CIS 678 - Machine Learning

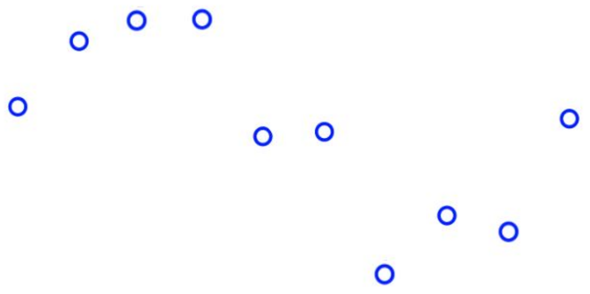
- Linear to Polynomial Regression
- Model Regularization

Plan

- LR to Polynomial Regression
- Regularization
  - Theory
  - Practical - Notebook presentation

Non linear data/function

- Does this data points seem familiar matching a known function?

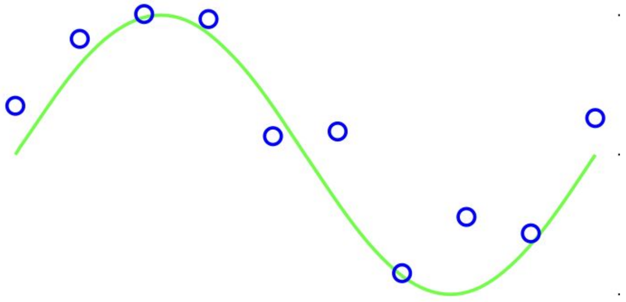


Non linear data/function

- Does this data points seem familiar matching a known function?

    - A Sinusoidal function

$$y(t) = A\sin(\omega t + \varphi) = A\sin(2\pi f t + \varphi)$$

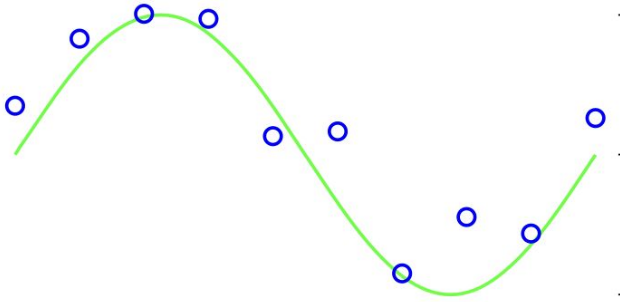


Non linear data/function

- Does this data points seem familiar matching a known function?

    - A Sinusoidal function

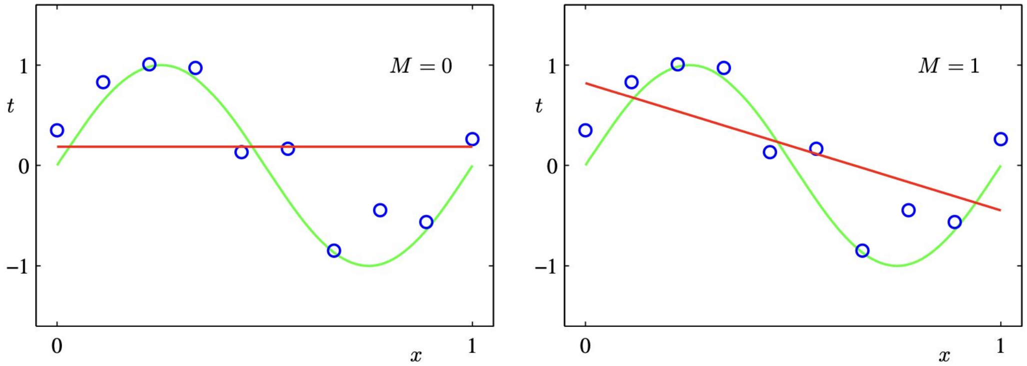
$$y(t) = A\sin(\omega t + \varphi) = A\sin(2\pi f t + \varphi)$$



Clearly this is not a linear function; right?

Non linear data/function

- Does this data points seem familiar matching a known function?
- Can we approximate this function using LR ?



$$\hat{y} = \beta_0 + \beta_1 x$$

LR will not work; right?

