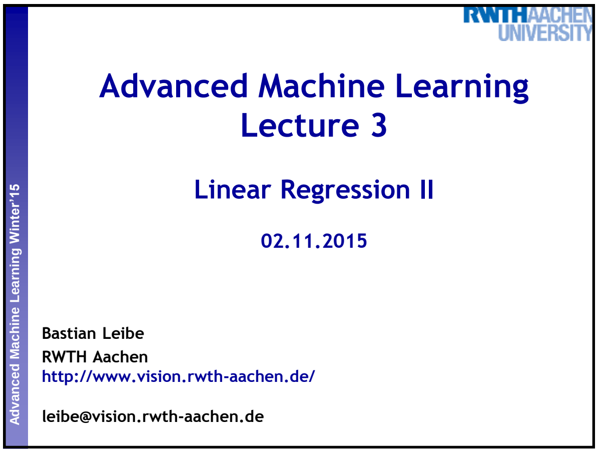


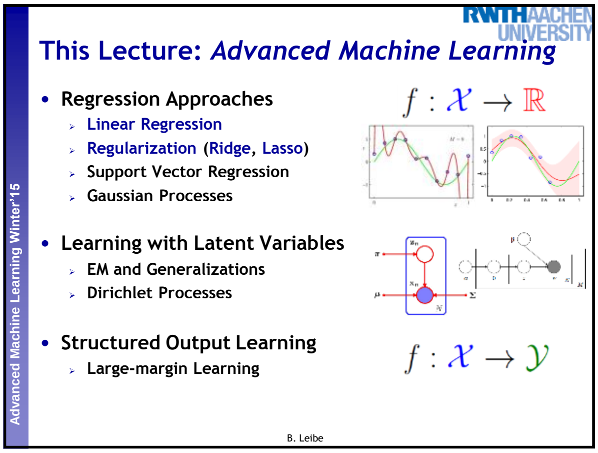
Advanced Machine Learning
Lecture 3

Linear Regression II

02.11.2015

Bastian Leibe
RWTH Aachen
http://www.vision.rwth-aachen.de/

leibe@vision.rwth-aachen.de

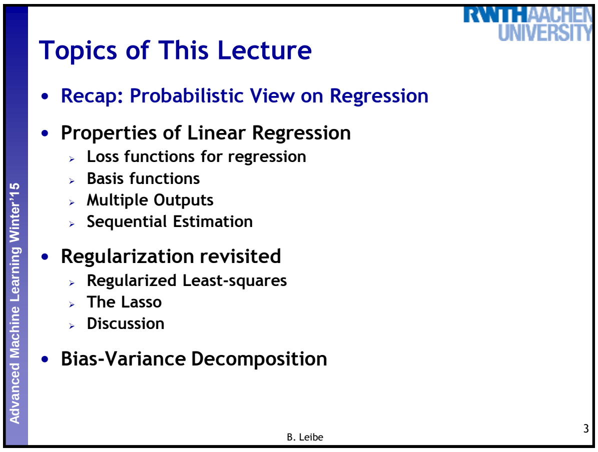


This Lecture: *Advanced Machine Learning*

- Regression Approaches
  - Linear Regression
  - Regularization (Ridge, Lasso)
  - Support Vector Regression
  - Gaussian Processes
- Learning with Latent Variables
  - EM and Generalizations
  - Dirichlet Processes
- Structured Output Learning
  - Large-margin Learning

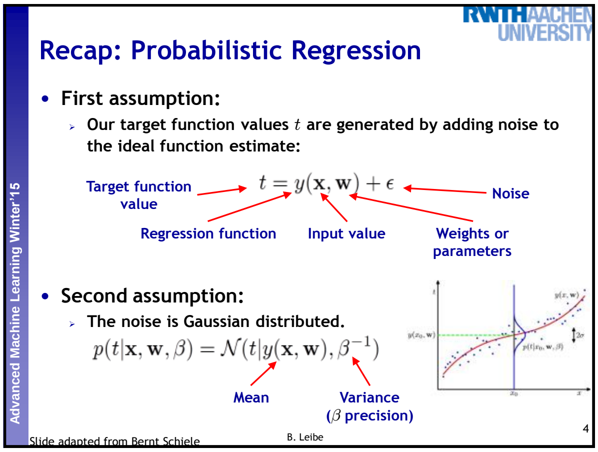
$f : \mathcal{X} \to \mathbb{R}$

$f : \mathcal{X} \to \mathcal{Y}$



Topics of This Lecture

- Recap: Probabilistic View on Regression
- Properties of Linear Regression
  - Loss functions for regression
  - Basis functions
  - Multiple Outputs
  - Sequential Estimation
- Regularization revisited
  - Regularized Least-squares
  - The Lasso
  - Discussion
- Bias-Variance Decomposition



Recap: Probabilistic Regression

- First assumption:
  - Our target function values t are generated by adding noise to the ideal function estimate:

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

Target function value

Noise

Regression function

Input value

Weights or parameters

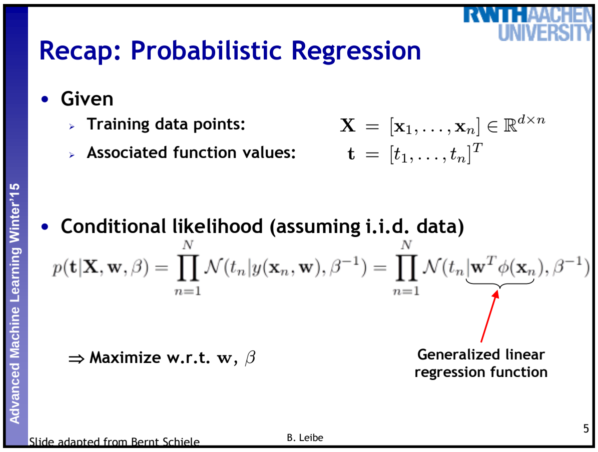
- Second assumption:
  - The noise is Gaussian distributed.

