

Introduction to Mobile Robotics

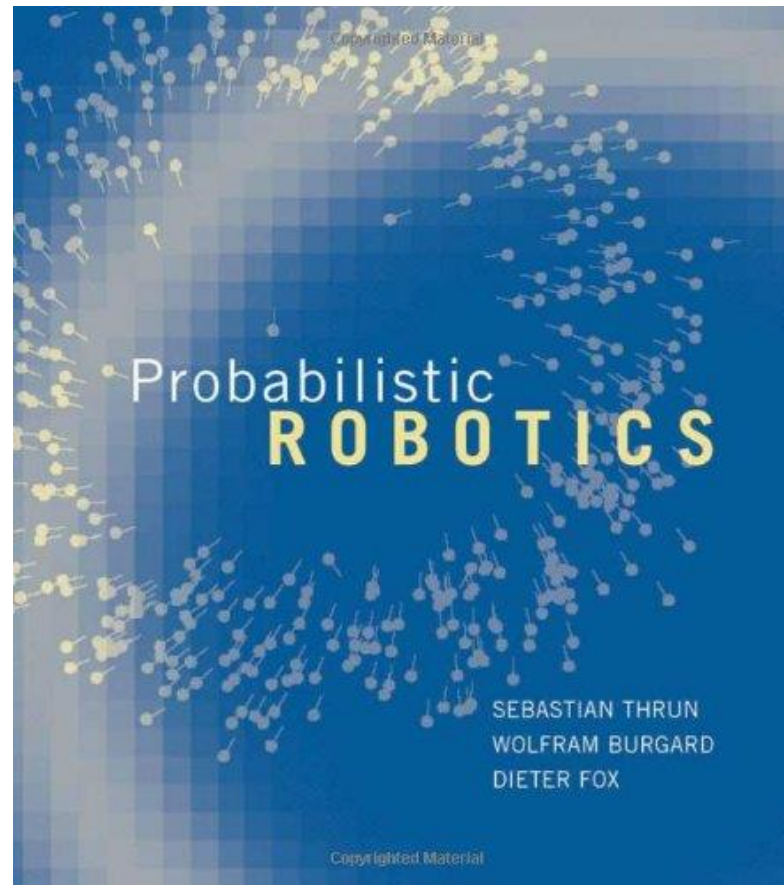
Compact Course on Linear Algebra

Wolfram Burgard, Bastian Steder



Reference Book

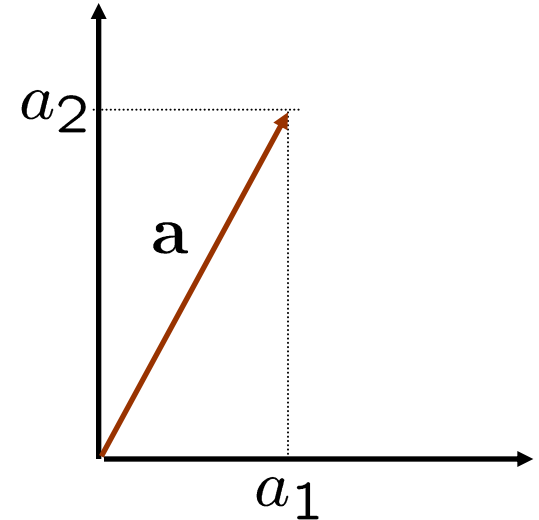
Thrun, Burgard, and Fox:
“Probabilistic Robotics”



Vectors

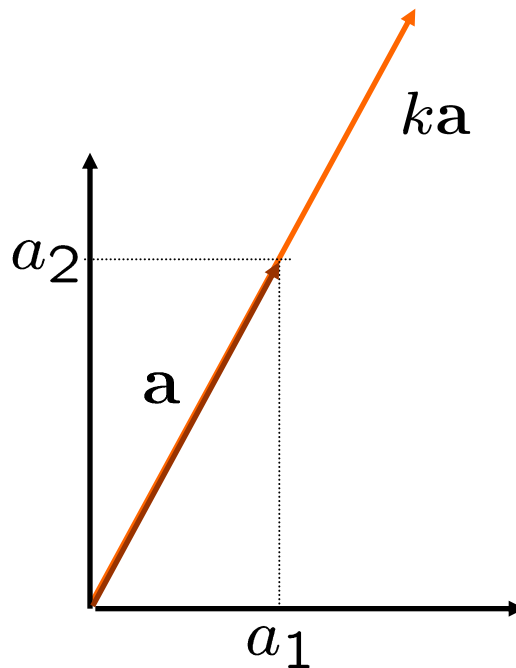
- Arrays of numbers
- Vectors represent a point in a n dimensional space

$$(a_1) \quad \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \quad \begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{pmatrix}$$



