

Analytical Geometry and Linear Algebra II, Lab 9

Eigenvalues and Eigenvectors

Diagonalization of a Matrix



How I spent last weekend



Hiking Club KFU "Tochka" event



Where it can be used

- Machine learning (transform data in more suitable form)
- Make some calculations easier (matrix^{100} – piece of cake)
- Predict the behavior of linear systems (physics, biology, etc)
- Design the controller for a system
- Estimate the complexity of calculations
- ...



Definition

In linear algebra, an **eigenvector or characteristic vector** of a linear transformation is a non-zero vector that changes by only a scalar factor when that linear transformation is applied to it. [Wiki](#)

$$Ax = \lambda x, \text{ where}$$

x - eigenvector (should be non-zero),

λ - eigenvalue,

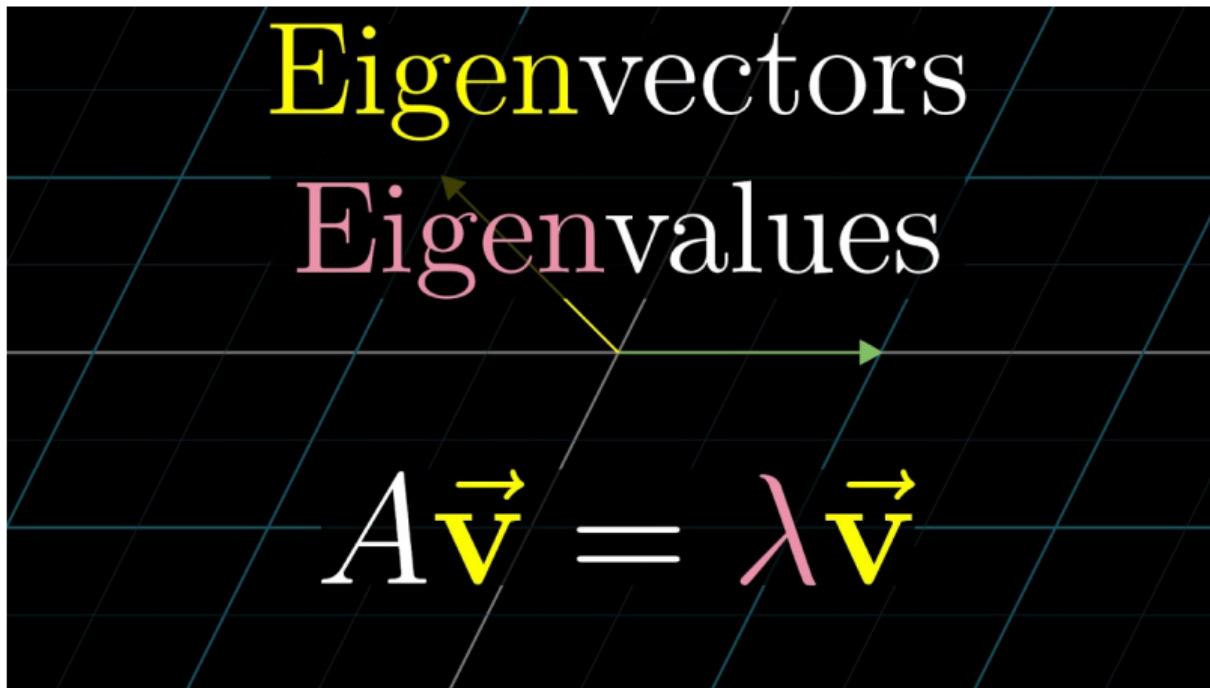
A - square matrix.

For $n \times n$ matrix - max amount of λ is a number of n .



EigenValues concept

Video





Calculation (1)

Classical approach (max 3x3)

Algorithm

There are 2 steps:

1. Find λ (eigenvalue) — $\det(A - \lambda I) = 0$
 - 2×2 matrix: $\det(A - \lambda I) = \lambda^2 - \text{trace}(A)\lambda + \det(A) = 0$, where $\text{trace}(A)$ — sum of diag values of A;
 - 3×3 matrix: $\det(A - \lambda I) = \lambda^3 - \text{trace}(A)\lambda^2 - \frac{1}{2}(\text{trace}(A^2) - \text{trace}(A)^2)\lambda - \det(A) = 0$
2. Find x for each λ — $(A - \lambda_i I)x = 0$