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

Mean

Variance (β precision)

Slide adapted from Bernt Schiele



Recap: Probabilistic Regression

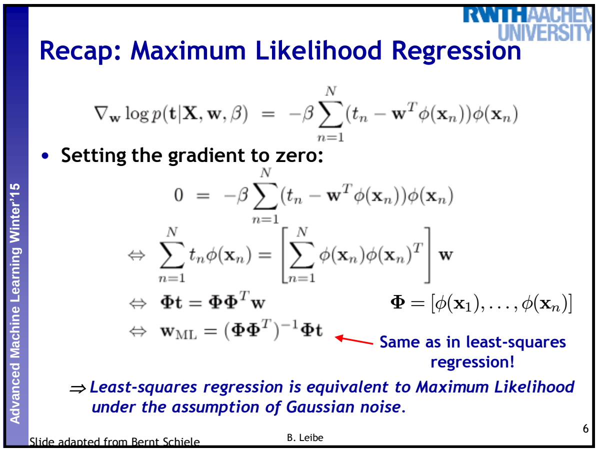
- Given
  - Training data points: $\mathbf{X} = [\mathbf{x}_1, \ldots, \mathbf{x}_n] \in \mathbb{R}^{d \times n}$
  - Associated function values: $\mathbf{t} = [t_1, \ldots, t_n]^T$
- Conditional likelihood (assuming i.i.d. data)

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

$\Rightarrow$ Maximize w.r.t. $\mathbf{w}$, β

Generalized linear regression function

Slide adapted from Bernt Schiele



Recap: Maximum Likelihood Regression

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

- Setting the gradient to zero:

$$0 = -\beta \sum_{n=1}^{N} (t_n - \mathbf{w}^T\phi(\mathbf{x}_n))\phi(\mathbf{x}_n)$$

$$\Leftrightarrow \sum_{n=1}^{N} t_n\phi(\mathbf{x}_n) = \left[\sum_{n=1}^{N} \phi(\mathbf{x}_n)\phi(\mathbf{x}_n)^T\right]\mathbf{w}$$

$$\Leftrightarrow \mathbf{\Phi t} = \mathbf{\Phi\Phi}^T\mathbf{w} \qquad \mathbf{\Phi} = [\phi(\mathbf{x}_1), \ldots, \phi(\mathbf{x}_n)]$$

$$\Leftrightarrow \mathbf{w}_{\mathrm{ML}} = (\mathbf{\Phi\Phi}^T)^{-1}\mathbf{\Phi t}$$

Same as in least-squares regression!

$\Rightarrow$ *Least-squares regression is equivalent to Maximum Likelihood under the assumption of Gaussian noise.*

Slide adapted from Bernt Schiele

Recap: Role of the Precision Parameter

- Also use ML to determine the precision parameter β:

$$\log p(\mathbf{t}|\mathbf{X},\mathbf{w},\beta) = -\frac{\beta}{2}\sum_{n=1}^{N}\{t_n - \mathbf{w}^T\phi(\mathbf{x}_n)\}^2 + \frac{N}{2}\log\beta - \frac{N}{2}\log(2\pi$$

- Gradient w.r.t. β:

$$\nabla_\beta \log p(\mathbf{t}|\mathbf{X},\mathbf{w},\beta) = -\frac{1}{2}\sum_{n=1}^{N}\{t_n - \mathbf{w}^T\phi(\mathbf{x}_n)\}^2 + \frac{N}{2}\frac{1}{\beta}$$

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

⇒ *The inverse of the noise precision is given by the residual variance of the target values around the regression function.*

Recap: Predictive Distribution

- Having determined the parameters $\mathbf{w}$ and β, we can now make predictions for new values of $\mathbf{x}$.

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

- This means
  - Rather than giving a point estimate, we can now also give an estimate of the estimation uncertainty.

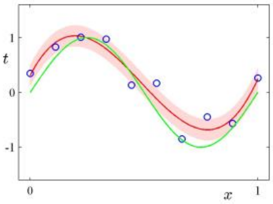


Image source: C.M. Bishop, 2006

Recap: Maximum-A-Posteriori Estimation

- Introduce a prior distribution over the coefficients $\mathbf{w}$.
  - For simplicity, assume a zero-mean Gaussian distribution

$$p(\mathbf{w}|\alpha) = \mathcal{N}(\mathbf{w}|\mathbf{0},\alpha^{-1}\mathbf{I}) = \left(\frac{\alpha}{2\pi}\right)^{(M+1)/2}\exp\left\{-\frac{\alpha}{2}\mathbf{w}^T\mathbf{w}\right\}$$

  - New hyperparameter α controls the distribution of model parameters.

- Express the posterior distribution over $\mathbf{w}$.
  - Using Bayes' theorem:

$$p(\mathbf{w}|\mathbf{X},\mathbf{t},\beta,\alpha) \propto p(\mathbf{t}|\mathbf{X},\mathbf{w},\beta)p(\mathbf{w}|\alpha)$$

  - We can now determine $\mathbf{w}$ by maximizing the posterior.
  - This technique is called maximum-a-posteriori (MAP).

Recap: MAP Solution

- Minimize the negative logarithm

$$-\log p(\mathbf{w}|\mathbf{X},\mathbf{t},\beta,\alpha) \propto -\log p(\mathbf{t}|\mathbf{X},\mathbf{w},\beta) - \log p(\mathbf{w}|\alpha)$$

$$-\log p(\mathbf{t}|\mathbf{X},\mathbf{w},\beta) = \frac{\beta}{2}\sum_{n=1}^{N}\{y(\mathbf{x}_n,\mathbf{w}) - t_n\}^2 + \mathrm{const}$$

$$-\log p(\mathbf{w}|\alpha) = \frac{\alpha}{2}\mathbf{w}^T\mathbf{w} + \mathrm{const}$$

- The MAP solution is therefore

$$\arg\min_{\mathbf{w}} \frac{\beta}{2}\sum_{n=1}^{N}\{y(\mathbf{x}_n,\mathbf{w}) - t_n\}^2 + \frac{\alpha}{2}\mathbf{w}^T\mathbf{w}$$

⇒ *Maximizing the posterior distribution is equivalent to minimizing the regularized sum-of-squares error* (with $\lambda = \frac{\alpha}{\beta}$).

