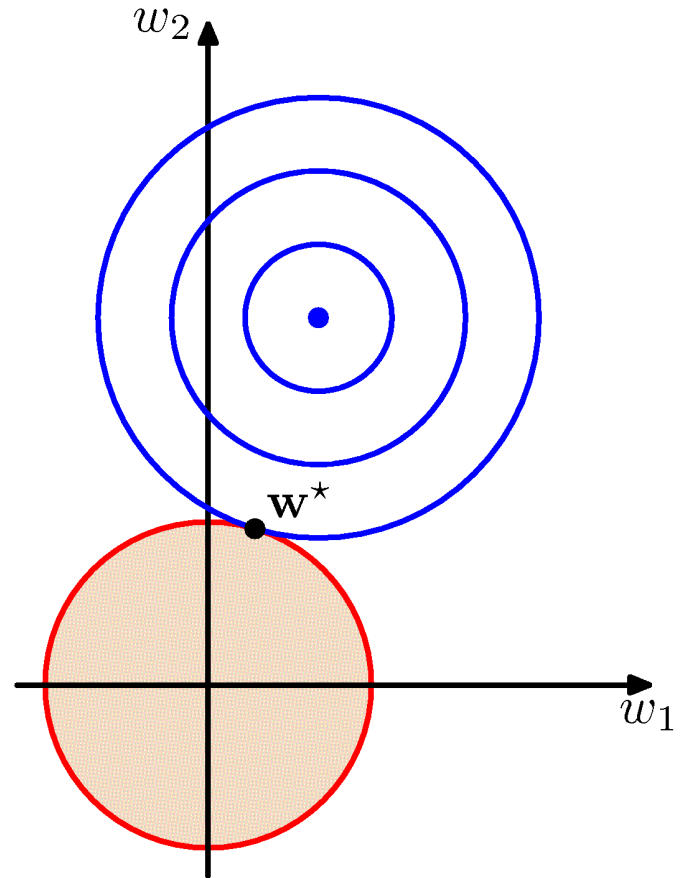
$$\mathbf{w} = \left(\lambda \mathbf{I} + \Phi^T \Phi \right)^{-1} \Phi^T \mathbf{t}.$$

Ridge regression

The solution adds a positive constant to the diagonal of $\Phi^T \Phi$. This makes the problem nonsingular, even if $\Phi^T \Phi$ is not of full rank (e.g. when the number of training examples is less than the number of basis functions).

Effect of Regularization

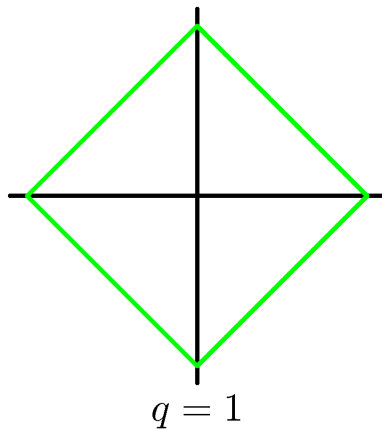
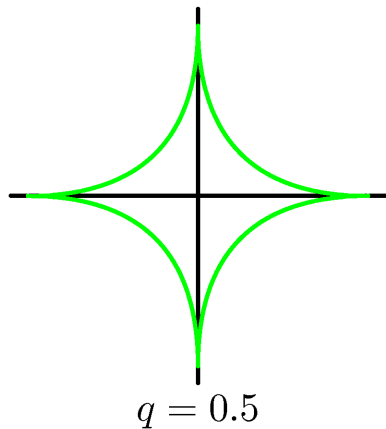
- The overall error function is the sum of two parabolic bowls.
- The combined minimum lies on the line between the minimum of the squared error and the origin.
- The regularizer shrinks model parameters to zero.



