Matrix Forensics

A brief guide to efficient linear algebra

RICHARD BARNES

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1 Nomenclature

$\mathbf{A}$	Matrix.
$\mathbf{a}$	(Column) vector.
a	Scalar.
$\mathbf{A}_{ij}$	Matrix indexed. Returns ith row and jth column.
$\mathbf{A} \circ \mathbf{B}$	Hadamard (element-wise) product of matrices A and B.
$\mathcal{N}(\mathbf{A})$	Nullspace of the matrix $\mathbf{A}$.
$\mathcal{R}(\mathbf{A})$	Range of the matrix $\mathbf{A}$.
$\det(\mathbf{A})$	Determinant of the matrix $\mathbf{A}$.
$\text{eig}(\mathbf{A})$	Eigenvalues of the matrix $\mathbf{A}$.
$\mathbf{A}^H$	Conjugate transpose of the matrix $\mathbf{A}$.
$\mathbf{A}^T$	Transpose of the matrix $\mathbf{A}$.
$\mathbf{A}^+$	Pseudoinverse of the matrix $\mathbf{A}$.
$\mathbf{x} \in \mathbb{R}^n$	The entries of the n-vector $\mathbf{x}$ are all real numbers.
$\mathbf{A} \in \mathbb{R}^{m,n}$	The entries of the matrix $\mathbf{A}$ with m rows and n columns are all real numbers.
$\mathbf{A} \in \mathbb{S}^n$	The matrix $\mathbf{A}$ is symmetric and has n rows and n columns.
$\mathbf{I}_n$	Identity matrix with n rows and n columns.
$\{0\}$	The empty set

2 Derivatives

For general $\mathbf{A}$ and $\mathbf{X}$ (no special structure):

$$\partial \mathbf{A} = 0 \quad \text{where } \mathbf{A} \text{ is a constant} \tag{1}$$
$$\partial(c\mathbf{X}) = c\partial\mathbf{X} \tag{2}$$
$$\partial(\mathbf{X}+\mathbf{Y}) = \partial\mathbf{X} + \partial\mathbf{Y} \tag{3}$$
$$\partial(\mathrm{tr}(\mathbf{X})) = \mathrm{tr}(\partial(\mathbf{X})) \tag{4}$$
$$\partial(\mathbf{X}\mathbf{Y}) = (\partial\mathbf{X})\mathbf{Y} + \mathbf{X}(\partial\mathbf{Y}) \tag{5}$$
$$\partial(\mathbf{X}\circ\mathbf{Y}) = (\partial\mathbf{X})\circ\mathbf{Y} + \mathbf{X}\circ(\partial\mathbf{Y}) \tag{6}$$
$$\partial(\mathbf{X}^{-1}) = -\mathbf{X}^{-1}(\partial\mathbf{X})\mathbf{X}^{-1} \tag{7}$$
$$\partial(\det(\mathbf{X})) = \mathrm{tr}(\mathrm{adj}(\mathbf{X})\partial\mathbf{X}) \tag{8}$$
$$\partial(\det(\mathbf{X})) = \det(\mathbf{X})\,\mathrm{tr}(\mathbf{X}^{-1}\partial\mathbf{X}) \tag{9}$$
$$\partial(\ln(\det(\mathbf{X}))) = \mathrm{tr}(\mathbf{X}^{-1}\partial\mathbf{X}) \tag{10}$$
$$\partial(\mathbf{X}^T) = (\partial\mathbf{X})^T \tag{11}$$
$$\partial(\mathbf{X}^H) = (\partial\mathbf{X})^H \tag{12}$$

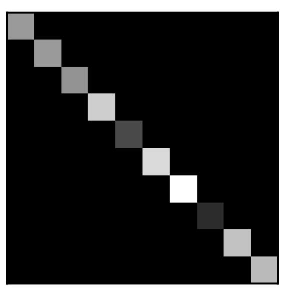
3 | Matrix Rogue Gallery

3.1 Non-Singular vs. Singular Matrices

For $\mathbf{A} \in \mathbb{R}^{n,n}$ (initially drawn from [1, p. 574]):

Non-Singular	**Singular**
$\mathbf{A}$ is invertible	$\mathbf{A}$ is not invertible
The columns are independent	The columns are dependent
The rows are independent	The rows are dependent
$\det(\mathbf{A}) \neq 0$	$\det(\mathbf{A}) = 0$
$\mathbf{Ax} = 0$ has one solution: $\mathbf{x} = 0$	$\mathbf{Ax} = 0$ has infinitely many solutions
$\mathbf{Ax} = \mathbf{b}$ has one solution: $\mathbf{x} = \mathbf{A}^{-1}\mathbf{b}$	$\mathbf{Ax} = \mathbf{b}$ has either no or infinitely many solutions
$\mathbf{A}$ has n nonzero pivots	$\mathbf{A}$ has $r < n$ pivots
$\mathbf{A}$ has full rank $r = n$	$\mathbf{A}$ has rank $r < n$
The reduced row echelon form is $\mathbf{R} = \mathbf{I}$	$\mathbf{R}$ has at least one zero row
The column space is all of $\mathbb{R}^n$	The column space has dimension $r < n$
The row space is all of $\mathbb{R}^n$	The row space has dimension $r < n$
All eigenvalues are nonzero	Zero is an eigenvalue of $\mathbf{A}$
$\mathbf{A}^T\mathbf{A}$ is symmetric positive definite	$\mathbf{A}^T\mathbf{A}$ is only semidefinite
$\mathbf{A}$ has n positive singular values	$\mathbf{A}$ has $r < n$ singular values

3.2 Diagonal Matrix



$$A = \operatorname{diag}(a_1, \dots, a_n) = \begin{bmatrix} a_1 & & \\ & \ddots & \\ & & a_n \end{bmatrix} \tag{13}$$

Square matrix. Entries above diagonal are equal to entries below diagonal.

Number of "free entries": $\frac{n(n+1)}{2}$.

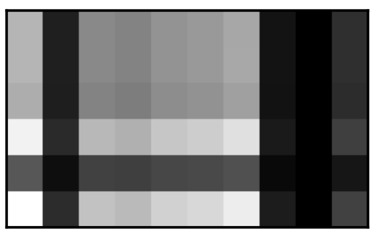
Special Properties

$$\mathrm{eig}(A) = a_1, \ldots, a_n \tag{14}$$

$$\det(A) = \prod_i a_i \tag{15}$$

$$A^{-1} = \begin{bmatrix} \frac{1}{a_1} & & \\ & \ddots & \\ & & \frac{1}{a_n} \end{bmatrix} \tag{16}$$

3.3 Dyads



$\mathbf{A} \in \mathbb{R}^{m,n}$ is a dyad if it can be written as

$$\mathbf{A} = \mathbf{u}\mathbf{v}^T \quad \mathbf{u} \in \mathbb{R}^m, \mathbf{v} \in \mathbb{R}^n \tag{17}$$

Special Properties

- The columns of $\mathbf{A}$ are copies of $\mathbf{u}$ scaled by the values of $\mathbf{v}$.
- The rows of $\mathbf{A}$ are copies of $\mathbf{u}^T$ scaled by the values of $\mathbf{v}$.
- If $\mathbf{A}$ is a dyad, it acts on a vector $\mathbf{x}$ as $\mathbf{A}\mathbf{x} = (\mathbf{u}\mathbf{v}^T)\mathbf{x} = (\mathbf{v}^T\mathbf{u})\mathbf{x}$.
- $\mathbf{A}\mathbf{x} = c\mathbf{u}$ ($\mathbf{A}$ scales $\mathbf{x}$ and points it along $\mathbf{u}$).
- $\mathbf{A}_{ij} = \mathbf{u}_i\mathbf{v}_j$.
- If $\mathbf{u}, \mathbf{v} \neq 0$, then $\mathrm{rank}(\mathbf{A}) = 1$.
- If $m = n$, $\mathbf{A}$ has one eigenvalue $\lambda = \mathbf{v}^T\mathbf{u}$ and eigenvector $\mathbf{u}$.