MAP Solution (2)

$$\nabla_{\mathbf{w}} \log p(\mathbf{w}|\mathbf{X},\mathbf{t},\beta,\alpha) = -\beta\sum_{n=1}^{N}(t_n - \mathbf{w}^T\phi(\mathbf{x}_n))\phi(\mathbf{x}_n) + \alpha\mathbf{w}$$

- Setting the gradient to zero:

$$0 = -\beta\sum_{n=1}^{N}(t_n - \mathbf{w}^T\phi(\mathbf{x}_n))\phi(\mathbf{x}_n) + \alpha\mathbf{w}$$

$$\Leftrightarrow \sum_{n=1}^{N} t_n\phi(\mathbf{x}_n) = \left[\sum_{n=1}^{N}\phi(\mathbf{x}_n)\phi(\mathbf{x}_n)^T\right]\mathbf{w} + \frac{\alpha}{\beta}\mathbf{w}$$

$$\Leftrightarrow \boldsymbol{\Phi}\mathbf{t} = \left(\boldsymbol{\Phi}\boldsymbol{\Phi}^T + \frac{\alpha}{\beta}\mathbf{I}\right)\mathbf{w} \qquad \boldsymbol{\Phi} = [\phi(\mathbf{x}_1),\ldots,\phi(\mathbf{x}_n)]$$

$$\Leftrightarrow \mathbf{w}_{\mathrm{MAP}} = \left(\boldsymbol{\Phi}\boldsymbol{\Phi}^T + \frac{\alpha}{\beta}\mathbf{I}\right)^{-1}\boldsymbol{\Phi}\mathbf{t}$$

Effect of regularization: Keeps the inverse well-conditioned

Recap: Bayesian Curve Fitting

- Given
  - Training data points: $\mathbf{X} = [\mathbf{x}_1,\ldots,\mathbf{x}_n] \in \mathbb{R}^{d\times n}$
  - Associated function values: $\mathbf{t} = [t_1,\ldots,t_n]^T$
  - Our goal is to predict the value of t for a new point $\mathbf{x}$.

- Evaluate the predictive distribution

$$p(t|x,\mathbf{X},\mathbf{t}) = \int \underbrace{p(t|x,\mathbf{w})}\underbrace{p(\mathbf{w}|\mathbf{X},\mathbf{t})}d\mathbf{w}$$

What we just computed for MAP

  - Noise distribition - again assume a Gaussian here

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

  - Assume that parameters α and β are fixed and known for now.

Bayesian Curve Fitting

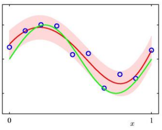
- Under those assumptions, the posterior distribution is a Gaussian and can be evaluated analytically:

$$p(t|x, \mathbf{X}, \mathbf{t}) = \mathcal{N}(t|m(x), s^2(x))$$

  - where the mean and variance are given by

$$m(x) = \beta\phi(x)^T \mathbf{S} \sum_{n=1}^{N} \phi(\mathbf{x}_n)t_n$$

$$s(x)^2 = \beta^{-1} + \phi(x)^T \mathbf{S}\phi(x)$$



  - and S is the regularized covariance matrix

$$\mathbf{S}^{-1} = \alpha\mathbf{I} + \beta \sum_{n=1}^{N} \phi(\mathbf{x}_n)\phi(\mathbf{x}_n)^T$$

Image source: C.M. Bishop, 2006

Analyzing the result

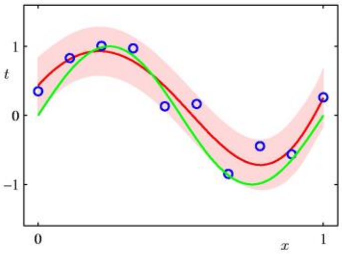
- Analyzing the variance of the predictive distribution

$$s(x)^2 = \underbrace{\beta^{-1}} + \underbrace{\phi(x)^T \mathbf{S}\phi(x)}$$

Uncertainty in the predicted value due to noise on the target variables (expressed already in ML)

Uncertainty in the parameters $\mathbf{w}$ (consequence of Bayesian treatment)

Bayesian Predictive Distribution



- Important difference to previous example
  - Uncertainty may vary with test point x!

Image source: C.M. Bishop, 2006

Discussion

- We now have a better understanding of regression
  - Least-squares regression: Assumption of Gaussian noise

  ⇒ We can now also plug in different noise models and explore how they affect the error function.
  - L2 regularization as a Gaussian prior on parameters $\mathbf{w}$.

  ⇒ We can now also use different regularizers and explore what they mean.

  ⇒ This lecture…
  - General formulation with basis functions $\phi(\mathbf{x})$.

  ⇒ We can now also use different basis functions.

Discussion

- General regression formulation
  - In principle, we can perform regression in arbitrary spaces and with many different types of basis functions
  - However, there is a caveat… Can you see what it is?
- Example: Polynomial curve fitting, $M = 3$

$$y(\mathbf{x}, \mathbf{w}) = w_0 + \sum_{i=1}^{D} w_i x_i + \sum_{i=1}^{D}\sum_{j=1}^{D} w_{ij}x_i x_j + \sum_{i=1}^{D}\sum_{j=1}^{D}\sum_{k=1}^{D} w_{ijk}x_i x_j x_k$$

⇒ Number of coefficients grows with D^M!

⇒ The approach becomes quickly unpractical for high dimensions.

  - This is known as the curse of dimensionality.
  - We will encounter some ways to deal with this later...

