

Feel free to work with other students, but make sure you write up the homework and code on your own (no copying homework *or* code; no pair programming). Feel free to ask students or instructors for help debugging code or whatever else, though. The starter code for problem 2 part c and d can be found under the Resource tab on course website.

Note: You need to create a Github account for submission of the coding part of the homework. Please create a repository on Github to hold all your code and include your Github account username as part of the answer to problem 2.

1 (Linear Transformation) Let $\mathbf{y} = A\mathbf{x} + \mathbf{b}$ be a random vector. show that expectation is linear:

$$\mathbb{E}[\mathbf{y}] = \mathbb{E}[A\mathbf{x} + \mathbf{b}] = A\mathbb{E}[\mathbf{x}] + \mathbf{b}.$$

Also show that

$$\text{cov}[\mathbf{y}] = \text{cov}[A\mathbf{x} + \mathbf{b}] = A\text{cov}[\mathbf{x}]A^\top = A\mathbf{\Sigma}A^\top.$$

Part 1:

Since \mathbb{E} is a weighted sum of all random variable, \mathbb{E} is a linear operator. First prove that

$$\mathbb{E}(aX + b) = a\mathbb{E}(X) + b$$

for a random variable.

If X is a random variables, and a and b are constants,

Case 1: if X is discrete:

$$\begin{aligned}\mathbb{E}[aX + b] &= \sum_{x \in X} (ax + b)p(x) \\ &= a \sum_{x \in X} xp(x) + \sum_{x \in X} bp(x) \\ &= a\mathbb{E}[X] + b\end{aligned}$$

Case 2: if X is continuous:

$$\begin{aligned}\mathbb{E}[aX + b] &= \int_{\mathbb{R}} (ax + b)p(x)dx \\ &= a \int_{\mathbb{R}} xp(x)dx + b \int_{\mathbb{R}} p(x)dx \\ &= a\mathbb{E}[X] + b\end{aligned}$$

Now, we show that this is true for a random vector: Let A be a constant $m \times n$ matrix, \mathbf{x} be a length n random vector, and \mathbf{b} be a length m constant vector. Consider a single

element in random vector \mathbf{y} :

$$\begin{aligned}\mathbb{E}[y_i] &= \mathbb{E}\left[\sum_{j=1}^n a_{i,j}x_j + b_i\right] \\ &= \sum_{j=1}^n a_{i,j}\mathbb{E}[x_j] + b_i\end{aligned}$$

Therefore we see that

$$\mathbb{E}[\mathbf{y}] = \mathbb{E}[A\mathbf{x} + \mathbf{b}] = A\mathbb{E}[\mathbf{x}] + \mathbf{b}$$

■

Part 2:

To prove this property, we first show that $\text{cov}[\mathbf{z} + \mathbf{b}] = \text{cov}[\mathbf{z}]$, then we show that $\text{cov}[A\mathbf{x}] = A\text{cov}[\mathbf{x}]A^T$.

For $\text{cov}[\mathbf{z} + \mathbf{b}] = \text{cov}[\mathbf{z}]$, let \mathbf{z} be a length n random vector and \mathbf{b} be a constant n -length vector. Let $\Sigma = \text{cov}[\mathbf{z} + \mathbf{b}]$.

$$\begin{aligned}\Sigma_{i,j} &= \text{cov}[z_i + b_i, z_j + b_j] \\ &= \mathbb{E}[(z_i + a_i) - \mathbb{E}[z_i + a_i]]((z_j + a_j) - \mathbb{E}[z_j + a_j])] \\ &= \mathbb{E}[(z_i + a_i - a_i - \mathbb{E}[z_i])(z_j + a_j - a_j - \mathbb{E}[z_j])] \\ &= \mathbb{E}[(z_i - \mathbb{E}[z_i])(z_j - \mathbb{E}[z_j])] \\ &= \text{cov}[z_i, z_j]\end{aligned}$$

Therefore, we see that $\text{cov}[\mathbf{z} + \mathbf{b}] = \text{cov}[\mathbf{z}]$.