Vectors: Scalar Product

- Scalar-Vector Product ka
- Changes the length of the vector, but **not** its direction

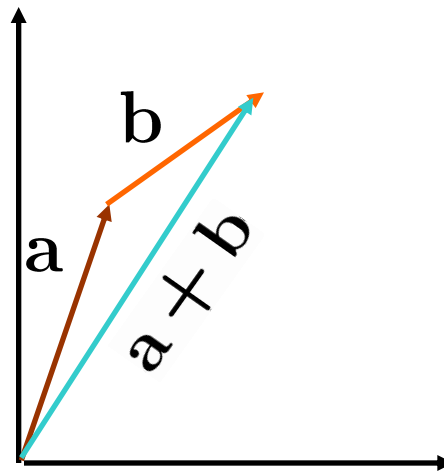


Vectors: Sum

- Sum of vectors (is commutative)

$$\begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{pmatrix} + \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{pmatrix} = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{pmatrix} + \begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{pmatrix}$$

- Can be visualized as “chaining” the vectors.

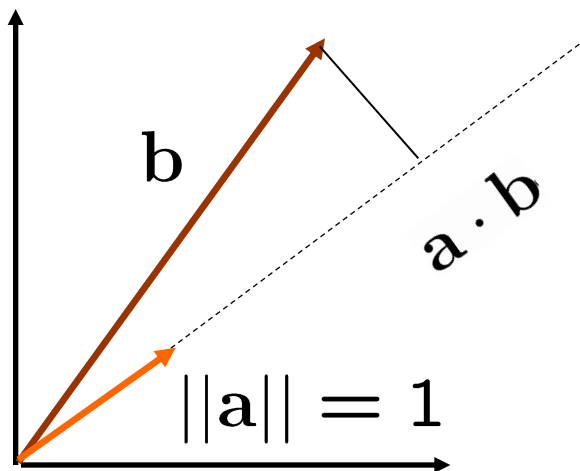


Vectors: Dot Product

- Inner product of vectors (is a scalar)

$$\mathbf{a} \cdot \mathbf{b} = \mathbf{b} \cdot \mathbf{a} = \sum_i a_i b_i$$

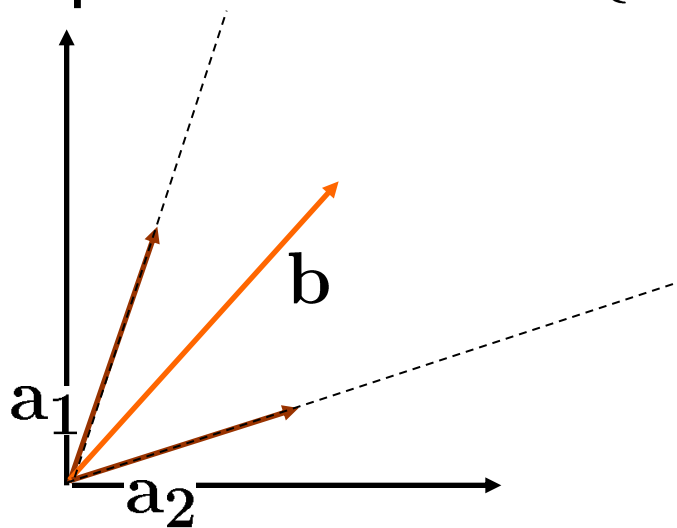
- If one of the two vectors, e.g. \mathbf{a} , has $\|\mathbf{a}\| = 1$ the inner product $\mathbf{a} \cdot \mathbf{b}$ returns the length of the projection of \mathbf{b} along the direction of \mathbf{a}