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Loss Functions for Regression

- Given $p(y, \mathbf{x}, \mathbf{w}, \beta)$, how do we actually estimate a function value y_t for a new point $\mathbf{x}_t$?
- We need a loss function, just as in the classification case

$$\begin{aligned} L: \quad \mathbb{R}\times\mathbb{R} \quad &\rightarrow \quad \mathbb{R}^+ \\ (t_n, y(\mathbf{x}_n)) \quad &\rightarrow \quad L(t_n, y(\mathbf{x}_n)) \end{aligned}$$

- Optimal prediction: Minimize the expected loss

$$\mathbb{E}[L] = \iint L(t, y(\mathbf{x}))p(\mathbf{x}, t)\,\mathrm{d}\mathbf{x}\,\mathrm{d}t$$

Slide adapted from Stefan Roth

Loss Functions for Regression

$$\mathbb{E}[L] = \iint L(t, y(\mathbf{x}))p(\mathbf{x}, t)\,\mathrm{d}\mathbf{x}\,\mathrm{d}t$$

- Simplest case
  - Squared loss: $L(t, y(\mathbf{x})) = \{y(\mathbf{x}) - t\}^2$
  - Expected loss

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

$$\begin{aligned} \frac{\partial \mathbb{E}[L]}{\partial y(\mathbf{x})} &= 2\int \{y(\mathbf{x}) - t\}\,p(\mathbf{x}, t)\mathrm{d}t \overset{!}{=} 0 \\ \Leftrightarrow \quad \int t p(\mathbf{x}, t)\mathrm{d}t &= y(\mathbf{x})\int p(\mathbf{x}, t)\mathrm{d}t \end{aligned}$$

Slide adapted from Stefan Roth

Loss Functions for Regression

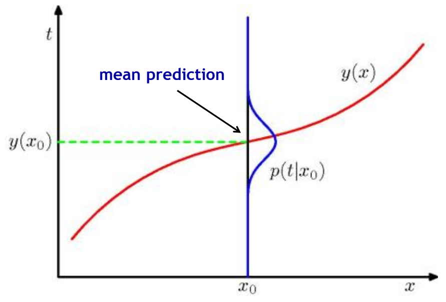
$$\begin{aligned} \int t p(\mathbf{x}, t)\mathrm{d}t &= y(\mathbf{x})\int p(\mathbf{x}, t)\mathrm{d}t \\ \Leftrightarrow \quad y(\mathbf{x}) &= \int t\frac{p(\mathbf{x}, t)}{p(\mathbf{x})}\mathrm{d}t = \int t p(t|\mathbf{x})\mathrm{d}t \\ \Leftrightarrow \quad y(\mathbf{x}) &= \mathbb{E}[t|\mathbf{x}] \end{aligned}$$

- Important result
  - Under Squared loss, the optimal regression function is the mean $\mathbb{E}\,[t\,|\,\mathbf{x}]$ of the posterior $p(t\,|\,\mathbf{x})$.
  - Also called mean prediction.
  - For our generalized linear regression function and square loss, we obtain as result

$$y(\mathbf{x}) = \int t\mathcal{N}(t|\mathbf{w}^T\phi(\mathbf{x}), \beta^{-1})\mathrm{d}t = \mathbf{w}^T\phi(\mathbf{x})$$

Slide adapted from Stefan Roth

Visualization of Mean Prediction



Slide adapted from Stefan Roth

Image source: C.M. Bishop, 2006

Loss Functions for Regression

- Different derivation: Expand the square term as follows

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

- Substituting into the loss function
  - The cross-term vanishes, and we end up with

$$\mathbb{E}[L] = \int \underbrace{\{y(\mathbf{x}) - \mathbb{E}[t|\mathbf{x}]\}^2}_{} p(\mathbf{x})\,\mathrm{d}\mathbf{x} + \int \underbrace{\mathrm{var}\,[t|\mathbf{x}]}_{} p(\mathbf{x})\,\mathrm{d}\mathbf{x}$$

Optimal least-squares predictor given by the conditional mean

Intrinsic variability of target data
⇒ Irreducible minimum value of the loss function

Other Loss Functions

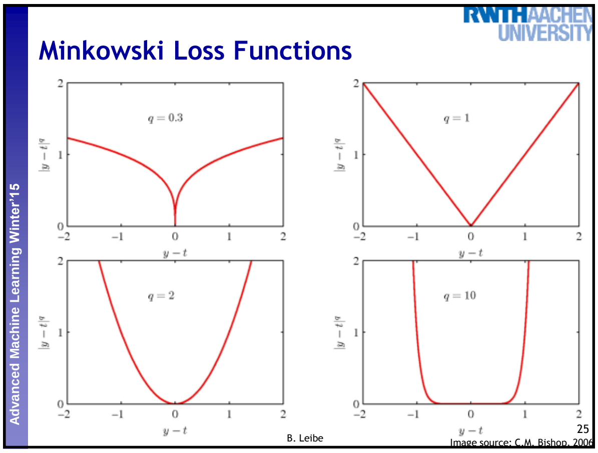
- The squared loss is not the only possible choice
  - Poor choice when conditional distribution $p(t\,|\,\mathbf{x})$ is multimodal.
- Simple generalization: Minkowski loss

$$L(t, y(\mathbf{x})) = |y(\mathbf{x}) - t|^q$$

  - Expectation

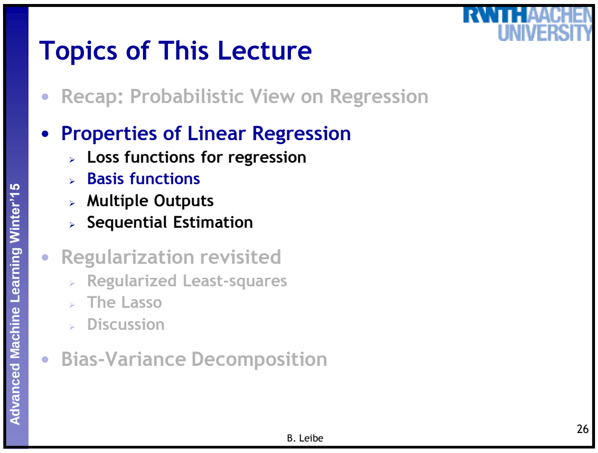
$$\mathbb{E}[L_q] = \iint |y(\mathbf{x}) - t|^q p(\mathbf{x}, t)\mathrm{d}\mathbf{x}\mathrm{d}t$$

- Minimum of $\mathbb{E}[L_q]$ is given by
  - Conditional mean for $q = 2$,
  - Conditional median for $q = 1$,
  - Conditional mode for $q = 0$.



