## Practical Linear Algebra for Data Science

From Core Concepts to Applications
Using Python

Mike X Cohen



## **Practical Linear Algebra for Data Science**

by Mike X Cohen

Copyright © 2023 Syncxpress BV. All rights reserved.

Printed in the United States of America.

Published by O'Reilly Media, Inc., 1005 Gravenstein Highway North, Sebastopol, CA 95472.

O'Reilly books may be purchased for educational, business, or sales promotional use. Online editions are also available for most titles (<a href="http://oreilly.com">http://oreilly.com</a>). For more information, contact our corporate/institutional sales department: 800-998-9938 or corporate@oreilly.com.

Acquisitions Editor: Jessica Haberman
Development Editor: Shira Evans
Production Editor: Jonathon Owen
Copyeditor: Piper Editorial Consulting, LLC
Proofreader: Shannon Turlington

**Cover Designer:** Karen Montgomery **Illustrator:** Kate Dullea

**Indexer:** Ellen Troutman

**Interior Designer:** David Futato

November 2022: First Edition

## Revision History for the First Edition

2022-09-25: First Release

See http://oreilly.com/catalog/errata.csp?isbn=9781098120610 for release details.

The O'Reilly logo is a registered trademark of O'Reilly Media, Inc. *Practical Linear Algebra for Data Science*, the cover image, and related trade dress are trademarks of O'Reilly Media, Inc.

The views expressed in this work are those of the authors, and do not represent the publisher's views. While the publisher and the author have used good faith efforts to ensure that the information and instructions contained in this work are accurate, the publisher and the author disclaim all responsibility for errors or omissions, including without limitation responsibility for damages resulting from the use of or reliance on this work. Use of the information and instructions contained in this work is at your own risk. If any code samples or other technology this work contains or describes is subject to open source licenses or the intellectual property rights of others, it is your responsibility to ensure that your use thereof complies with such licenses and/or rights.

## **Table of Contents**

Pre	Preface	
1.	Introduction	. 1
	What Is Linear Algebra and Why Learn It?	1
	About This Book	2
	Prerequisites	2
	Math	3
	Attitude	3
	Coding	3
	Mathematical Proofs Versus Intuition from Coding	4
	Code, Printed in the Book and Downloadable Online	5
	Code Exercises	5
	How to Use This Book (for Teachers and Self Learners)	6
2.	Vectors, Part 1	7
	Creating and Visualizing Vectors in NumPy	7
	Geometry of Vectors	10
	Operations on Vectors	11
	Adding Two Vectors	11
	Geometry of Vector Addition and Subtraction	12
	Vector-Scalar Multiplication	13
	Scalar-Vector Addition	14
	Transpose	15
	Vector Broadcasting in Python	16
	Vector Magnitude and Unit Vectors	17
	The Vector Dot Product	18
	The Dot Product Is Distributive	20
	Geometry of the Dot Product	21