- If $\mathbf{a} \cdot \mathbf{b} = 0$, the two vectors are **orthogonal**

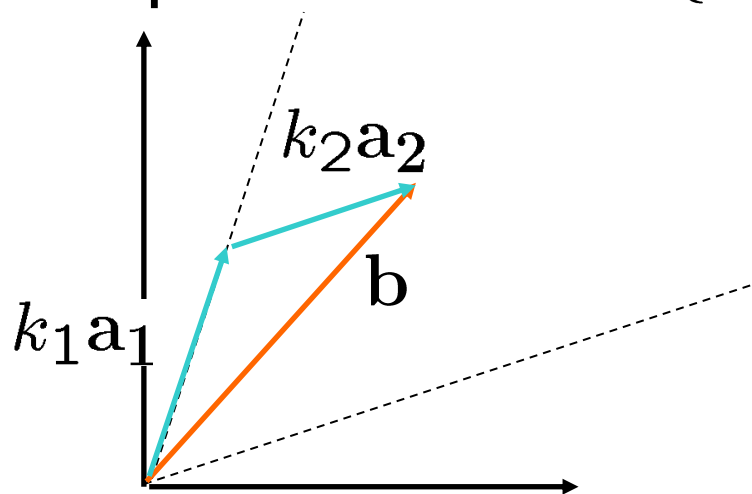
Vectors: Linear (In)Dependence

- A vector \mathbf{b} is **linearly dependent** from $\{\mathbf{a}_1, \mathbf{a}_2, \dots, \mathbf{a}_n\}$ if $\mathbf{b} = \sum_i k_i \mathbf{a}_i$
- In other words, if \mathbf{b} can be obtained by summing up the \mathbf{a}_i properly scaled
- If there exist no $\{k_i\}$ such that $\mathbf{b} = \sum_i k_i \mathbf{a}_i$ then \mathbf{b} is independent from $\{\mathbf{a}_i\}$



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Matrices

- A matrix is written as a table of values

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & & & \\ a_{n1} & a_{n2} & \cdots & a_{nm} \end{pmatrix} \quad \mathbf{A} : \underset{\substack{\uparrow \\ \text{rows}}}{n} \times \underset{\substack{\uparrow \\ \text{columns}}}{m}$$

- **1st index** refers to the **row**
- **2nd index** refers to the **column**
- Note: a d-dimensional vector is equivalent to a $d \times 1$ matrix

Matrices as Collections of Vectors

- Column vectors

$$\mathbf{A} = \begin{pmatrix} \boxed{\begin{matrix} a_{11} \\ a_{21} \\ \vdots \\ a_{n1} \end{matrix}} & \boxed{\begin{matrix} a_{12} \\ a_{22} \\ \vdots \\ a_{n2} \end{matrix}} & \cdots & \boxed{\begin{matrix} a_{1m} \\ a_{2m} \\ \vdots \\ a_{nm} \end{matrix}} \end{pmatrix}$$

$\begin{matrix} \uparrow & \uparrow & & \uparrow \\ \mathbf{a}_{*1} & \mathbf{a}_{*2} & \cdots & \mathbf{a}_{*m} \end{matrix}$

Matrices as Collections of Vectors

- Row vectors

$$\mathbf{A} = \begin{pmatrix} \boxed{a_{11} \quad a_{12} \quad \cdots \quad a_{1m}} \\ \boxed{a_{21} \quad a_{22} \quad \cdots \quad a_{2m}} \\ \vdots \\ \boxed{a_{n1} \quad a_{n2} \quad \cdots \quad a_{nm}} \end{pmatrix} \begin{matrix} \longrightarrow \\ \longrightarrow \\ \longrightarrow \end{matrix} \begin{pmatrix} \mathbf{a}_{1*}^T \\ \mathbf{a}_{2*}^T \\ \vdots \\ \mathbf{a}_{n*}^T \end{pmatrix}$$

Important Matrices Operations

- Multiplication by a scalar
- Sum (commutative, associative)
- Multiplication by a vector
- Product (not commutative)
- Inversion (square, full rank)
- Transposition

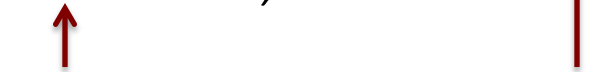
Scalar Multiplication & Sum

- In the scalar multiplication, every element of the vector or matrix is multiplied with the scalar
- The sum of two vectors is a vector consisting of the pair-wise sums of the individual entries
- The sum of two matrices is a matrix consisting of the pair-wise sums of the individual entries

