

# 1 Ridge Regression

## 1.1 Deriving the Ridge Estimator

Recalling that  $\|\mathbf{x}\|_2^2 = \mathbf{x}^T \mathbf{x}$ , we'll rewrite  $\|\mathbf{Ax} - \mathbf{b}\|_2^2 + \gamma \|\mathbf{x}\|_2^2$ :

$$\arg \max_x \|\mathbf{Ax} - \mathbf{b}\|_2^2 + \gamma \|\mathbf{x}\|_2^2 \quad (1)$$

$$\begin{aligned} \|\mathbf{Ax} - \mathbf{b}\|_2^2 + \gamma \|\mathbf{x}\|_2^2 &= \\ &= (\mathbf{Ax} - \mathbf{b})^T (\mathbf{Ax} - \mathbf{b}) + \gamma \mathbf{x}^T \mathbf{x} \\ &= ((\mathbf{Ax})^T - \mathbf{b}^T) (\mathbf{Ax} - \mathbf{b}) + \gamma \mathbf{x}^T \mathbf{x} \\ &= (\mathbf{x}^T \mathbf{A}^T - \mathbf{b}^T) (\mathbf{Ax} - \mathbf{b}) + \gamma \mathbf{x}^T \mathbf{x} \\ &= \mathbf{x}^T \mathbf{A}^T \mathbf{Ax} - \mathbf{x}^T \mathbf{A}^T \mathbf{b} - \mathbf{b}^T \mathbf{Ax} + \mathbf{b}^T \mathbf{b} + \gamma \mathbf{x}^T \mathbf{x} \end{aligned}$$

Before we proceed further, I'll define what  $\mathbf{A}$ ,  $\mathbf{b}$ , and  $\mathbf{x}$  are. We want a least-squares fit to an  $m$ -degree polynomial  $p_m(x) = a_0 + a_1 * x + \dots + a_m * x^m$  where we have  $n$  data points  $\{x_0, b_0\}$ . To have our system be overdetermined, we also assume  $n > m$ .

$$\mathbf{A} = \begin{bmatrix} 1 & x_0 & x_0^2 & \dots & x_0^m \\ 1 & x_1 & x_1^2 & \dots & x_1^m \\ 1 & x_2 & x_2^2 & \dots & x_2^m \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_n & x_n^2 & \dots & x_n^m \end{bmatrix} \quad \mathbf{x} = \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_m \end{bmatrix} \quad \mathbf{b} = \begin{bmatrix} b_0 \\ b_1 \\ \vdots \\ b_n \end{bmatrix}$$

Where  $\dim(\mathbf{A}) = (n+1) \times (m+1)$ ,  $\dim(\mathbf{x}) = (m+1) \times (1)$ , and  $\dim(\mathbf{b}) = (n+1) \times (1)$ .

I'll now prove  $\mathbf{x}^T \mathbf{A}^T \mathbf{b} = \mathbf{b}^T \mathbf{Ax}$ . Note first that  $(\mathbf{b}^T \mathbf{Ax})^T = \mathbf{x}^T \mathbf{A}^T \mathbf{b}$ . Further,  $\dim(\mathbf{x}^T \mathbf{A}^T \mathbf{b}) = (1) \times (1) = \dim(\mathbf{b}^T \mathbf{Ax})$ . Also, note that the transpose of a  $1 \times 1$  matrix is the same matrix:  $[c]^T = [c]$ . It then follows that  $\mathbf{x}^T \mathbf{A}^T \mathbf{b} = \mathbf{b}^T \mathbf{Ax}$ , completing the proof.

So,

$$\begin{aligned} \mathbf{x}^T \mathbf{A}^T \mathbf{Ax} - \mathbf{x}^T \mathbf{A}^T \mathbf{b} - \mathbf{b}^T \mathbf{Ax} + \mathbf{b}^T \mathbf{b} + \gamma \mathbf{x}^T \mathbf{x} &= \\ = \mathbf{x}^T \mathbf{A}^T \mathbf{Ax} - 2\mathbf{b}^T \mathbf{Ax} + \mathbf{b}^T \mathbf{b} + \gamma \mathbf{x}^T \mathbf{x} &= \\ = (\mathbf{Ax})^T (\mathbf{Ax}) - 2\mathbf{b}^T \mathbf{Ax} + \mathbf{b}^T \mathbf{b} + \gamma \mathbf{x}^T \mathbf{x} \end{aligned} \quad (2)$$