Minkowski Loss Functions

Image source: C.M. Bishop, 2006



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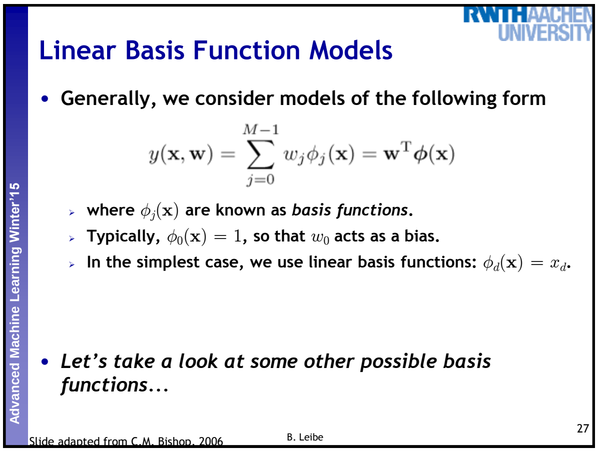


Linear Basis Function Models

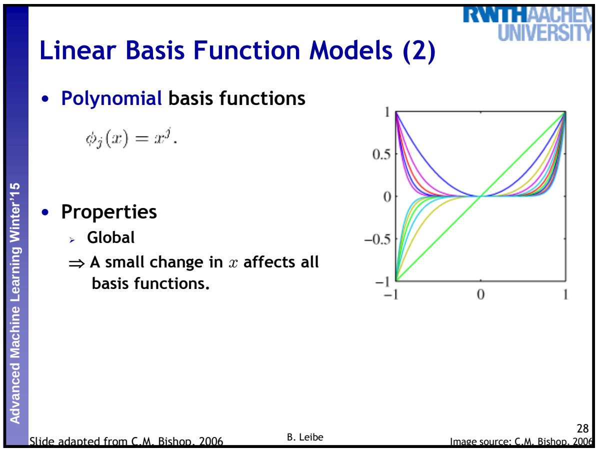
- Generally, we consider models of the following form

$$y(\mathbf{x}, \mathbf{w}) = \sum_{j=0}^{M-1} w_j \phi_j(\mathbf{x}) = \mathbf{w}^{\mathrm{T}} \boldsymbol{\phi}(\mathbf{x})$$

  - where $\phi_j(\mathbf{x})$ are known as *basis functions*.
  - Typically, $\phi_0(\mathbf{x}) = 1$, so that w_0 acts as a bias.
  - In the simplest case, we use linear basis functions: $\phi_d(\mathbf{x}) = x_d$.

- ***Let's take a look at some other possible basis functions...***

Slide adapted from C.M. Bishop, 2006



Linear Basis Function Models (2)

- Polynomial basis functions

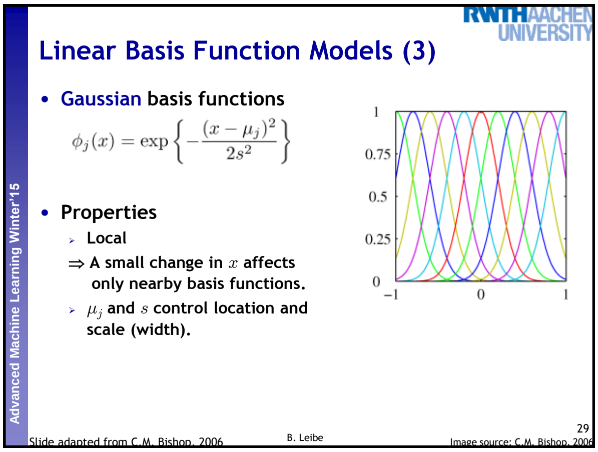
$$\phi_j(x) = x^j.$$

- Properties
  - Global

  ⇒ A small change in x affects all basis functions.

Slide adapted from C.M. Bishop, 2006

Image source: C.M. Bishop, 2006



Linear Basis Function Models (3)

- Gaussian basis functions

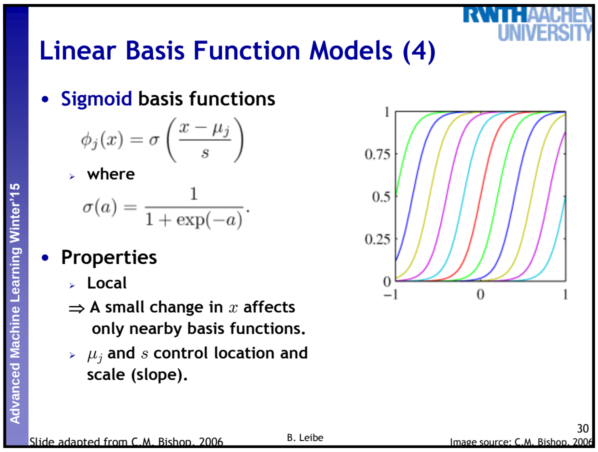
$$\phi_j(x) = \exp\left\{-\frac{(x-\mu_j)^2}{2s^2}\right\}$$

- Properties
  - Local

  ⇒ A small change in x affects only nearby basis functions.
  - μ_j and s control location and scale (width).