- A dyad can always be written in a normalized form $c\tilde{\mathbf{u}}\tilde{\mathbf{v}}^T$.

3.4 Hermitian Matrix

$\mathbf{H} \in \mathbb{C}^{m,n}$ is Hermitian iff

$$\mathbf{H} = \mathbf{H}^H \tag{18}$$

where $\mathbf{H}^H$ is the conjugate transpose of $\mathbf{H}$.

For $\mathbf{H} \in \mathbb{R}^{m,n}$, Hermitian and symmetric matrices are equivalent.

Special Properties

$$\begin{aligned}
\mathbf{H}_{ii} &\in \mathbb{R} && (19)\\
\mathbf{H}\mathbf{H}^H &= \mathbf{H}^H\mathbf{H} && (20)\\
\mathbf{x}^H\mathbf{H}\mathbf{x} &\in \mathbb{R} \quad \forall \mathbf{x} \in \mathbb{C} && (21)\\
\mathbf{H}_1 + \mathbf{H}_2 &= \text{Hermitian} && (22)\\
\mathbf{H}^{-1} &= \text{Hermitian} && (23)\\
\mathbf{A} + \mathbf{A}^H &= \text{Hermitian} && (24)\\
\mathbf{A} - \mathbf{A}^H &= \text{Skew-Hermitian} && (25)\\
\mathbf{A}\mathbf{B} &= \text{Hermitian iff } \mathbf{A}\mathbf{B} = \mathbf{B}\mathbf{A} && (26)\\
\det(\mathbf{H}) &\in \mathbb{R} && (27)\\
\mathrm{eig}(\mathbf{H}) &\in \mathbb{R} && (28)
\end{aligned}$$

3.5 Idempotent Matrix

A matrix $\mathbf{A}$ is idempotent iff

$$\mathbf{A}\mathbf{A} = \mathbf{A} \tag{29}$$

Special Properties

$$\mathbf{A}^n = A \;\; \forall n \tag{30}$$
$$\mathbf{I} - \mathbf{A} \;\; \text{is idempotent} \tag{31}$$
$$\mathbf{A}^H \;\; \text{is idempotent} \tag{32}$$
$$\mathbf{I} - \mathbf{A}^H \;\; \text{is idempotent} \tag{33}$$
$$\text{rank}(\mathbf{A}) = \text{tr}(\mathbf{A}) \tag{34}$$
$$\mathbf{A}(I - \mathbf{A}) = 0 \tag{35}$$
$$\mathbf{A}^+ = \mathbf{A} \tag{36}$$
$$f(s\mathbf{I} + t\mathbf{A}) = (\mathbf{I} - \mathbf{A})f(s) + \mathbf{A}f(s+t) \tag{37}$$
$$\mathbf{AB} = \mathbf{BA} \implies \mathbf{AB} \text{ is idempotent} \tag{38}$$
$$\text{eig}(\mathbf{A})_i \in \{0, 1\} \tag{39}$$
$$\mathbf{A} \text{ is always diagonalizable} \tag{40}$$

$\mathbf{A} - \mathbf{I}$ may not be idempotent.

3.6 Orthogonal Matrix

$$U = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \tag{41}$$

A matrix $\mathbf{U}$ is orthogonal iff:

$$\mathbf{U}^T\mathbf{U} = \mathbf{U}\mathbf{U}^T = I \tag{42}$$

Square matrix. The columns form an orthonormal basis of $\mathbb{R}^n$.

Special Properties

- The eigenvalues of $\mathbf{U}$ are placed on the unit circle.
- The eigenvectors of $\mathbf{U}$ are unitary (have length one).
- $\mathbf{U}^{-1}$ is orthogonal.

$$\mathbf{U}^T = \mathbf{U}^{-1} \tag{43}$$
$$\mathbf{U}^{-T} = \mathbf{U} \tag{44}$$
$$\mathbf{U}^T\mathbf{U} = \mathbf{I} \tag{45}$$
$$\mathbf{U}\mathbf{U}^T = \mathbf{I} \tag{46}$$
$$\det(\mathbf{U}) = \pm 1 \tag{47}$$

Orthogonal matrices preserve the lengths and angles of the vectors they operator on. The converse is true: any matrix which preserves lengths and angles is orthogonal.

$$\|\mathbf{U}\mathbf{x}\|_2^2 = (\mathbf{U}\mathbf{x})^T(\mathbf{U}\mathbf{x}) = \mathbf{x}^T\mathbf{U}^T\mathbf{U}\mathbf{x} = \mathbf{x}^T\mathbf{x} = \|\mathbf{x}\|_2^2 \quad \forall \mathbf{x} \tag{48}$$

$$\|\mathbf{U}\mathbf{A}\mathbf{V}\|_F = \|\mathbf{A}\|_F \quad \forall \mathbf{A}, \mathbf{U}, \mathbf{V} \text{ with } U, V orthogonal \tag{49}$$

3.7 Positive Definite

$\mathbf{A} \in \mathbb{S}^n$ is positive definite (denoted $\mathbf{A} \succ 0$) if any of the following are true:

- $\mathbf{x}^T\mathbf{A}\mathbf{x} > 0, \forall \mathbf{x} \in \mathbb{R}^n$.
- $\text{eig}(\mathbf{A}) > 0$

Special Properties

- If $\mathbf{A}$ is PD and invertible, $\mathbf{A}^{-1}$ is also PD.
- If $\mathbf{A}$ is PD and $c \in \mathbb{R}$ then $c\mathbf{A}$ is PD.
- The diagonal entries $\mathbf{A}_{ii}$ are real and non-negative, so $\text{tr}(\mathbf{A}) \geq 0$.
- $\det(\mathbf{A}) > 0$
- For $\mathbf{A} \in \mathbb{R}^{m,n}$, $\mathbf{A}^T\mathbf{A} \succ 0 \iff \mathbf{A}$ is full-column rank ($\text{rank}(\mathbf{A}) = n$)
- For $\mathbf{A} \in \mathbb{R}^{m,n}$, $\mathbf{A}\mathbf{A}^T \succ 0 \iff \mathbf{A}$ is full-row rank ($\text{rank}(\mathbf{A}) = m$)
- $\mathbf{P} \succ 0$ defines a full-dimensional, bounded ellipsoid centered at the origin and defined by the set $\mathcal{E} = \{\mathbf{x} \in \mathbb{R}^n : x^T\mathbf{P}^{-1}x \leq 1\}$. The eigenvalues λ_i and eigenvectors u_i of $\mathbf{P}$ define the orientation and shape of the ellipsoid. u_i are the semi-axes while the lengths of the semi-axes are given by $\sqrt{\lambda_i}$. Using the Cholesky decomposition, $\mathbf{P}^{-1} = \mathbf{A}^T\mathbf{A}$, an equivalent definition of the ellipsoid is $\mathcal{E} = \{\mathbf{x} \in \mathbb{R}^n : \|\mathbf{A}\mathbf{x}\|_2 \leq 1\}$.

