Nuclear Norm stuff

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ABSTRACT

some cool stuff about the nuclear norm

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Singular Value Decomposition

Consider a real matrix $A \in \mathbb{R}^{m\times n}$. For any such matrix there are four fundamental subspaces associated with it. These are $null(A) \subset \mathbb{R}^n$, $null(A^T) \subset \mathbb{R}^m$, $col(A) \subset \mathbb{R}^m$, and $col(A^T) \subset \mathbb{R}^n$. It can easily be shown that $null(A) \perp col(A^T)$ and $null(A^T) \perp col(A)$ and furthermore are orthogonal complements of each other.

Lemma 0.0.1. *$null(A)$ and $col(A^T)$ are orthogonal complements in $\mathbb{R}^n$.*

Proof. Let $v \in null(A)$ and $u \in col(A^T)$. Then $\langle u, v\rangle = \langle A^T b, v\rangle$ for some $b \in \mathbb{R}^m$, so $\langle A^T b, v\rangle = (A^T b)^T v = b^T A v = b^T 0 = 0$. Thus, $null(A) \perp col(A^T)$. Since $dim(col(A^T)) = rank(A)$ the rank-nullity theorem tells us that the sum of the dimensions of $col(A^T)$ and $null(A)$ is n. So, every vector in $\mathbb{R}^n$ is in $null(A)$ or $col(A^T)$. Thus they are orthogonal complements. $\square$

Theorem 1. Let $A \in \mathbb{R}^{m\times n}$. Then there exists $U \in \mathbb{R}^{m\times m}$, $V \in \mathbb{R}^{n\times n}$, $\Sigma \in \mathbb{R}^{m\times n}$ such that U, V are orthogonal and Σ is diagonal-like with $A = U\Sigma V^T$.

Proof.

Let $A \in \mathbb{R}^{m\times n}$ then define $L = A^T A \in R^{n\times n}$. Note that L is positive semi-definite since for $x \in \mathbb{R}^n$ we have $\langle Lx, x\rangle = \langle A^T A x, x\rangle = \langle Ax, Ax\rangle = \|Ax\|^2 \geq 0$. Similarly, define $M = AA^T \in \mathbb{R}^{m\times m}$ which is also positive semi-definite.

Let $x \in null(A)$ then $Ax = 0 \implies A^T A x = A^T 0 = 0 \implies Lx = 0 \implies x \in null(L)$.

Let $x \in null(L)$ then $Lx = 0 \implies \langle Lx, x\rangle = \langle 0, x\rangle = 0 \implies \langle A^T A x, x\rangle = 0 \implies \langle Ax, Ax\rangle = 0 \implies \|Ax\|^2 = 0 \implies Ax = 0$, so $x \in null(A)$ and $null(A) = null(L)$.

Consequently, we have $range(L) = range(L^T) = null(L)^\perp = null(A)^\perp = range(A^T)$.

Similarly, $range(M) = range(A)$ and $null(A^T) = null(M)$.

Since $rank(A) = rank(A^T)$ we have $rank(L) = rank(A^T) = rank(A) = rank(M) = \rho$.

Now we need to find orthonormal bases for $null(A) = null(L)$, $null(A^T) = null(M)$, $range(A^T) = range(L)$, and $range(A) = range(M)$.

Since L is positive semi-definite there exists an orthonormal basis for $null(L) = null(A)$ given by $\phi_1, ..., \phi_{N_A}$ which are eigenvectors of L corresponding to the eigenvalue 0.

Since M is positive semi-definite there exists an orthonormal basis for $null(M) = null(A^T)$ given by $\psi_1, ..., \psi_{N_A}$ which are eigenvectors of M corresponding to the eigenvalue 0.

Since L is positive semi-definite there exist positive eigenvalues $\lambda_1 \geq ... \geq \lambda_\rho > 0$ and their eigenvectors $v_1, ..., v_\rho$ form an orthonormal basis for $range(L) = range(A^T)$.