What no-linear functions we are aware of?

- Can you recall any nonlinear function you learned at your high school/colleges?

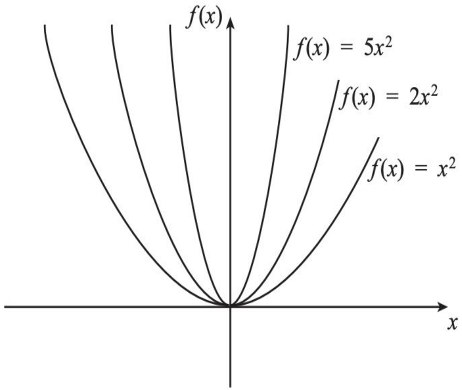
ref

What no-linear functions we are aware of?

- Can you recall any nonlinear function you learned at your high school/colleges?
- **Quadratic (x^2)**

$$f(x) = x^2, \qquad f(x) = 2x^2, \qquad f(x) = 5x^2.$$

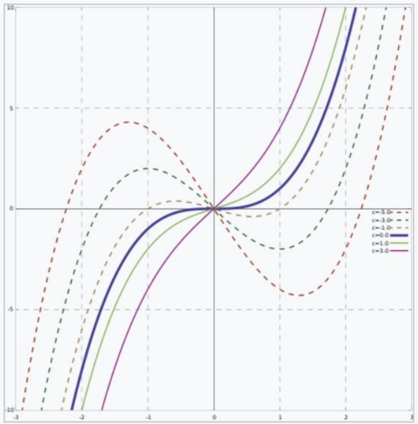
What is the impact of changing the coefficient of x^2 as we have done in these examples? One way to find out is to sketch the graphs of the functions.



ref

What no-linear functions we are aware of?

- Can you recall any nonlinear function you learned at your high school/colleges?
- **Cubic (x^3)**



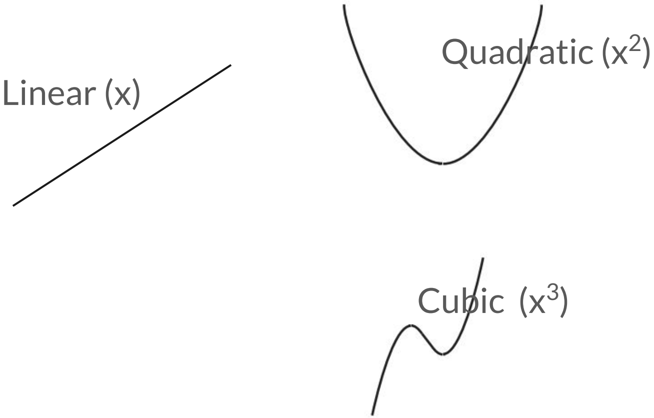
Cubic functions of the form
$y = x^3 + cx.$
The graph of any cubic function is similar to such a curve.

ref

What no-linear functions we are aware of?

- Can you recall any nonlinear function you learned at your high school/colleges?
- Quadratic (x^2)
- Cubic (x^3)
-

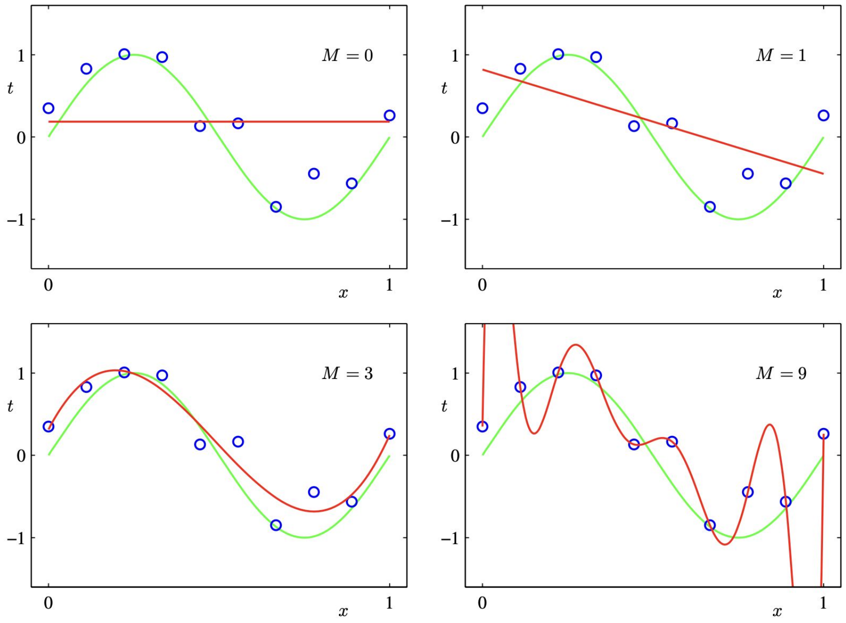
$$\hat{y} = \beta_0 + \beta_1 x$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3 + \ldots$$