3.8 Positive Semi-Definite

$\mathbf{A}$ is positive semi-definite (denoted $\mathbf{A} \succeq 0$) if any of the following are true:

- $\mathbf{x}^T\mathbf{A}\mathbf{x} \geq 0, \forall \mathbf{x} \in \mathbb{R}^n$.
- $\text{eig}(\mathbf{A}) \geq 0$

Special Properties

- For $\mathbf{A} \in \mathbb{R}^{m,n}$, $\mathbf{A}^T\mathbf{A} \succeq 0$
- For $\mathbf{A} \in \mathbb{R}^{m,n}$, $\mathbf{A}\mathbf{A}^T \succeq 0$
- The positive semi-definite matrices $\mathbb{S}^n_+$ form a convex cone. For any two PSD matrices $\mathbf{A}, \mathbf{B} \in \mathbb{S}^n_+$ and some $\alpha \in [0, 1]$:

$$\mathbf{x}^T(\alpha\mathbf{A} + (1-\alpha)\mathbf{B})\mathbf{x} = \alpha\mathbf{x}^T\mathbf{A}\mathbf{x} + (1-\alpha)\mathbf{x}^T\mathbf{B}\mathbf{x} \geq 0 \quad \forall \mathbf{x} \tag{50}$$

$$\alpha\mathbf{A} + (1-\alpha)\mathbf{B} \in \mathbb{S}^n_+ \tag{51}$$

- For $\mathbf{A} \in \mathbb{S}^n_+$ and $\alpha \geq 0$, $\alpha\mathbf{A} \succeq 0$, so $\mathbb{S}^n_+$ is a cone.

3.9 Projection Matrix

A square matrix $\mathbf{P}$ is a projection matrix that projects onto a vector space $\mathcal{S}$ iff

$$\mathbf{P} \text{ is idempotent} \tag{52}$$

$$\mathbf{P}\mathbf{x} \in \mathcal{S} \quad \forall \mathbf{x} \tag{53}$$

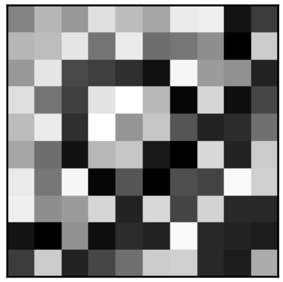
$$\mathbf{P}\mathbf{z} = \mathbf{z} \quad \forall \mathbf{z} \in \mathcal{S} \tag{54}$$

3.10 Singular Matrix

A square matrix that is not invertible.

$\mathbf{A} \in \mathbb{R}^{n,n}$ is singular iff $\det \mathbf{A} = 0$ iff $\mathcal{N}(A) \neq \{0\}$.

3.11 Symmetric Matrix



$\mathbf{A} \in \mathbb{S}^n$ is a symmetric matrix if $\mathbf{A} = \mathbf{A}^T$ (entries above diagonal are equal to entries below diagonal).

$$\begin{bmatrix} a & b & c & d & e & f \\ b & g & l & m & o & p \\ c & l & h & n & q & r \\ d & m & n & i & s & t \\ e & o & q & s & j & u \\ f & p & r & t & u & k \end{bmatrix} \tag{55}$$

Special Properties

$$\mathbf{A} = \mathbf{A}^T \tag{56}$$

Number of “free entries”: $\frac{n(n+1)}{2}$.

If $\mathbf{A}$ is real, it can be decomposed into $\mathbf{A} = \mathbf{Q}^T\mathbf{D}\mathbf{Q}$ where $\mathbf{Q}$ is a real orthogonal matrix (the columns of which are eigenvectors of $\mathbf{A}$) and $\mathbf{D}$ is real and diagonal containing the eigenvalues of $\mathbf{A}$.

For a real, symmetric matrix with non-negative eignevalues, the eigenvalues and singular values coincide.

3.12 Skew-Hermitian

A matrix $\mathbf{H} \in \mathbb{C}^{m,n}$ is Skew-Hermitian iff

$$\mathbf{H} = -\mathbf{H}^H \tag{57}$$

3.13 Toeplitz Matrix, General Form

Constant values on descending diagonals.

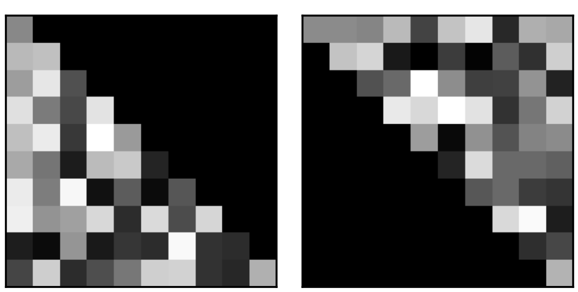
$$\begin{bmatrix} a_0 & a_{-1} & a_{-2} & \dots & \dots & a_{-(n-1)} \\ a_1 & a_0 & a_{-1} & \ddots & & \vdots \\ a_2 & a_1 & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & a_{-1} & a_{-2} \\ \vdots & & \ddots & a_1 & a_0 & a_{-1} \\ a_{n-1} & \dots & \dots & a_2 & a_1 & a_0 \end{bmatrix} \tag{58}$$

3.14 Toeplitz Matrix, Discrete Convolution

Constant values on main and subdiagonals.

$$\begin{bmatrix} h_m & 0 & 0 & \dots & 0 & 0 \\ \vdots & h_m & 0 & \dots & 0 & 0 \\ h_1 & \vdots & h_m & \dots & 0 & 0 \\ 0 & h_1 & \ddots & \ddots & 0 & 0 \\ 0 & 0 & h_1 & \ddots & h_m & 0 \\ 0 & 0 & 0 & \ddots & \vdots & h_m \\ 0 & 0 & 0 & \dots & h_1 & \vdots \\ 0 & 0 & 0 & \dots & 0 & h_1 \end{bmatrix} \tag{59}$$

3.15 Triangular Matrix



$$\begin{bmatrix} a & b & c & d & e & f \\ & g & h & i & j & k \\ & & l & m & n & o \\ & & & p & q & r \\ & & & & s & t \\ & & & & & u \end{bmatrix} \quad \begin{bmatrix} a & & & & & \\ b & g & & & & \\ c & h & l & & & \\ d & i & m & p & & \\ e & j & n & q & s & \\ f & k & o & r & t & u \end{bmatrix} \tag{60}$$

Square matrices in which all elements either above or below the main diagonal are zero. An upper (left) and a lower (right) triangular matrix are shown above.

