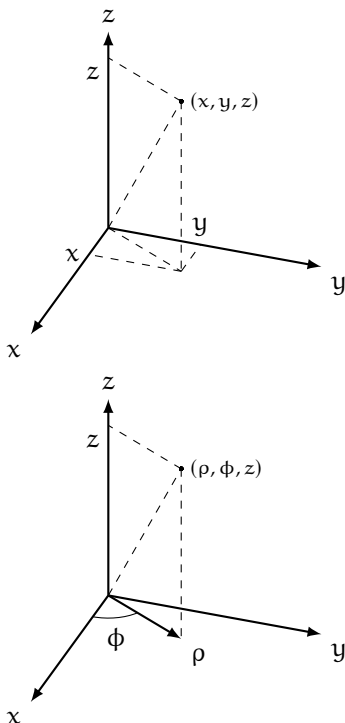


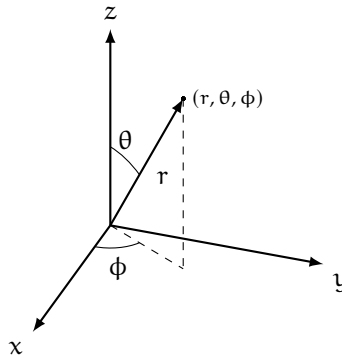
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Things You Just Gotta Know

Coordinate Systems



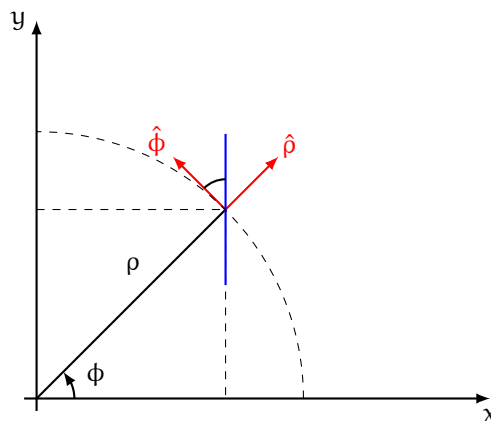


We want to focus on vector-valued functions of coordinates.

$$\vec{V}(\mathbf{r}) = V_x(x, y)\hat{i} + V_y(x, y)\hat{j}.$$

Notice that a vector function uses the coordinate system twice. Once for the function's inputs, once for the vectors themselves.

Polar Coordinates



We can also express the inputs to \vec{V} in polar coordinates, (ρ, ϕ) .

$$\vec{V}(\mathbf{r}) = V_\rho(\rho, \phi)\hat{i} + V_\phi(\rho, \phi)\hat{j}.$$

To extract the input functions, we take

$$V_x = \hat{i} \cdot \vec{V}$$

$$V_y = \hat{j} \cdot \vec{V}.$$

Alternatively, we can project \vec{V} onto the $\hat{\rho}, \hat{\phi}$ axis:

$$\vec{V}(\mathbf{r}) = V_\rho(\rho, \phi)\hat{\rho} + V_\phi(\rho, \phi)\hat{\phi},$$

and we extract

$$V_\rho = \hat{\rho} \cdot \vec{V}$$

$$V_\phi = \hat{\phi} \cdot \vec{V}.$$

Notice that \mathbf{r} is an abstract vector; we need to project it onto a basis.

For instance, we can take the position vector and project it onto the cartesian and polar axes:

$$\begin{aligned}
 \mathbf{s} &= x\hat{i} + y\hat{j} \\
 &= \rho \cos \phi \hat{i} + \rho \sin \phi \hat{j} \\
 &= \rho \hat{\rho} \\
 &= \sqrt{x^2 + y^2} \hat{\rho}
 \end{aligned}$$

The main reason we avoided using the $\hat{\rho}, \hat{\phi}$ axis up until this point is that ρ and ϕ are *position-dependent*, while the \hat{i}, \hat{j} axis is position-independent.

Now, we must figure out the position-dependence of $\hat{\rho}$ and $\hat{\phi}$:

$$d\mathbf{r} = \frac{\partial \mathbf{r}}{\partial \rho} d\rho + \frac{\partial \mathbf{r}}{\partial \phi} d\phi.$$

If we hold ϕ constant, it must be the case that any change in ρ is in the $\hat{\rho}$ direction. Therefore,

$$\begin{aligned}
 \hat{\rho} &= \frac{\frac{\partial \mathbf{r}}{\partial \rho}}{\left\| \frac{\partial \mathbf{r}}{\partial \rho} \right\|} \\
 &= \frac{\cos \phi \hat{i} + \sin \phi \hat{j}}{|\cos \phi \hat{i} + \sin \phi \hat{j}|} \\
 &= \cos \phi \hat{i} + \sin \phi \hat{j}.
 \end{aligned}$$

Similarly,

$$\begin{aligned}
 \hat{\phi} &= \frac{\frac{\partial \mathbf{r}}{\partial \phi}}{\left\| \frac{\partial \mathbf{r}}{\partial \phi} \right\|} \\
 &= \frac{-\rho \sin \phi \hat{i} + \rho \cos \phi \hat{j}}{\|-\rho \sin \phi \hat{i} + \rho \cos \phi \hat{j}\|} \\
 &= -\sin \phi \hat{i} + \cos \phi \hat{j}.
 \end{aligned}$$

Thus, we can see that the $\hat{\rho}, \hat{\phi}$ axis is orthogonal.

$$\begin{aligned}
 \frac{\partial \hat{\rho}}{\partial \phi} &= -\sin \phi \hat{i} + \cos \phi \hat{j} \\
 &= \hat{\phi}, \\
 \frac{\partial \hat{\phi}}{\partial \phi} &= -\hat{\rho}, \\
 \frac{\partial \hat{\phi}}{\partial \rho} &= 0,
 \end{aligned}$$

and

$$\frac{\partial \hat{\rho}}{\partial \rho} = 0$$

Example (Velocity).

$$\mathbf{v} = \frac{d\mathbf{s}}{dt}$$

$$= \frac{d}{dt} (x\hat{i}) + \frac{d}{dt} (y\hat{j}).$$

In the case of cartesian coordinates, \hat{i} and \hat{j} are constants.

