Origins of Matrix/Vector and Matrix/Matrix Mutiplication

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1 Algebraic properties of Matrices

Why is matrix/vector and matrix/matrix multiplication defined the way it is? One motivation is to try to extend the (albeit trivial) solution of linear equations in 1 dimension to n dimensions. To do this, we go through the solution of the 1 dimensional case in careful detail.

The scalar problem is:

$$a\,x = b \tag{1}$$

Here is a very explicit solution keeping an eye towards generalization.

$$\begin{aligned}
a\,x &= b && (2)\\
a^{-1}(a\,x) &= a^{-1}b && \text{(Multiply by Inverse)} \quad (3)\\
(a^{-1}a)x &= a^{-1}b && \text{(Use associativity of multiplication)} \quad (4)\\
1\,x &= a^{-1}b && \text{(What Inverse multiplication does)} \quad (5)\\
x &= a^{-1}b && \text{(What identity multiplication does)} \quad (6)
\end{aligned}$$

The multi-dimensional problem has a lot more variables and coefficients. To start, we need to be more systematic about the naming of these coefficients. With this in mind, the multi-dimensional linear problem can be written:

$$\begin{aligned}
a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n &= b_1\\
a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n &= b_2\\
\cdots &= \cdots\\
a_{n1}x_1 + a_{n2}x_2 + \cdots + a_{nn}x_n &= b_n
\end{aligned}$$

Here, a_{ij} is the coefficient in the i^{th} row and j^{th} column.

To make this look like the 1 dimensional case, we need to think of the b's are a single unit. Our single unit will be the *vector* of the b's.

The the multi-dimensional case can be rewritten in vector terms as:

$$\begin{bmatrix} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n \\ \cdots \\ a_{n1}x_1 + a_{n2}x_2 + \cdots + a_{nn}x_n \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{bmatrix} \tag{7}$$

Two things need to be done: treat the x's as a unit – as we did with the b's and separate the a coefficients from the x's. This must be done formally and yet have the same meaning as the original problem formulation. This is done in the most natural of ways:

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & & & \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{bmatrix} \tag{8}$$

Taking the (matrix) collection of a's to be A; the (vector) collection of x's to be $\mathbf{x}$; and the collection of the b's to be $\mathbf{b}$; we may write (8) as:

$$A\,\mathbf{x} = \mathbf{b} \tag{9}$$

This now looks like the scalar problem, (1). How do we make sense of this matrix/vector syntax? It should have the proper meaning; that is, (8) should have the same meaning as (7).

Examining (8) and the left hand side of (7), gives us our definition of matrix/vector multiplication:

$$[A\,\mathbf{x}]_i \equiv \sum_{j=1}^{n} A_{ij}x_j \tag{10}$$

That is, A acts on a vector, $\mathbf{x}$, to create a new vector, $A\,\mathbf{x}$, whose i^{th} entry is the i^{th} entry of the left hand side of (7).

Another way to write this is:

$$A\mathbf{x} = \sum_{i=1}^{n} x_i \mathbf{A}^i \tag{11}$$

Here, $\mathbf{A}^i$ is the i^{th} column of A. Applying A to the special vectors, $\mathbf{e}_i$ – which are 0 everywhere except at i where they are 1 – we see that $A\,\mathbf{e}_i = \mathbf{A}^i$. Consequently, this matrix/vector multiplication determines A uniquely – if there is another matrix, its columns would have to match A.

To complete the solution outline, matrix/matrix multiplication is needed via (4). How must this be defined? Well, we need to make sense of:

$$(A^{-1}A)\mathbf{x} = A^{-1}(A\,\mathbf{x}) \tag{12}$$

This involves the inverse of the matrix A, which we also need to define. Also, the above says nothing about arbitrary matrix multiplication between to $n \times n$ matrices, A and B. Let us generalize the requirement of

(12) and define matrix multiplication of two $n \times n$ matrices as:[1]

$$(B\,A)\mathbf{x} \quad \equiv \quad B(A\,\mathbf{x}) \tag{13}$$

This definition would mean that $B\,A$ is a new $n \times n$ matrix whose i^{th} entry – when acting on an arbitrary vector $\mathbf{x}$ – is (using (10) twice):

$$[(B\,A)\mathbf{x}]_i \quad = \quad \sum_{k=1}^{n} B_{ik} \left(\sum_{j=1}^{n} A_{kj} x_j \right) \tag{14}$$