For an upper triangular matrix $A_{ij} = 0$ whenever $i > j$; for a lower triangular matrix $A_{ij} = 0$ whenever $i < j$.

Special Properties

$$\operatorname{eig}(A) = \operatorname{diag}(A) \tag{61}$$

$$\det(A) = \prod_i \operatorname{diag}(A)_i \tag{62}$$

The product of two upper (lower) triangular matrices is still upper (lower) triangular.

The inverse of a nonsingular upper (lower) triangular matrix is still upper (lower) triangular.

3.16 Vandermonde Matrix

$$V = \begin{bmatrix} 1 & \alpha_1 & \alpha_1^2 & \dots & \alpha_1^{n-1} \\ 1 & \alpha_2 & \alpha_2^2 & \dots & \alpha_2^{n-1} \\ 1 & \alpha_3 & \alpha_3^2 & \dots & \alpha_3^{n-1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & \alpha_m & \alpha_m^2 & \dots & \alpha_m^{n-1} \end{bmatrix} \tag{63}$$

Alternatively,

$$V_{i,j} = \alpha_i^{j-1} \tag{64}$$

Uses

Polynomial interpolation of data.

Special Properties

- $\det(V) = \prod_{1 \leq i < j \leq n}(x_j - x_i)$

4 | Matrix Decompositions

4.1 LLT/UTU: Cholesky Decomposition

If $\mathbf{A}$ is symmetric, positive definite, square, then

$$\mathbf{A} = \mathbf{U}^T\mathbf{U} = \mathbf{L}\mathbf{L}^T \tag{65}$$

where $\mathbf{U}$ is a unique upper triangular matrix and $\mathbf{L}$ is a unique lower-triangular matrix.

4.2 LDLT

If $\mathbf{A}$ is a non-singular symmetric definite square matrix, then

$$\mathbf{A} = \mathbf{L}\mathbf{D}\mathbf{L}^T = \mathbf{L}^T\mathbf{D}\mathbf{L} \tag{66}$$

where $\mathbf{L}$ is a unit lower triangular matrix and $\mathbf{D}$ is a diagonal matrix. If $\mathbf{A} \succ 0$, then $\mathbf{D}_{ii} > 0$.

4.3 PCA: Principle Components Analysis

Find normalized directions in data space such that the variance of the projections of the centered data points is maximal. For centered data $\tilde{\mathbf{X}}$, the mean-square variation of data along a vector $\mathbf{x}$ is $\mathbf{x}^T\tilde{\mathbf{X}}\tilde{\mathbf{X}}^T\mathbf{x}$.

$$\max_{\mathbf{x}\in\mathbb{R}^n,\ \|\mathbf{x}\|_2=1} \mathbf{x}^T\tilde{\mathbf{X}}\tilde{\mathbf{X}}^T\mathbf{x} \tag{67}$$

Taking an SVD of $\tilde{\mathbf{X}}\tilde{\mathbf{X}}^T$ gives $H = \mathbf{U}_r\mathbf{D}^2\mathbf{U}^T$, which is maximized by taking $\mathbf{x} = \mathbf{u}_1$. By repeatedly removing the first principal components and recalculating, all the principal axes can be found.

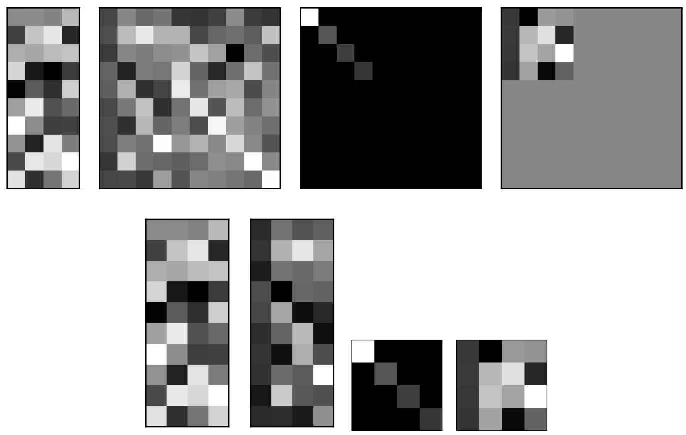
4.4 QR: Orthogonal-triangular

For $\mathbf{A} \in \mathbb{R}^{n,n}$, $\mathbf{A} = \mathbf{Q}\mathbf{R}$ where $\mathbf{Q}$ is orthogonal and $\mathbf{R}$ is an upper triangular matrix. If $\mathbf{A}$ is non-singular, then $\mathbf{Q}$ and $\mathbf{R}$ are uniquely defined if $\text{diag}(\mathbf{R})$ are imposed to be positive.

Algorithms

Gram-Schmidt.

4.5 SVD: Singular Value Decomposition



Any matrix $\mathbf{A} \in \mathbb{R}^{m,n}$ can be written as

$$\mathbf{A} = \mathbf{U}\mathbf{D}\mathbf{V}^T = \sum_{i=1}^{r} \sigma_i u_i v_i^T \tag{68}$$

where

$$U = \text{eigenvectors of } \mathbf{A}\mathbf{A}^T \qquad \mathbb{R}^{m,m} \tag{69}$$

$$D = \text{diag}(\sigma_i) = \sqrt{\text{diag}(\text{eig}(\mathbf{A}\mathbf{A}^T))} \qquad \mathbb{R}^{n,m} \tag{70}$$

$$V = \text{eigenvectors of } \mathbf{A}^T\mathbf{A} \qquad \mathbb{R}^{n,n} \tag{71}$$

Let σ_i be the non-zero singular values for $i = 1, \ldots, r$ where r is the rank of $\mathbf{A}$; $\sigma_1 \geq \ldots \geq \sigma_r$.

We also have that

$$\mathbf{A}\mathbf{v}_i = \sigma_i \mathbf{u}_i \tag{72}$$

$$\mathbf{A}^T\mathbf{u}_i = \sigma_i \mathbf{v}_i \tag{73}$$

$$\mathbf{U}^T\mathbf{U} = \mathbf{I} \tag{74}$$

$$\mathbf{V}^T\mathbf{V} = \mathbf{I} \tag{75}$$

$\mathbf{D}$ can be written in an expanded form:

$$\tilde{\mathbf{D}} = \begin{bmatrix} \mathbf{D} & 0_{r,n-r} \\ 0_{m-r,r} & 0_{m-r,n-r} \end{bmatrix} \tag{76}$$

The final $n - r$ columns of $\mathbf{V}$ give an orthonormal basis spanning $\mathcal{N}(\mathbf{A})$. An orthonormal basis spanning the range of $\mathbf{A}$ is given by the first r columns of $\mathbf{U}$.

$$\|\mathbf{A}\|_F^2 = \text{Frobenius norm} = \text{tr}(\mathbf{A}^T\mathbf{A}) = \sum_{i=1}^{r} \sigma_i^2 \tag{77}$$

$$\|\mathbf{A}\|_2^2 = \sigma_1^2 \tag{78}$$

$$\|\mathbf{A}\|_* = \text{nuclear norm} = \sum_{i=1}^{r} \sigma_i \tag{79}$$

The **condition number** κ of an invertible matrix $\mathbf{A} \in \mathbb{R}^{n,n}$ is the ratio of the largest and smallest singular value. Matrices with large condition numbers are closer to being singular and more sensitive to changes.