Now, I'll show what each of the above values (since each matrix is  $1 \times 1$ , meaning it's a scalar) actually is:

$$\begin{aligned}
\mathbf{Ax} &= \\
&= \begin{bmatrix} 1 & x_0 & x_0^2 & \dots & x_0^m \\ 1 & x_1 & x_1^2 & \dots & x_1^m \\ 1 & x_2 & x_2^2 & \dots & x_2^m \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_n & x_n^2 & \dots & x_n^m \end{bmatrix} \times \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_m \end{bmatrix} \\
&= \begin{bmatrix} a_0 + a_1x_0 + a_2x_0^2 + \dots + a_mx_0^m \\ a_0 + a_1x_1 + a_2x_1^2 + \dots + a_mx_1^m \\ a_0 + a_1x_2 + a_2x_2^2 + \dots + a_mx_2^m \\ \vdots \\ a_0 + a_1x_n + a_2x_n^2 + \dots + a_mx_n^m \end{bmatrix}
\end{aligned} \tag{3}$$

Then,  $(\mathbf{Ax})^T \mathbf{Ax}$  is just a simple inner product (we will use the result from 3):

$$\begin{aligned}
(\mathbf{Ax})^T \mathbf{Ax} &= \\
&= \begin{bmatrix} a_0 + a_1x_0 + a_2x_0^2 + \dots + a_mx_0^m \\ a_0 + a_1x_1 + a_2x_1^2 + \dots + a_mx_1^m \\ a_0 + a_1x_2 + a_2x_2^2 + \dots + a_mx_2^m \\ \vdots \\ a_0 + a_1x_n + a_2x_n^2 + \dots + a_mx_n^m \end{bmatrix}^T \times \begin{bmatrix} a_0 + a_1x_0 + a_2x_0^2 + \dots + a_mx_0^m \\ a_0 + a_1x_1 + a_2x_1^2 + \dots + a_mx_1^m \\ a_0 + a_1x_2 + a_2x_2^2 + \dots + a_mx_2^m \\ \vdots \\ a_0 + a_1x_n + a_2x_n^2 + \dots + a_mx_n^m \end{bmatrix} \\
&= (a_0 + a_1x_0 + \dots + a_mx_0^m)^2 + (a_0 + a_1x_1 + \dots + a_mx_1^m)^2 \\
&\quad + \dots + (a_0 + a_1x_n + \dots + a_mx_n^m)^2
\end{aligned} \tag{4}$$

$$\begin{aligned}
2\mathbf{b}^T \mathbf{Ax} &= \\
&= 2 \times [b_0 \quad b_1 \quad \dots \quad b_n] \times \begin{bmatrix} 1 & x_0 & x_0^2 & \dots & x_0^m \\ 1 & x_1 & x_1^2 & \dots & x_1^m \\ 1 & x_2 & x_2^2 & \dots & x_2^m \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_n & x_n^2 & \dots & x_n^m \end{bmatrix} \times \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_m \end{bmatrix} \\
&= 2 \times \begin{bmatrix} b_0 + b_1 + b_2 + \dots + b_n \\ b_0x_0 + b_1x_1 + b_2x_2 + \dots + b_nx_n \\ b_0x_0^2 + b_1x_1^2 + b_2x_2^2 + \dots + b_nx_n^2 \\ \vdots \\ b_0x_0^m + b_1x_1^m + b_2x_2^m + \dots + b_nx_n^m \end{bmatrix}^T \times \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_m \end{bmatrix} \\
&= 2(a_0(b_0 + b_1 + \dots + b_n) + a_1(b_0x_0 + b_1x_1 + \dots + b_nx_n) + \dots + a_m(b_0x_0^m + b_1x_1^m + \dots + b_nx_n^m))
\end{aligned} \tag{5}$$

$$\begin{aligned}
\gamma \mathbf{x}^T \mathbf{x} &= \\
&\text{This is a simple inner product multiplied by a scalar} \\
&= \gamma a_0^2 + \gamma a_1^2 + \dots + \gamma a_m^2
\end{aligned} \tag{6}$$

Great! Now lets take the derivates of 4, 5, and 6 with respect to  $\mathbf{x}$  to get the derivative of 1 with respect to  $\mathbf{x}$ . In effect, we'll get a vector where the  $i$ -th element is the derivative of 1 with respect to  $a_i$ .