ref

LR to Polynomial Regression

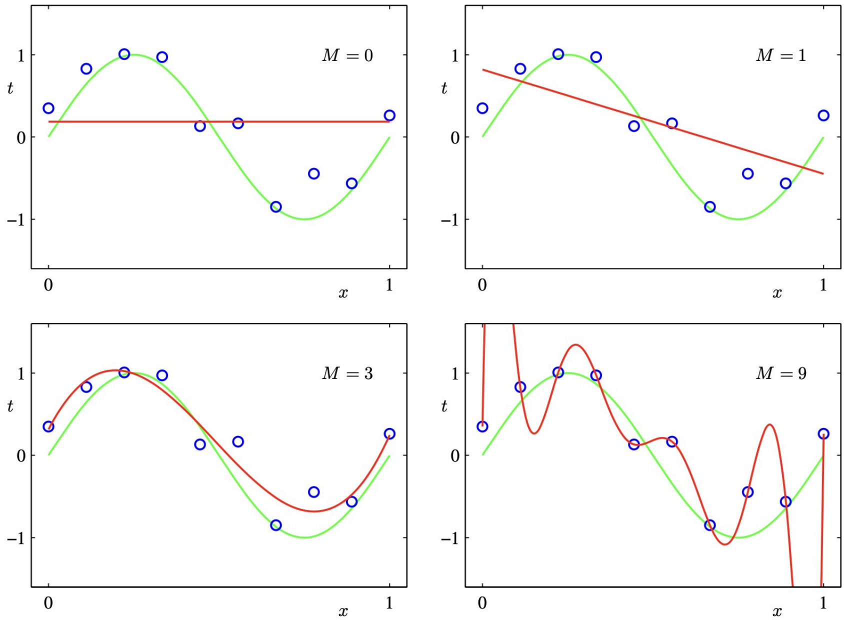
- Polynomial function
  - ***M* is the order/degree of polynomial ..**



$$\hat{y} = \beta_0 + \beta_1 x$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3 + \ldots$$

LR to Polynomial Regression

- Polynomial function
  - *M* is the order/degree of polynomial ..
  - **Where to stop? What is the best *M*?**



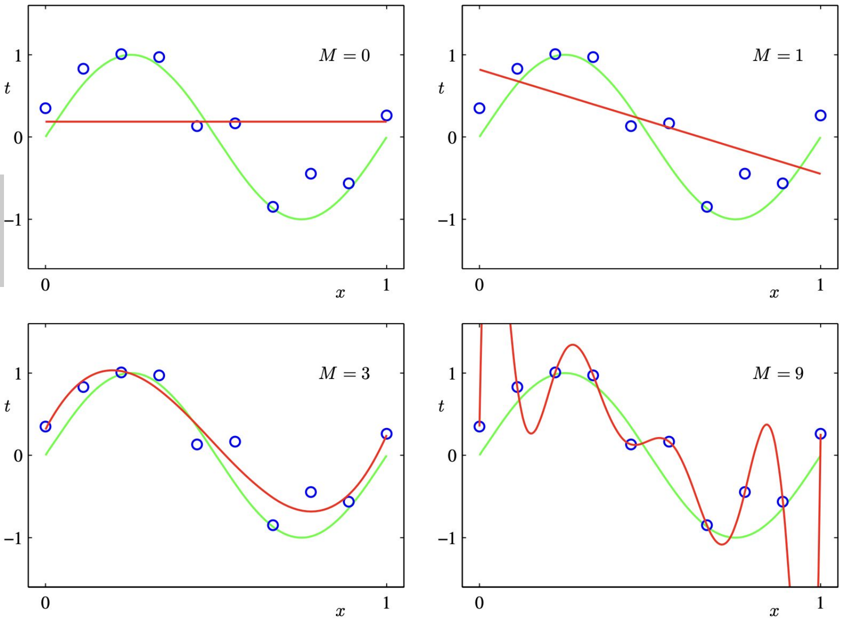
$$\hat{y} = \beta_0 + \beta_1 x$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3 + \ldots$$