$$\kappa(\mathbf{A}) = \frac{\sigma_1}{\sigma_n} = \|A\|_2 \cdot \left\|A^{-1}\right\|_2 \tag{80}$$

Low-Rank Approximation

Approximating $\mathbf{A} \in \mathbb{R}^{m,n}$ by a matrix $\mathbf{A}_k$ of rank $k > 0$ can be formulated as the optimization probem

$$\min_{\mathbf{A}_k \in \mathbb{R}^{m,n}} \|\mathbf{A} - \mathbf{A}_k\|_F^2 : \text{rank}\, \mathbf{A}_k = k, 1 \leq k \leq \text{rank}(\mathbf{A}) \tag{81}$$

The optimal solution of this problem is given by

$$\mathbf{A}_k = \sum_{i=1}^{k} \sigma_i \mathbf{u}_i \mathbf{v}_i^T \tag{82}$$

where

$$\frac{\|\mathbf{A}_k\|_F^2}{\|\mathbf{A}\|_F^2} = \frac{\sigma_1^2 + \ldots + \sigma_k^2}{\sigma_1^2 + \ldots + \sigma_r^2} \tag{83}$$

$$1 - \frac{\|\mathbf{A}_k\|_F^2}{\|\mathbf{A}\|_F^2} = \frac{\sigma_{k+1}^2 + \ldots + \sigma_r^2}{\sigma_1^2 + \ldots + \sigma_r^2} \tag{84}$$

is the fraction of the total variance in $\mathbf{A}$ explained by the approximation $\mathbf{A}_k$.

Range and Nullspace

$$\mathcal{N}(\mathbf{A}) = \mathcal{R}(\mathbf{V}_{nr}) \tag{85}$$

$$\mathcal{N}(\mathbf{A})^\perp \equiv \mathcal{R}(\mathbf{A}^T) = \mathcal{R}(\mathbf{V}_r) \tag{86}$$

$$\mathcal{R}(\mathbf{A}) = \mathcal{R}(\mathbf{U}_r) \tag{87}$$

$$\mathcal{R}(\mathbf{A})^\perp \equiv \mathcal{N}(\mathbf{A}^T) = \mathcal{R}(\mathbf{U}_{nr}) \tag{88}$$

where $\mathbf{V}_r$ is the first r columns of V and $V_n r$ are the last $[r+1, n]$ columns; similarly for $\mathbf{U}$.

Projectors

The projection of $\mathbf{x}$ onto $\mathcal{N}(\mathbf{A})$ is $(\mathbf{V}_{nr}\mathbf{V}_{nr}^T)\mathbf{x}$. Since $\mathbf{I}_n = \mathbf{V}_r\mathbf{V}_r^T + \mathbf{V}_{nr}\mathbf{V}_{nr}^T$, $(\mathbf{I}_n - \mathbf{V}_r\mathbf{V}_r^T)\mathbf{x}$ also works. The projection of $\mathbf{x}$ onto $\mathcal{R}(\mathbf{A})$ is $(\mathbf{U}_r\mathbf{U}_r^T)\mathbf{x}$.

If $\mathbf{A} \in \mathbb{R}^{m,n}$ is full row rank ($\mathbf{A}\mathbf{A}^T \succ 0$), then the minimum distance to an affine set $\{x : \mathbf{A}\mathbf{x} = \mathbf{b}\}, \mathbf{b} \in \mathbb{R}^m$ is given by $\mathbf{x}^* = \mathbf{A}^T(\mathbf{A}\mathbf{A}^T)^{-1}\mathbf{b}$.

If $\mathbf{A} \in \mathbb{R}^{m,n}$ is full column rank ($\mathbf{A}^T\mathbf{A} \succ 0$), then the minimum distance to an affine set $\{x : \mathbf{A}\mathbf{x} = \mathbf{b}\}, \mathbf{b} \in \mathbb{R}^m$ is given by $\mathbf{x}^* = \mathbf{A}(\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{b}$.

Computational Notes

Since $\sigma \approx 0$, a *numerical rank* can be estimated for the matrix as the largest k such that $\sigma_k > \epsilon\sigma_1$ for $\epsilon \geq 0$.

4.6 Eigenvalue Decomposition for Diagonalizable Matrices

For a square, diagonalizable matrix $\mathbf{A} \in \mathbb{R}^{n,n}$

$$\mathbf{A} = U\Lambda U^{-1} \tag{89}$$

where $U \in \mathbb{C}^{n,n}$ is an invertible matrix whose columns are the eigenvectors of $\mathbf{A}$ and Λ is a diagonal matrix containing the eigenvalues $\lambda_1, \ldots, \lambda_n$ of $\mathbf{A}$ in the diagonal.

The columns $\mathbf{u}_1, \ldots, \mathbf{u}_n$ satisfy

$$\mathbf{A}\mathbf{u}_i = \lambda_i\mathbf{u}_i \quad i = 1, \ldots, n \tag{90}$$

4.7 Eigenvalue (Spectral) Decomposition for Symmetric Matrices

A symmetric matrix $\mathbf{A} \in \mathbb{R}^{n,n}$ can be factored as

$$\mathbf{A} = U\Lambda U^T = \sum_i^n \lambda_i\mathbf{u}_i\mathbf{u}_i^T \tag{91}$$

where $U \in \mathbb{R}^{n,n}$ is an orthogonal matrix whose columns $\mathbf{u}_i$ are the eigenvectors of $\mathbf{A}$ and Λ is a diagonal matrix containing the eigenvalues $\lambda_1 \geq \ldots \geq \lambda_n$ of $\mathbf{A}$ in the diagonal. These eigenvalues are always real. The eigenvectors can always be chosen to be real and to form an orthonormal basis.

The columns $\mathbf{u}_1, \ldots, \mathbf{u}_n$ satisfy

$$\mathbf{A}\mathbf{u}_i = \lambda_i \mathbf{u}_i \quad i = 1, \ldots, n \tag{92}$$

4.8 Schur Complements

For $\mathbf{A} \in \mathbb{S}^n$, $\mathbf{B} \in \mathbb{S}^n$, $\mathbf{X} \in \mathbb{R}^{n,m}$ with $\mathbf{B} \succ 0$ and the block matrix

$$\mathbf{M} = \begin{bmatrix} \mathbf{A} & \mathbf{X} \\ \mathbf{X}^T & \mathbf{B} \end{bmatrix} \tag{93}$$

and the Schur complement of $\mathbf{A}$ in $\mathbf{M}$

$$S = \mathbf{A} - \mathbf{X}\mathbf{B}^{-1}\mathbf{X}^T \tag{94}$$

Then

$$\mathbf{M} \succeq 0 \iff S \succeq 0 \tag{95}$$

$$\mathbf{M} \succ 0 \iff S \succ 0 \tag{96}$$

5 | Matrix Properties

$$\mathbf{A}(\mathbf{B}+\mathbf{C}) = \mathbf{AB}+\mathbf{AC} \quad \text{(left distributivity)} \tag{97}$$

$$(\mathbf{B}+\mathbf{C})\mathbf{A} = \mathbf{BA}+\mathbf{CA} \quad \text{(right distributivity)} \tag{98}$$

$$\mathbf{AB} \neq \mathbf{BA} \quad \text{(in general)} \tag{99}$$

$$(\mathbf{AB})\mathbf{C} = \mathbf{A}(\mathbf{BC}) \quad \text{(associativity)} \tag{100}$$

