

# EECS 127/227AT Optimization Models in Engineering

## Spring 2020

## Homework 1

**This homework is due Friday, January 31, 2020 at 23:00 (11pm).**

**Self grades are due Friday, February 7, 2020 at 23:00 (11pm).**

**Submission Format:** Your homework submission should consist of a single PDF file that contains all of your answers (any handwritten answers should be scanned).

### 1. Course setup

Please complete the following steps to get access to all course resources.

- Visit the course website at <http://www.eecs127.xyz/> and familiarize yourself with the syllabus.
- Register for the class Piazza at <https://piazza.com/class/k5j2k0fnzj91vh>.
- Register for the class Gradescope at <https://www.gradescope.com/login> using code **MYJ5YZ**.
- When are self grades due for this homework? In general, when are self grades due? Where can you find the link to generate self grades? Where should they be submitted?
- How many homework drops do you get? Are there exceptions?

### 2. What prerequisites have you taken?

The prerequisites for this course are

- EECS 16A & 16B (Designing Information Devices and Systems I & II) **OR** MATH 54 (Linear Algebra & Differential Equations),
- CS 70 (Discrete Mathematics & Probability Theory), and
- MATH 53 (Multivariable Calculus).

Please list which of these courses you have taken. If you have taken equivalent courses at a separate institution, please list them here.<sup>1</sup>

We are updating the course material this semester and will rely on knowledge from these prerequisite courses. If you feel shaky on this material, please use the first week to reacquaint yourself with it.

### 3. Vector spaces and rank

The *rank* of a  $m \times n$  matrix  $A$ ,  $\text{rk}(A)$ , is the dimension of its *range*<sup>2</sup>,  $\mathcal{R}(A) := \{A\vec{x} : \vec{x} \in \mathbb{R}^n\}$ .

- Assume that  $A \in \mathbb{R}^{m \times n}$  takes the form  $A = \vec{u}\vec{v}^\top$ , with  $\vec{u} \in \mathbb{R}^m$ ,  $\vec{v} \in \mathbb{R}^n$ ,  $\vec{v} \neq \vec{0}$ . (Note that a matrix of this form is known as a *dyad*.) Find rank of  $A$ . *Hint:* Consider the quantity  $A\vec{x}$  for arbitrary  $\vec{x}$ , i.e., what happens when you multiply any vector by matrix  $A$ .

<sup>1</sup>If you are unsure of course material overlap, please refer to the EECS 16A, EECS 16B, and CS 70 websites (<https://www.eecs16a.org/>, <https://www.eecs16b.org/>, and <http://www.eecs70.org/>, respectively) and the MATH 53 textbook (*Multivariable Calculus* by James Stewart).

<sup>2</sup>Also called span.

- (b) Show that for arbitrary  $A, B \in \mathbb{R}^{m \times n}$ ,

$$\text{rk}(A + B) \leq \text{rk}(A) + \text{rk}(B),$$

i.e., the rank of the sum of two matrices is less than or equal to the sum of their ranks.

*Hint:* First, show that  $\mathcal{R}(A + B) \subseteq \mathcal{R}(A) + \mathcal{R}(B)$ , meaning that any vector in the range of  $A + B$  can be expressed as the sum of two vectors, each in the range of  $A$  and  $B$ , respectively. Remember that for any matrix  $A$ ,  $\mathcal{R}(A)$  is a subspace, and for any two subspaces  $S_1$  and  $S_2$ ,  $\dim(S_1 + S_2) \leq \dim(S_1) + \dim(S_2)$ .<sup>3</sup> (Note that the sum of vector spaces  $S_1 + S_2$  is not equivalent to  $S_1 \cup S_2$ , but is defined as  $S_1 + S_2 := \{\vec{s}_1 + \vec{s}_2 \mid \vec{s}_1 \in S_1, \vec{s}_2 \in S_2\}$ .)

- (c) Consider an  $m \times n$  matrix  $A$  that takes the form  $A = UV^\top$ , with  $U \in \mathbb{R}^{m \times k}$ ,  $V \in \mathbb{R}^{n \times k}$ . Show that the rank of  $A$  is less or equal than  $k$ . *Hint:* Use parts (a) and (b), and remember that this decomposition can also be written as the *dyadic expansion*

$$A = UV^\top = \begin{bmatrix} \vec{u}_1 & \dots & \vec{u}_k \end{bmatrix} \begin{bmatrix} \vec{v}_1^\top \\ \vdots \\ \vec{v}_k^\top \end{bmatrix} = \sum_{i=1}^k \vec{u}_i \vec{v}_i^\top,$$

for  $U = [\vec{u}_1 \ \dots \ \vec{u}_k]$  and  $V = [\vec{v}_1 \ \dots \ \vec{v}_k]$ .