Slide adapted from C.M. Bishop, 2006

Image source: C.M. Bishop, 2006



Linear Basis Function Models (4)

- Sigmoid basis functions

$$\phi_j(x) = \sigma\left(\frac{x-\mu_j}{s}\right)$$

  - where

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

- Properties
  - Local

  ⇒ A small change in x affects only nearby basis functions.
  - μ_j and s control location and scale (slope).

Slide adapted from C.M. Bishop, 2006

Image source: C.M. Bishop, 2006

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Multiple Outputs

- Multiple Output Formulation
  - So far only considered the case of a single target variable t.
  - We may wish to predict $K > 1$ target variables in a vector $\mathbf{t}$.
  - We can write this in matrix form

$$\mathbf{y}(\mathbf{x}, \mathbf{W}) = \mathbf{W}^T \phi(\mathbf{x})$$

  - where

$$\mathbf{y} = [y_1, \ldots, y_K]^T$$

$$\phi(\mathbf{x}) = [1, \phi_1(\mathbf{x}), \cdots, \phi_{M-1}(\mathbf{x}),]^T$$

$$\mathbf{W} = \begin{bmatrix} w_{0,1} & \cdots & w_{0,K} \\ \vdots & \ddots & \vdots \\ w_{M-1,1} & \cdots & w_{M-1,K} \end{bmatrix}^T$$

Multiple Outputs (2)

- Analogously to the single output case we have:

$$\begin{aligned} p(\mathbf{t}|\mathbf{x}, \mathbf{W}, \beta) &= \mathcal{N}(\mathbf{t}|\mathbf{y}(\mathbf{W}, \mathbf{x}), \beta^{-1}\mathbf{I}) \\ &= \mathcal{N}(\mathbf{t}|\mathbf{W}^{\mathrm{T}}\boldsymbol{\phi}(\mathbf{x}), \beta^{-1}\mathbf{I}). \end{aligned}$$

- Given observed inputs, $\mathbf{X} = \{\mathbf{x}_1, \ldots, \mathbf{x}_N\}$, and targets, $\mathbf{T} = [\mathbf{t}_1, \ldots, \mathbf{t}_N]^{\mathrm{T}}$, we obtain the log likelihood function

$$\begin{aligned} \ln p(\mathbf{T}|\mathbf{X}, \mathbf{W}, \beta) &= \sum_{n=1}^{N} \ln \mathcal{N}(\mathbf{t}_n|\mathbf{W}^{\mathrm{T}}\boldsymbol{\phi}(\mathbf{x}_n), \beta^{-1}\mathbf{I}) \\ &= \frac{NK}{2} \ln\left(\frac{\beta}{2\pi}\right) - \frac{\beta}{2}\sum_{n=1}^{N} \left\|\mathbf{t}_n - \mathbf{W}^{\mathrm{T}}\boldsymbol{\phi}(\mathbf{x}_n)\right\|^2. \end{aligned}$$

Slide adapted from C.M. Bishop, 2006

Multiple Outputs (3)

- Maximizing with respect to $\mathbf{W}$, we obtain

$$\mathbf{W}_{\mathrm{ML}} = \left(\boldsymbol{\Phi}^{\mathrm{T}}\boldsymbol{\Phi}\right)^{-1} \boldsymbol{\Phi}^{\mathrm{T}}\mathbf{T}.$$

- If we consider a single target variable, t_k, we see that

$$\mathbf{w}_k = \left(\boldsymbol{\Phi}^{\mathrm{T}}\boldsymbol{\Phi}\right)^{-1} \boldsymbol{\Phi}^{\mathrm{T}}\mathbf{t}_k = \boldsymbol{\Phi}^{\dagger}\mathbf{t}_k$$

where $\mathbf{t}_k = [t_{1k}, \ldots, t_{Nk}]^{\mathrm{T}}$, which is identical with the single output case.

Slide adapted from C.M. Bishop, 2006

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Sequential Learning

- Up to now, we have mainly considered batch methods
  - All data was used at the same time
  - Instead, we can also consider data items one at a time (a.k.a. online learning)
- Stochastic (sequential) gradient descent:

$$\begin{aligned} \mathbf{w}^{(\tau+1)} &= \mathbf{w}^{(\tau)} - \eta \nabla E_n \\ &= \mathbf{w}^{(\tau)} + \eta(t_n - \mathbf{w}^{(\tau)\mathrm{T}}\boldsymbol{\phi}(\mathbf{x}_n))\boldsymbol{\phi}(\mathbf{x}_n). \end{aligned}$$

- This is known as the least-mean-squares (LMS) algorithm.
- Issue: how to choose the learning rate η?

Slide adapted from C.M. Bishop, 2006

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  - Discussion
- Bias-Variance Decomposition

Regularization Revisited

- Consider the error function

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

Data term + Regularization term

- With the sum-of-squares error function and a quadratic regularizer, we get

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

- which is minimized by

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

λ is called the regularization coefficient.

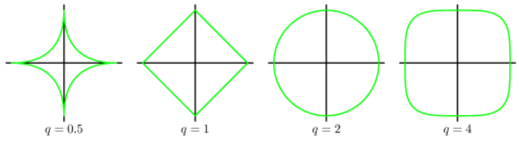
Slide adapted from C.M. Bishop, 2006

Regularized Least-Squares

- Let's look at more general regularizers

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

- "L$_q$ norms"



"Lasso"

"Ridge Regression"

Slide adapted from C.M. Bishop, 2006

Image source: C.M. Bishop, 2006

Recall: Lagrange Multipliers

Regularized Least-Squares

- We want to minimize

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

- This is equivalent to minimizing

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

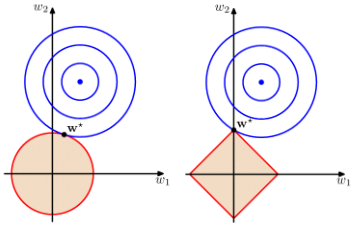
  - subject to the constraint

$$\sum_{j=1}^{M}|w_j|^q \leq \eta$$

  - (for some suitably chosen η)

Regularized Least-Squares

- Effect: Sparsity for $q \leq 1$.
  - Minimization tends to set many coefficients to zero



- *Why is this good?*
- *Why don't we always do it, then? Any problems?*

Image source: C.M. Bishop, 2006

The Lasso

- Consider the following regressor

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

  - This formulation is known as the Lasso.