Using (10) on the left hand side yields:

$$\sum_{j=1}^{n} (B\,A)_{ij} x_j \quad = \quad \sum_{k=1}^{n} B_{ik} \left(\sum_{j=1}^{n} A_{kj} x_j \right) \tag{15}$$

Or,

$$\sum_{j=1}^{n} (B\,A)_{ij} x_j \quad = \quad \sum_{k=1}^{n} \sum_{j=1}^{n} B_{ik} A_{kj} x_j \tag{16}$$

Changing the order of summation on the right hand side, this is:

$$\sum_{j=1}^{n} (B\,A)_{ij} x_j \quad = \quad \sum_{j=1}^{n} \left(\sum_{k=1}^{n} B_{ik} A_{kj} \right) x_j \tag{17}$$

But this says that the $i^{\text{th}}, j^{\text{th}}$ entry of the matrix $(B\,A)$ is given (in terms of A and B) as:

$$(B\,A)_{ij} \quad = \quad \sum_{k=1}^{n} B_{ik} A_{kj} \tag{18}$$

To see that this follows, notice that (17) must hold for all vectors $\mathbf{x}$. Setting $\mathbf{x}$ to the successive $\mathbf{e}_i$ vectors defined above yields (18).

By (6) we need to identify a $n \times n$ matrix which serves as an identity (in terms of matrix/vector multiplication). Let us suppose that we have such a matrix and let's call it I. Then we must have $I\,\mathbf{x} = \mathbf{x}$ for all $\mathbf{x} \in R^n$. Then, it is not hard to see that $I\,\mathbf{e}_i = \mathbf{e}_i$. Also $I\,\mathbf{e}_i = I^i$. Therefore, I must have the property that $\mathbf{I^i} = \mathbf{e}_i$. Consequently I must have the form:

$$I \quad = \quad \begin{bmatrix} 1 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & \cdots & 1 \end{bmatrix} \tag{19}$$

That is $I_{ij} = \delta_{ij}$.[2] We have shown that the only candidate matrix that has the identity property, is the

[1] We know from above that defining how a given matrix acts on all vector via matrix/vector multiplication uniquely determines the matrix. So, this is a proper definition of matrix/matrix multiplication.

[2] $\delta_{ij} = \begin{cases} 1 & \text{if } i = j; \\ 0 & \text{otherwise.} \end{cases}$

matrix, I. That is, if there is an identity matrix, it must be I. Does it satisfy the property of being an identity matrix (again, in the matrix/vector multiplication world)? Do we have $I\mathbf{x} = \mathbf{x}$ for all $\mathbf{x} \in R^n$? Using the definition of matrix/vector multiplication, (10), we have for any given, i:

$$\begin{aligned} [I\mathbf{x}]_i &= \sum_{i=1}^{n} I_{ij} x_j \\ &= \sum_{i=1}^{n} \delta_{ij} x_j \\ &= x_i \\ &= [\mathbf{x}]_i \end{aligned} \tag{20}$$

One can show that this identity matrix, I, is also the identity operator for matrix/matrix multiplication.

The only thing left is to know when a matrix inverse exists and how to compute it.

2 Qualitative Features of Solutions

Here is what we can say about the scalar problem:

Unique Solution: If a^{-1} exists ($a \neq 0$), there is a unique solution.

No Solution; If a^{-1} does not exist ($a = 0$) *AND* $b \neq 0$, then there is no solution.

Infinite Solutions; If a^{-1} does not exist ($a = 0$) *AND* $b = 0$, then there are an infinite number of solutions.

Here is the analog of this solution categorization for the multi-dimensional case:

Unique Solution: If A^{-1} exists, there is a unique solution.

No Solution; If A^{-1} does not exist *AND* $\mathbf{b} \notin \mathcal{R}(A)$ ($\mathbf{b} \notin \mathcal{N}(A^T)^{\perp}$), then there is no solution.

No Solution; If A^{-1} does not exist *AND* $\mathbf{b} \in \mathcal{R}(A)$ ($\mathbf{b} \in \mathcal{N}(A^T)^{\perp}$), then there are an infinite number of solutions.