LR to Polynomial Regression

- Polynomial function
  - *M* is the order/degree of polynomial ..
  - **Where to stop? What is the best M?**

Good news is our gradient descent (iterative learning) remains the same!

$$\hat{y} = \beta_0 + \beta_1 x$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3 + \dots$$

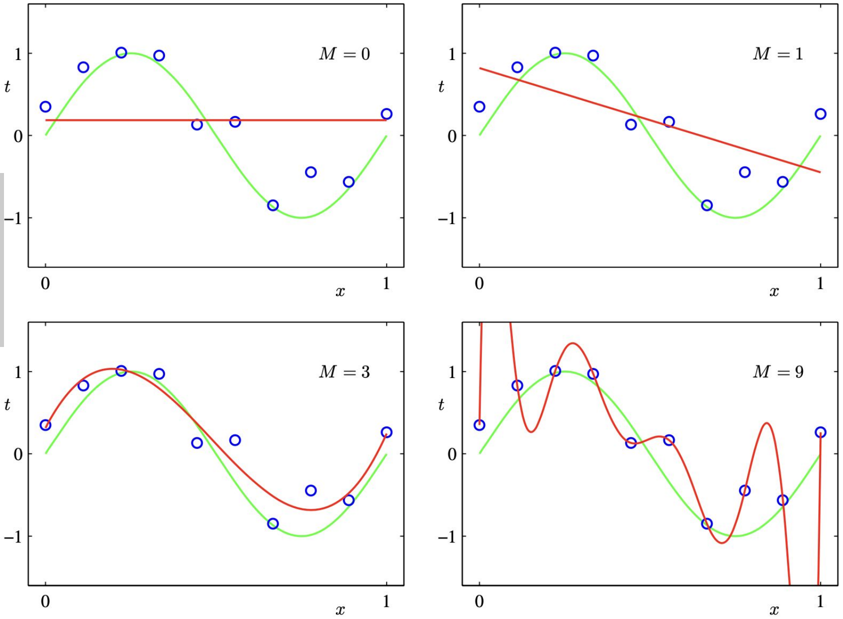


LR to Polynomial Regression

- Polynomial function
  - M is the order ..
  - **Where to stop? What is the best M?**

- Good news is our gradient descent (iterative learning) remains the same!
- You only need to change your objective function (from LR to Polynomial LR)

$$\hat{y} = \beta_0 + \beta_1 x$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3 + \ldots$$



LR to Polynomial Regression

$$\hat{y} = \beta_0 + \beta_1 x$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3 + \dots$$

Model

$$\hat{y} = \beta_0 + \beta_1 x$$

$$\Theta = \{\beta_0, \beta_1\}$$

$$\epsilon = |\hat{y} - y|$$

Optimization function

$$E_\Theta = \frac{1}{2} \sum_{i=1}^{N} (\hat{y}_i - y_i)^2$$

$$\Theta^* = \operatorname{argmin}_\Theta E\{(x_i, y_i)\}_{i=1,\cdots,N}$$

Our model got a little bigger: 2 params to *M* param

GPT

I know one of your tricks; get you soon!!