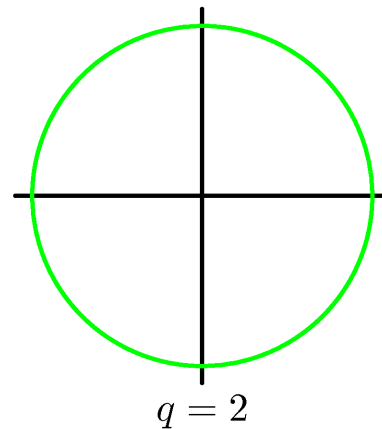
Other Regularizers

Using a more general regularizer, we get:

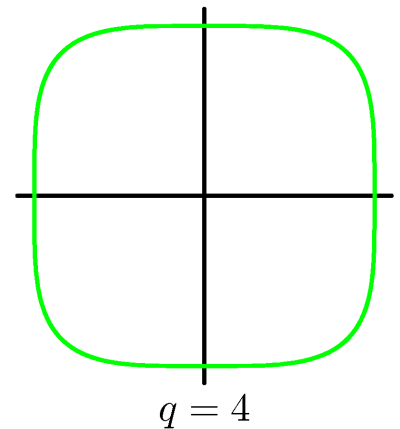
$$\frac{1}{2} \sum_{n=1}^N \{t_n - \mathbf{w}^T \phi(\mathbf{x}_n)\}^2 + \frac{\lambda}{2} \sum_{j=1}^M |w_j|^q$$



Lasso



Quadratic



The Lasso

- Penalize the absolute value of the weights:

$$\mathbf{w}^{lasso} = \underset{\mathbf{w}}{\operatorname{argmin}} \left[\frac{1}{2} \sum_{n=1}^N (t_n - \mathbf{w}^T \phi(\mathbf{x}_n))^2 + \frac{\lambda}{2} \sum_{j=1}^{M-1} |w_j| \right].$$

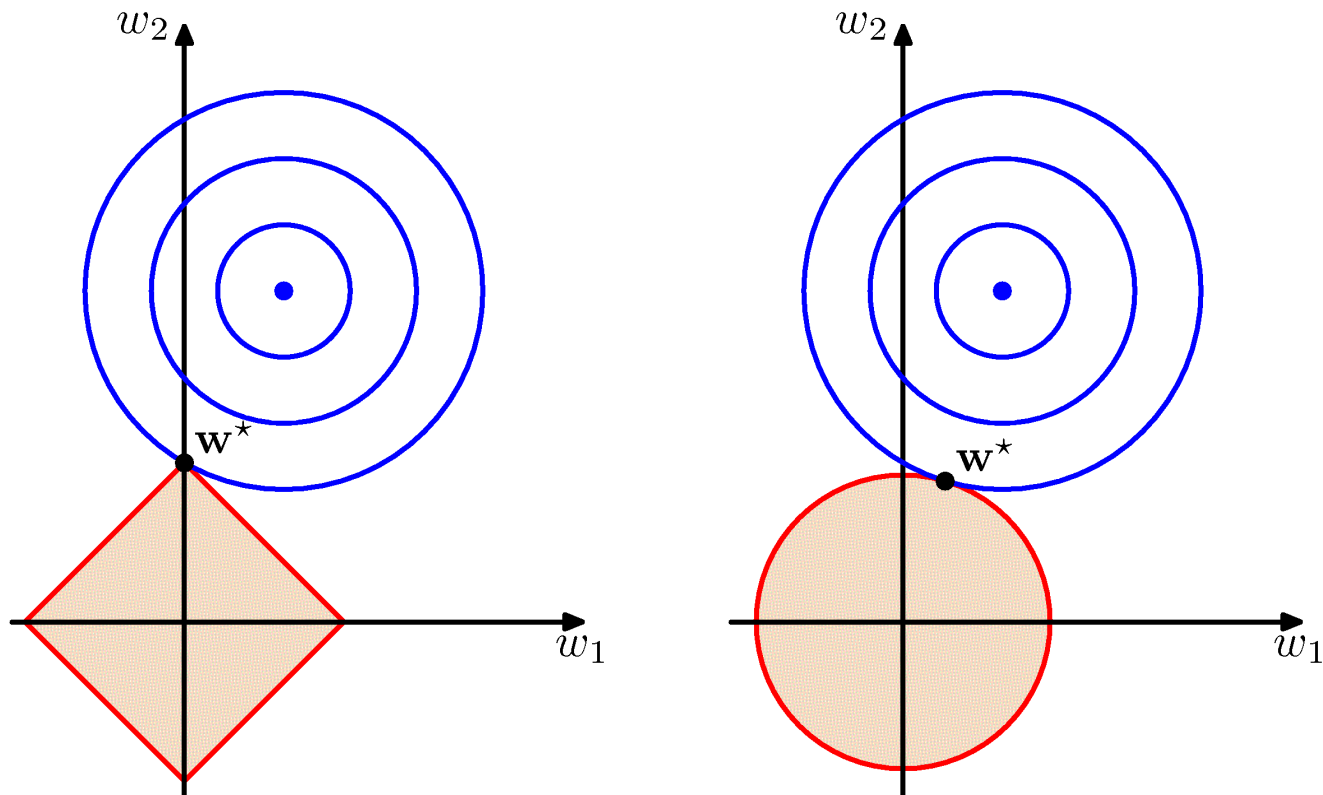
- For sufficiently large λ , some of the coefficients will be driven to exactly zero, leading to a sparse model.
- The above formulation is equivalent to:

