

Lecture 6: April 15, 2021

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1 Singular Value Decomposition

Let V, W be finite-dimensional inner product spaces and let $\varphi : V \rightarrow W$ be a linear transformation. Since the domain and range of φ are different, we cannot analyze it in terms of eigenvectors. However, we can use the spectral theorem to analyze the operators $\varphi^* \varphi : V \rightarrow V$ and $\varphi \varphi^* : W \rightarrow W$ and use their eigenvectors to derive a nice decomposition of φ . This is known as the singular value decomposition (SVD) of φ .

Proposition 1.1 *Let $\varphi : V \rightarrow W$ be a linear transformation. Then $\varphi^* \varphi : V \rightarrow V$ and $\varphi \varphi^* : W \rightarrow W$ are self-adjoint positive semidefinite linear operators with the same non-zero eigenvalues.*

Proof: The self-adjointness and positive semidefiniteness of the operators $\varphi \varphi^*$ and $\varphi^* \varphi$ follows from the exercise characterizing positive semidefinite operators in the previous lecture. Specifically, we can see that for any $w_1, w_2 \in W$,

$$\langle w_1, \varphi \varphi^*(w_2) \rangle = \langle w_1, \varphi(\varphi^*(w_2)) \rangle = \langle \varphi^*(w_1), \varphi^*(w_2) \rangle = \langle \varphi \varphi^*(w_1), w_2 \rangle .$$

This gives that $\varphi \varphi^*$ is self-adjoint. Similarly, we get that for any $w \in W$

$$\langle w, \varphi \varphi^*(w) \rangle = \langle w, \varphi(\varphi^*(w)) \rangle = \langle \varphi^*(w), \varphi^*(w) \rangle \geq 0 .$$

This implies that the Rayleigh quotient $\mathcal{R}_{\varphi \varphi^*}$ is non-negative for any $w \neq 0$ which implies that $\varphi \varphi^*$ is positive semidefinite. The proof for $\varphi^* \varphi$ is identical (using the fact that $(\varphi^*)^* = \varphi$).

Let $\lambda \neq 0$ be an eigenvalue of $\varphi^* \varphi$. Then there exists $v \neq 0$ such that $\varphi^* \varphi(v) = \lambda \cdot v$. Applying φ on both sides, we get $\varphi \varphi^*(\varphi(v)) = \lambda \cdot \varphi(v)$. However, note that if $\lambda \neq 0$ then $\varphi(v)$ cannot be zero (why?) Thus $\varphi(v)$ is an eigenvector of $\varphi \varphi^*$ with the same eigenvalue λ . ■

We can notice the following from the proof of the above proposition.

Proposition 1.2 *Let v be an eigenvector of $\varphi^* \varphi$ with eigenvalue $\lambda \neq 0$. Then $\varphi(v)$ is an eigenvector of $\varphi \varphi^*$ with eigenvalue λ . Similarly, if w is an eigenvector of $\varphi \varphi^*$ with eigenvalue $\lambda \neq 0$, then $\varphi^*(w)$ is an eigenvector of $\varphi^* \varphi$ with eigenvalue λ .*

We can also conclude the following.

Proposition 1.3 *Let the subspaces V_λ and W_λ be defined as*

$$V_\lambda := \{v \in V \mid \varphi^* \varphi(v) = \lambda \cdot v\} \text{ and } W_\lambda := \{w \in W \mid \varphi \varphi^*(w) = \lambda \cdot w\}.$$

Then for any $\lambda \neq 0$, $\dim(V_\lambda) = \dim(W_\lambda)$.

Using the above properties, we can prove the following useful proposition, which extends the concept of eigenvectors to cases when we have $\varphi : V \rightarrow W$ and it might not be possible to define eigenvectors since $V \neq W$ (also φ may not be self-adjoint so we may not get orthonormal eigenvectors).

Proposition 1.4 *Let $\sigma_1^2 \geq \sigma_2^2 \geq \dots \geq \sigma_r^2 > 0$ be the non-zero eigenvalues of $\varphi^* \varphi$, and let v_1, \dots, v_r be a corresponding orthonormal eigenvectors (since $\varphi^* \varphi$ is self-adjoint, these are a subset of some orthonormal eigenbasis). For w_1, \dots, w_r defined as $w_i = \varphi(v_i) / \sigma_i$, we have that*

1. $\{w_1, \dots, w_r\}$ form an orthonormal set.