Our model yesterday

Our model got a little bigger: 2 params to *M* param

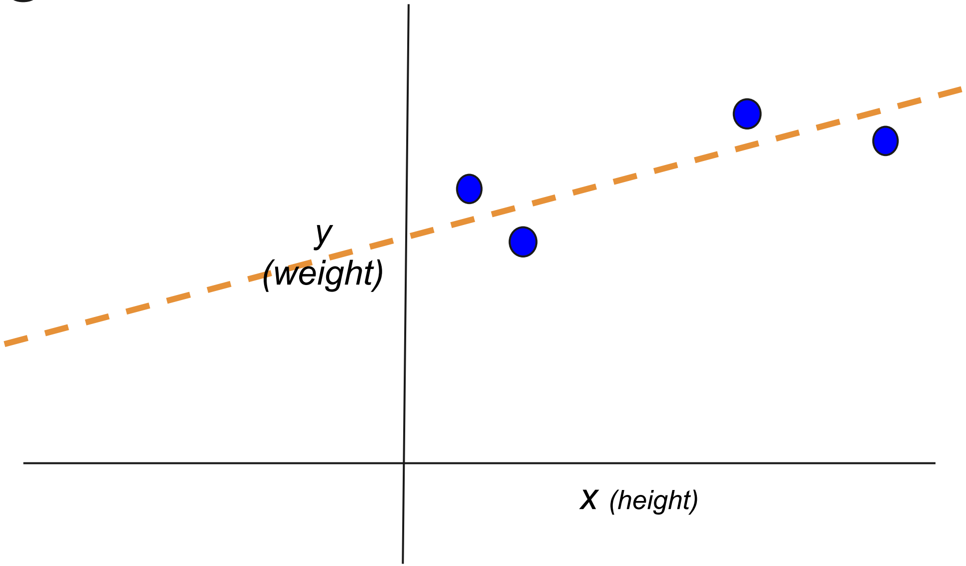
GPT

I know one of your tricks; get you soon!!

Our model today

Regularization

Regularization



So, essentially we are fitting a function; right?