We have an orthonormal basis of $range(L) = range(A^T)$ consisting of eigenvectors $v_1, ..., v_\rho$ corresponding to eigenvalues $\lambda_1 \geq ... \geq \lambda_\rho > 0$. So, $Lv_j = \lambda_j v_j$. Define $w_j = Av_j$. Then $\langle w_i, w_j \rangle = \langle Av_i, Av_j \rangle = \langle v_i, A^T Av_j \rangle = \langle v_i, Lv_j \rangle = \langle v_i, \lambda_j v_j \rangle$. This equals 0 when $i \neq j$ and λ_j when $i = j$. So, $w_1, ...w_\rho$ are orthogonal, but $\|w_j\|^2 = \lambda_j$. Define $u_j = \frac{w_j}{\|w_j\|} = \frac{w_j}{\sqrt{\lambda_j}}$ then $u_1, ..., u_\rho$ form an orthonormal basis for $range(M) = range(A)$. Denote $\sigma_j = \sqrt{\lambda_j}$ we call these the singular values of A. Note that $u_j = \frac{w_j}{\sigma_j} = \frac{Av_j}{\sigma_j} \implies Av_j = \sigma_j u_j$ and $A^T u_j = \frac{A^T Av_j}{\sigma_j} = \frac{Lv_j}{\sigma_j} = \frac{\lambda_j v_j}{\sigma_j} = \sigma_j v_j$. This is the fundamental relation of singular values.

Now that we have orthonormal bases, we can construct the matrices $U = [u_1 ... u_\rho \, \psi_1 ... \psi_{N_{A^T}}] \in \mathbb{R}^{m \times m}$ and $V = [v_1 ... v_\rho \, \phi_1 ... \phi_{N_A}] \in \mathbb{R}^{n \times n}$. Note that both U and V are orthogonal since they are constructed from orthonormal column vectors. Then we have $AV = [Av_1 ... Av_\rho \, A\phi_1 ... A\phi_{N_A}] = [\sigma_1 u_1 ... \sigma_\rho u_\rho \, 0 ... 0]$. It follows that

$$U^T AV = \begin{bmatrix} u_1^T \\ \vdots \\ u_\rho^T \\ \psi_1^T \\ \vdots \\ \psi_{N_{A^T}}^T \end{bmatrix} \begin{bmatrix} \sigma_1 u_1 & ... & \sigma_\rho u_\rho & 0 & ... & 0 \end{bmatrix} = \begin{bmatrix} \sigma_1 & 0 & ... & 0 & 0 & ... & 0 \\ 0 & \sigma_2 & ... & 0 & 0 & ... & 0 \\ \vdots & & & & & & \\ 0 & 0 & ... & \sigma_\rho & 0 & ... & 0 \\ 0 & 0 & ... & 0 & 0 & ... & 0 \\ \vdots & & & & & & \\ 0 & 0 & ... & 0 & 0 & ... & 0 \end{bmatrix} = \Sigma \tag{0.0.1}$$

And by the orthogonality of U^T and V we have $A = U\Sigma V^T$.

□

Fenchel Conjugate

Definition 1. For any function $f : \mathbb{R}^n \to \overline{\mathbb{R}}$ the **Fenchel conjugate** $f^* : \mathbb{R}^n \to \overline{\mathbb{R}}$ is defined by

$$
\begin{aligned}
f^*(v) &= \sup\{\langle v, x\rangle - f(x) \mid x \in \mathbb{R}^n\} \\
f^*(v) &= \sup\{\langle v, x\rangle - f(x) \mid x \in \mathrm{dom}(f)\}
\end{aligned}
$$

Note that the Fenchel conjugate is always convex as it is the supremum of a family of affine functions, and it is order reversing in the sense that $f(x) \leq g(x)$ for all $x \in \mathbb{R}^n$ implies that $f^*(v) \geq g^*(v)$ since for all $v \in \mathbb{R}^n$.

$$f^*(v) = \sup\{\langle v, x\rangle - f(x) \mid x \in \mathbb{R}^n\} \leq \sup\{\langle v, x\rangle - g(x) \mid x \in \mathbb{R}^n\} = g^*(v).$$

Lemma 0.0.2. *Let $f : \mathbb{R}^n \to \overline{\mathbb{R}}$ be a function with $\mathrm{dom}(f) \neq \emptyset$. Then we have $\langle v, x\rangle \leq f(x) + f^*(v)$ for all $x, v \in \mathbb{R}^n$.*

Proof. From the definition of the Fenchel conjugate it follows

$$
\begin{aligned}
f^*(v) &= \sup\{\langle v, x\rangle - f(x) \mid \forall x \in \mathbb{R}^n\} \\
f^*(v) &\geq \langle v, x\rangle - f(x) \\
f^*(v) + f(x) &\geq \langle v, x\rangle
\end{aligned}
$$

□

Theorem 2. For any convex function $f : \mathbb{R}^n \to \overline{\mathbb{R}}$ and any $\overline{x} \in \mathrm{dom}(f)$, we have $v \in \partial f(\overline{x})$ if and only if $f(\overline{x}) + f^*(v) = \langle v, \overline{x}\rangle$.