- Properties
  - L_1 regularization ⇒ The solution will be sparse (only few coefficients will be non-zero)
  - The L_1 penalty makes the problem non-linear.

  ⇒ There is no closed-form solution.

  ⇒ Need to solve a quadratic programming problem.
  - However, efficient algorithms are available with the same computational cost as for ridge regression.

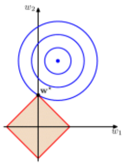


Image source: C.M. Bishop, 2006

Lasso as Bayes Estimation

- Interpretation as Bayes Estimation

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

  - We can think of $|w_j|^q$ as the log-prior density for w_j.

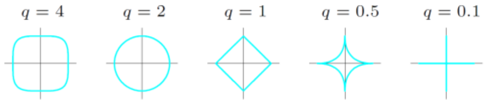
- Prior for Lasso ($q = 1$): Laplacian distribution

$$p(\mathbf{w}) = \frac{1}{2\tau}\exp\{-|\mathbf{w}|/\tau\} \qquad \text{with} \qquad \tau = \frac{1}{\lambda}$$

Image source: Friedman, Hastie, Tibshirani, 2009

Analysis

- Equicontours of the prior distribution



- Analysis
  - For $q \leq 1$, the prior is not uniform in direction, but concentrates more mass on the coordinate directions.
  - The case $q = 1$ (lasso) is the smallest q such that the constraint region is convex.

  ⇒ Non-convexity makes the optimization problem more difficult.
  - Limit for $q = 0$: regularization term becomes $\sum_{j=1..M} 1 = M$.

  ⇒ This is known as Best Subset Selection.

Image source: Friedman, Hastie, Tibshirani, 2009

Discussion

- Bayesian analysis
  - Lasso, Ridge regression and Best Subset Selection are Bayes estimates with different priors.
  - However, derived as maximizers of the posterior.
  - Should ideally use the posterior mean as the Bayes estimate!

  ⇒ Ridge regression solution is also the posterior mean, but Lasso and Best Subset Selection are not.

- We might also try using other values of q besides $0,1,2$…
  - However, experience shows that this is not worth the effort.
  - Values of $q \in (1,2)$ are a compromise between lasso and ridge
  - However, $|w_j|^q$ with $q > 1$ is differentiable at 0.

  ⇒ Loses the ability of lasso for setting coefficients exactly to zero.

Topics of This Lecture

- Recap: Probabilistic View on Regression
- Properties of Linear Regression
  - Loss functions for regression
  - Basis functions
  - Multiple Outputs
  - Sequential Estimation
- Regularization revisited
  - Regularized Least-squares
  - The Lasso
  - Discussion
- Bias-Variance Decomposition

Bias-Variance Decomposition

- Recall the *expected squared loss*,

$$\mathbb{E}[L] = \int\{y(\mathbf{x}) - h(\mathbf{x})\}^2 p(\mathbf{x})\,\mathrm{d}\mathbf{x} + \iint\underbrace{\{h(\mathbf{x}) - t\}^2 p(\mathbf{x},t)\,\mathrm{d}\mathbf{x}\,\mathrm{d}t}$$

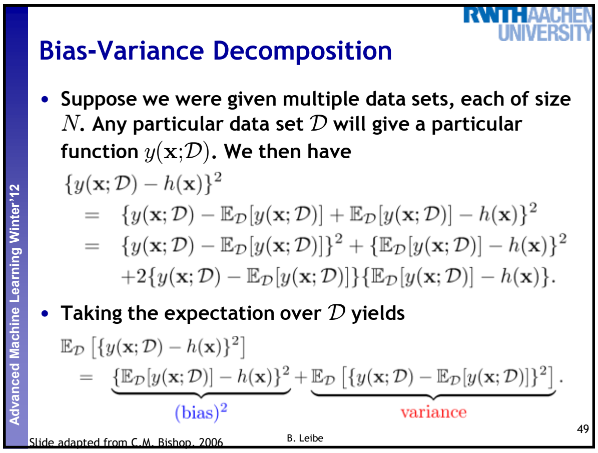
  - where

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

- The second term of $\mathbb{E}[L]$ corresponds to the noise inherent in the random variable t.

- What about the first term?

Slide adapted from C.M. Bishop, 2006



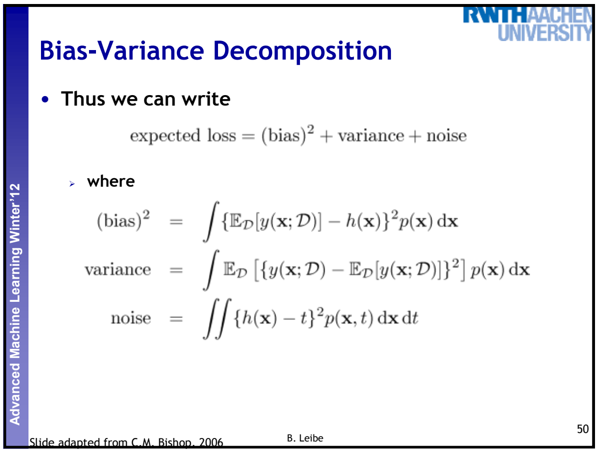
Bias-Variance Decomposition

- Suppose we were given multiple data sets, each of size N. Any particular data set $\mathcal{D}$ will give a particular function $y(\mathbf{x};\mathcal{D})$. We then have