Model

$$\hat{y} = \beta_0 + \beta_1 x$$

$$\Theta = \{\beta_0, \beta_1\}$$

Fitting Error

$$\epsilon = |\hat{y} - y|$$

Optimization function

$$E_\Theta = \frac{1}{2}\sum_{i=1}^{N}(\hat{y}_i - y_i)^2$$

$$\Theta^* = \mathrm{argmin}_\Theta\, E\{(x_i, y_i)\}_{i=1,\cdots,N}$$

Regularization

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

Same model, two different notations

Model

$$\hat{y} = \beta_0 + \beta_1 x$$

$$\Theta = \{\beta_0, \beta_1\}$$

$$\epsilon = |\hat{y} - y|$$

Optimization function

$$E_\Theta = \frac{1}{2}\sum_{i=1}^{N}(\hat{y}_i - y_i)^2$$

$$\Theta^* = \operatorname{argmin}_\Theta E\{(x_i, y_i)\}_{i=1,\cdots,N}$$

Regularization

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

Model

$$\hat{y} = \beta_0 + \beta_1 x$$

$$\Theta = \{\beta_0, \beta_1\}$$

$$\epsilon = |\hat{y} - y|$$

Essentially, the same formulation

Optimization function

$$E_\Theta = \frac{1}{2}\sum_{i=1}^{N}(\hat{y}_i - y_i)^2$$

$$\Theta^* = \mathrm{argmin}_\Theta\, E\{(x_i, y_i)\}_{i=1,\cdots,N}$$

Generally **ML** vs **Math** conventions

Regularization

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

x : scalar
$\boldsymbol{x}$, $\mathbf{x}$: vector
$\mathbf{X}$: Matrix

Model

$$\hat{y} = \beta_0 + \beta_1 x$$

$$\Theta = \{\beta_0, \beta_1\}$$

$$\epsilon = |\hat{y} - y|$$

Optimization function

$$E_\Theta = \frac{1}{2}\sum_{i=1}^{N}(\hat{y}_i - y_i)^2$$

Essentially, the same formulation

Generally ML vs Math conventions

$$\boxed{W^* = \text{argmin}_W\, E\{(x_i, t_i)\}_{i=1,\cdots,N}}$$

$$\boxed{\Theta^* = \text{argmin}_\Theta\, E\{(x_i, y_i)\}_{i=1,\cdots,N}}$$

Regularization

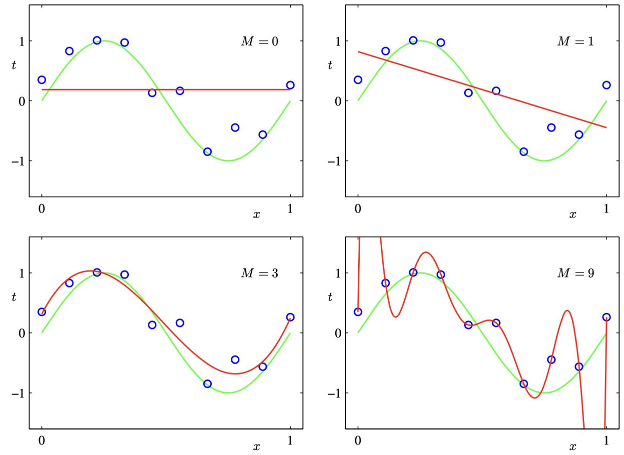


Table 1.1 Table of the coefficients $\mathbf{w}^\star$ for polynomials of various order. Observe how the typical magnitude of the coefficients increases dramatically as the order of the polynomial increases.

	$M = 0$	$M = 1$	$M = 6$	$M = 9$
$w_0^\star$	0.19	0.82	0.31	0.35
$w_1^\star$		-1.27	7.99	232.37
$w_2^\star$			-25.43	-5321.83
$w_3^\star$			17.37	48568.31
$w_4^\star$				-231639.30
$w_5^\star$				640042.26
$w_6^\star$				-1061800.52
$w_7^\star$				1042400.18
$w_8^\star$				-557682.99
$w_9^\star$				125201.43

Regularization

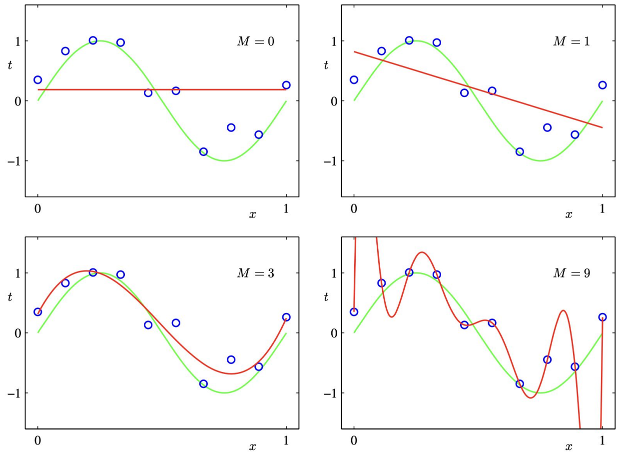
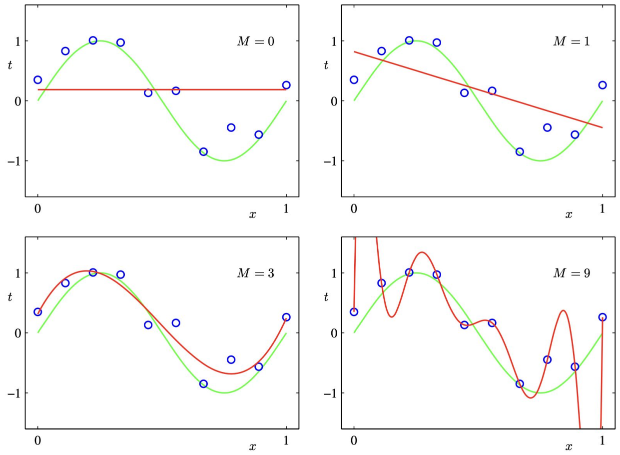


Table 1.1 Table of the coefficients $\mathbf{w}^\star$ for polynomials of various order. Observe how the typical magnitude of the coefficients increases dramatically as the order of the polynomial increases.