2. For all $i \in [r]$

$$\varphi(v_i) = \sigma_i \cdot w_i \text{ and } \varphi^*(w_i) = \sigma_i \cdot v_i.$$

Proof: For any $i, j \in [r], i \neq j$, we note that

$$\begin{aligned} \langle w_i, w_j \rangle &= \left\langle \frac{\varphi(v_i)}{\sigma_i}, \frac{\varphi(v_j)}{\sigma_j} \right\rangle = \frac{1}{\sigma_i \sigma_j} \cdot \langle \varphi(v_i), \varphi(v_j) \rangle = \frac{1}{\sigma_i \sigma_j} \cdot \langle \varphi^* \varphi(v_i), v_j \rangle \\ &= \frac{\sigma_i}{\sigma_j} \cdot \langle v_i, v_j \rangle = 0. \end{aligned}$$

Thus, the vectors $\{w_1, \dots, w_r\}$ form an orthonormal set. We also get $\varphi(v_i) = \sigma_i \cdot w_i$ from the definition of w_i . For proving $\varphi^*(w_i) = v_i$, we note that

$$\varphi^*(w_i) = \varphi^* \left(\frac{\varphi(v_i)}{\sigma_i} \right) = \frac{1}{\sigma_i} \cdot \varphi^* \varphi(v_i) = \frac{\sigma_i^2}{\sigma_i} \cdot v_i = \sigma_i \cdot v_i,$$

which completes the proof. ■

The values $\sigma_1, \dots, \sigma_r$ are known as the (non-zero) singular values of φ . For each $i \in [r]$, the vector v_i is known as the right singular vector and w_i is known as the left singular vector corresponding to the singular value σ_i .

Proposition 1.5 *Let r be the number of non-zero eigenvalues of $\varphi^* \varphi$. Then,*

$$\text{rank}(\varphi) = \dim(\text{im}(\varphi)) = r.$$

Using the above, we can write φ in a particularly convenient form. We first need the following definition.

Definition 1.6 Let V, W be inner product spaces and let $v \in V, w \in W$ be any two vectors. The outer product of w with v , denoted as $|w\rangle\langle v|$, is a linear transformation from V to W such that

$$|w\rangle\langle v|(u) := \langle v, u \rangle \cdot w.$$

In matrix form, over the reals, the outer product of w with v is the rank-1 matrix wv^T , as opposed to the inner product $w^T v$. And then the statement is that $(wv^T)u = w(v^T u)$.

Note that if $\|v\| = 1$, then $|w\rangle\langle v|(v) = w$ and $|w\rangle\langle v|(u) = 0$ for all $u \perp v$.

Exercise 1.7 Show that for any $v \in V$ and $w \in W$, we have

$$\text{rank}(|w\rangle\langle v|) = \dim(\text{im}(|w\rangle\langle v|)) = 1.$$

We can then write $\varphi : V \rightarrow W$ in terms of outer products of its singular vectors.

Proposition 1.8 Let V, W be finite dimensional inner product spaces and let $\varphi : V \rightarrow W$ be a linear transformation with non-zero singular values $\sigma_1, \dots, \sigma_r$, right singular vectors v_1, \dots, v_r and left singular vectors w_1, \dots, w_r . Then,

$$\varphi = \sum_{i=1}^r \sigma_i \cdot |w_i\rangle\langle v_i|.$$

Exercise 1.9 If $\varphi : V \rightarrow V$ is a self-adjoint operator with $\dim(V) = n$, then the real spectral theorem proves the existence of an orthonormal basis of eigenvectors, say $\{v_1, \dots, v_n\}$ with corresponding eigenvalues $\lambda_1, \dots, \lambda_n$. Check that in this case, we can write φ as

$$\varphi = \sum_{i=1}^n \lambda_i \cdot |v_i\rangle\langle v_i|.$$

Note that while the above decomposition has possibly negative coefficients (the λ_i s), the singular value decomposition only has positive coefficients (the σ_i s).