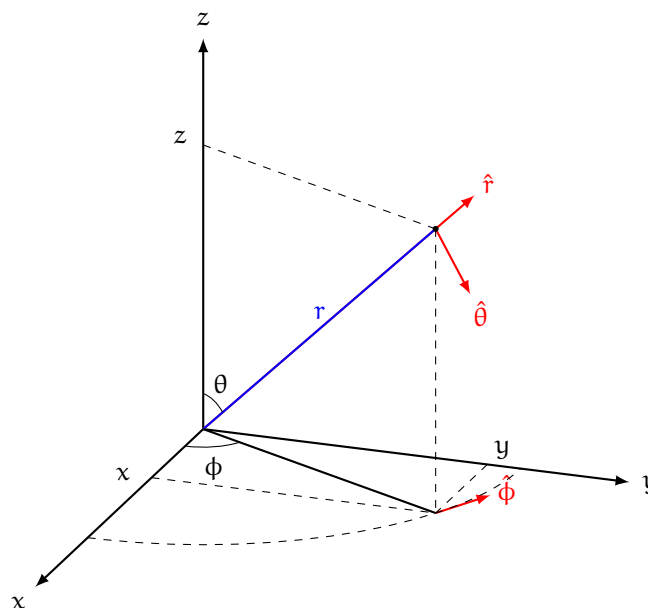
$$= v_x\hat{i} + v_y\hat{j}$$

When we examine polar coordinates, since $\hat{\rho}$ and $\hat{\phi}$ are position-dependent, we must use the chain rule.¹

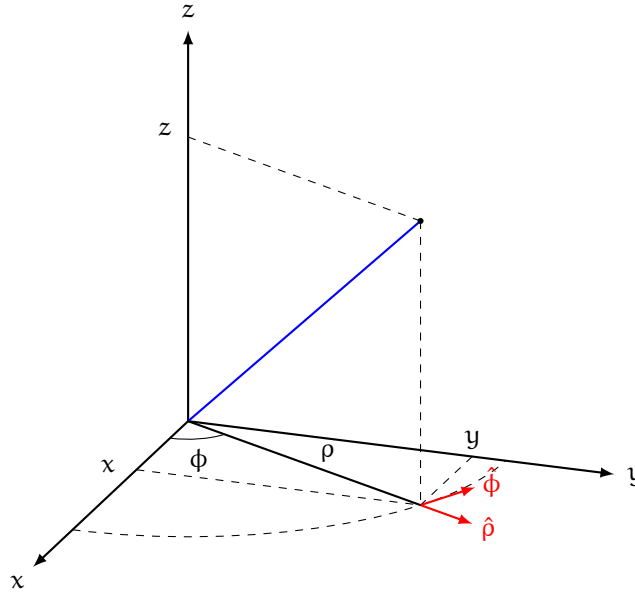
$$\begin{aligned} \mathbf{v} &= \frac{d\mathbf{s}}{dt} \\ &= \frac{d\rho}{dt}\hat{\rho} + \rho \frac{d\hat{\rho}}{dt} \\ &= \frac{d\rho}{dt}\hat{\rho} + \rho \left(\frac{\partial \hat{\rho}}{\partial \rho} \frac{d\rho}{dt} + \underbrace{\frac{\partial \hat{\rho}}{\partial \phi} \frac{d\phi}{dt}}_{=\hat{\phi}} \right) \\ &= \frac{d\rho}{dt}\hat{\rho} + \rho \frac{d\phi}{dt}\hat{\phi} \\ &= \dot{\rho}\hat{\rho} + \rho\dot{\phi}\hat{\phi}. \end{aligned}$$

Notice that $\dot{\rho}$ is the radial velocity and $\dot{\phi} = \omega$ is the angular velocity.

Spherical and Cylindrical Coordinates



¹Note that $\hat{\rho} = \hat{\rho}(\rho, \phi)$ and $\hat{\phi} = \hat{\phi}(\rho, \phi)$.



Polar	Cylindrical	Spherical
$\mathbf{s} = s(\rho, \phi)$	$\mathbf{s} = s(\rho, \phi, z)$	$\mathbf{s} = s(r, \phi, \theta)$
$\mathbf{s} = \begin{pmatrix} \rho \cos \phi \\ \rho \sin \phi \end{pmatrix}$	$\mathbf{s} = \begin{pmatrix} \rho \cos \phi \\ \rho \sin \phi \\ z \end{pmatrix}$	$\mathbf{s} = \begin{pmatrix} r \cos \phi \sin \theta \\ r \sin \phi \sin \theta \\ r \cos \theta \end{pmatrix}$

Here,¹¹ ϕ denotes the polar angle and θ denotes the azimuthal angle. Notice that $\phi \in [0, 2\pi)$ and $\theta \in [0, \pi]$.

We can see that $\hat{\rho}$, $\hat{\phi}$, and $\hat{\theta}$ in spherical coordinates are also position-dependent.

$$\begin{aligned}
 \hat{r} &= \frac{\frac{\partial \mathbf{s}}{\partial r}}{\left\| \frac{\partial \mathbf{s}}{\partial r} \right\|} \\
 &= \sin \theta \cos \phi \hat{i} + \sin \theta \sin \phi \hat{j} + \cos \theta \hat{k} \\
 \hat{\phi} &= \frac{\frac{\partial \mathbf{s}}{\partial \phi}}{\left\| \frac{\partial \mathbf{s}}{\partial \phi} \right\|} \\
 &= -\sin \phi \hat{i} + \cos \phi \hat{j} \\
 \hat{\theta} &= \frac{\frac{\partial \mathbf{s}}{\partial \theta}}{\left\| \frac{\partial \mathbf{s}}{\partial \theta} \right\|} \\
 &= \cos \phi \cos \theta \hat{i} + \cos \theta \sin \phi \hat{j} - \sin \theta \hat{k}
 \end{aligned}$$

Scale Factors and Jacobians

Coordinate System	Line Element	Area Element	Volume Element
Polar	$d\mathbf{s} = \hat{\rho} d\rho + \rho \hat{\phi} d\phi$	$d\mathbf{a} = r dr d\phi$	—
Cylindrical	$d\mathbf{s} = \hat{\rho} d\rho + \rho \hat{\phi} d\phi + \hat{k} dz$	—	$d\mathbf{v} = r dr d\phi dz$
Spherical	$d\mathbf{s} = \hat{r} dr + r \sin \theta \hat{\phi} d\phi + r \hat{\theta} d\theta$	$d\mathbf{a} = r^2 \sin \theta d\phi d\theta$	$d\mathbf{v} = r^2 \sin \theta dr d\phi d\theta$

¹¹Physicists amirite?