Matrix Vector Product

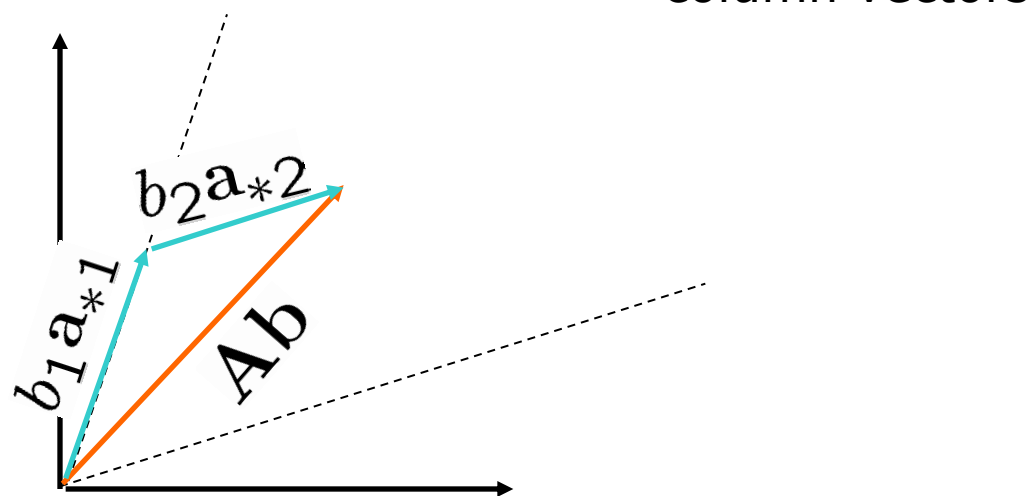
- The i^{th} component of $\mathbf{A}\mathbf{b}$ is the dot product $\mathbf{a}_{i*}^T \cdot \mathbf{b}$.
- The vector $\mathbf{A}\mathbf{b}$ is linearly dependent from the column vectors $\{\mathbf{a}_{*i}\}$ with coefficients $\{b_i\}$

$$\mathbf{A}\mathbf{b} = \begin{pmatrix} \mathbf{a}_{1*}^T \\ \mathbf{a}_{2*}^T \\ \vdots \\ \mathbf{a}_{n*}^T \end{pmatrix} \cdot \mathbf{b} = \begin{pmatrix} \mathbf{a}_{1*}^T \cdot \mathbf{b} \\ \mathbf{a}_{2*}^T \cdot \mathbf{b} \\ \vdots \\ \mathbf{a}_{n*}^T \cdot \mathbf{b} \end{pmatrix} = \sum_k \mathbf{a}_{*k} b_k$$


row vectors
column vectors

Matrix Vector Product

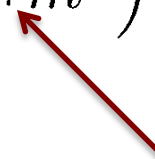
- If the column vectors of A represent a reference system, the product Ab computes the global transformation of the vector b according to $\{a_{*i}\}$



Matrix Matrix Product

- Can be defined through
 - the dot product of row and column vectors
 - the linear combination of the columns of **A** scaled by the coefficients of the columns of **B**

$$\begin{aligned} \mathbf{C} &= \mathbf{AB} \\ &= \begin{pmatrix} \mathbf{a}_{1*}^T \cdot \mathbf{b}_{*1} & \mathbf{a}_{1*}^T \cdot \mathbf{b}_{*2} & \cdots & \mathbf{a}_{1*}^T \cdot \mathbf{b}_{*m} \\ \mathbf{a}_{2*}^T \cdot \mathbf{b}_{*1} & \mathbf{a}_{2*}^T \cdot \mathbf{b}_{*2} & \cdots & \mathbf{a}_{2*}^T \cdot \mathbf{b}_{*m} \\ \vdots & & & \\ \mathbf{a}_{n*}^T \cdot \mathbf{b}_{*1} & \mathbf{a}_{n*}^T \cdot \mathbf{b}_{*2} & \cdots & \mathbf{a}_{n*}^T \cdot \mathbf{b}_{*m} \end{pmatrix} \\ &= \begin{pmatrix} \mathbf{Ab}_{*1} & \mathbf{Ab}_{*2} & \cdots & \mathbf{Ab}_{*m} \end{pmatrix} \end{aligned}$$

 column vectors

Matrix Matrix Product

- If we consider the second interpretation, we see that the columns of **C** are the “transformations” of the columns of **B** through **A**
- All the interpretations made for the matrix vector product hold

$$\begin{aligned} \mathbf{C} &= \mathbf{AB} \\ &= \left(\mathbf{Ab}_{*1} \quad \mathbf{Ab}_{*2} \quad \dots \quad \mathbf{Ab}_{*m} \right) \\ \mathbf{c}_{*i} &= \mathbf{Ab}_{*i} \end{aligned}$$



column vectors

Rank

- **Maximum** number of linearly independent rows (columns)
- Dimension of the **image** of the transformation $f(\mathbf{x}) = A\mathbf{x}$
- When A is $m \times n$ we have
 - $\text{rank}(A) \geq 0$ and the equality holds iff A is the null matrix
 - $\text{rank}(A) \leq \min(m, n)$
- Computation of the rank is done by
 - Gaussian elimination on the matrix
 - Counting the number of non-zero rows