6 | Transpose Properties

$$(\mathbf{AB})^T = \mathbf{B}^T \mathbf{A}^T \tag{101}$$

$$(\mathbf{A} + \mathbf{B})^T = \mathbf{A}^T + \mathbf{B}^T \tag{102}$$

$$(\mathbf{A}^{-1})^T = (\mathbf{A}^T)^{-1} \tag{103}$$

7 Determinant Properties

Geometrically, if a unit volume is acted on by $\mathbf{A}$, then $|\det(\mathbf{A})|$ indicates the volume after the transformation.

$$\det(I_n) = 1 \tag{104}$$

$$\det(\mathbf{A}^T) = \det(\mathbf{A}) \tag{105}$$

$$\det(\mathbf{A}^{-1}) = \frac{1}{\det(\mathbf{A})} = \det(\mathbf{A})^{-1} \tag{106}$$

$$\det(AB) = \det(BA) \tag{107}$$

$$\det(AB) = \det(A)\det(B) \quad \mathbf{A}, \mathbf{B} \in \mathbb{R}^{n,n} \tag{108}$$

$$\det(c\mathbf{A}) = c^n \det(\mathbf{A}) \quad \mathbf{A} \in \mathbb{R}^{n,n} \tag{109}$$

$$\det(\mathbf{A}) = \prod \operatorname{eig}(\mathbf{A}) \tag{110}$$

8 Trace Properties

For $\mathbf{A} \in \mathbb{R}^{n,n}$

$$\operatorname{tr}(\mathbf{A}) = \sum_{i=1}^{n} \mathbf{A}_{ii} \tag{111}$$

$$\operatorname{tr}(\mathbf{A} + \mathbf{B}) = \operatorname{tr}(\mathbf{A}) + \operatorname{tr}(\mathbf{B}) \tag{112}$$

$$\operatorname{tr}(c\mathbf{A}) = c \operatorname{tr}(\mathbf{A}) \tag{113}$$

$$\operatorname{tr}(\mathbf{A}) = \operatorname{tr}(\mathbf{A}^T) \tag{114}$$

For $\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}$ of compatible dimensions,

$$\operatorname{tr}(\mathbf{A}^T\mathbf{B}) = \operatorname{tr}(\mathbf{A}\mathbf{B}^T) = \operatorname{tr}(\mathbf{B}^T\mathbf{A}) = \operatorname{tr}(\mathbf{B}\mathbf{A}^T) \tag{115}$$

$$\operatorname{tr}(\mathbf{ABCD}) = \operatorname{tr}(\mathbf{BCDA}) = \operatorname{tr}(\mathbf{CDAB}) = \operatorname{tr}(\mathbf{DABC}) \tag{116}$$

(Invariant under cyclic permutations)

9 Inverse Properties

The inverse of $\mathbf{A} \in \mathbb{C}^{n,n}$ is denoted $\mathbf{A}^{-1}$ and defined such that

$$\mathbf{A}\mathbf{A}^{-1} = \mathbf{A}^{-1}\mathbf{A} = \mathbf{I}_n \tag{117}$$

where $\mathbf{I}_n$ is the $n \times n$ identity matrix. $\mathbf{A}$ is nonsingular if $\mathbf{A}^{-1}$ exists; otherwise, $\mathbf{A}$ is singular.

If individual inverses exist

$$(\mathbf{A}\mathbf{B})^{-1} = \mathbf{B}^{-1}\mathbf{A}^{-1} \tag{118}$$

more generally

$$(\mathbf{A}_1\mathbf{A}_2 \ldots \mathbf{A}_n)^{-1} = \mathbf{A}_n^{-1} \ldots \mathbf{A}_2^{-1}\mathbf{A}_1^{-1} \tag{119}$$

$$(\mathbf{A}^{-1})^T = (\mathbf{A}^T)^{-1} \tag{120}$$

10 Pseudo-Inverse Properties

For $\mathbf{A} \in \mathbb{R}^{m,n}$, a pseudoinverse satisfies:

$$\mathbf{A}\mathbf{A}^{+}\mathbf{A} = \mathbf{A} \tag{121}$$
$$\mathbf{A}^{+}\mathbf{A}\mathbf{A}^{+} = \mathbf{A}^{+} \tag{122}$$
$$(\mathbf{A}\mathbf{A}^{+})^{T} = \mathbf{A}\mathbf{A}^{+} \tag{123}$$
$$(\mathbf{A}^{+}\mathbf{A})^{T} = \mathbf{A}^{+}\mathbf{A} \tag{124}$$

10.1 Moore-Penrose Pseudoinverse

$$\mathbf{A}^{+} = \mathbf{V}\mathbf{D}^{-1}\mathbf{U}^{T} \tag{125}$$

where the foregoing comes from a singular-value decomposition and $\mathbf{D}^{-1} = \mathrm{diag}(\frac{1}{\sigma_1}, \ldots, \frac{1}{\sigma_r})$

Special Properties

- $\mathbf{A}^{+} = \mathbf{A}^{-1}$ if $\mathbf{A} \in \mathbb{R}^{n,n}$ and $\mathbf{A}$ is square and nonsingular.
- $\mathbf{A}^{+} = (\mathbf{A}^{T}\mathbf{A})^{-1}\mathbf{A}^{T}$, if $\mathbf{A} \in \mathbb{R}^{m,n}$ is full column rank ($r = n \leq m$). $\mathbf{A}^{+}$ is a left inverse of $\mathbf{A}$, so $\mathbf{A}^{+}\mathbf{A} = \mathbf{V}_r\mathbf{V}_r^{T} = \mathbf{V}\mathbf{V}^{T} = \mathbf{I}_n$.
- $\mathbf{A}^{+} = \mathbf{A}^{T}(\mathbf{A}\mathbf{A}^{T})^{-1}$, if $\mathbf{A} \in \mathbb{R}^{m,n}$ is full row rank ($r = m \leq n$). $\mathbf{A}^{+}$ is a right inverse of $\mathbf{A}$, so $\mathbf{A}\mathbf{A}^{+} = \mathbf{U}_r\mathbf{U}_r^{T} = \mathbf{U}\mathbf{U}^{T} = \mathbf{I}_m$.