Example

Case study, 2×2 matrix: $A = \begin{bmatrix} 4 & 3 \\ -2 & -3 \end{bmatrix}$

1. $\text{trace}(A) = 4 + (-3) = 1$,
 $\det(A) = 4(-3) - 3(-2) = -6$, hence
 $\lambda^2 - \lambda - 6 = (\lambda - 3)(\lambda + 2)$, \rightarrow
 $\rightarrow \lambda_1 = 3, \lambda_2 = -2$

2. 2.1 $A - 3I = \begin{bmatrix} 1 & 3 \\ -2 & -6 \end{bmatrix}; x_{\lambda=3} = \begin{bmatrix} 3 \\ -1 \end{bmatrix}$
- 2.2 $A + 2I = \begin{bmatrix} 6 & 3 \\ -2 & -1 \end{bmatrix}; x_{\lambda=2} = \begin{bmatrix} 1 \\ -2 \end{bmatrix}$



Task 1

Find the eigenvalues and eigenvectors:

$$1. \ A = \begin{bmatrix} 2 & 7 \\ 7 & 2 \end{bmatrix}$$

$$2. \ A = \begin{bmatrix} 3 & -1 \\ 1 & 3 \end{bmatrix}$$



Task 1

Find the eigenvalues and eigenvectors:

$$1. A = \begin{bmatrix} 2 & 7 \\ 7 & 2 \end{bmatrix}$$

$$2. A = \begin{bmatrix} 3 & -1 \\ 1 & 3 \end{bmatrix}$$

Answer

$$1. \lambda_1 = -5, \lambda_2 = 9$$

$$x_{\lambda=-5} = \begin{bmatrix} -0.5 \\ 0.5 \end{bmatrix}, x_{\lambda=9} = \begin{bmatrix} 0.5 \\ 0.5 \end{bmatrix}$$

$$2. \lambda_1 = 3 + 1i, \lambda_2 = 3 - 1i$$

$$x_{\lambda=3+1i} = \begin{bmatrix} 3+1i \\ 0 \\ 0 \end{bmatrix},$$

$$x_{\lambda=3-1i} = \begin{bmatrix} 3-1i \\ 0 \\ 0 \end{bmatrix}$$



Calculation (2)

Real life approach (Iterative algorithms)

Due to the reason that computers appeared recently, eigenpairs weren't used frequently.

Nowadays, it can be found easily by iteration method, which implemented in most programming languages.

Method	Applies to	Produces	Cost per step	Convergence
Lanczos algorithm	Hermitian	m largest/smallest eigenpairs		
Power iteration	general	eigenpair with largest value	$O(n^2)$	linear
Inverse iteration	general	eigenpair with value closest to μ		
Rayleigh quotient iteration	Hermitian	any eigenpair		cubic
Preconditioned inverse iteration ^[11] or LOBPCG algorithm	positive-definite real symmetric	eigenpair with value closest to μ		
Bisection method	real symmetric tridiagonal	any eigenvalue		linear
Laguerre iteration	real symmetric tridiagonal	any eigenvalue		cubic ^[12]
QR algorithm	Hessenberg	all eigenvalues	$O(n^2)$	
		all eigenpairs	$6n^3 + O(n^2)$	cubic
Jacobi eigenvalue algorithm	real symmetric	all eigenvalues	$O(n^3)$	quadratic
Divide-and-conquer	Hermitian tridiagonal	all eigenvalues	$O(n^2)$	
		all eigenpairs	$(\frac{4}{3})n^3 + O(n^2)$	

Eigenvector and eigenvalue iterative algorithms

[Wiki](#)



Eigenpair properties and features

- $\sum \lambda = \text{trace}(A)$
- $\det(A) = \prod_{i=1}^n \lambda_i$
- $A_{\text{new}} = A_{\text{old}} + aI$, \rightarrow eigenvectors won't change, $\lambda_{\text{new}} = \lambda_{\text{old}} + a$
- The matrix A is invertible if and only if every eigenvalue is nonzero.
- If matrix is triangular – the eigenvalues are on the main diagonal
- If matrix is symmetric – λ is *definitely* real
- If matrix is not symmetric – λ *can* contain imaginary part
- $Ax = \lambda x \rightarrow A^2x = Ax$ (*left mult*) $\rightarrow A^2x = Ax(\lambda \text{ is const}) = \lambda^2x$