Proof.

By the previous lemma we have $\langle v, \overline{x}\rangle \leq f(\overline{x}) + f^*(v)$. Since $v \in \partial f(\overline{x})$ we have for all

$x \in \mathbb{R}^n$

$$\begin{aligned} f(\overline{x}) + \langle v, x \rangle - f(x) &\leq \langle v, \overline{x} \rangle \\ f(\overline{x}) + \sup\{\langle v, x \rangle - f(x)\} &\leq \langle v, \overline{x} \rangle \\ f(\overline{x}) + f^*(v) &\leq \langle v, \overline{x} \rangle \end{aligned}$$

Conversely, we have

$$\begin{aligned} f(\overline{x}) + f^*(v) &= \langle v, \overline{x} \rangle \\ f(\overline{x}) + \sup\{\langle v, x - f(x) \mid \forall x \in \mathbb{R}^n\} &= \langle v, \overline{x} \rangle \\ f(\overline{x}) + \langle v, x \rangle - f(x) &\leq \langle v, \overline{x} \rangle \\ \langle v, x - \overline{x} \rangle &\leq f(x) - f(\overline{x}) \end{aligned}$$

Thus, $v \in \partial f(\overline{x})$. $\square$

Symmetric Functions

We define the function $[\cdot] : \mathbb{R}^n \to \mathbb{R}^n$ to map x to the vector consisting of the components of x in nonincreasing order. We call a function $f : \mathbb{R}^n \to \mathbb{R}^n$ symmetric if $f(x) = f([x])$. Note that for $x, y \in \mathbb{R}^n$ we have $x^T y \leq [x]^T[y]$ since $x^T y = x_1 y_1 + ... + x_n y_n$ and $[x]^T[y] = [x]_1[y]_1 + ... + [x]_n[y]_n$ and for each $i = 1, ..., n$ we have $x_i \leq [x]_i$ and $y_i \leq [y]_i$.

Definition 2. The spectral function is defined as $\lambda : \mathbb{S}^n \to \mathbb{R}^n$ assigning $X \in \mathbb{S}^n$ to the vector $x \in \mathbb{R}^n$ such that $x = (\lambda_1(X), \lambda_2(X), ..., \lambda_n(X))$ where each $\lambda_i(X)$ is an eigenvalue of X and $\lambda_1(X) \geq \lambda_2(X) \geq ... \geq \lambda_n(X)$.

Definition 3. Two matrices $X, Y \in \mathbb{S}^n$ have a **simultaneous ordered spectral** decomposition if there exists a matrix $U \in \mathbb{O}^n$ with $X = U^T(\mathrm{Diag}(\lambda(\mathrm{X})))\mathrm{U}$ and $Y = U^T(\mathrm{Diag}(\lambda(\mathrm{Y})))\mathrm{U}$.

Theorem 3. Any matrices X and Y in $\mathbb{S}^n$ satisfy the inequality

$$\mathrm{tr(XY)} \leq \lambda(\mathrm{X})^{\mathrm{T}}\lambda(\mathrm{Y})$$

Equality holds if and only if X and Y have a simultaneous ordered spectral decomposition

Theorem 4. If $f : \mathbb{R}^n \to \overline{\mathbb{R}}$ is a symmetric function, then $(f \circ \lambda)^* = (f^* \circ \lambda)$.