11 Hadamard Identities

$$(\mathbf{A} \circ \mathbf{B})_{ij} = A_{ij} B_{ij} \;\forall\; i, j \tag{126}$$

$$\mathbf{A} \circ \mathbf{B} = \mathbf{B} \circ \mathbf{A} \tag{127}$$ [2]

$$\mathbf{A} \circ (\mathbf{B} \circ \mathbf{C}) = (\mathbf{A} \circ \mathbf{B}) \circ \mathbf{C} \tag{128}$$

$$\mathbf{A} \circ (\mathbf{B} + \mathbf{C}) = \mathbf{A} \circ \mathbf{B} + \mathbf{A} \circ \mathbf{C} \tag{129}$$ [2]

$$a(\mathbf{A} \circ \mathbf{B}) = (a\mathbf{A}) \circ \mathbf{B} = \mathbf{A} \circ (a\mathbf{B}) \tag{130}$$ [2]

$$(\mathbf{A}^T \circ \mathbf{B}^T) = (\mathbf{A} \circ \mathbf{B})^T \tag{131}$$

$$(\mathbf{A}^T \circ \mathbf{B}^T) = (\mathbf{A} \circ \mathbf{B})^T \tag{132}$$

$$(x^T \mathbf{A} x) = \sum_{i,j} \big((x x^T) \circ \mathbf{A}\big) \tag{133}$$

12 | Eigenvalue Properties

$\lambda \in \mathbb{C}$ is an eigenvalue of $\mathbf{A} \in \mathbb{R}^{n,n}$ and $u \in \mathbb{C}^n$ is a corresponding eigenvector if $\mathbf{Au} = \lambda\mathbf{u}$ and $\mathbf{u} \neq 0$. Equivalantly, $(\lambda\mathbf{I}_n - \mathbf{A})\mathbf{u} = 0$ and $\mathbf{u} \neq 0$. Eigenvalues satisfy the equation $\det(\lambda\mathbf{I}_n - \mathbf{A}) = 0$.

Any matrix $\mathbf{A} \in \mathbb{R}^{n,n}$ has n eigenvalues, though some may be repeated. λ_1 is the largest eigenvalue and λ_n the smallest.

$$\operatorname{eig}(\mathbf{A}\mathbf{A}^T) = \operatorname{eig}(\mathbf{A}^T\mathbf{A}) \tag{134}$$

(Note that the number of entries in $\mathbf{A}\mathbf{A}^T$ and $\mathbf{A}^T\mathbf{A}$ may differ significantly leading to different compute times.)

$$\operatorname{eig}(\mathbf{A}^T\mathbf{A}) \geq 0 \tag{135}$$

Computation

TODO: eigsh, small eigen value extraction, top-k

13 Norms

13.1 Matrices

Matrix norms satisfy some properties:

$$f(\mathbf{A}) \geq 0 \tag{136}$$
$$f(\mathbf{A}) = 0 \iff \mathbf{A} = 0 \tag{137}$$
$$f(c\mathbf{A}) = |c| f(\mathbf{A}) \tag{138}$$
$$f(\mathbf{A}+\mathbf{B}) \leq f(\mathbf{A}) + f(\mathbf{B}) \tag{139}$$

Many popular matrix norms also satisfy "sub-multiplicativity": $f(\mathbf{AB}) \leq f(\mathbf{A})f(\mathbf{B})$.

13.1.1 Frobenius norm

$$\|\mathbf{A}\|_F = \sqrt{\operatorname{tr} \mathbf{A}\mathbf{A}^H} \tag{140}$$
$$= \sqrt{\sum_{i=1}^{m} \sum_{j=1}^{n} |\mathbf{A}_{ij}|^2} \tag{141}$$
$$= \sqrt{\sum_{i=1}^{m} \operatorname{eig}(A^H A)_i} \tag{142}$$

Special Properties

$$\|\mathbf{A}\mathbf{x}\|_2 \leq \|\mathbf{A}\|_F \|\mathbf{x}\|_2 \quad \mathbf{x} \in \mathbb{R}^n \tag{143}$$

$$\|\mathbf{AB}\|_F \leq \|\mathbf{A}\|_F \|\mathbf{B}\|_F \tag{144}$$

13.1.2 Operator Norms

For $p = 1, 2, \infty$ or other values, an operator norm indicates the maximum input-output gain of the matrix.

$$\|\mathbf{A}\|_p = \max_{\|\mathbf{u}\|_p = 1} \|\mathbf{A}\mathbf{u}\|_p \tag{145}$$

$$\|\mathbf{A}\|_1 = \max_{\|\mathbf{u}\|_1=1} \|\mathbf{A}\mathbf{u}\|_1 \tag{146}$$
$$= \max_{j=1,\ldots,n} \sum_{i=1}^{m} |\mathbf{A}_{ij}| \tag{147}$$
$$= \text{Largest absolute column sum} \tag{148}$$

$$\|\mathbf{A}\|_\infty = \max_{\|\mathbf{u}\|_\infty=1} \|\mathbf{A}\mathbf{u}\|_\infty \tag{149}$$
$$= \max_{j=1,\ldots,m} \sum_{i=1}^{n} |\mathbf{A}_{ij}| \tag{150}$$
$$= \text{Largest absolute row sum} \tag{151}$$

$$\|\mathbf{A}\|_2 = \text{``spectral norm''} \tag{152}$$
$$= \max_{\|\mathbf{u}\|_2=1} \|\mathbf{A}\mathbf{u}\|_2 \tag{153}$$
$$= \sqrt{\max(\text{eig}(\mathbf{A}^T\mathbf{A}))} \tag{154}$$
$$= \text{Square root of largest eigenvalue of } \mathbf{A}^T\mathbf{A} \tag{155}$$

Special Properties

$$\|\mathbf{A}\mathbf{u}\|_p \leq \|\mathbf{A}\|_p \|\mathbf{u}\|_p \tag{156}$$
$$\|\mathbf{A}\mathbf{B}\|_p \leq \|\mathbf{A}\|_p \|\mathbf{B}\|_p \tag{157}$$
$$\tag{158}$$

13.1.3 Spectral Radius

Not a proper norm.

$$\rho(\mathbf{A}) = \text{spectral radius}(\mathbf{A}) = \max_{i=1,\ldots,n} |\,\text{eig}(\mathbf{A})_i| \tag{159}$$

Special Properties

$$\rho(\mathbf{A}) \leq \|\mathbf{A}\|_p \tag{160}$$
$$\rho(\mathbf{A}) \leq \min(\ \|\mathbf{A}\|_1, \|\mathbf{A}\|_\infty) \tag{161}$$
$$\tag{162}$$

13.2 Vectors

P-norm:

$$\|\mathbf{x}\|_p = (\sum_i |\mathbf{x}_i|^p)^{1/p} \tag{163}$$

14 | Bounds

14.1 Matrix Gain

$$\lambda_{\min}(\mathbf{A}^T\mathbf{A}) \leq \frac{\|\mathbf{A}\mathbf{x}\|_2^2}{\|\mathbf{x}\|_2^2} \leq \lambda_{\max}(\mathbf{A}^T\mathbf{A}) \tag{164}$$

$$\max_{\mathbf{x}\neq 0} \frac{\|\mathbf{A}\mathbf{x}\|_2}{\|\mathbf{x}\|_2} = \|\mathbf{A}\|_2 = \sqrt{\lambda_{\max}(\mathbf{A}^T\mathbf{A})} \implies \mathbf{x} = u_1 \tag{165}$$

$$\min_{\mathbf{x}\neq 0} \frac{\|\mathbf{A}\mathbf{x}\|_2}{\|\mathbf{x}\|_2} = \sqrt{\lambda_{\min}(\mathbf{A}^T\mathbf{A})} \implies \mathbf{x} = u_n \tag{166}$$

14.2 Norms

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

$$\frac{1}{\sqrt{n}}\|\mathbf{x}\|_2 \leq \|\mathbf{x}\|_\infty \leq \|\mathbf{x}\|_2 \leq \|\mathbf{x}\|_1 \leq \sqrt{\operatorname{card}(\mathbf{x})}\|\mathbf{x}\|_2 \leq \sqrt{n}\|\mathbf{x}\|_2 \leq n\|\mathbf{x}\|_\infty \tag{167}$$

For any $0 < p < q$ we have that $\|\mathbf{x}\|_q \leq \|\mathbf{x}\|_p$.