#### 4. Diagonalization and singular value decomposition

Let matrix  $A = \begin{bmatrix} 0 & 1 \\ \frac{1}{2} & \frac{1}{2} \end{bmatrix}$ .

- (a) Compute the eigenvalues and associated eigenvectors of  $A$ .

Note that the expressions above are valid eigenvectors for any nonzero values of  $\alpha_1$  and  $\alpha_2$ .

- (b) Express  $A$  as  $P\Lambda P^{-1}$ , where  $\Lambda$  is a diagonal matrix and  $PP^{-1} = I$ . State  $P$ ,  $\Lambda$ , and  $P^{-1}$  explicitly.
- (c) Compute  $\lim_{k \rightarrow \infty} A^k$ .
- (d) Give the singular values  $\sigma_1$  and  $\sigma_2$  of  $A$ .

#### 5. Determinants

Consider a unit box  $\mathcal{B}$  in  $\mathbb{R}^2$  — i.e., the square with corners  $\begin{bmatrix} 0 \\ 0 \end{bmatrix}$ ,  $\begin{bmatrix} 0 \\ 1 \end{bmatrix}$ ,  $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$ , and  $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$ . Define  $A(\mathcal{B})$  as the parallelogram generated by applying matrix  $A$  to every point in  $\mathcal{B}$ .

- (a) For  $A = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}$ , calculate the location of each corner of  $A(\mathcal{B})$ .

- (b) Write the area of  $A(\mathcal{B})$  as a function of  $\det A$ . *Hint:* How are the basis vectors  $\begin{bmatrix} 0 \\ 1 \end{bmatrix}$  and  $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$  transformed by the matrix multiplication?

- (c) Calculate the area of  $A(\mathcal{B})$  for each of the following values of  $A$ .

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<sup>3</sup>This fact can be proved by taking a basis of  $S_1$  and extending it to a basis of  $S_2$  (during which we can only add at most  $\dim(S_2)$  basis vectors). This extended basis must now also be a basis of  $S_1 + S_2$ . Thus,  $\dim(S_1 + S_2) \leq \dim(S_1) + \dim(S_2)$ .

- i.  $A = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}$
- ii.  $A = \begin{bmatrix} 2 & 1 \\ 4 & 3 \end{bmatrix}$
- iii.  $A = \begin{bmatrix} 1 & 2 \\ 2 & 4 \end{bmatrix}$
- iv.  $A = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$

## 6. Least squares

The Michaelis-Menten model for enzyme kinetics relates the rate  $y$  of an enzymatic reaction to the concentration  $x$  of a substrate, as follows:

$$y = \frac{\beta_1 x}{\beta_2 + x},$$

for constants  $\beta_1, \beta_2 > 0$ .

- (a) Show that the model can be expressed as a linear relation between the values  $1/y = y^{-1}$  and  $1/x = x^{-1}$ . Specifically, give an equation of the form  $y^{-1} = w_1 + w_2 x^{-1}$ , specifying the values of  $w_1$  and  $w_2$  in terms of  $\beta_1$  and  $\beta_2$ .
- (b) In general, reaction parameters  $\beta_1$  and  $\beta_2$  (and, thus,  $w_1$  and  $w_2$ ) are not known a priori and must be fitted from data — for example, using least squares. Suppose you collect  $m$  measurements  $(x_i, y_i)$ ,  $i = 1, \dots, m$  over the course of a reaction. Formulate the least squares problem

$$\vec{w}^* = \arg \min_{\vec{w}} \|X\vec{w} - \vec{y}\|_2^2,$$

where  $\vec{w}^* = [w_1^* \ w_2^*]^\top$ , and you must specify  $X \in \mathbb{R}^{m \times 2}$  and  $\vec{y} \in \mathbb{R}^m$ . Specifically, your solution should include explicit expressions for  $X$  and  $\vec{y}$  as a function of  $(x_i, y_i)$  values and a final expression for  $\vec{w}^*$  in terms of  $X$  and  $\vec{y}$ , which should contain only matrix multiplications, transposes, and inverses.

- (c) Assume that we have used the above procedure to calculate values for  $w_1^*$  and  $w_2^*$ , and we now want to estimate  $\hat{\vec{\beta}} = [\hat{\beta}_1 \ \hat{\beta}_2]^\top$ . Write an expression for  $\hat{\vec{\beta}}$  in terms of  $w_1^*$  and  $w_2^*$ .

## 7. Homework process

Whom did you work with on this homework? List the names and SIDs of your group members.