$$\mathbf{w}^{lasso} = \underset{\mathbf{w}}{\operatorname{argmin}} \underbrace{\frac{1}{2} \sum_{n=1}^N (t_n - \mathbf{w}^T \phi(\mathbf{x}_n))^2}_{\text{unregularized sum-of-squares error}}, \text{ subject to } \sum_{j=1}^{M-1} |w_j| \leq \tau.$$

- The two approaches are related using Lagrange multipliers.
- The Lasso solution is a quadratic programming problem: can be solved efficiently.

Lasso vs. Quadratic Penalty

Lasso tends to generate sparser solutions compared to a quadratic regularizer (sometimes called L_1 and L_2 regularizers).



Bias-Variance Decomposition

- Introducing a regularization term can help us control overfitting. But how can we determine a suitable value of the regularization coefficient?
- Let us examine the expected squared loss function. Remember:

$$\mathbb{E}[L] = \int \{y(\mathbf{x}) - h(\mathbf{x})\}^2 p(\mathbf{x}) d\mathbf{x} + \underbrace{\int \int \{h(\mathbf{x}) - t\}^2 p(\mathbf{x}, t) d\mathbf{x} dt}_{\text{intrinsic variability of the target values: The minimum achievable value of expected loss}}$$

for which the optimal prediction is given by the conditional expectation:

$$h(\mathbf{x}) = \mathbb{E}[t|\mathbf{x}] = \int tp(t|\mathbf{x}) dt.$$

intrinsic variability of the target values: The minimum achievable value of expected loss

- If we model $h(\mathbf{x})$ using a parametric function $y(\mathbf{x}, \mathbf{w})$, then from a Bayesian perspective, the uncertainty in our model is expressed through the posterior distribution over parameters \mathbf{w} .
- We first look at the frequentist perspective.

Bias-Variance Decomposition

- From a frequentist perspective: we make a point estimate of \mathbf{w}^* based on the dataset D .
- We next interpret the uncertainty of this estimate through the following thought experiment:
 - Suppose we had a large number of datasets, each of size N , where each dataset is drawn independently from $p(\mathbf{x}, t)$.
 - For each dataset D , we can obtain a prediction function $y(\mathbf{x}; \mathcal{D})$.
 - Different datasets will give different prediction functions.
 - The performance of a particular learning algorithm is then assessed by taking the average over the ensemble of these datasets.