For $\text{cov}[A\mathbf{x}] = A\text{cov}[\mathbf{x}]A^T$, let A be a $m \times n$ matrix and let \mathbf{x} be a length n vector. Let $\Sigma' = \text{cov}[A\mathbf{x}]$. Consider element (i, j) in Σ' .

$$\begin{aligned}\Sigma'_{i,j} &= \text{cov}\left(\sum_{k=1}^n a_{i,k}x_k, \sum_{k=1}^n a_{j,k}x_k\right) \\ &= \mathbb{E}\left[\left(\sum_{k=1}^n a_{i,k}x_k - \mathbb{E}\left[\sum_{k=1}^n a_{i,k}x_k\right]\right)\left(\sum_{k=1}^n a_{j,k}x_k - \mathbb{E}\left[\sum_{k=1}^n a_{j,k}x_k\right]\right)\right] \\ &= \mathbb{E}\left[\left(\sum_{k=1}^n a_{i,k}x_k - \sum_{k=1}^n a_{i,k}\mathbb{E}[x_k]\right)\left(\sum_{k=1}^n a_{j,k}x_k - \sum_{k=1}^n a_{j,k}\mathbb{E}[x_k]\right)\right] \\ &= \mathbb{E}\left[\sum_{k=1}^n a_{i,k}(x_k - \mathbb{E}[x_k])(x_k - \mathbb{E}[x_k])\sum_{k=1}^n a_{j,k}\right] \\ &= \sum_{k=1}^n a_{i,k}(\mathbb{E}[(x_k - \mathbb{E}[x_k])(x_k - \mathbb{E}[x_k])])\sum_{k=1}^n a_{j,k}\end{aligned}$$

From this, we see that $\Sigma' = A\text{cov}[\mathbf{x}]A^T$, If we let $\text{cov}[\mathbf{x}] = \Sigma$, then $\Sigma' = A\Sigma A^T$.

Since we have proven both of these properties, we can simply substitute \mathbf{z} for $A\mathbf{x}$:

$$\begin{aligned}\text{cov}[A\mathbf{x} + \mathbf{b}] &= \text{cov}[\mathbf{z} + \mathbf{b}] \\ &= \text{cov}[\mathbf{z}] \\ &= \text{cov}[A\mathbf{x}] \\ &= A\Sigma A^T\end{aligned}$$

■

■

2 Given the dataset $\mathcal{D} = \{(x, y)\} = \{(0, 1), (2, 3), (3, 6), (4, 8)\}$

- Find the least squares estimate $y = \theta^\top \mathbf{x}$ by hand using Cramer's Rule.
- Use the normal equations to find the same solution and verify it is the same as part (a).
- Plot the data and the optimal linear fit you found.
- Find randomly generate 100 points near the line with white Gaussian noise and then compute the least squares estimate (using a computer). Verify that this new line is close to the original and plot the new dataset, the old line, and the new line.

(a)

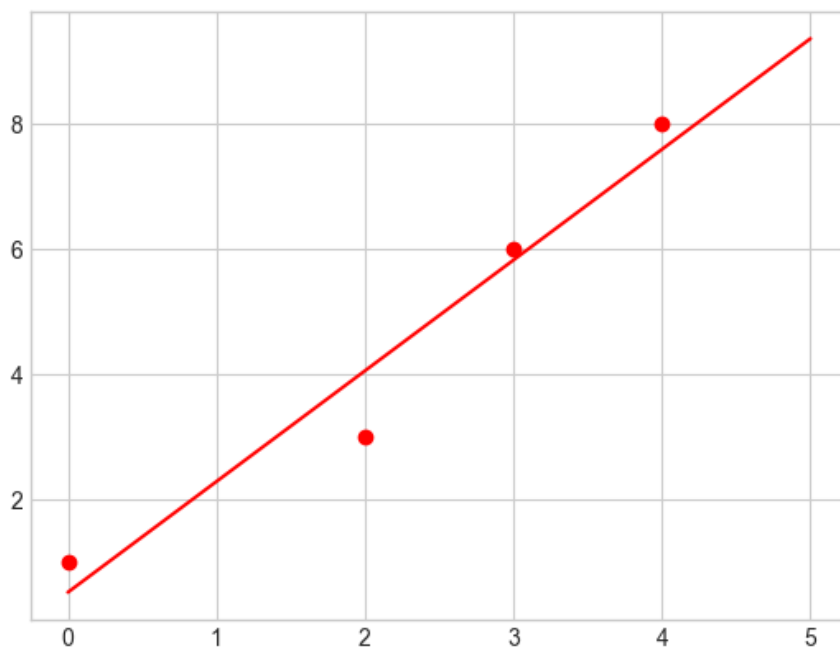
	x_i	y_i	x_i^2	$x_i y_i$
	0	1	0	0
	2	3	4	6
	3	6	9	18
	4	8	16	32
sum	9	18	29	56

