

Matrix Algebra - Row Reduction - Solutions to Linear Systems

1. We known, by counterexamples, that matrix multiplication is a non-commutative binary operation. We define a commutator as a function, which takes in two matrices and returns one and is, in some sense, a measure of the binary operations lack of commutativity. We define the commutator and anti-commutation functions on matrices as,

$$[A, B] = AB - BA, \quad \{A, B\} = AB + BA. \quad (1)$$

The following matrices are the so-called Pauli spin matrices and have interesting commutation and anti-commutation relations and gives us fine setting to practice our matrix algebra. <sup>1</sup>

$$\sigma_1 = \sigma_x = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad \sigma_2 = \sigma_y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}, \quad \sigma_3 = \sigma_z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}. \quad (2)$$

Using the previous definitions show the following:

- (a)  $\sigma_i^2 = \mathbf{I}$  for  $i = 1, 2, 3$ . <sup>2</sup>  
(b)  $[\sigma_i, \sigma_j] = 2i \sum_{k=1}^3 \epsilon_{ijk} \sigma_k$  for  $i = 1, 2, 3$  and  $j = 1, 2, 3$ . <sup>3</sup>  
(c)  $\{\sigma_i, \sigma_j\} = 2\delta_{ij} \mathbf{I}$  for  $i = 1, 2, 3$  and  $j = 1, 2, 3$ . <sup>4</sup>

2. Given the linear system

$$\begin{aligned} 6x_1 + 18x_2 - 4x_3 &= 20 \\ -x_1 - 3x_2 + 8x_3 &= 4 \\ 5x_1 + 15x_2 - 9x_3 &= 11. \end{aligned}$$

Determine the general solution set to the linear system and describe this set geometrically. <sup>5</sup>

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<sup>1</sup>The Pauli spin matrices are a set of Hermitian matrices, which are *unitary*. They have found several uses including describing strong interaction symmetries in particle physics and representing logic gates in quantum information theory.

<sup>2</sup>This statement encapsulates both the symmetric unitary properties of the matrices.

<sup>3</sup>Here we are using the so-called Levi-Civita symbol. This symbol is used to encode the following commonly encountered information,

$$\epsilon_{ijk} = \begin{cases} 1, & \text{if } (i, j, k) \text{ is } (1, 2, 3), (2, 3, 1) \text{ or } (3, 1, 2), \\ -1, & \text{if } (i, j, k) \text{ is } (3, 2, 1), (1, 3, 2) \text{ or } (2, 1, 3), \\ 0, & \text{if } i = j \text{ or } j = k \text{ or } k = i \end{cases} \quad (3)$$

<sup>4</sup>Here we use the so-called Kronecker delta function, which encodes the, also common, information,

$$\delta_{ij} = \begin{cases} 1, & \text{if } i = j, \\ 0, & \text{if } i \neq j \end{cases} \quad (4)$$

<sup>5</sup>Another way to ask this: 'Are there a set of points in  $\mathbb{R}^3$  where the three previous planes intersect one another? If so, then what geometric object do the collection of these points form?' I hope that it is clear that if there a solution then these points could only form a point, line, or plane, depending on the number of free-variables you find by row-reduction.

3. Given the following augmented matrix

$$\left[ \begin{array}{cc|c} 1 & 3 & 2 \\ 3 & h & k \end{array} \right].$$

Determine  $h$  and  $k$  such that the corresponding linear system: <sup>6</sup>

- (a) Is inconsistent.
- (b) Is consistent with infinitely many solutions.
- (c) Is consistent with a unique solution.

4. Suppose  $a, b, c,$  and  $d$  are constants such the system

$$ax_1 + bx_2 = 0$$

$$cx_1 + dx_2 = 0$$

with  $a \neq 0$ . Using row reduction solve for  $x_1$  and  $x_2$  and list any constraints needed, on  $a, b, c, d,$  for unique solutions. <sup>7</sup>

5. Given the matrix  $\mathbf{A}$  and the vector  $\mathbf{b}$ .

$$\mathbf{A} = \begin{bmatrix} 5 & 3 \\ -4 & 7 \\ 9 & -2 \end{bmatrix}, \quad \mathbf{b} = \begin{bmatrix} 22 \\ 20 \\ 15 \end{bmatrix}$$

Are there constants  $x_1$  and  $x_2$  such that  $\mathbf{b}$  can be formed as a linear combination of the columns of  $\mathbf{A}$ ? If so then what are they?<sup>8</sup>

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<sup>6</sup>Hint: You will not need to find the reduced row-echelon form. Only the row-echelon form is needed.

<sup>7</sup>What we are trying to do here is find conditions on the coefficients  $a, b, c, d$  that will guarantee a single solution to the system. Remember that in 1-D we require that to have a unique solution to,  $ax = 0$ ,  $a$  must be different from zero.

<sup>8</sup>Another way of asking this: 'Is  $\mathbf{b}$  a *linear combination* of the columns of  $\mathbf{A}$ ?'