- Let us consider the expression:

$$\{y(\mathbf{x}; \mathcal{D}) - h(\mathbf{x})\}^2.$$

- Note that this quantity depends on a particular dataset D .

Bias-Variance Decomposition

- Consider:

$$\{y(\mathbf{x}; \mathcal{D}) - h(\mathbf{x})\}^2.$$

- Adding and subtracting the term $\mathbb{E}_{\mathcal{D}}[y(\mathbf{x}; \mathcal{D})]$, we obtain

$$\begin{aligned} & \{y(\mathbf{x}; \mathcal{D}) - h(\mathbf{x})\}^2 \\ &= \{y(\mathbf{x}; \mathcal{D}) - \mathbb{E}_{\mathcal{D}}[y(\mathbf{x}; \mathcal{D})] + \mathbb{E}_{\mathcal{D}}[y(\mathbf{x}; \mathcal{D})] - h(\mathbf{x})\}^2 \\ &= \{y(\mathbf{x}; \mathcal{D}) - \mathbb{E}_{\mathcal{D}}[y(\mathbf{x}; \mathcal{D})]\}^2 + \{\mathbb{E}_{\mathcal{D}}[y(\mathbf{x}; \mathcal{D})] - h(\mathbf{x})\}^2 \\ & \quad + 2\{y(\mathbf{x}; \mathcal{D}) - \mathbb{E}_{\mathcal{D}}[y(\mathbf{x}; \mathcal{D})]\}\{\mathbb{E}_{\mathcal{D}}[y(\mathbf{x}; \mathcal{D})] - h(\mathbf{x})\}. \end{aligned}$$

- Taking the expectation over \mathcal{D} , the last term vanishes, so we get:

$$\begin{aligned} & \mathbb{E}_{\mathcal{D}} [\{y(\mathbf{x}; \mathcal{D}) - h(\mathbf{x})\}^2] \\ &= \underbrace{\{\mathbb{E}_{\mathcal{D}}[y(\mathbf{x}; \mathcal{D})] - h(\mathbf{x})\}^2}_{(\text{bias})^2} + \underbrace{\mathbb{E}_{\mathcal{D}} [\{y(\mathbf{x}; \mathcal{D}) - \mathbb{E}_{\mathcal{D}}[y(\mathbf{x}; \mathcal{D})]\}^2]}_{\text{variance}}. \end{aligned}$$

Bias-Variance Trade-off

$$\text{expected loss} = (\text{bias})^2 + \text{variance} + \text{noise}$$

Average predictions over all datasets differ from the optimal regression function.

Solutions for individual datasets vary around their averages -- how sensitive is the function to the particular choice of the dataset.

Intrinsic variability of the target values.

$$(\text{bias})^2 = \int \{\mathbb{E}_{\mathcal{D}}[y(\mathbf{x}; \mathcal{D})] - h(\mathbf{x})\}^2 p(\mathbf{x}) d\mathbf{x}$$