Inverse

$$\mathbf{AB} = \mathbf{I}$$

- If \mathbf{A} is a square matrix of full rank, then there is a unique matrix $\mathbf{B} = \mathbf{A}^{-1}$ such that $\mathbf{AB} = \mathbf{I}$ holds
- The i^{th} row of \mathbf{A} is and the j^{th} column of \mathbf{A}^{-1} are:
 - orthogonal (if $i \neq j$)
 - or their dot product is 1 (if $i = j$)

Matrix Inversion

$$\mathbf{A}\mathbf{B} = \mathbf{I}$$

- The j^{th} column of \mathbf{A}^{-1} can be found by solving the following linear system:

$$\mathbf{A}\mathbf{a}^{-1}_{*j} = \mathbf{i}_{*j} \quad \leftarrow \text{This is the } j^{th} \text{ column of the identity matrix}$$

Determinant (det)

- Only defined for **square matrices**
- The inverse of \mathbf{A} exists if and only if $\det(\mathbf{A}) \neq 0$
- For 2×2 matrices:

Let $\mathbf{A} = [a_{ij}]$ and $|\mathbf{A}| = \det(\mathbf{A})$, then

$$\begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = a_{11} \cdot a_{22} - a_{12} \cdot a_{21}$$

- For 3×3 matrices the Sarrus rule holds:

$$\begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix} = a_{11}a_{22}a_{33} + a_{12}a_{23}a_{31} + a_{13}a_{21}a_{32} \\ - a_{11}a_{23}a_{32} - a_{12}a_{21}a_{33} - a_{13}a_{22}a_{11}$$

Determinant

- For **general** $n \times n$ matrices?

Let \mathbf{A}_{ij} be the submatrix obtained from \mathbf{A} by deleting the i -th row and the j -th column

$$\begin{bmatrix} 1 & 2 & 5 & 0 \\ 2 & 3 & 4 & -1 \\ -5 & 8 & 0 & 0 \\ 0 & 4 & -2 & 0 \end{bmatrix} \quad \rightarrow \quad \mathbf{A}_{32} = \begin{bmatrix} 1 & 5 & 0 \\ 2 & 4 & -1 \\ 0 & -2 & 0 \end{bmatrix}$$

Rewrite determinant for 3×3 matrices:

$$\begin{aligned} \det(\mathbf{A}^{3 \times 3}) &= a_{11}a_{22}a_{33} + a_{12}a_{23}a_{31} + a_{13}a_{21}a_{32} \\ &\quad - a_{11}a_{23}a_{32} - a_{12}a_{21}a_{33} - a_{13}a_{22}a_{11} \\ &= a_{11} \cdot \det(\mathbf{A}_{11}) - a_{12} \cdot \det(\mathbf{A}_{12}) + a_{13} \cdot \det(\mathbf{A}_{13}) \end{aligned}$$

Determinant

- For **general** $n \times n$ matrices?

$$\begin{aligned} \det(\mathbf{A}) &= a_{11}\det(\mathbf{A}_{11}) - a_{12}\det(\mathbf{A}_{12}) + \dots + (-1)^{1+n}a_{1n}\det(\mathbf{A}_{1n}) \\ &= \sum_{j=1}^n (-1)^{1+j}a_{1j}\det(\mathbf{A}_{1j}) \end{aligned}$$

Let $\mathbf{C}_{ij} = (-1)^{i+j}\det(\mathbf{A}_{ij})$ be the (i,j) -cofactor, then

$$\begin{aligned} \det(\mathbf{A}) &= a_{11}\mathbf{C}_{11} + a_{12}\mathbf{C}_{12} + \dots + a_{1n}\mathbf{C}_{1n} \\ &= \sum_{j=1}^n a_{1j}\mathbf{C}_{1j} \end{aligned}$$

This is called the **cofactor expansion** across the first row

Determinant

- **Problem:** Take a 25 x 25 matrix (which is considered small). The cofactor expansion method requires $n!$ multiplications. For $n = 25$, this is 1.5×10^{25} multiplications for which a today supercomputer would take **500,000 years**.
- There are **much faster methods**, namely using **Gauss elimination** to bring the matrix into triangular form.

$$\mathbf{A} = \begin{bmatrix} d_1 & * & * & * \\ 0 & d_2 & * & * \\ 0 & 0 & d_3 & * \\ 0 & 0 & 0 & d_4 \end{bmatrix} \quad \det(\mathbf{A}) = \prod_{i=1}^n d_i$$

Because for **triangular matrices** the determinant is the product of diagonal elements