Diagonalization

Key idea / Follow each eigenvector separately / n simple problems

Eigenvector matrix X

Assume independent x 's

Then X is invertible

$$AX = A \begin{bmatrix} x_1 & \cdots & x_n \end{bmatrix} = \begin{bmatrix} \lambda_1 x_1 & \cdots & \lambda_n x_n \end{bmatrix}$$

$$\boxed{\begin{aligned} AX &= X\Lambda \\ X^{-1}AX &= \Lambda \\ A &= X\Lambda X^{-1} \end{aligned}}$$

$$\begin{bmatrix} \lambda_1 x_1 & \cdots & \lambda_n x_n \end{bmatrix} = \begin{bmatrix} x_1 & \cdots & x_n \end{bmatrix} \begin{bmatrix} \lambda_1 & & \\ & \ddots & \\ & & \lambda_n \end{bmatrix}$$



Diagonalization properties

Some matrices are not diagonalizable

They don't have n independent vectors

$$A = \begin{bmatrix} 3 & 6 \\ 0 & 3 \end{bmatrix} \text{ has } \lambda = 3 \text{ and } 3$$

That A has double eigenvalue, single eigenvector

Only one $x = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$



Task 2

$$A = \begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}$$

- Find eigenpairs;
- Write down A in diagonal form;
- Draw several vectors: one, which are parallel to an eigenvector, other – not.
- Multiply chosen vectors on A, draw the new ones.



Task 2

Answer

$$Ax = \lambda x; A = \begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}$$

$$\det(A - \lambda I) = 0$$

$$\lambda^2 - 4\lambda + 3 = 0$$

$$D = 16 - 4 \cdot 1 \cdot 3 = 4$$

$$\lambda_1 = \frac{4 \pm \sqrt{4}}{2} \Rightarrow \lambda_1 = 1$$

$$\textcircled{1} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} x = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \Rightarrow$$

$$\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \end{bmatrix} = x = \begin{bmatrix} 1 \\ 1 \end{bmatrix} t, \text{ for instance } x = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

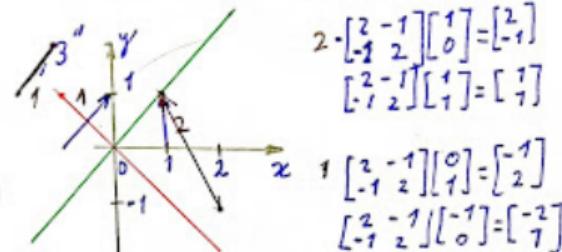
$$\textcircled{2} \begin{bmatrix} -1 & -1 \\ -1 & -1 \end{bmatrix} x = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \Rightarrow x = \begin{bmatrix} 1 \\ 1 \end{bmatrix} t \rightarrow x = \begin{bmatrix} -1 \\ 1 \end{bmatrix}$$

" $S^{-1} = S^T$ if orthonormal, here not appl.

$$S = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \Rightarrow S^{-1} = \begin{bmatrix} 0.5 & 0.5 \\ -0.5 & 0.5 \end{bmatrix}$$

$$\Lambda = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix} \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} = S^{-1} AS$$

$$A = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 3 \end{bmatrix} \begin{bmatrix} 0.5 & 0.5 \\ -0.5 & 0.5 \end{bmatrix}$$



It's scale + shear



Task 3

True or false: If the columns of X (eigenvectors of A) are linearly independent, then

- (a) A is invertible (b) A is diagonalizable
- (c) X is invertible (d) X is diagonalizable.



Task 3

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- (a) A is invertible (b) A is diagonalizable
- (c) X is invertible (d) X is diagonalizable.

Answer

- (a) False: We are not given the λ 's (b) True (c) True (d) False: For this we would need the eigenvectors of X



Task 4

If the eigenvectors of A are the columns of I , then A is a _____ matrix. If the eigenvector matrix X is triangular, then X^{-1} is triangular. Prove that A is also triangular.



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If the eigenvectors of A are the columns of I , then A is a _____ matrix. If the eigenvector matrix X is triangular, then X^{-1} is triangular. Prove that A is also triangular.

Answer

With $X = I$, $A = X\Lambda X^{-1} = \Lambda$ is a diagonal matrix. If X is triangular, then X^{-1} is triangular, so $X\Lambda X^{-1}$ is also triangular.