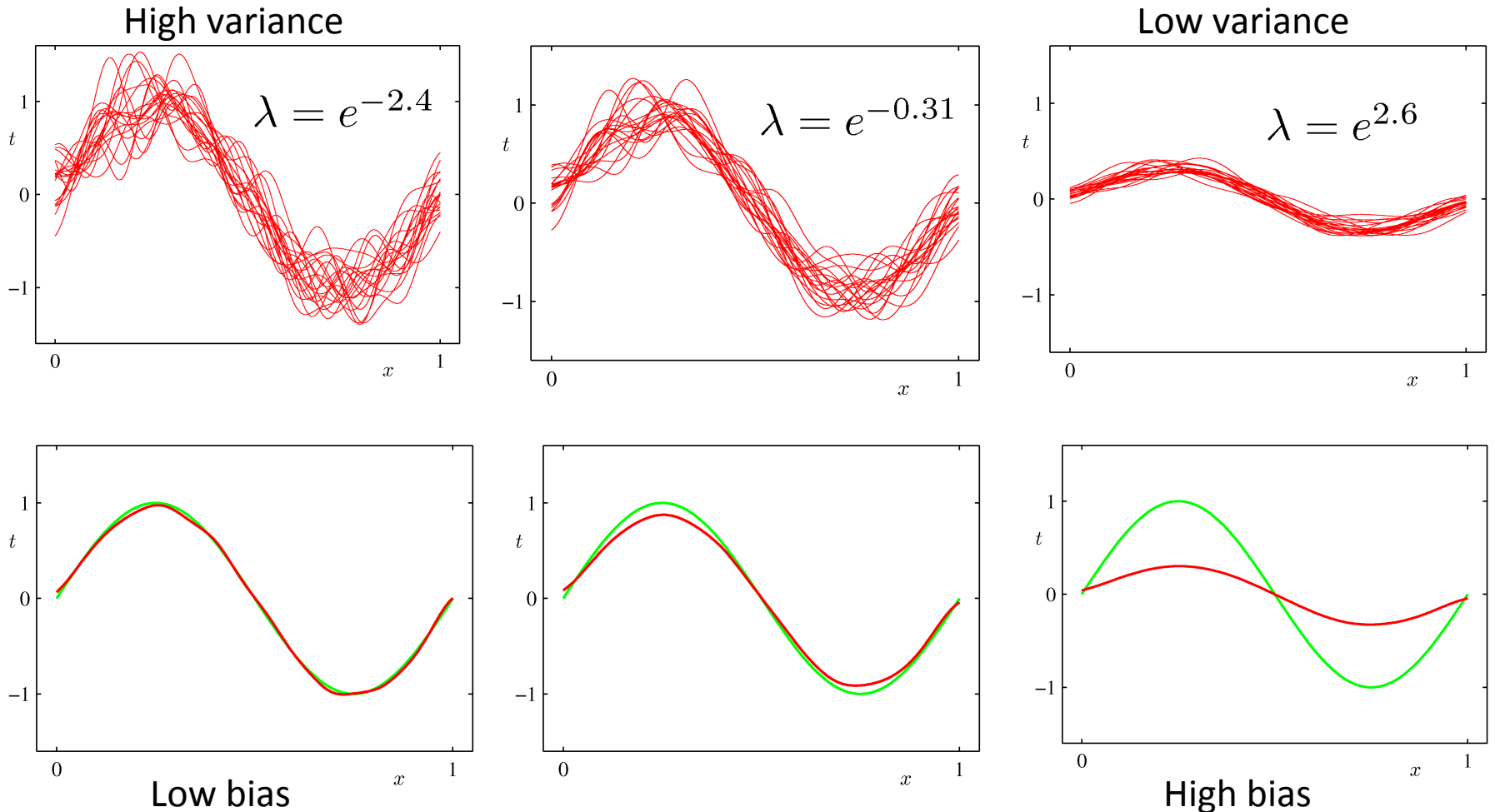
$$\text{variance} = \int \mathbb{E}_{\mathcal{D}} [\{y(\mathbf{x}; \mathcal{D}) - \mathbb{E}_{\mathcal{D}}[y(\mathbf{x}; \mathcal{D})]\}^2] p(\mathbf{x}) d\mathbf{x}$$