Determinant: Properties

- **Row operations** (\mathbf{A} is still a $n \times n$ square matrix)
 - If \mathbf{B} results from \mathbf{A} by interchanging two rows, then $\det(\mathbf{B}) = -\det(\mathbf{A})$
 - If \mathbf{B} results from \mathbf{A} by multiplying one row with a number c , then $\det(\mathbf{B}) = c \cdot \det(\mathbf{A})$
 - If \mathbf{B} results from \mathbf{A} by adding a multiple of one row to another row, then $\det(\mathbf{B}) = \det(\mathbf{A})$
- **Transpose:** $\det(\mathbf{A}^T) = \det(\mathbf{A})$
- **Multiplication:** $\det(\mathbf{A} \cdot \mathbf{B}) = \det(\mathbf{A}) \cdot \det(\mathbf{B})$
- Does **not** apply to addition! $\det(\mathbf{A} + \mathbf{B}) \neq \det(\mathbf{A}) + \det(\mathbf{B})$

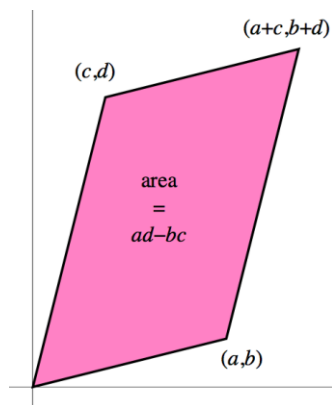
Determinant: Applications

- Compute **Eigenvalues**:

Solve the characteristic polynomial $\det(\mathbf{A} - \lambda \cdot \mathbf{I}) = 0$

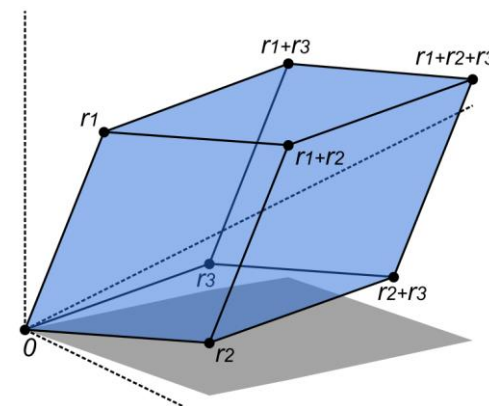
- **Area and Volume:** $\text{area} = |\det(\mathbf{A})|$

$$\mathbf{A} = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$$



$$\mathbf{A} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix}$$

(r_i is i -th row)



Orthogonal Matrix

- A matrix Q is **orthogonal** iff its column (row) vectors represent an **orthonormal** basis

$$q_{*i}^T \cdot q_{*j} = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases}, \forall i, j$$

- As linear transformation, it is **norm** preserving
- Some properties:
 - The transpose is the inverse $QQ^T = Q^TQ = I$
 - Determinant has unity norm (± 1)

$$1 = \det(I) = \det(Q^TQ) = \det(Q)\det(Q^T) = \det(Q)^2$$

Rotation Matrix

- A Rotation matrix is an orthonormal matrix with $\det = +1$

- 2D Rotations $R(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}$

- 3D Rotations along the main axes

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) \\ 0 & \sin(\theta) & \cos(\theta) \end{bmatrix} \quad R_y(\theta) = \begin{bmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{bmatrix}$$

- **IMPORTANT: Rotations are not commutative**

$$R_x\left(\frac{\pi}{4}\right) \cdot R_y\left(\frac{\pi}{4}\right) = \begin{bmatrix} 0.707 & 0 & -0.707 \\ -0.5 & 0.707 & -0.5 \\ 0.5 & 0.707 & 0.5 \end{bmatrix}, \quad R_x\left(\frac{\pi}{4}\right) \cdot R_y\left(\frac{\pi}{4}\right) \cdot \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} = \begin{bmatrix} -1.414 \\ 0.586 \\ 3.414 \end{bmatrix}$$

$$R_y\left(\frac{\pi}{4}\right) \cdot R_x\left(\frac{\pi}{4}\right) = \begin{bmatrix} 0.707 & -0.5 & -0.5 \\ 0 & 0.707 & -0.707 \\ 0.707 & 0.5 & 0.5 \end{bmatrix}, \quad R_y\left(\frac{\pi}{4}\right) \cdot R_x\left(\frac{\pi}{4}\right) \cdot \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} = \begin{bmatrix} -1.793 \\ 0.707 \\ 3.207 \end{bmatrix}$$

Matrices to Represent Affine Transformations

- A general and easy way to describe a 3D transformation is via matrices

Diagram illustrating the decomposition of an affine transformation matrix A into a rotation matrix R and a translation vector t .