First, let's take the derivatives of 4:

$$\begin{aligned}
& \frac{d}{d\mathbf{x}} (\mathbf{Ax})^T \mathbf{Ax} = \\
& = \begin{bmatrix} \frac{d}{da_0} (\mathbf{Ax})^T \mathbf{Ax} \\ \frac{d}{da_1} (\mathbf{Ax})^T \mathbf{Ax} \\ \vdots \\ \frac{d}{da_m} (\mathbf{Ax})^T \mathbf{Ax} \end{bmatrix} \\
& = \begin{bmatrix} 2(a_0 + a_1x_0 + \dots + a_mx_0^m) + 2(a_0 + a_1x_1 + \dots + a_mx_1^m) + \dots + 2(a_0 + a_1x_n + \dots + a_mx_n^m) \\ 2x_0(a_0 + a_1x_0 + \dots + a_mx_0^m) + 2x_1(a_0 + a_1x_1 + \dots + a_mx_1^m) + \dots + 2x_n(a_0 + a_1x_n + \dots + a_mx_n^m) \\ \vdots \\ 2x_0^m(a_0 + a_1x_0 + \dots + a_mx_0^m) + 2x_1^m(a_0 + a_1x_1 + \dots + a_mx_1^m) + \dots + 2x_n^m(a_0 + a_1x_n + \dots + a_mx_n^m) \end{bmatrix} \\
& = 2 \times \begin{bmatrix} a_0 \sum_{i=0}^n 1 + a_1 \sum_{i=0}^n x_i + a_2 \sum_{i=0}^n x_i^2 + \dots + a_m \sum_{i=0}^n x_i^m \\ a_0 \sum_{i=0}^n x_i + a_1 \sum_{i=0}^n x_i^2 + a_2 \sum_{i=0}^n x_i^3 + \dots + a_m \sum_{i=0}^n x_i^{m+1} \\ \vdots \\ a_0 \sum_{i=0}^n x_i^m + a_1 \sum_{i=0}^n x_i^{m+1} + a_2 \sum_{i=0}^n x_i^{m+2} + \dots + a_m \sum_{i=0}^n x_i^{2m} \end{bmatrix} \\
& = 2 \times \begin{bmatrix} \sum_{i=0}^n 1 & \sum_{i=0}^n x_i & \sum_{i=0}^n x_i^2 & \dots & \sum_{i=0}^n x_i^m \\ \sum_{i=0}^n x_i & \sum_{i=0}^n x_i^2 & \sum_{i=0}^n x_i^3 & \dots & \sum_{i=0}^n x_i^{m+1} \\ \sum_{i=0}^n x_i^2 & \sum_{i=0}^n x_i^3 & \sum_{i=0}^n x_i^4 & \dots & \sum_{i=0}^n x_i^{m+2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \sum_{i=0}^n x_i^m & \sum_{i=0}^n x_i^{m+1} & \sum_{i=0}^n x_i^{m+2} & \dots & \sum_{i=0}^n x_i^{2m} \end{bmatrix} \times \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \vdots \\ a_m \end{bmatrix} \\
& = 2 \times \begin{bmatrix} 1 & 1 & 1 & \dots & 1 \\ x_0 & x_1 & x_2 & \dots & x_n \\ x_0^2 & x_1^2 & x_2^2 & \dots & x_n^2 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_0^m & x_1^m & x_2^m & \dots & x_n^m \end{bmatrix} \times \begin{bmatrix} 1 & x_0 & x_0^2 & \dots & x_0^m \\ 1 & x_1 & x_1^2 & \dots & x_1^m \\ 1 & x_2 & x_2^2 & \dots & x_2^m \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_n & x_n^2 & \dots & x_n^m \end{bmatrix} \times \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \vdots \\ a_m \end{bmatrix} \\
& = 2\mathbf{A}^T \mathbf{Ax}
\end{aligned} \tag{7}$$