In cylindrical coordinates, we can use the chain rule to find the value of $d\mathbf{r}$:

$$d\mathbf{r} = \hat{\rho}d\rho + \rho\hat{\phi}d\phi + \hat{k}dz.$$

The extra factor of ρ in the expression of $\rho\hat{\phi}d\phi$ is the *scale factor* on ϕ .

Similarly, in spherical coordinates, we have

$$d\mathbf{r} = \hat{r}dr + r\sin\theta\hat{\phi}d\phi + r\hat{\theta}d\theta,$$

with scale factors of $r\sin\theta$ on $\hat{\phi}d\phi$ and r on $\hat{\theta}d\theta$.

When we go from line elements (of the form $d\mathbf{r}$) to area elements (of the form $d\mathbf{a}$), we can see that the area element in polar coordinates is $d\mathbf{a} = \rho d\rho d\phi$ — we need the extra factor of ρ to account for the fact that the magnitude of the area element scales with the radius.

Similarly, the volume element in cylindrical coordinates is $dv = r dr d\phi dz$ and the volume element in spherical coordinates is $r^2 \sin\theta dr d\phi d\theta$.

Recall that the definition of an angle ϕ that subtends an arc length s is $\phi = \frac{s}{r}$, where r is the radius of a circle. We can imagine a similar concept on a sphere — a *solid angle* measured in steradians is of the form $\Omega = \frac{A}{r^2}$, where A denotes the surface area subtended by the angle Ω . In particular, since $d\Omega = \frac{dA}{r^2}$, we find that $d\Omega = \sin\theta d\phi d\theta$.

When we are dealing with products of scale factors, we need to use the Jacobian to determine the proper scale factor on any given element:

$$\begin{aligned} d\mathbf{a} &= dx dy \\ &= |J| du dv, \end{aligned}$$

where $|J|$ denotes the determinant of the Jacobian matrix. We write the Jacobian as follows:

$$\begin{aligned} J &= \frac{\partial(x, y)}{\partial(u, v)} \\ &= \begin{pmatrix} \frac{\partial x}{\partial u} & \frac{\partial y}{\partial u} \\ \frac{\partial x}{\partial v} & \frac{\partial y}{\partial v} \end{pmatrix}. \end{aligned}$$

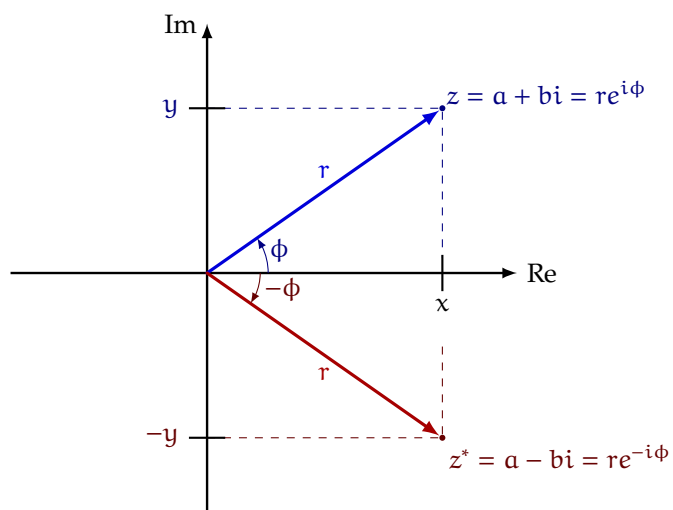
We specifically desire the determinant:

$$|J| = \frac{\partial x}{\partial u} \frac{\partial y}{\partial v} - \frac{\partial y}{\partial u} \frac{\partial x}{\partial v}.$$

Complex Numbers

Quantity	Expression and/or Criterion
Cartesian form	$z = a + bi$
Polar form	$z = re^{i\phi}$
r	$\sqrt{a^2 + b^2}$
ϕ	$\arg z = \arctan\left(\frac{b}{a}\right)$
Cartesian z^*	$z^* = a - bi$
Polar z^*	$z^* = re^{-i\phi}$
$ z $	$\sqrt{zz^*}$
$\text{Re}(z)$	$\text{Re}(z) = \frac{z+z^*}{2}$
$\text{Im}(z)$	$\text{Im}(z) = \frac{z-z^*}{2i}$
$\cos \phi$	$\frac{e^{i\phi} + e^{-i\phi}}{2}$
$\sin \phi$	$\frac{e^{i\phi} - e^{-i\phi}}{2i}$
$e^{i\phi}$	$\cos \phi + i \sin \phi$
$e^{in\phi}$	$\cos(n\phi) + i \sin(n\phi)$

Introduction



A complex number is denoted

$$z = a + bi$$

where $i^2 = -1$ and $a, b \in \mathbb{R}$. This is known as the cartesian representation. However, we can also imagine z as the polar representation:

$$z = re^{i\phi},$$

where $\phi = \arg z$ is known as the argument, and $r = |z|$ is the modulus. We can see the relation between the cartesian and polar representations through Euler's identity:^{III}

$$r(\cos \phi + i \sin \phi) = re^{i\phi}.$$

We denote the conjugate of z as z^* ^{IV}, found by $z^* = a - bi = re^{-i\phi}$.

We find $\text{Re}(z)$ and $\text{Im}(z)$, the real and imaginary parts of z , by

$$\begin{aligned}\text{Re}(z) &= \frac{z + z^*}{2} \\ \text{Im}(z) &= \frac{z - z^*}{2i}.\end{aligned}$$

We say that a complex number of the form $e^{i\phi}$ is a *pure phase*, as $|e^{i\phi}| = 1$.