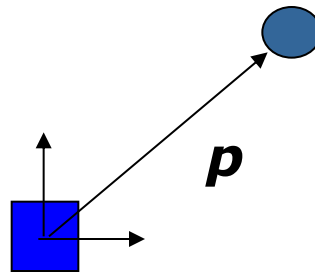
$$A = \begin{pmatrix} R & t \\ 0 & 1 \end{pmatrix} \quad A^{-1} = \begin{pmatrix} R^T & -R^T t \\ 0 & 1 \end{pmatrix} \quad p = \begin{pmatrix} t \\ 1 \end{pmatrix}$$

The diagram shows the matrix A on the left, its inverse A^{-1} in the middle, and a point p on the right. A box labeled "Translation Vector" has arrows pointing to the t in A , the $-R^T t$ in A^{-1} , and the t in p . A box labeled "Rotation Matrix" has arrows pointing to the R in A and the R^T in A^{-1} .

- Takes naturally into account the non-commutativity of the transformations
- Homogeneous coordinates

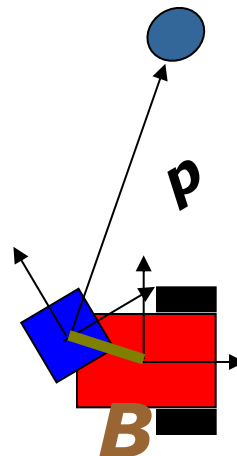
Combining Transformations

- A simple interpretation: chaining of transformations (represented as homogeneous matrices)
 - Matrix **A** represents the pose of a **robot** in the space
 - Matrix **B** represents the position of a sensor on the robot
 - The **sensor** perceives an **object** at a given location **p** , in its own frame [the sensor has no clue on where it is in the world]
 - Where is the object in the global frame?



Combining Transformations

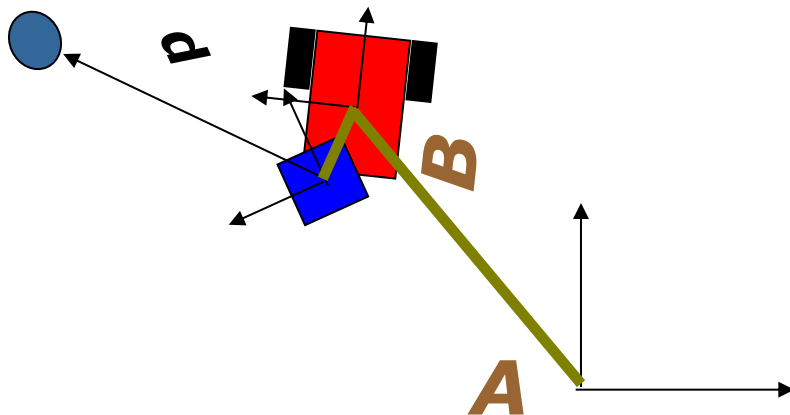
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Bp gives the pose of the object wrt the robot

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Bp gives the pose of the object wrt the robot

ABp gives the pose of the object wrt the world

Positive Definite Matrix

- The analogous of positive number
- Definition $M > 0$ iff $z^T M z > 0 \forall z \neq 0$
- Example
 - $M_1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $\begin{bmatrix} z_1 & z_2 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = z_1^2 + z_2^2 > 0$

Positive Definite Matrix

- Properties
 - **Invertible**, with positive definite inverse
 - All real **eigenvalues** > 0
 - **Trace** is > 0
 - **Cholesky** decomposition $A = LL^T$

Linear Systems (1)

$$\mathbf{Ax} = \mathbf{b}$$

Interpretations:

- A set of linear equations
- A way to find the coordinates \mathbf{x} in the reference system of \mathbf{A} such that \mathbf{b} is the result of the transformation of \mathbf{Ax}
- Solvable by Gaussian elimination

Gaussian Elimination

A method to solve systems of linear equations.

Example for three variables:

$$a_{11}x_1 + a_{12}x_2 + a_{13}x_3 = b_1$$

$$a_{21}x_1 + a_{22}x_2 + a_{23}x_3 = b_2$$

$$a_{31}x_1 + a_{32}x_2 + a_{33}x_3 = b_3$$

We want to transform this to

$$\tilde{a}_{11}x_1 + \tilde{a}_{12}x_2 + \tilde{a}_{13}x_3 = \tilde{b}_1$$

$$\tilde{a}_{22}x_2 + \tilde{a}_{23}x_3 = \tilde{b}_2$$

$$\tilde{a}_{33}x_3 = \tilde{b}_3.$$

Gaussian Elimination

Written as an extended coefficient matrix:

$$\left(\begin{array}{ccc|c} a_{11} & a_{12} & a_{13} & b_1 \\ a_{21} & a_{22} & a_{23} & b_2 \\ a_{31} & a_{32} & a_{33} & b_3 \end{array} \right) \rightarrow \left(\begin{array}{ccc|c} \tilde{a}_{11} & \tilde{a}_{12} & \tilde{a}_{13} & \tilde{b}_1 \\ 0 & \tilde{a}_{22} & \tilde{a}_{23} & \tilde{b}_2 \\ 0 & 0 & \tilde{a}_{33} & \tilde{b}_3 \end{array} \right)$$