$$\text{noise} = \iint \{h(\mathbf{x}) - t\}^2 p(\mathbf{x}, t) d\mathbf{x} dt$$

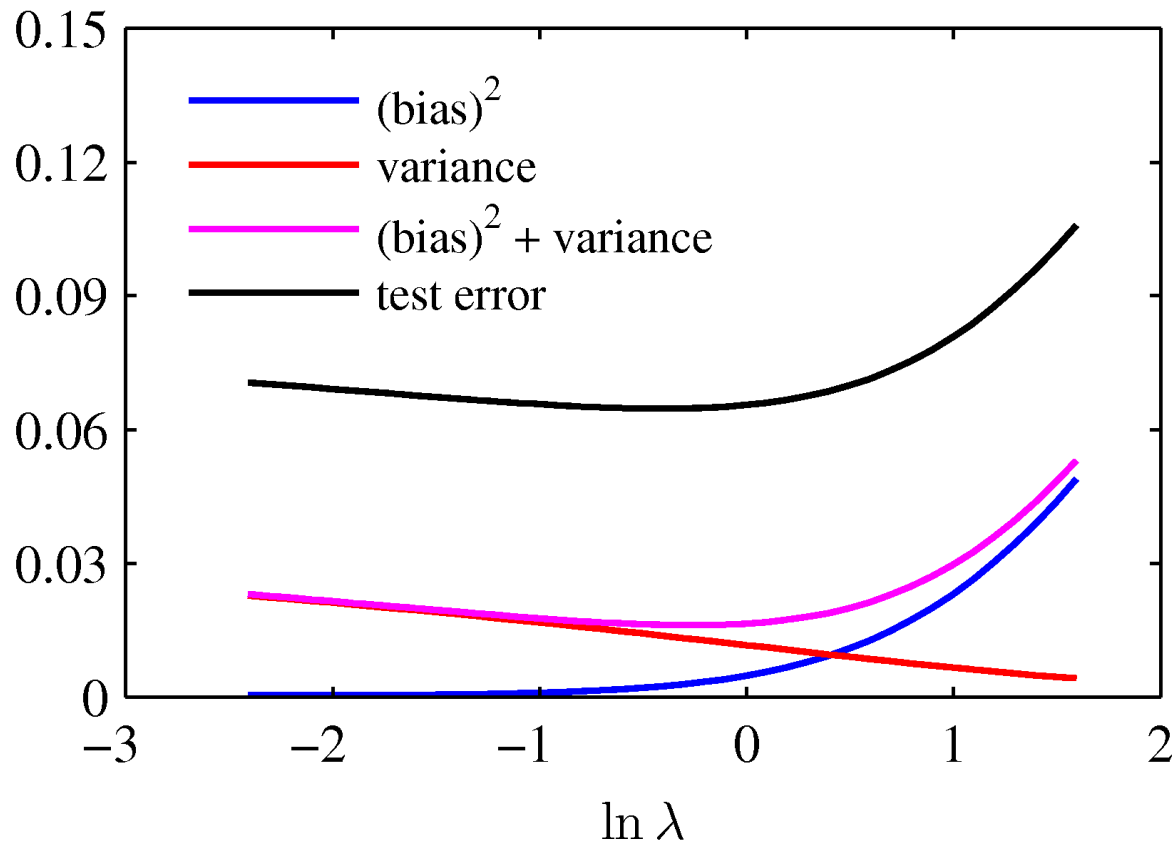
- Trade-off between bias and variance: With very flexible models (high complexity) we have low bias and high variance; With relatively rigid models (low complexity) we have high bias and low variance.
- The model with the optimal predictive capabilities has to balance between bias and variance.

Bias-Variance Trade-off

- Consider the sinusoidal dataset. We generate 100 datasets, each containing $N=25$ points, drawn independently from $h(x) = \sin 2\pi x$.



Bias-Variance Trade-off



From these plots note that over-regularized model (large λ) has high bias, and under-regularized model (low λ) has high variance.

Beating the Bias-Variance Trade-off

- We can reduce the variance by averaging over many models trained on different datasets:
 - In practice, we only have a single observed dataset. If we had many independent training sets, we would be better off combining them into one large training dataset. With more data, we have less variance.
- Given a standard training set D of size N , we could generate new training sets, N , by sampling examples from D uniformly and with replacement.
 - This is called bagging and it works quite well in practice.
- Given enough computation, we could also resort to the Bayesian framework:
 - Combine the predictions of many models using the posterior probability of each parameter vector as the combination weight.