Secondly, let's take the derivatives of 5:

$$\begin{aligned}
\frac{d}{d\mathbf{x}} 2\mathbf{b}^T \mathbf{A}\mathbf{x} &= \\
&= \begin{bmatrix} \frac{d}{da_0} 2\mathbf{b}^T \mathbf{A}\mathbf{x} \\ \frac{d}{da_1} 2\mathbf{b}^T \mathbf{A}\mathbf{x} \\ \vdots \\ \frac{d}{da_m} 2\mathbf{b}^T \mathbf{A}\mathbf{x} \end{bmatrix} \\
&= 2 \times \begin{bmatrix} b_0 + b_1 + \dots + b_n \\ b_0 x_0 + b_1 x_1 + \dots + b_n x_n \\ b_0 x_0^2 + b_1 x_1^2 + \dots + b_n x_n^2 \\ \vdots \\ b_0 x_0^m + b_1 x_1^m + \dots + b_n x_n^m \end{bmatrix} \\
&= 2 \times \begin{bmatrix} 1 & 1 & 1 & \dots & 1 \\ x_0 & x_1 & x_2 & \dots & x_n \\ x_0^2 & x_1^2 & x_2^2 & \dots & x_n^2 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_0^m & x_1^m & x_2^m & \dots & x_n^m \end{bmatrix} \times \begin{bmatrix} b_0 \\ b_1 \\ \vdots \\ b_n \end{bmatrix} \\
&= 2\mathbf{A}^T \mathbf{b}
\end{aligned} \tag{8}$$

Lastly, let's take the derivatives of 6:

$$\begin{aligned}
\frac{d}{d\mathbf{x}} \gamma \mathbf{x}^T \mathbf{x} &= \\
&= \begin{bmatrix} \frac{d}{da_0} \gamma \mathbf{x}^T \mathbf{x} \\ \frac{d}{da_1} \gamma \mathbf{x}^T \mathbf{x} \\ \vdots \\ \frac{d}{da_m} \gamma \mathbf{x}^T \mathbf{x} \end{bmatrix} \\
&= \gamma \times \begin{bmatrix} 2a_0 \\ 2a_1 \\ 2a_2 \\ \vdots \\ 2a_m \end{bmatrix} \\
&= 2 \times \gamma \times \begin{bmatrix} 1 & 0 & 0 & \dots & 0 \\ 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & 1 \end{bmatrix} \times \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \vdots \\ a_m \end{bmatrix} \\
&= 2\gamma \mathbf{I} \mathbf{x}
\end{aligned} \tag{9}$$

Now we can recall 2 and note that to find the minimum of the least squares equation given by 1 we can find where the derivative of 2 is equal to zero:

$$\begin{aligned}
\frac{d}{d\mathbf{x}} ( (\mathbf{Ax})^T(\mathbf{Ax}) - 2\mathbf{b}^T\mathbf{Ax} + \mathbf{b}^T\mathbf{b} + \gamma\mathbf{x}^T\mathbf{x} ) &= 0 \\
2\mathbf{A}^T\mathbf{Ax} - 2\mathbf{A}^T\mathbf{b} + 2\gamma\mathbf{Ix} &= 0 \\
\mathbf{A}^T\mathbf{Ax} - \mathbf{A}^T\mathbf{b} + \gamma\mathbf{Ix} &= 0 \\
\mathbf{A}^T\mathbf{Ax} + \gamma\mathbf{Ix} - \mathbf{A}^T\mathbf{b} &= 0 \\
(\mathbf{A}^T\mathbf{A} + \gamma\mathbf{I})\mathbf{x} - \mathbf{A}^T\mathbf{b} &= 0 \\
(\mathbf{A}^T\mathbf{A} + \gamma\mathbf{I})\mathbf{x} &= \mathbf{A}^T\mathbf{b} \\
\mathbf{x} &= (\mathbf{A}^T\mathbf{A} + \gamma\mathbf{I})^{-1}\mathbf{A}^T\mathbf{b}
\end{aligned} \tag{10}$$

We have now arrived at the equation for Ridge Regression! We note that there is a typo in the project description for the equation  $E_{ridge} = (\mathbf{A}^T\mathbf{A} + \gamma\mathbf{I})^{-1}\mathbf{A}^T$ , where there is no trailing  $\mathbf{b}$ .