$$\begin{aligned}
 m &= \frac{n \sum_{i=1}^n x_i y_i - (\sum_{i=1}^n x_i) (\sum_{i=1}^n y_i)}{(n \sum_{i=1}^n x_i^2) - (\sum_{i=1}^n x_i)^2} \\
 &= \frac{4 \cdot 56 - 9 \cdot 18}{4 \cdot 29 - 81} \\
 &= \boxed{\frac{62}{35}} \\
 b &= \frac{(\sum_{i=1}^n x_i^2) (\sum_{i=1}^n y_i) - (\sum_{i=1}^n x_i) (\sum_{i=1}^n x_i y_i)}{n (\sum_{i=1}^n x_i^2) - (\sum_{i=1}^n x_i)^2} \\
 &= \frac{29 \cdot 18 - 9 \cdot 56}{4 \cdot 29 - 81} \\
 &= \boxed{\frac{18}{35}}
 \end{aligned}$$

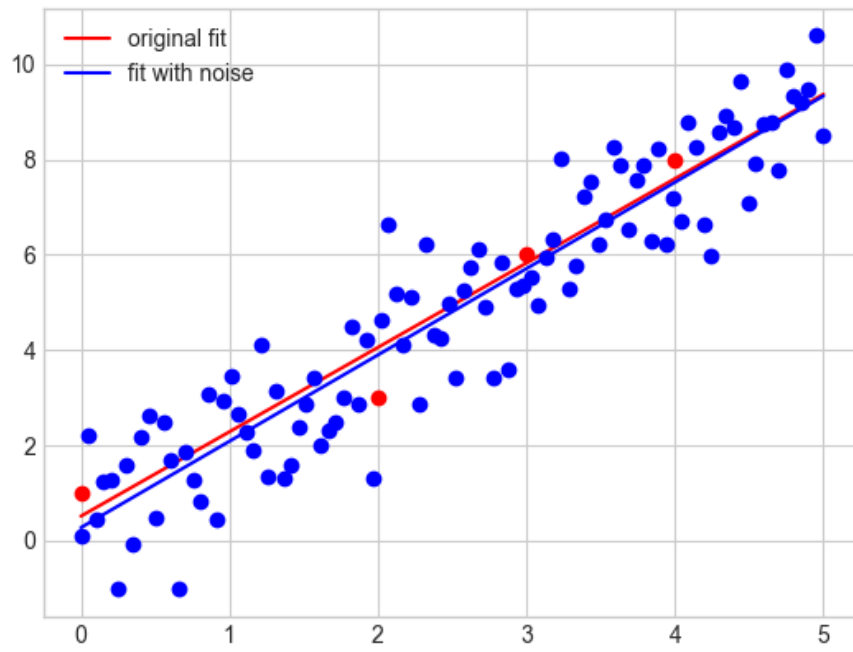
(b)

$$\begin{aligned}\theta &= (X^T X)^{-1} X^T \mathbf{y} \\&= \begin{bmatrix} 4 & 9 \\ 9 & 29 \end{bmatrix}^{-1} \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & 2 & 3 & 4 \end{bmatrix} \begin{bmatrix} 1 \\ 3 \\ 6 \\ 8 \end{bmatrix} \\&= \frac{1}{35} \begin{bmatrix} 29 & -9 \\ -9 & 4 \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & 2 & 3 & 4 \end{bmatrix} \begin{bmatrix} 1 \\ 3 \\ 6 \\ 8 \end{bmatrix} \\&= \frac{1}{35} \begin{bmatrix} 29 & 11 & 2 & -7 \\ -9 & -1 & 3 & 7 \end{bmatrix} \begin{bmatrix} 1 \\ 3 \\ 6 \\ 8 \end{bmatrix} \\&= \frac{1}{35} \begin{bmatrix} 18 \\ 62 \end{bmatrix} \\&= \begin{bmatrix} 18/35 \\ 62/35 \end{bmatrix}\end{aligned}$$

(c) See python file hw1pr2.py



(d) See python file hw1pr2.py



■