A^k

A^k becomes easy

$$A^k = (X\Lambda X^{-1})(X\Lambda X^{-1}) \cdots (X\Lambda X^{-1})$$

Same eigenvectors in X

$$\boxed{A^k = X\Lambda^k X^{-1}} \quad \Lambda^k = (\text{eigenvalues})^k$$

$$\begin{bmatrix} 1 & 2 \\ 0 & 3 \end{bmatrix}^4 = X\Lambda^4 X^{-1} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1^4 & 0 \\ 0 & 3^4 \end{bmatrix} \begin{bmatrix} 1 & -1 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 81 \\ 0 & 81 \end{bmatrix} \begin{bmatrix} 1 & -1 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 80 \\ 0 & 81 \end{bmatrix}$$

Question: When does $A^k \rightarrow$ zero matrix ?

Answer: **All** $|\lambda_i| < 1$



Applications (1)

Fast Calculations

Task: Find 50th Fibonacci value

Dummy approach:
calculate it by iterative summarization.

Smart approach: use magic and diagonalization

$$U_{k+1} = U_k + U_{k-1} \text{ - Fibonacci}$$

Let's represent it as $Ax=b$

$$\begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} U_k \\ U_{k-1} \end{bmatrix} = \begin{bmatrix} U_{k+1} \\ ? \end{bmatrix}$$

We need matrix $2 \times 2 \rightarrow$ make a useless second eq.

$$\begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} U_k \\ U_{k-1} \end{bmatrix} = \begin{bmatrix} U_{k+1} \\ U_k \end{bmatrix} \text{ or } \begin{cases} U_k + U_{k-1} = U_{k+1} \\ U_k = U_k \end{cases} \Rightarrow$$

$$\Rightarrow A \begin{bmatrix} U_k \\ U_{k-1} \end{bmatrix} = \begin{bmatrix} U_{k+1} \\ U_k \end{bmatrix}$$

$$\text{We know } U_0 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$A U_0 = U_1; U_1 = A U_0 = A A U_0 = A^2 U_0 = \underbrace{A^{k+1}}_{U_{k+1}} U_0$$

Let's find diag of A , hence we need to find λ, \vec{x}

$$A = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \dots \lambda = \frac{1 \pm \sqrt{1+4}}{2} \approx 1,618$$

$$\vec{x}_1 = \begin{bmatrix} 2_1 \\ 1 \end{bmatrix}, \vec{x}_2 = \begin{bmatrix} 2_2 \\ 1 \end{bmatrix}$$

Result

$$F_{50} = [\vec{x}_1 \ \vec{x}_2] \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} [\vec{x}_1 \ \vec{x}_2]^{-1} \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

Lecture 22. Diagonalization and Powers of A



Task 5

$A^k = X\Lambda^k X^{-1}$ approaches the zero matrix as $k \rightarrow \infty$ if and only if every λ has absolute value less than _____. Which of these matrices has $A^k \rightarrow 0$?

$$A_1 = \begin{bmatrix} .6 & .9 \\ .4 & .1 \end{bmatrix} \quad \text{and} \quad A_2 = \begin{bmatrix} .6 & .9 \\ .1 & .6 \end{bmatrix}.$$



Task 5

$A^k = X\Lambda^k X^{-1}$ approaches the zero matrix as $k \rightarrow \infty$ if and only if every λ has absolute value less than _____. Which of these matrices has $A^k \rightarrow 0$?

$$A_1 = \begin{bmatrix} .6 & .9 \\ .4 & .1 \end{bmatrix} \quad \text{and} \quad A_2 = \begin{bmatrix} .6 & .9 \\ .1 & .6 \end{bmatrix}.$$

Answer: **Markov matrix** is a prob. matrix, where a summary in each column should be 1. It has a property, that $\lambda_{max} = 1$.

$A^k = X\Lambda^k X^{-1}$ approaches zero **if and only if every** $|\lambda| < 1$; A_1 is a Markov matrix so $\lambda_{max} = 1$ and $A_1^k \rightarrow A_1^\infty$, A_2 has $\lambda = .6 \pm .3$ so $A_2^k \rightarrow 0$.