Hadamard Multiplication Outer Product Cross and Triple Products Orthogonal Vector Decomposition Summary	2 2	22 23 24 24 28
Cross and Triple Products Orthogonal Vector Decomposition Summary	2 2	24 24
Orthogonal Vector Decomposition Summary	2	24
Summary		
•	2	8
Cala Francisca		
Code Exercises	2	29
3. Vectors, Part 2.	3	3
Vector Sets	3	3
Linear Weighted Combination	3	34
Linear Independence	3	35
The Math of Linear Independence	3	37
Independence and the Zeros Vector	3	8
Subspace and Span	3	8
Basis	4	1
Definition of Basis	4	4
Summary	4	16
Code Exercises		
	4	ŀ6
4. Vector Applications		l6
<b>4. Vector Applications.</b> Correlation and Cosine Similarity	4	
··		19
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering		19 19 33
Correlation and Cosine Similarity Time Series Filtering and Feature Detection		19 19
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering		19 19 33
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering Code Exercises Correlation Exercises Filtering and Feature Detection Exercises		19 19 33
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering Code Exercises Correlation Exercises		19 19 19 19 19
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering Code Exercises Correlation Exercises Filtering and Feature Detection Exercises		19 19 19 19 19 19 19 19 19
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering Code Exercises Correlation Exercises Filtering and Feature Detection Exercises K-Means Exercises  5. Matrices, Part 1 Creating and Visualizing Matrices in NumPy		19 52 53 57 58
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering Code Exercises Correlation Exercises Filtering and Feature Detection Exercises K-Means Exercises  5. Matrices, Part 1.		19 52 57 58 50
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering Code Exercises Correlation Exercises Filtering and Feature Detection Exercises K-Means Exercises  5. Matrices, Part 1 Creating and Visualizing Matrices in NumPy		19 52 53 57 58 50
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering Code Exercises Correlation Exercises Filtering and Feature Detection Exercises K-Means Exercises  5. Matrices, Part 1. Creating and Visualizing Matrices in NumPy Visualizing, Indexing, and Slicing Matrices Special Matrices Matrix Math: Addition, Scalar Multiplication, Hadamare		19 19 52 57 58 50 51
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering Code Exercises Correlation Exercises Filtering and Feature Detection Exercises K-Means Exercises  5. Matrices, Part 1. Creating and Visualizing Matrices in NumPy Visualizing, Indexing, and Slicing Matrices Special Matrices		19 52 53 57 58 51 51
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering Code Exercises Correlation Exercises Filtering and Feature Detection Exercises K-Means Exercises  5. Matrices, Part 1 Creating and Visualizing Matrices in NumPy Visualizing, Indexing, and Slicing Matrices Special Matrices Matrix Math: Addition, Scalar Multiplication, Hadamare Addition and Subtraction "Shifting" a Matrix		19 52 53 57 58 50 51 53 55
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering Code Exercises Correlation Exercises Filtering and Feature Detection Exercises K-Means Exercises  5. Matrices, Part 1. Creating and Visualizing Matrices in NumPy Visualizing, Indexing, and Slicing Matrices Special Matrices Matrix Math: Addition, Scalar Multiplication, Hadamare Addition and Subtraction		19 19 19 19 19 19 19 19 19 19 19 19 19 1
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering Code Exercises Correlation Exercises Filtering and Feature Detection Exercises K-Means Exercises  5. Matrices, Part 1. Creating and Visualizing Matrices in NumPy Visualizing, Indexing, and Slicing Matrices Special Matrices Matrix Math: Addition, Scalar Multiplication, Hadamare Addition and Subtraction "Shifting" a Matrix Scalar and Hadamard Multiplications Standard Matrix Multiplication		19 52 53 57 58 50 51 51 53 55 55
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering Code Exercises Correlation Exercises Filtering and Feature Detection Exercises K-Means Exercises  5. Matrices, Part 1 Creating and Visualizing Matrices in NumPy Visualizing, Indexing, and Slicing Matrices Special Matrices Matrix Math: Addition, Scalar Multiplication, Hadamare Addition and Subtraction "Shifting" a Matrix Scalar and Hadamard Multiplications Standard Matrix Multiplication Rules for Matrix Multiplication Validity		19 19 19 19 19 19 19 19 19 19 19 19 19 1
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering Code Exercises Correlation Exercises Filtering and Feature Detection Exercises K-Means Exercises  5. Matrices, Part 1. Creating and Visualizing Matrices in NumPy Visualizing, Indexing, and Slicing Matrices Special Matrices Matrix Math: Addition, Scalar Multiplication, Hadamare Addition and Subtraction "Shifting" a Matrix Scalar and Hadamard Multiplications Standard Matrix Multiplication		19 19 19 19 19 19 19 19 19 19 19 19 19 1
Correlation and Cosine Similarity Time Series Filtering and Feature Detection K-Means Clustering Code Exercises Correlation Exercises Filtering and Feature Detection Exercises K-Means Exercises  5. Matrices, Part 1 Creating and Visualizing Matrices in NumPy Visualizing, Indexing, and Slicing Matrices Special Matrices Matrix Math: Addition, Scalar Multiplication, Hadamare Addition and Subtraction "Shifting" a Matrix Scalar and Hadamard Multiplications Standard Matrix Multiplication Rules for Matrix Multiplication Validity		19 19 19 19 19 19 19 19 19 19 19 19 19 1

	Dot and outer product notation	73
	Matrix Operations: LIVE EVIL (Order of Operations)	73
	Symmetric Matrices	74
	Creating Symmetric Matrices from Nonsymmetric Matrices	74
	Summary	75
	Code Exercises	76
6.	Matrices, Part 2	. 81
	Matrix Norms	82
	Matrix Trace and Frobenius Norm	83
	Matrix Spaces (Column, Row, Nulls)	84
	Column Space	84
	Row Space	88
	Null Spaces	88
	Rank	91
	Ranks of Special Matrices	94
	Rank of Added and Multiplied Matrices	96
	Rank of Shifted Matrices	97
	Theory and Practice	98
	Rank Applications	99
	In the Column Space?	99
	Linear Independence of a Vector Set	100
	Determinant	101
	Computing the Determinant	102
	Determinant with Linear Dependencies	103
	The Characteristic Polynomial	104
	Summary	106
	Code Exercises	107
7.	Matrix Applications	113
	Multivariate Data Covariance Matrices	113
	Geometric Transformations via Matrix-Vector Multiplication	116
	Image Feature Detection	120
	Summary	124
	Code Exercises	124
	Covariance and Correlation Matrices Exercises	124
	Geometric Transformations Exercises	126
	Image Feature Detection Exercises	127
8.	Matrix Inverse	131
	The Matrix Inverse	131
	Types of Inverses and Conditions for Invertibility	132