To find if some complex number z is purely real or purely imaginary, we can use the following criterion:

$$\begin{aligned}z \in \mathbb{R} &\Leftrightarrow z = z^* \\ z \in i\mathbb{R} &\Leftrightarrow z = -z^*.\end{aligned}$$

Example (Real, Imaginary, or Complex?). Consider

$$z_1 = i^i.$$

To find if this is purely real or complex, we take

$$\begin{aligned}z_1^* &= (-i)^{-i} \\ &= \left(\frac{1}{-i}\right)^i \\ &= i^i.\end{aligned}$$

Thus, $z_1 \in \mathbb{R}$. In order to determine the value of i^i , we substitute the polar form:

$$\begin{aligned}z_1 &= \left(e^{i\frac{\pi}{2}}\right)^i \\ &= e^{-\frac{\pi}{2}}.\end{aligned}$$

Some Trigonometry with Complex Exponentials

Consider $z = \cos \phi + i \sin \phi$. We can see that

$$\begin{aligned}\text{Re}(z) &= \cos \phi \\ &= \frac{(\cos \phi + i \sin \phi) + (\cos \phi - i \sin \phi)}{2} \\ &= \frac{e^{i\phi} + e^{-i\phi}}{2} \\ \text{Im}(z) &= \sin \phi \\ &= \frac{(\cos \phi + i \sin \phi) - (\cos \phi - i \sin \phi)}{2i} \\ &= \frac{e^{i\phi} - e^{-i\phi}}{2i}.\end{aligned}$$

We can actually define $\sin \phi$ and $\cos \phi$ with the above derivation.

^{III}This can be proven relatively easily through substitution into the Taylor series, which is allowed because e^z is entire.

^{IV}Physicists amirite?

Theorem (De Moivre).

$$\begin{aligned} e^{inx} &= \cos(nx) + i \sin(nx) \\ &= \left(e^{ix}\right)^n \\ &= (\cos x + i \sin x)^n. \end{aligned}$$

Example (Finding $\cos(2x)$ and $\sin(2x)$).

$$\begin{aligned} \cos(2x) + i \sin(2x) &= (\cos x + i \sin x)^2 \\ &= (\cos^2 x - \sin^2 x) + i(2 \sin x \cos x). \end{aligned}$$

Since the real parts and imaginary parts have to be equal, this means

$$\begin{aligned} \cos 2x &= \cos^2 x - \sin^2 x \\ \sin^2 x &= 2 \sin x \cos x. \end{aligned}$$

In particular, we can see that $e^{in\pi} = (-1)^n$ and $e^{in\frac{\pi}{2}} = i^n$.^v

Additionally, we can see that for $z = re^{i\phi}$,

$$\begin{aligned} z^{1/m} &= \left(re^{i\phi+2\pi n}\right)^{1/m} \\ &= r^{1/m} e^{i\frac{1}{m}(\phi+2\pi n)}, \end{aligned}$$

where $n \in \mathbb{N}$ and m is fixed. For $r = 1$, we call these values the m roots of unity.

Example (Waves and Oscillations). Recall that for a wave with spatial frequency k , angular frequency ω , and amplitude A , the wave is represented by

$$f(x, t) = A \cos(kx - \omega t).$$

The speed of a wave v is equal to $\frac{\omega}{k}$.

Simple harmonic motion is characterized by the solution to the differential equation $\ddot{x} = -\omega^2 x$, where x denotes position. In simple harmonic motion, there is no spatial motion, meaning our function is only of time:

$$\begin{aligned} f(t) &= A \cos \omega t \\ &= \operatorname{Re} \left(A e^{i\omega t} \right). \end{aligned}$$

As a result of the representation of complex numbers in polar form, we can do math entirely in exponentials, then take the real part of our solution to find $f(t)$.

Unfortunately, in the real world, there is friction; as a result, our oscillation is damped by an exponential factor.

Example (Hyperbolic Sine and Hyperbolic Cosine). We wish to calculate $\cos ix$ and $\sin ix$.

$$\begin{aligned} \cos ix &= \frac{1}{2} \left(e^{i(ix)} + e^{-i(ix)} \right) \\ &= \frac{e^{-x} + e^x}{2} \end{aligned}$$

^vThis will be especially useful when we get to Fourier series.

We define $\cosh x = \cos(ix)$. Additionally,

$$\begin{aligned} -i \sin ix &= -i \frac{1}{2i} (e^{i(ix)} - e^{-i(ix)}) \\ &= i \frac{e^{ix} - e^{-ix}}{2i} \\ &= \frac{e^x - e^{-x}}{2}. \end{aligned}$$

We define $\sinh x = -i \sin(ix)$.

Similar to how $\cos^2 x + \sin^2 x = 1$, we can find that $\cosh^2 x - \sinh^2 x = 1$.

Index Algebra

We usually denote vectors by either \vec{A} , \mathbf{A} , or

$$\begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{pmatrix},$$

which is defined by a basis.

If we imagine we are in n -dimensional space, we can let A_i where $i = 1, 2, \dots, n$ denote both

- the i th component of \vec{A} ;
- the entire vector \vec{A} (since i can be arbitrary).

Contractions and Dummy Indices

Consider $C = AB$, where A, B are $n \times m$ and $m \times p$ matrices respectively.

$$C = \begin{pmatrix} A_{11} & A_{12} & \cdots & A_{1m} \\ \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & \cdots & A_{nm} \end{pmatrix} \begin{pmatrix} B_{11} & B_{12} & \cdots & B_{1p} \\ \vdots & \vdots & \ddots & \vdots \\ B_{m1} & B_{m2} & \cdots & B_{mp} \end{pmatrix}.$$

Definition (Matrix Multiplication in Index Notation). For matrices A and B , where A is an $m \times n$ and B is a $n \times p$ matrix, we write

$$C_{ij} = \sum_{k=1}^n A_{ik} B_{kj}$$

We say that k is a dummy index, since k takes values from 1 to n . Note that the value we calculate is C_{ij} ; in other words, in the sum $\sum_k A_{ik} B_{kj}$, the indices of the form ij are the “net indices” from the multiplication.

