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Chapters
Linear Algebra Home
Systems of Equations and Matrices
Determinants
Eucldean n-Space
Vector Spaces
Eigenvalues and Eigenvectors
Misc
Contact Me
Downloads
FAQ
Links
My Students
Site Map
Terms of Use

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[Section](#)
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### Fundamental Subspaces

In this section we want to take a look at some important subspaces that are associated with matrices. In fact they are so important that they are often called the fundamental subspaces of a matrix. We've actually already seen one of the fundamental subspaces, the null space, [previously](#) although we will give its definition here again for the sake of completeness.

Before we give the formal definitions of the fundamental subspaces we need to quickly review a concept that we first saw back when we were looking at matrix arithmetic.

Given an  $m \times n$  matrix

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}$$

The **row vectors** (we called them row matrices at the time) are the vectors in  $\mathbb{R}^n$  formed out of the rows of  $A$ . The **column vectors** (again we called them column matrices at the time) are the vectors in  $\mathbb{R}^m$  that are formed out of the columns of  $A$ .

**Example 1** Write down the row vectors and column vectors for

$$A = \begin{bmatrix} -1 & 5 \\ 0 & -4 \\ 9 & 2 \\ 3 & -7 \end{bmatrix}$$

**Solution**

The row vectors are,

$$\mathbf{r}_1 = \begin{bmatrix} -1 & 5 \end{bmatrix} \quad \mathbf{r}_2 = \begin{bmatrix} 0 & -4 \end{bmatrix} \quad \mathbf{r}_3 = \begin{bmatrix} 9 & 2 \end{bmatrix} \quad \mathbf{r}_4 = \begin{bmatrix} 3 & -7 \end{bmatrix}$$

The column vectors are

$$\mathbf{c}_1 = \begin{bmatrix} -1 \\ 0 \\ 9 \\ 3 \end{bmatrix} \quad \mathbf{c}_2 = \begin{bmatrix} 5 \\ -4 \\ 2 \\ -7 \end{bmatrix}$$

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**David Lerner**



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**Mathematical Reviews**, 2005 *Conformal Graph Directed Markov Systems on Carnot Groups* Vasileios Chousionis, Jeremy T. Tyson, Mariusz Urbanski, 2020-09-28 The authors develop a comprehensive theory of conformal graph directed Markov systems in the non Riemannian setting of Carnot groups equipped with a sub Riemannian metric In particular they develop the thermodynamic formalism and show that under natural hypotheses the limit set of an Carnot conformal GDMS has Hausdorff dimension given by Bowen's parameter They illustrate their results for a variety of examples of both linear and nonlinear iterated function systems and graph directed Markov systems in such sub Riemannian spaces These include the Heisenberg continued fractions introduced by Lukyanenko and Vandehey as well as Kleinian and Schottky groups associated to the non real classical rank one hyperbolic spaces Lecture Notes in Linear Algebra Tanush Shaska, 2005-08-01 *Books Out-of-print*, 1986 □□□□□□□□, 1977 **Notes for linear algebra** Warren Brisley, 1983

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## **Table of Contents Pauls Notes Linear Algebra**

1. Understanding the eBook Pauls Notes Linear Algebra
  - The Rise of Digital Reading Pauls Notes Linear Algebra
  - Advantages of eBooks Over Traditional Books
2. Identifying Pauls Notes Linear Algebra
  - Exploring Different Genres
  - Considering Fiction vs. Non-Fiction
  - Determining Your Reading Goals
3. Choosing the Right eBook Platform
  - Popular eBook Platforms
  - Features to Look for in an Pauls Notes Linear Algebra
  - User-Friendly Interface
4. Exploring eBook Recommendations from Pauls Notes Linear Algebra
  - Personalized Recommendations
  - Pauls Notes Linear Algebra User Reviews and Ratings
  - Pauls Notes Linear Algebra and Bestseller Lists
5. Accessing Pauls Notes Linear Algebra Free and Paid eBooks
  - Pauls Notes Linear Algebra Public Domain eBooks
  - Pauls Notes Linear Algebra eBook Subscription Services
  - Pauls Notes Linear Algebra Budget-Friendly Options

6. Navigating Pauls Notes Linear Algebra eBook Formats
  - ePub, PDF, MOBI, and More
  - Pauls Notes Linear Algebra Compatibility with Devices
  - Pauls Notes Linear Algebra Enhanced eBook Features
7. Enhancing Your Reading Experience
  - Adjustable Fonts and Text Sizes of Pauls Notes Linear Algebra
  - Highlighting and Note-Taking Pauls Notes Linear Algebra
  - Interactive Elements Pauls Notes Linear Algebra
8. Staying Engaged with Pauls Notes Linear Algebra
  - Joining Online Reading Communities
  - Participating in Virtual Book Clubs
  - Following Authors and Publishers Pauls Notes Linear Algebra
9. Balancing eBooks and Physical Books Pauls Notes Linear Algebra
  - Benefits of a Digital Library
  - Creating a Diverse Reading Collection Pauls Notes Linear Algebra
10. Overcoming Reading Challenges
  - Dealing with Digital Eye Strain
  - Minimizing Distractions
  - Managing Screen Time
11. Cultivating a Reading Routine Pauls Notes Linear Algebra
  - Setting Reading Goals Pauls Notes Linear Algebra
  - Carving Out Dedicated Reading Time
12. Sourcing Reliable Information of Pauls Notes Linear Algebra
  - Fact-Checking eBook Content of Pauls Notes Linear Algebra
  - Distinguishing Credible Sources
13. Promoting Lifelong Learning
  - Utilizing eBooks for Skill Development
  - Exploring Educational eBooks
14. Embracing eBook Trends
  - Integration of Multimedia Elements

- Interactive and Gamified eBooks

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