14.3 Rayleigh quotients

The Rayleigh quotient of $\mathbf{A} \in \mathbb{S}^n$ is given by

$$\frac{\mathbf{x}^T\mathbf{A}\mathbf{x}}{\mathbf{x}^T\mathbf{x}} \quad \mathbf{x} \neq 0 \tag{168}$$

$$\lambda_{\min}(\mathbf{A}) \leq \frac{\mathbf{x}^T\mathbf{A}\mathbf{x}}{\mathbf{x}^T\mathbf{x}} \leq \lambda_{\max}(\mathbf{A}) \quad \mathbf{x} \neq 0 \tag{169}$$

$$\lambda_{\max}(A) = \max_{\mathbf{x}:\|\mathbf{x}\|_2=1} \mathbf{x}^T\mathbf{A}\mathbf{x} = u_1 \tag{170}$$

$$\lambda_{\min}(A) = \min_{\mathbf{x}:\|\mathbf{x}\|_2=1} \mathbf{x}^T\mathbf{A}\mathbf{x} = u_n \tag{171}$$

where u_1 and u_n are the eigenvectors associated with $\lambda_{\max}$ and $\lambda_{\min}$, respectively.

15 Linear Equations

The linear equation $\mathbf{Ax} = \mathbf{y}$ with $\mathbf{A} \in \mathbb{R}^{m,n}$ admits a solution iff $\text{rank}([\mathbf{Ay}]) = \text{rank}(\mathbf{A})$. If this is satisfied, the set of all solutions is an affine set $\mathcal{S} = \{\mathbf{x} = \bar{\mathbf{x}} + z : z \in \mathcal{N}(\mathbf{A})\}$ where $\bar{\mathbf{x}}$ is any vector such that $\mathbf{A}\bar{\mathbf{x}} = \mathbf{y}$. The solution is unique if $\mathcal{N}(\mathbf{A}) = \{0\}$.

$\mathbf{Ax} = \mathbf{y}$ is *overdetermined* if it is tall/skinny ($m > n$); that is, if there are more equations than unknowns. If $\text{rank}(\mathbf{A}) = n$ then $\dim \mathcal{N}(\mathbf{A}) = 0$, so there is either no solution or one solution. Overdetermined systems often have no solution ($\mathbf{y} \notin \mathcal{R}(\mathbf{A})$), so an approximate solution is necessary.

$\mathbf{Ax} = \mathbf{y}$ is *underdetermined* if it is short/wide ($n > m$); that is, if has more unknowns than equations. If $\text{rank}(\mathbf{A}) = m$ then $\mathcal{R}(\mathbf{A}) = \mathbb{R}^m$, so $\dim \mathcal{N}(\mathbf{A}) = n - m > 0$, so the set of solutions is infinite. Therefore, finding a single solution that optimizes some quantity is of interest.

$\mathbf{Ax} = \mathbf{y}$ is *square* if $n = m$. If $\mathbf{A}$ is invertible, then the equations have the unique solution $\mathbf{x} = \mathbf{A}^{-1}\mathbf{y}$.

15.1 Least-Squares

For an overdetermined system we wish to find:

$$\min_{\mathbf{x}} \|\mathbf{Ax} - \mathbf{y}\|_2^2 \tag{172}$$

Since $\mathbf{Ax} \in \mathcal{R}(\mathbf{A})$, we need a point $\tilde{\mathbf{y}} = \mathbf{Ax}^* \in \mathcal{R}(\mathbf{A})$ closest to $\mathbf{y}$. This point lies in the nullspace of $\mathbf{A}^T$, so we have $\mathbf{A}^T(\mathbf{y} - \mathbf{Ax}^*) = 0$. There is always a solution to this problem and, if $\text{rank}(\mathbf{A}) = n$, it is unique.

$$\mathbf{x}^* = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{y} \tag{173}$$

15.2 Minimum Norm Solutions

For undertermined systems in which $\mathbf{A} \in \mathbb{R}^{m,n}$ with $m < n$. We wish to find

$$\min_{\mathbf{x}:\mathbf{Ax}=\mathbf{y}} \|\mathbf{x}\|_2 \tag{174}$$

The solution $\mathbf{x}^*$ must be orthogonal to $\mathcal{N}(\mathbf{A})$, so $\mathbf{x}^* \in \mathcal{R}(\mathbf{A}^T)$, so $\mathbf{x}^* = \mathbf{A}^T c$ for some c, so $\mathbf{A}\mathbf{A}^T c = \mathbf{y}$, therefore:

$$\mathbf{x}^* = \mathbf{A}^T(\mathbf{A}\mathbf{A}^T)^{-1}\mathbf{y} \tag{175}$$

16 $\mathbf{1}_r^T \mathbf{A} \mathbf{1}_c$

Reduces to: Scalar

Notation: For $\mathbf{A} \in \mathbb{R}^{r \times c}$, $\mathbf{1}_r$ is in $\mathbb{R}^{r \times 1}$ and $\mathbf{1}_c$ is in $\mathbb{R}^{c \times 1}$.

Plain English: The sum of the elements of the matrix.

Algorithm: Traverse all the element of the matrix in order keeping track of the sum. For applications where accuracy is important and the matrices have a large dynamic range, Kahan summation or a similar technique should be used.

Update Algorithm: If an entry changes, subtract its old value from the sum and add its new value to the sum.

17 $\mathbf{x}^T\mathbf{A}\mathbf{x}$

Reduces to: Scalar

Notation: $\mathbf{A}$ must be in $\mathbb{R}^{i\times i}$. $\mathbf{x}$ is in $\mathbb{R}^{i\times 1}$.

Plain English: TODO

Algorithm: TODO

Update Algorithm: We make use of the identity $(\mathbf{x}^T\mathbf{A}\mathbf{x}) = \sum_{i,j}\left((\mathbf{x}\mathbf{x}^T)\circ\mathbf{A}\right)$. If an entry $\mathbf{A}_{i,j}$ in the matrix changes subtract its old value $\mathbf{x}_i\mathbf{x}_j\mathbf{A}_{ij}$ and add the new value $\mathbf{x}_i\mathbf{x}_j\mathbf{A}'_{ij}$. If an entry $\mathbf{x}_i$ changes TODO.

18 | Algorithms

18.1 Gram-Schmidt

TODO

Bibliography

[1] Gilbert Strang. *Introduction to Linear Algebra*. 2016.

[2] Elizabeth Million. The hadamard product. http://buzzard.ups.edu/courses/2007spring/projects/million-paper.pdf, 2007.