	Computing the Inverse	133
	Inverse of a $2 \times 2$ Matrix	133
	Inverse of a Diagonal Matrix	135
	Inverting Any Square Full-Rank Matrix	136
	One-Sided Inverses	138
	The Inverse Is Unique	141
	Moore-Penrose Pseudoinverse	141
	Numerical Stability of the Inverse	142
	Geometric Interpretation of the Inverse	144
	Summary	145
	Code Exercises	146
9.	Orthogonal Matrices and QR Decomposition	149
	Orthogonal Matrices	149
	Gram-Schmidt	151
	QR Decomposition	152
	Sizes of Q and R	153
	QR and Inverses	155
	Summary	156
	Code Exercises	157
10.	Row Reduction and LU Decomposition	161
	Systems of Equations	161
	Converting Equations into Matrices	162
	Working with Matrix Equations	163
	Row Reduction	165
	Gaussian Elimination	167
	Gauss-Jordan Elimination	168
	Matrix Inverse via Gauss-Jordan Elimination	169
	LU Decomposition	171
	Row Swaps via Permutation Matrices	172
	Summary	173
	Code Exercises	174
11.	General Linear Models and Least Squares	177
	General Linear Models	178
	Terminology	178
	Setting Up a General Linear Model	178
	Solving GLMs	180
	Is the Solution Exact?	181
	A Geometric Perspective on Least Squares	182
	Why Does Least Squares Work?	183

	GLM in a Simple Example	185
	Least Squares via QR	189
	Summary	190
	Code Exercises	191
12.	Least Squares Applications	197
	Predicting Bike Rentals Based on Weather	197
	Regression Table Using statsmodels	202
	Multicollinearity	203
	Regularization	204
	Polynomial Regression	205
	Grid Search to Find Model Parameters	208
	Summary	211
	Code Exercises	212
	Bike Rental Exercises	212
	Multicollinearity Exercise	213
	Regularization Exercise	214
	Polynomial Regression Exercise	215
	Grid Search Exercises	215
13.	Eigendecomposition	217
	Interpretations of Eigenvalues and Eigenvectors	218
	Geometry	218
	Statistics (Principal Components Analysis)	219
	Noise Reduction	220
	Dimension Reduction (Data Compression)	221
	Finding Eigenvalues	221
	Finding Eigenvectors	224
	Sign and Scale Indeterminacy of Eigenvectors	226
	Diagonalizing a Square Matrix	226
	The Special Awesomeness of Symmetric Matrices	228
	Orthogonal Eigenvectors	228
	Real-Valued Eigenvalues	230
	Eigendecomposition of Singular Matrices	231
	Quadratic Form, Definiteness, and Eigenvalues	232
	The Quadratic Form of a Matrix	232
	Definiteness	234
	$\mathbf{A}^{\mathrm{T}}\mathbf{A}$ Is Positive (Semi)definite	235
	Generalized Eigendecomposition	236
	Summary	237
	Code Exercises	238

14.	Singular Value Decomposition	245
	The Big Picture of the SVD	245
	Singular Values and Matrix Rank	247
	SVD in Python	247
	SVD and Rank-1 "Layers" of a Matrix	248
	SVD from EIG	250
	SVD of $\mathbf{A}^{\mathrm{T}}\mathbf{A}$	251
	Converting Singular Values to Variance, Explained	251
	Condition Number	252
	SVD and the MP Pseudoinverse	253
	Summary	254
	Code Exercises	255
15.	Eigendecomposition and SVD Applications	259
	PCA Using Eigendecomposition and SVD	259
	The Math of PCA	260
	The Steps to Perform a PCA	262
	PCA via SVD	263
	Linear Discriminant Analysis	263
	Low-Rank Approximations via SVD	266
	SVD for Denoising	266
	Summary	267
	Exercises	268
	PCA	268
	Linear Discriminant Analyses	273
	SVD for Low-Rank Approximations	276
	SVD for Image Denoising	279
16.	Python Tutorial	283
	Why Python, and What Are the Alternatives?	283
	IDEs (Interactive Development Environment)	284
	Using Python Locally and Online	284
	Working with Code Files in Google Colab	285
	Variables	286
	Data Types	287
	Indexing	288
	Functions	289
	Methods as Functions	290
	Writing Your Own Functions	291
	Libraries	292
	numPy	292
	Indexing and Slicing in NumPy	293

	Visualization	294
	Translating Formulas to Code	297
	Print Formatting and f-Strings	300
	Control Flow	301
	Comparators	301
	if statements	301
	for Loops	303
	Nested Control Statements	304
	Measuring Computation Time	304
	Getting Help and Learning More	305
	What to Do When Things Go Awry	305
	Summary	306
Ind	dex	307