Note that if $C = BA$, then

$$\begin{aligned} C_{ij} &= \sum_{k=1}^n B_{ik} A_{kj} \\ &= \sum_{k=1}^n A_{kj} B_{ik} \end{aligned}$$

$$\neq \sum_{k=1}^n A_{ik} B_{kj}.$$

The corresponding fact is that $AB \neq BA$ necessarily.

Note that the index that is summed over always appears exactly twice.

Definition (Symmetric Matrix). Let C be a matrix. Then, we say C is symmetric if

$$C_{ij} = C_{ji}$$

Definition (Antisymmetric Matrix). Let C be a matrix. We say C is antisymmetric if

$$C_{ij} = -C_{ji}.$$

We can always decompose a random matrix into the sum of a symmetric matrix and an antisymmetric matrix.

Two Special Tensors

Name	Notation	Definition
Kronecker Delta	δ_{ij}	$\delta_{ij} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$
Levi-Civita Symbol	ϵ_{ijk}	$\epsilon_{ijk} = \begin{cases} 1 & (i, j, k) = (1, 2, 3) \text{ cyclically} \\ -1 & (i, j, k) = (2, 1, 3) \text{ cyclically} \\ 0 & \text{else} \end{cases}$

Order of (i, j, k)	Value of ϵ_{ijk}
1, 2, 3	1
3, 1, 2	1
2, 3, 1	1
1, 3, 2	-1
2, 1, 3	-1
3, 2, 1	-1
else	0

Value	Index Notation
$\mathbf{A} \times \mathbf{B}$	$\sum_{i,j,k} \epsilon_{ijk} A_i B_j \hat{e}_k$
$(\mathbf{A} \times \mathbf{B})_\ell$	$\sum_{i,j} \epsilon_{ij\ell} A_i B_j$
$(\hat{e}_i \times \hat{e}_j) \cdot \hat{e}_k$	ϵ_{ijk}
B_i	$\sum_{\alpha} B_{\alpha} \delta_{\alpha i}$
$\mathbf{A} \cdot \mathbf{B}$	$\sum_{i,j} A_i B_j \delta_{ij}$
$\sum_{j,k} \epsilon_{mjk} \epsilon_{njk}$	$2\delta_{mn}$
$\sum_{\ell} \epsilon_{mnl} \epsilon_{ijl}$	$\delta_{mi} \delta_{nj} - \delta_{mj} \delta_{ni}$

Definition (Kronecker Delta). The Kronecker Delta, δ_{ij} , is the tensor that denotes the identity matrix.

$$\delta_{ij} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$$

Example (Extracting an Index). Consider A as vector. Then,

$$\sum_i A_i \delta_{ij} = A_j.$$

In other words, the Kronecker Delta collapses the sum to the j th index.

Example (Orthonormal Basis from Kronecker Delta). Let $\{\hat{e}_i\}_{i=1}^n$ be a basis for some vector space V . If

$$\hat{e}_i \cdot \hat{e}_j = \delta_{ij}$$

for every i, j , then $\{\hat{e}_i\}_{i=1}^n$ is an orthonormal basis for V .

Definition (Levi-Civita Symbol). In two dimensions, as a matrix, we write

$$\epsilon_{ij} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix},$$

meaning

$$\epsilon_{ij} = \begin{cases} 1 & i = 1, j = 2 \\ -1 & i = 2, j = 1 \\ 0 & \text{else} \end{cases}.$$

The Levi-Civita Symbol is antisymmetric, just as the Kronecker Delta is symmetric.

In three dimensions, we define

$$\epsilon_{ijk} = \begin{cases} 1 & (i, j, k) = (1, 2, 3) \text{ cyclically} \\ -1 & (i, j, k) = (2, 1, 3) \text{ cyclically} \\ 0 & \text{else} \end{cases}.$$

In other words, $\epsilon_{ijk} = -\epsilon_{jik}$.

Exercise (Relations between δ_{ij} and ϵ_{ijk}).

$$\sum_{j,k} \epsilon_{mjk} \epsilon_{njk} = 2\delta_{mn}$$

$$\sum_{\ell} \epsilon_{mnl} \epsilon_{ijl} = \delta_{mi} \delta_{nj} - \delta_{mj} \delta_{ni}$$

Definition (Dot Product). Let $\{\hat{e}_i\}_{i=1}^n$ be an orthonormal basis for V . Let $\mathbf{A} = \sum_i A_i \hat{e}_i$ and $\mathbf{B} = \sum_i B_i \hat{e}_i$. Then,

$$\begin{aligned} \mathbf{A} \cdot \mathbf{B} &= \sum_{i,j} (A_i \hat{e}_i) \cdot (B_j \hat{e}_j) \\ &= \sum_{i,j} A_i B_j (\hat{e}_i \cdot \hat{e}_j) \\ &= \sum_{i,j} A_i B_j \delta_{ij} \\ &= \sum_i A_i B_i \end{aligned}$$

Definition (Cross Product). Let $\{\hat{e}_i\}_{i=1}^3$ be the standard basis over \mathbb{R}^3 . Let $\mathbf{A} = \sum_i A_i \hat{e}_i$ and $\mathbf{B} = \sum_i B_i \hat{e}_i$. Then,

$$\begin{aligned}\mathbf{A} \times \mathbf{B} &= \sum_{i,j} (A_i \hat{e}_i) \times (B_j \hat{e}_j) \\ &= \sum_{i,j} A_i B_j (\hat{e}_i \times \hat{e}_j) \\ &= \sum_{i,j,k} A_i B_j (\epsilon_{ijk} \hat{e}_k).\end{aligned}$$

Instead of asking about $\mathbf{A} \times \mathbf{B}$, we ask about $(\mathbf{A} \times \mathbf{B})_\ell$, yielding

$$\begin{aligned}(\mathbf{A} \times \mathbf{B})_\ell &= (\mathbf{A} \times \mathbf{B}) \cdot \hat{e}_\ell \\ &= \left(\sum_{i,j,k} A_i B_j (\epsilon_{ijk} \hat{e}_k) \right) \cdot \hat{e}_\ell \\ &= \sum_{i,j} \epsilon_{ij\ell} A_i B_j.\end{aligned}$$