Applications (2)

Computer Vision

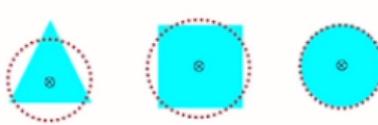
Task: we want to know the orientation of the object

Needed terms: Centroid, Image moments

Solution: use equivalent ellipse method. We consider an ellipse:

- centred at the object's centroid;
- has same moments of inertia about centroid.

Afterwards, we find an ellipse using eigenvalues and eigenvectors



Equivalent ellipse

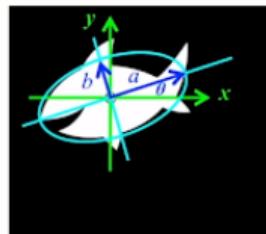
An ellipse with the inertia matrix

$$\mathbf{J} = \begin{pmatrix} \mu_{20} & \mu_{11} \\ \mu_{11} & \mu_{02} \end{pmatrix}$$

has radii

$$a = 2\sqrt{\frac{\lambda_1}{m_{00}}}, \quad b = 2\sqrt{\frac{\lambda_2}{m_{00}}}$$

where $\lambda_1 > \lambda_2$ are the eigenvalues of \mathbf{J}



major axis length a
minor axis length b

$$\text{Orientation is } \theta = \tan^{-1} \frac{v_y}{v_x}$$

Where V is the eigenvector corresponding to the largest eigenvalue

Feature extraction masterclass video



Applications (3)

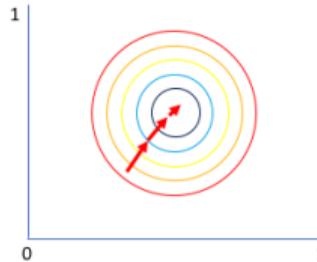
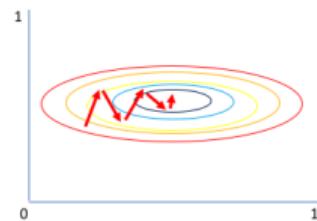
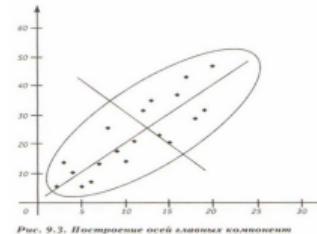
Machine learning + optimization

Task: we have data, which depicted on figure. We need to *find local minimum* of it.

Dummy approach: let's use gradient descent w/o preprocessing.

Result of dummy approach: It can disconvergent, or solved very slow, because of big difference between step size in x and y direction.

Smart approach: let's firstly represent it as a *circle* (**transform all data in eigenbasis**) and make gradient descent on it. In this case we have almost the same step size for x and y direction.



Represent data as an ellipse

Gradient descent Issue

Represent data as a circle



Applications (4)

Predict the behavior of linear systems

Task: I have a system and want to understand, how it will work.

Afterwards, I want to control it (design a controller).

Solution:

- **Estimate Stability using Eigenpairs.** Looking on eigenvalues we can predict stability of our linear system;
- **Coupled Oscillators.** Example of Eigenvalues and Eigenvectors in the context of coupled oscillators (masses connected by springs)



Task 6

(Recommended) Suppose $Ax = \lambda x$. If $\lambda = 0$ then x is in the nullspace. If $\lambda \neq 0$ then x is in the column space. Those spaces have dimensions $(n - r) + r = n$. So why doesn't every square matrix have n linearly independent eigenvectors?



Task 6

(Recommended) Suppose $Ax = \lambda x$. If $\lambda = 0$ then x is in the nullspace. If $\lambda \neq 0$ then x is in the column space. Those spaces have dimensions $(n - r) + r = n$. So why doesn't every square matrix have n linearly independent eigenvectors?

Answer

Two problems: The nullspace and column space can overlap, so x could be in both.
There may not be r independent eigenvectors in the column space.



Reference material

- Lecture 21, Eigenvalues and Eigenvectors
- Lecture 22, Diagonalization and Powers of A
- "*Linear Algebra and Applications*", pdf pages 270–306
Eigenvalues and Eigenvectors 5.1–5.3
- "*Introduction to Linear Algebra*", pdf pages 299–329
Eigenvalues and Eigenvectors 6.1–6.2
- [The eigenvalue problem | Lectures 32 – 38](#)
Video from Matrix Algebra for Engineers course

Deserve “A” grade!

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🚪 Room 105 (Underground robotics lab)