To reach this form we only need two elementary row operations:



- Add to one row a scalar multiple of another.
- Swap the positions of two rows.

Another commonly used term for Gaussian Elimination is *row reduction*.

Linear Systems (2)

$$\mathbf{Ax} = \mathbf{b}$$

Notes:

- Many efficient solvers exist, e.g., conjugate gradients, sparse Cholesky decomposition
- One can obtain a reduced system $(\mathbf{A}', \mathbf{b}')$ by considering the matrix (\mathbf{A}, \mathbf{b}) and suppressing all the rows which are linearly dependent
- Let $\mathbf{A}'\mathbf{x}=\mathbf{b}'$ the reduced system with $\mathbf{A}':n'\times m$ and $\mathbf{b}':n'\times 1$ and $\text{rank } \mathbf{A}' = \min(n', m)$ rows  columns 
- The system might be either over-constrained ($n' > m$) or under-constrained ($n' < m$)

Over-Constrained Systems

- “More (ind.) equations than variables”
- An over-constrained system does not admit an **exact solution**
- However, if $\text{rank } \mathbf{A}' = \text{cols}(\mathbf{A})$ one often computes a **minimum norm solution**

$$\mathbf{x} = \underset{\mathbf{x}}{\operatorname{argmin}} \|\mathbf{A}'\mathbf{x} - \mathbf{b}'\|$$

Note: rank = Maximum number of linearly independent rows/columns

Under-Constrained Systems

- “More variables than (ind.) equations”
- The system is **under-constrained** if the number of linearly independent rows of \mathbf{A}' is smaller than the dimension of \mathbf{b}'
- An under-constrained system admits infinite solutions
- The degree of these infinite solutions is $cols(\mathbf{A}') - rows(\mathbf{A}')$

Jacobian Matrix

- It is a **non-square matrix** $n \times m$ in general
- Given a vector-valued function

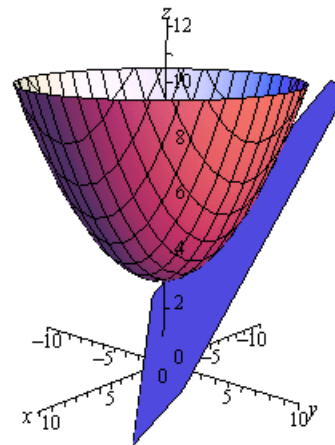
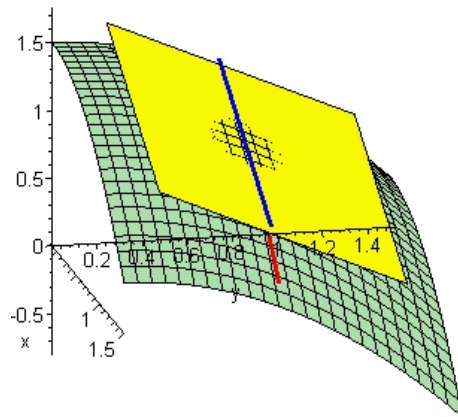
$$f(\mathbf{x}) = \begin{bmatrix} f_1(\mathbf{x}) \\ f_2(\mathbf{x}) \\ \vdots \\ f_m(\mathbf{x}) \end{bmatrix}$$

- Then, the **Jacobian matrix** is defined as

$$\mathbf{F}_{\mathbf{x}} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \cdots & \frac{\partial f_2}{\partial x_n} \\ \vdots & \vdots & \cdots & \vdots \\ \frac{\partial f_m}{\partial x_1} & \frac{\partial f_m}{\partial x_2} & \cdots & \frac{\partial f_m}{\partial x_n} \end{bmatrix}$$

Jacobian Matrix

- It is the orientation of the **tangent plane** to the vector-valued function at a given point



- **Generalizes the gradient** of a scalar valued function

Further Reading

- A “quick and dirty” guide to matrices is the Matrix Cookbook.
Just google for ‘matrix cook book’ to find the pdf version.