Remark: This notation for $\mathbf{A} \times \mathbf{B}$ automatically shows us that

$$\begin{aligned}(\mathbf{B} \times \mathbf{A})_\ell &= \sum_{i,j} \epsilon_{ij\ell} B_i A_j \\ &= - \sum_{i,j} \epsilon_{ji\ell} B_i A_j \\ &= - \sum_{i,j} \epsilon_{ji\ell} A_j B_i \\ &= - \sum_{i,j} \epsilon_{ij\ell} A_i B_j && i, j \text{ are dummy indices} \\ &= -(\mathbf{A} \times \mathbf{B})_\ell.\end{aligned}$$

Example (Central Force and Angular Momentum). A central force is defined by

$$\mathbf{F} = f(r) \hat{\mathbf{r}},$$

where $\hat{\mathbf{r}}$ is a radial vector.

Angular momentum is defined by

$$\mathbf{L} = \mathbf{r} \times \mathbf{p},$$

where \mathbf{r} denotes position and \mathbf{p} denotes momentum. Then,

$$\begin{aligned}\frac{d\mathbf{L}}{dt} &= \frac{d}{dt} (\mathbf{r} \times \mathbf{p}) \\ &= \left(\frac{d}{dt} \mathbf{r} \times \mathbf{p} \right) + \mathbf{r} \times \left(\frac{d\mathbf{p}}{dt} \right) \\ &= m \left(\frac{d}{dt} \mathbf{r} \times \frac{d}{dt} \mathbf{r} \right) + \mathbf{r} \times (f(r) \hat{\mathbf{r}}) \\ &= f(r) (\mathbf{r} \times \hat{\mathbf{r}}).\end{aligned}$$

This implies that $\frac{d\mathbf{L}}{dt} = 0$ under a central force.

Example (Determinant). Let $\mathbf{M} = M_{ij}$ be square. We denote \mathbf{M}_i to be the vector denoting the i th-row. Then,

$$\begin{aligned} m &= |\mathbf{M}| \\ &= \mathbf{M}_1 \cdot (\mathbf{M}_2 \times \mathbf{M}_3) \\ &= \mathbf{M}_3 \cdot (\mathbf{M}_1 \times \mathbf{M}_2) \\ &= \mathbf{M}_2 \cdot (\mathbf{M}_3 \times \mathbf{M}_1). \end{aligned}$$

Example (Trace). Let $\mathbf{M} = M_{ij}$ be a square matrix. We define $\text{tr}(\mathbf{M}) = \sum_i M_{ii}$. Equivalently,

$$\begin{aligned} \text{tr}(\mathbf{M}) &= \sum_{ij} M_{ij} \delta_{ij} \\ &= \sum_i M_{ii}. \end{aligned}$$

Note that

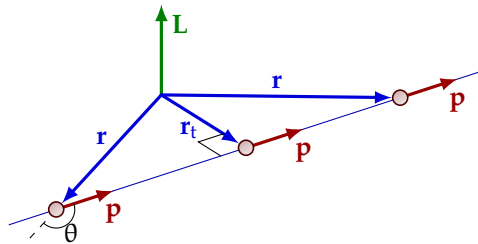
$$\begin{aligned} \text{tr}(\mathbf{I}_n) &= \sum_i \delta_{ii} \\ &= n. \end{aligned}$$

When we upgrade to 3 matrices, we take

$$\begin{aligned} \text{tr}(ABC) &= \sum_{i,j} \left(\sum_{k,\ell} A_{ik} B_{k\ell} C_{\ell j} \right) \delta_{ij} \\ &= \sum_{i,k,\ell} A_{ik} B_{k\ell} C_{\ell i} \\ &= \sum_{i,k,\ell} C_{\ell i} A_{ik} B_{k\ell} \\ &= \text{tr}(CAB). \end{aligned}$$

In other words, the trace is invariant under cyclic permutations.

Example (Angular Momentum, Revisited).



Recall that

$$\begin{aligned} \mathbf{L} &= \mathbf{r} \times \mathbf{p}, \\ &= I\boldsymbol{\omega}. \end{aligned}$$

where $\mathbf{p} = m\dot{\mathbf{x}}$, and I denotes the moment of inertia. Note that $I \sim mr^2$. On a more fundamental level, it is the case that the first equation, $\mathbf{L} = \mathbf{r} \times \mathbf{p}$, is the “true” definition of \mathbf{L} .

Consider a small portion m_α about some axis at radius r_α and momentum \mathbf{p}_α . Then, we have

$$\mathbf{L}_\alpha = \sum_\alpha \mathbf{r}_\alpha \times \mathbf{p}_\alpha$$

$$= \sum_{\alpha} m_{\alpha} (\mathbf{r}_{\alpha} \times (\boldsymbol{\omega} \times \mathbf{r}_{\alpha})).$$

In the infinitesimal case (i.e., as $\alpha \rightarrow 0$), we get

$$\mathbf{L} = \int \mathbf{r} \times (\boldsymbol{\omega} \times \mathbf{r}) \rho \, d\tau,$$

where ρ denotes volume density. Applying the identity $\mathbf{A} \times (\mathbf{B} \times \mathbf{C}) = \mathbf{B}(\mathbf{A} \cdot \mathbf{C}) - \mathbf{C}(\mathbf{A} \cdot \mathbf{B})$, we find

$$\mathbf{L} = \int (\boldsymbol{\omega}(\mathbf{r} \cdot \mathbf{r}) - \mathbf{r}(\mathbf{r} \cdot \boldsymbol{\omega})) \rho \, d\tau.$$

Switching to index notation, we have

$$\begin{aligned} L_i &= \int \left(\omega_i r^2 - r_i \sum_j r_j \omega_j \right) \rho \, d\tau \\ &= \sum_j \int \omega_j \left(\delta_{ij} r^2 - r_i r_j \right) \rho \, d\tau \\ &= \sum_j \omega_j \underbrace{\left(\int \left(\delta_{ij} r^2 - r_i r_j \right) \rho \, d\tau \right)}_{\text{moment of inertia tensor}} \\ &= \sum_j I_{ij} \omega_j. \end{aligned}$$

Binomial Theorem

The binomial theorem allows us to calculate the expansion

$$(x + y)^n = \sum_{m=0}^n \binom{n}{m} x^{n-m} y^m.$$

In the case of $(x + y)^2 = x^2 y^0 + 2x^1 y^1 + x^0 y^2 = x^2 + 2xy + y^2$. Recall that

$$\binom{n}{m} = \frac{n!}{m!(n-m)!}.$$

Recall that $0! = 1$.