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

- Taking the expectation over $\mathcal{D}$ yields

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



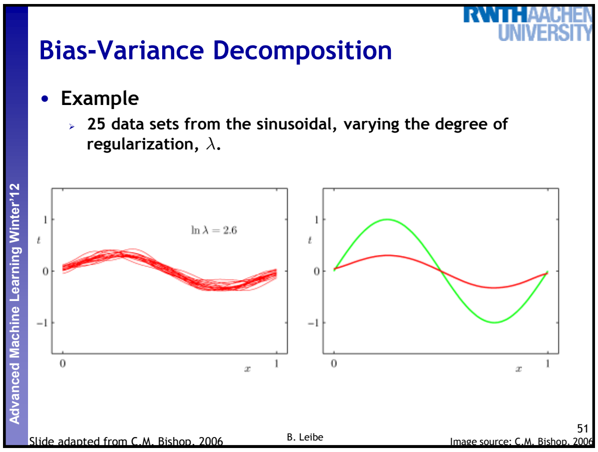
Bias-Variance Decomposition

- Thus we can write

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

  - where

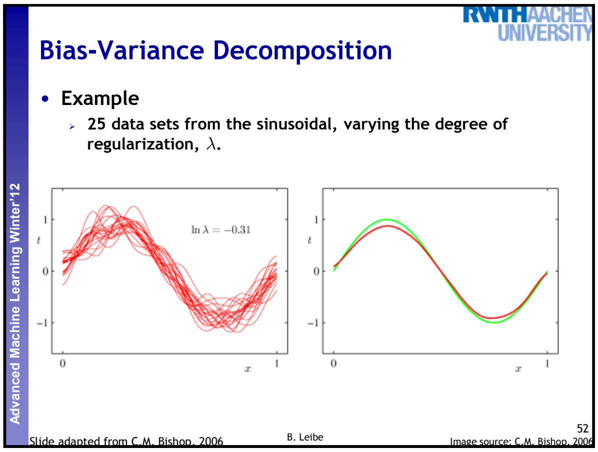
$$\begin{aligned}(\text{bias})^2 &= \int \{\mathbb{E}_{\mathcal{D}}[y(\mathbf{x};\mathcal{D})] - h(\mathbf{x})\}^2 p(\mathbf{x})\,\mathrm{d}\mathbf{x}\\ \text{variance} &= \int \mathbb{E}_{\mathcal{D}}\left[\{y(\mathbf{x};\mathcal{D}) - \mathbb{E}_{\mathcal{D}}[y(\mathbf{x};\mathcal{D})]\}^2\right] p(\mathbf{x})\,\mathrm{d}\mathbf{x}\\ \text{noise} &= \iint \{h(\mathbf{x}) - t\}^2 p(\mathbf{x},t)\,\mathrm{d}\mathbf{x}\,\mathrm{d}t\end{aligned}$$



Bias-Variance Decomposition

- Example
  - 25 data sets from the sinusoidal, varying the degree of regularization, λ.

Image source: C.M. Bishop, 2006



Bias-Variance Decomposition

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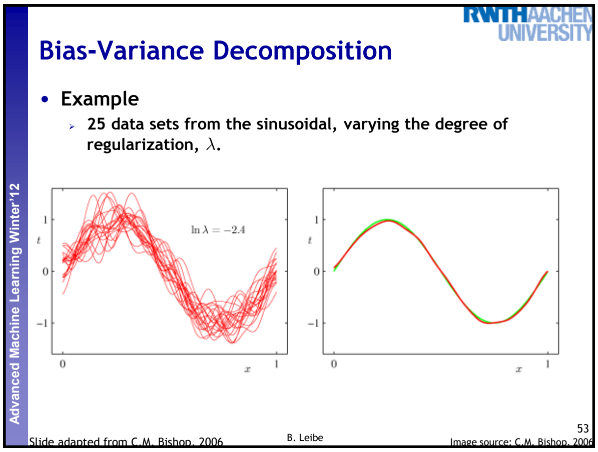
Image source: C.M. Bishop, 2006



Bias-Variance Decomposition

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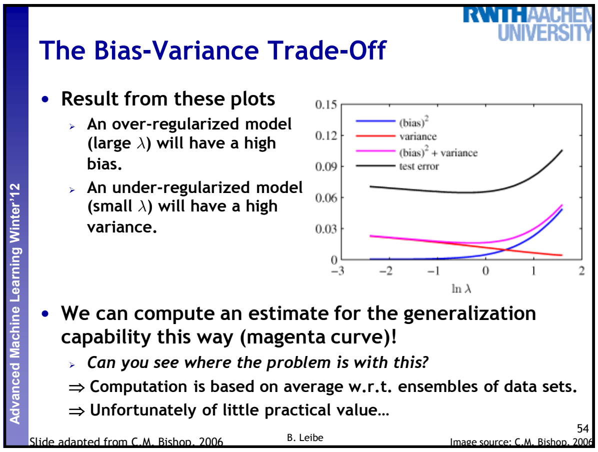


The Bias-Variance Trade-Off

- Result from these plots
  - An over-regularized model (large λ) will have a high bias.
  - An under-regularized model (small λ) will have a high variance.

- We can compute an estimate for the generalization capability this way (magenta curve)!
  - *Can you see where the problem is with this?*

⇒ Computation is based on average w.r.t. ensembles of data sets.

⇒ Unfortunately of little practical value…

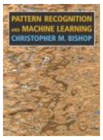
Image source: C.M. Bishop, 2006

References and Further Reading

- More information on linear regression, including a discussion on regularization can be found in Chapters 1.5.5 and 3.1-3.2 of the Bishop book.

Christopher M. Bishop
Pattern Recognition and Machine Learning
Springer, 2006

T. Hastie, R. Tibshirani, J. Friedman
Elements of Statistical Learning
2nd edition, Springer, 2009



- Additional information on the Lasso, including efficient algorithms to solve it, can be found in Chapter 3.4 of the Hastie book.