	$M=0$	$M=1$	$M=6$	$M=9$
$w_0^\star$	0.19	0.82	0.31	0.35
$w_1^\star$		-1.27	7.99	232.37
$w_2^\star$			-25.43	-5321.83
$w_3^\star$			17.37	48568.31
$w_4^\star$				-231639.30
$w_5^\star$				640042.26
$w_6^\star$				-1061800.52
$w_7^\star$				1042400.18
$w_8^\star$				-557682.99
$w_9^\star$				125201.43

Absolute values are increasing

Regularization



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

Regularizer

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

Regularization

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

Regularizer

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

Table 1.1 Table of the coefficients $\mathbf{w}^\star$ for polynomials of various order. Observe how the typical magnitude of the coefficients increases dramatically as the order of the polynomial increases.

	$M=0$	$M=1$	$M=6$	$M=9$
$w_0^\star$	0.19	0.82	0.31	0.35
$w_1^\star$		-1.27	7.99	232.37
$w_2^\star$			-25.43	-5321.83
$w_3^\star$			17.37	48568.31
$w_4^\star$				-231639.30
$w_5^\star$				640042.26
$w_6^\star$				-1061800.52
$w_7^\star$				1042400.18
$w_8^\star$				-557682.99
$w_9^\star$				125201.43

Abs values
Are increasing

Regularization

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

$||\mathbf{W}||^2$

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

decreasing

Table 1.1 Table of the coefficients $\mathbf{w}^\star$ for polynomials of various order. Observe how the typical magnitude of the coefficients increases dramatically as the order of the polynomial increases.

	$M = 0$	$M = 1$	$M = 6$	$M = 9$
$w_0^\star$	0.19	0.82	0.31	0.35
$w_1^\star$		-1.27	7.99	232.37
$w_2^\star$			-25.43	-5321.83
$w_3^\star$			17.37	48568.31
$w_4^\star$				-231639.30
$w_5^\star$				640042.26
$w_6^\star$				-1061800.52
$w_7^\star$				1042400.18
$w_8^\star$				-557682.99
$w_9^\star$				125201.43

Abs values
Are increasing

Regularization

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

||W||^2

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

decreasing

Table 1.1 Table of the coefficients $\mathbf{w}^\star$ for polynomials of various order. Observe how the typical magnitude of the coefficients increases dramatically as the order of the polynomial increases.

	$M=0$	$M=1$	$M=6$	$M=9$
$w_0^\star$	0.19	0.82	0.31	0.35
$w_1^\star$		-1.27	7.99	232.37
$w_2^\star$			-25.43	-5321.83
$w_3^\star$			17.37	48568.31
$w_4^\star$				-231639.30
$w_5^\star$				640042.26
$w_6^\star$				-1061800.52
$w_7^\star$				1042400.18
$w_8^\star$				-557682.99
$w_9^\star$				125201.43

Abs values
Are increasing

Regularization

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

||W||^2

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

decreasing

Table 1.1 Table of the coefficients $\mathbf{w}^\star$ for polynomials of various order. Observe how the typical magnitude of the coefficients increases dramatically as the order of the polynomial increases.

	$M = 0$	$M = 1$	$M = 6$	$M = 9$
$w_0^\star$	0.19	0.82	0.31	0.35
$w_1^\star$		-1.27	7.99	232.37
$w_2^\star$			-25.43	-5321.83
$w_3^\star$			17.37	48568.31
$w_4^\star$				-231639.30
$w_5^\star$				640042.26
$w_6^\star$				-1061800.52
$w_7^\star$				1042400.18
$w_8^\star$				-557682.99
$w_9^\star$				125201.43

How to control this?

Regularization

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

||W||^2

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

Table 1.1 Table of the coefficients $\mathbf{w}^\star$ for polynomials of various order. Observe how the typical magnitude of the coefficients increases dramatically as the order of the polynomial increases.