Infinite Series

Let

$$S = \sum_{k=0}^{\infty} a_k$$

be an infinite series. We are often curious as to the convergence of this sum (for a variety of reasons). Formally, we have to invoke partial sums

$$S_N = \sum_{k=0}^N a_k,$$

and see if the sequence of partial sums is convergent. However, we will prefer to use series convergence tests.

Example (Geometric Series). Let

$$\begin{aligned} S &= \sum_{k=0}^{\infty} r^k \\ &= 1 + r + r^2 + \dots \end{aligned}$$

Then, we have

$$\begin{aligned} S_N &= \sum_{k=0}^N r^k \\ rS_N &= \sum_{k=0}^N r^{k+1} \end{aligned}$$

Subtracting, we get

$$\begin{aligned} (1 - r)S_N &= 1 - r^{N+1} \\ S_N &= \frac{1 - r^{N+1}}{1 - r}. \end{aligned}$$

In the limit, we expect that if $r \rightarrow \infty$, and $r < 1$, then $r^{N+1} \rightarrow 0$. In the infinite case, we have

$$\begin{aligned} S &= \sum_{k=0}^{\infty} r^k \\ &= \frac{1}{1 - r}, \end{aligned}$$

if $r < 1$.

There are a few prerequisites for series convergence:

- there exists some K for which for all $k \geq K$, $a_{k+1} \leq a_k$;
- $\lim_{k \rightarrow \infty} a_k < \infty$;
- we need the series to reduce “quickly” enough.

Example (Ratio Test). A series $S = \sum_k a_k$ converges if the ratio of consecutive terms is (eventually) less than 1:

$$r = \lim_{k \rightarrow \infty} \frac{a_{k+1}}{a_k} < 1.$$

Example (Applying the Ratio Test). Consider $S = \sum_k \frac{1}{k!}$. Then,

$$\begin{aligned} r &= \lim_{k \rightarrow \infty} \frac{\frac{1}{(k+1)!}}{\frac{1}{k!}} \\ &= \lim_{k \rightarrow \infty} \frac{1}{k+1} \\ &= 0 < 1 \end{aligned}$$

Example (Riemann Zeta Function). We write

$$\zeta(s) = \sum_{k=1}^{\infty} \frac{1}{k^s}.$$

In order to evaluate the convergence of the Riemann zeta function. We have

$$\begin{aligned} r &= \lim_{k \rightarrow \infty} \frac{\frac{1}{(k+1)^s}}{\frac{1}{k^s}} \\ &= \lim_{k \rightarrow \infty} \left(\frac{k}{k+1} \right)^s \\ &= 1. \end{aligned}$$

Unfortunately, this means the ratio test is inconclusive.

For examples of evaluations of the zeta function, we have

$$\begin{aligned} \zeta(1) &= 1 + \frac{1}{2} + \frac{1}{3} + \cdots \\ \zeta(2) &= 1 + \frac{1}{4} + \frac{1}{9} + \cdots \\ &= \frac{\pi^2}{6}. \end{aligned}$$

Example (Absolute Convergence). In our original ratio test, we had assumed that a_k are real and positive. However, if the $a_k \in \mathbb{C}$, we have to look at the convergence in modulus:

$$r = \lim_{k \rightarrow \infty} \left| \frac{a_{k+1}}{a_k} \right|.$$

If $\sum_k |a_k|$ converges, this is known as absolute convergence.

Example (Alternating Series Test). If the series

$$\sum_{k=0}^{\infty} (-1)^k a_k$$

has the following conditions:

- $a_{k+1} < a_k$ for $k > K$;
- $\lim_{k \rightarrow \infty} a_k = 0$;

then $\sum_k (-1)^k a_k$ converges.

For instance, the alternating harmonic series converges

$$\sum_{k=1}^{\infty} (-1)^{k+1} \frac{1}{k} = \ln 2.$$

Power Series

Consider the function

$$S(x) = \sum_{k=0}^{\infty} a_k x^k.$$

This is a series both in a_k and in x . In order to determine convergence, we use the ratio test as follows:

$$\lim_{k \rightarrow \infty} \left| \frac{a_{k+1} x^{k+1}}{a_k x^k} \right| = |x| \lim_{k \rightarrow \infty} \left| \frac{a_{k+1}}{a_k} \right|$$

$$\equiv |x| r.$$

In particular, for convergence, it must be the case that

$$|x| r < 1.$$

We define

$$R = \begin{cases} \frac{1}{r} & 0 < r < \infty \\ 0 & r = \infty \\ \infty & r = 0 \end{cases}.$$

In particular, this means

$$|x| < R.$$

Definition (Radius of Convergence). For a power series $\sum_k a_k x^k$, the series converges for $|x| < R$,^{vi} where

$$r = \lim_{k \rightarrow \infty} \left| \frac{a_{k+1}}{a_k} \right|$$

$$R = \begin{cases} \frac{1}{r} & 0 < r < \infty \\ 0 & r = \infty \\ \infty & r = 0 \end{cases}.$$

Note that convergence for $|x| < R$ does not provide information regarding convergence at the boundary.

Example (Geometric Series). We have

$$\frac{1}{1-x} = \sum_{k=0}^{\infty} x^k$$

has $R = 1$, meaning the power series converges for $|x| < 1$.

Example (Exponential Function). We have

$$e^x = \sum_{k=0}^{\infty} \frac{x^k}{k!},$$

with $R = \infty$.