Proof. By Fan's inequality for $Y \in \mathbb{S}^n$ it follows that

$$\begin{aligned}
(f \circ \lambda)^*(Y) &= \sup_{X \in \mathbb{S}^n} \{\mathrm{tr}(XY) - f(\lambda(X))\} \\
&\leq \sup_{X \in \mathbb{S}^n} \{\lambda(X)^T\lambda(Y) - f(\lambda(X))\} \\
&\leq \sup_{x \in \mathbb{R}^n} \{x^T\lambda(Y) - f(x)\} \\
&= f^*(\lambda(Y))
\end{aligned}$$

Then by using the spectral decomposition $Y = U^T(\mathrm{Diag}(\lambda(Y)))U$ for some $U \in \mathbb{O}^n$ we have the inequality

$$
\begin{aligned}
f^*(\lambda(Y)) &= \sup_{x\in\mathbb{R}^n}\{x^T\lambda(Y) - f(x)\} \\
&= \sup_{x}\{\mathrm{tr}(\mathrm{Diag}(x)UYU^T) - f(x)\} \\
&= \sup_{x}\{\mathrm{tr}(U^T(\mathrm{Diag}(x)UY)) - f(\lambda(U^T\,\mathrm{Diag}(x)U))\} \\
&\leq \sup_{X\in\mathbb{S}^n}\{\mathrm{tr}(XY) - f(\lambda(X))\} \\
&= (f\circ\lambda)^*(Y)
\end{aligned}
$$

□

Theorem 5. If $f : \mathbb{R}^n \to \overline{\mathbb{R}}$ is a symmetric function, then for any matrices $X, Y \in \mathbb{S}^n$ the following are equivalent:
(i) $Y \in \partial(f\circ\lambda)(X)$.
(ii) X and Y have a simultaneous ordered spectral decomposition and satisfy $\lambda(Y) \in \partial f(\lambda(X))$.
(iii) $X = U^T(\mathrm{Diag}(x))U$ and $Y = U^T(\mathrm{Diag}(y))U$ for some matrix $U \in \mathbb{O}^n$ and vectors $x, y \in \mathbb{R}^n$ with $y \in \partial f(x)$.

Proof.

($i \implies ii$) Let $Y \in \partial(f\circ\lambda)(X)$. By Fan's inequality we have $\mathrm{tr}(XY) \leq \lambda(Y)^T\lambda(X)$. Since Y is in the subdifferential it follows from the preceeding theorem and a lemma about the Fenchel conjugate that:

$$
\begin{aligned}
(f\circ\lambda)(X) + (f\circ\lambda)^*(Y) &= \langle X, Y\rangle = \mathrm{tr}(XY) \\
f(\lambda(X)) + f^*(\lambda(Y)) &= \mathrm{tr}(XY) \\
\langle \lambda(Y), \lambda(X)\rangle &\leq \mathrm{tr}(XY) \\
\lambda(Y)^T\lambda(X) &\leq \mathrm{tr}(XY)
\end{aligned}
$$

Since $\mathrm{tr}(XY) = \lambda(Y)^T\lambda(X)$ it follows that X and Y have a simultaneous ordered spectral decomposition. Using the fact that X and Y have a simultaneous ordered spectral decomposition we get

$$
\begin{aligned}
(f\circ\lambda)(X) + (f\circ\lambda)^*(Y) &= \langle X, Y\rangle = \mathrm{tr}(XY) \\
(f\circ\lambda)(X) + (f\circ\lambda)^*(Y) &= \lambda(X)^T\lambda(Y) \\
f(\lambda(X)) + f^*(\lambda(Y)) &= \langle \lambda(X), \lambda(Y)\rangle
\end{aligned}
$$

So, by the lemma we have $\lambda(Y) \in \partial f(\lambda(X))$.

($ii \implies i$) Since X and Y have a simultaneous ordered spectral decomposition it follows from the definition of $\lambda(Y) \in \partial f(\lambda(X))$ that

$$\begin{aligned}
\langle \lambda(Y), \lambda(\overline{X}) - \lambda(X) \rangle &\leq f(\lambda(Y)) - f(\lambda(X)) \\
\langle \lambda(Y), \lambda(\overline{X}) \rangle - \langle \lambda(Y), \lambda(X) \rangle &\leq (f \circ \lambda)(Y) - (f \circ \lambda)(X) \\
\mathrm{tr}(Y\overline{X}) - \mathrm{tr}(YX) &\leq (f \circ \lambda)(Y) - (f \circ \lambda)(X) \\
\mathrm{tr}(Y(\overline{X} - X) &\leq (f \circ \lambda)(Y) - (f \circ \lambda)(X) \\
\langle Y, \overline{X} - X \rangle &\leq (f \circ \lambda)(Y) - (f \circ \lambda)(X)
\end{aligned}$$

Thus, $Y \in \partial(f \circ \lambda)(X)$.

$\square$