	$M=0$	$M=1$	$M=6$	$M=9$
$w_0^\star$	0.19	0.82	0.31	0.35
$w_1^\star$		-1.27	7.99	232.37
$w_2^\star$			-25.43	-5321.83
$w_3^\star$			17.37	48568.31
$w_4^\star$				-231639.30
$w_5^\star$				640042.26
$w_6^\star$				-1061800.52
$w_7^\star$				1042400.18
$w_8^\star$				-557682.99
$w_9^\star$				125201.43

Who to control this?

Regularization

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

||W||^2

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

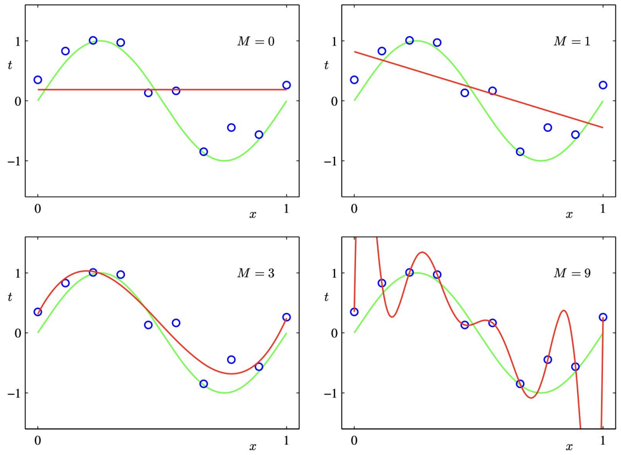
Table 1.1 Table of the coefficients $\mathbf{w}^{\star}$ for polynomials of various order. Observe how the typical magnitude of the coefficients increases dramatically as the order of the polynomial increases.

	$M=0$	$M=1$	$M=6$	$M=9$
$w_0^{\star}$	0.19	0.82	0.31	0.35
$w_1^{\star}$		-1.27	7.99	232.37
$w_2^{\star}$			-25.43	-5321.83
$w_3^{\star}$			17.37	48568.31
$w_4^{\star}$				-231639.30
$w_5^{\star}$				640042.26
$w_6^{\star}$				-1061800.52
$w_7^{\star}$				1042400.18
$w_8^{\star}$				-557682.99
$w_9^{\star}$				125201.43

Who to control this?

Lamda is called the
Hyper Parameter of this model

Polynomial Regression with Regularization

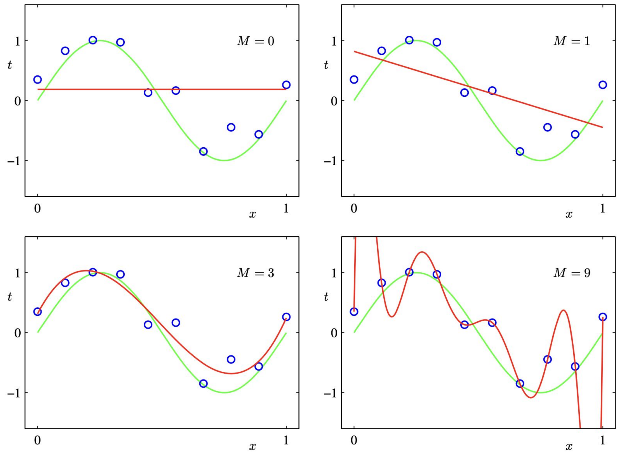


Learned function is **nonlinear**

$$\hat{y} = \beta_0$$
$$\hat{y} = \beta_0 + \beta_1 x$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3 + \ldots$$

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

Polynomial Regression with Regularization



Learned function is **nonlinear**

$$\hat{y} = \beta_0$$
$$\hat{y} = \beta_0 + \beta_1 x$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3$$
$$\hat{y} = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_2 x^3 + \ldots$$

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

Model (still) **linear**

Classification

- General Idea (two steps process)
  - LR (Bias Only)
  - LR (general)

Notebook presentation

- Without regularizer
- With regularizer

Predictive modeling: Regression (diabetes)

Predictive modeling: Classification