Example (Natural Log). We have

$$\ln(1+x) = x - \frac{1}{2}x^2 + \frac{1}{3}x^3 - \dots$$

In particular, since $R = 1$, we know that the radius of convergence is $|x| < 1$. However, the series does converge on the boundary when $x = 2$, but not when $x = 0$ (for obvious reasons).

Example (Why Radius of Convergence?). Consider two series

$$\frac{1}{1-x^2} = \sum_{k=0}^{\infty} x^{2k}$$

^{vi}The definition is not the true radius of convergence; it is actually that $r = \limsup_{k \rightarrow \infty} \sqrt[k]{|a_k|}$. It just happens to be the case that the ratio test and root test return the same value when they're regular limits (rather than limits superior).

$$\frac{1}{1+x^2} = \sum_{k=0}^{\infty} (-1)^k x^{2k}.$$

We can see that the first series converges for $|x| < 1$. However, even though $\frac{1}{1+x^2}$ has a domain across the entire real numbers, it is still the case that the *series* converges for $|x| < 1$.

The primary reason that the radius of convergence is defined as such is because, over the complex numbers, it is the case that $x^2 + 1 = 0$ at $x = \pm i$, meaning $\frac{1}{1+z^2}$ has singularities at those values of z .

The main reason power series are useful is that, when truncated, they are simply polynomials. In particular, with power series, we can reverse the order of sum and derivative.

Taylor Series

Function	Taylor Series
$f(x)$	$\sum_{k=0}^{\infty} \frac{(x-x_0)^k}{k!} \left(\frac{d^k f}{dx^k} \Big _{x=x_0} \right)$
e^x	$\sum_{n=0}^{\infty} \frac{x^n}{n!}$
$\cos x$	$\sum_{n=0}^{\infty} \frac{(-1)^n x^{2n}}{(2n)!}$
$\sin x$	$\sum_{n=0}^{\infty} \frac{(-1)^{n+1} x^{2n+1}}{(2n+1)!}$

Definition. The Taylor series of a function $f(x)$ about x_0 is defined by

$$f(x) = \sum_{n=0}^{\infty} \frac{(x-x_0)^n}{n!} \left(\frac{d^n f}{dx^n} \Big|_{x=x_0} \right).$$

Remark: The reason we write $\frac{d^n f}{dx^n}$ is because $\frac{d^n}{dx^n}$ is an operator in and of itself.

Example (The Most Important Taylor Series).

$$\begin{aligned} e^x &= \sum_{n=0}^{\infty} \frac{x^n}{n!} \\ \cos x &= \sum_{n=0}^{\infty} \frac{(-1)^n x^{2n}}{(2n)!} \\ \sin x &= \sum_{n=0}^{\infty} \frac{(-1)^{n+1} x^{2n+1}}{(2n+1)!} \end{aligned}$$

Example (Equilibrium Points). Let $U(x)$ denote a potential over x . Then, $F = -\nabla U$. We have

$$U(x) = U(x_0) + (x-x_0) U'(x_0) + \frac{1}{2!} (x-x_0)^2 U''(x_0) + \frac{1}{3!} (x-x_0)^3 U'''(x_0) + \dots$$

When we analyze an equilibrium point, we disregard the $U(x_0)$ term, and see that the derivative of U is zero; thus, we can truncate our series at the second derivative close to $x = x_0$:

$$\begin{aligned} U(x) &\approx \frac{1}{2} U''(x_0) (x-x_0)^2 \\ &= \frac{1}{2} m\omega^2 (x-x_0)^2. \end{aligned}$$

In other words, when we are very close to equilibrium, we have simple harmonic motion.

Example (Faster Taylor Series). Consider the function

$$\exp\left(\frac{x}{1-x}\right).$$

In order to create its Taylor series, we can create this Taylor series piecewise:

$$\exp\left(\frac{x}{1-x}\right) = 1 + \left(\frac{x}{1-x}\right) + \frac{1}{2!} \left(\frac{x}{1-x}\right)^2 + \frac{1}{3!} \left(\frac{x}{1-x}\right)^3.$$

Now, we expand the denominators as geometric series:

$$= 1 + x \left(\sum_{k=0}^{\infty} x^k \right) + \frac{x^2}{2!} \left(\sum_{k=0}^{\infty} x^k \right)^2 + \frac{x^3}{3!} \left(\sum_{k=0}^{\infty} x^k \right) + \dots$$

If we want to expand through x^3 , we have to expand by keeping track of *every* term:

$$= 1 + x + \frac{3}{2}x^2 + \frac{13}{6}x^3 + O(x^4).$$

We say we have expanded the series through the third order; the lowest order correction, denoted $O(x^n)$, is the fourth order (in this case).

Example (Exponentiated Operator). Consider a (square) matrix M . Then, we define

$$e^M = \sum_{k=0}^{\infty} \frac{M^k}{k!},$$

where $M^k = \prod_{i=1}^k M$; we define $M^0 = I$. Similarly,

$$e^{\frac{d}{dx}} = \sum_{k=0}^{\infty} \frac{d^k}{dx^k} \frac{1}{k!}.$$

In particular, $e^{\frac{d}{dx}}$ is the Taylor series operator.

Remark: In quantum mechanics, the momentum operator is

$$P = -i\hbar \frac{d}{dx}.$$

Example (Binomial Expansion). For any $\alpha \in \mathbb{R}^+$ and $|x| < 1$, we have

$$(1+x)^\alpha = 1 + \alpha x + \frac{\alpha(\alpha-1)}{2!}x^2 + \frac{\alpha(\alpha-1)(\alpha-2)}{3!}x^3 + \dots$$

Note that if $\alpha \in \mathbb{Z}^+$, then the series truncates (and we recover the binomial theorem again).

The main use of the binomial expansion is with very small quantities. For instance,

$$\begin{aligned} E &\sim \frac{1}{(x^2 + a^2)^{3/2}} \\ &= \frac{1}{x^3 \left(1 + \frac{a^2}{x^2}\right)^{3/2}} \\ &\approx \frac{1}{x^3} \left(1 - \frac{3}{2} \frac{a^2}{x^2}\right) \end{aligned}$$

For $x \gg a$