# Things You Just Gotta Know

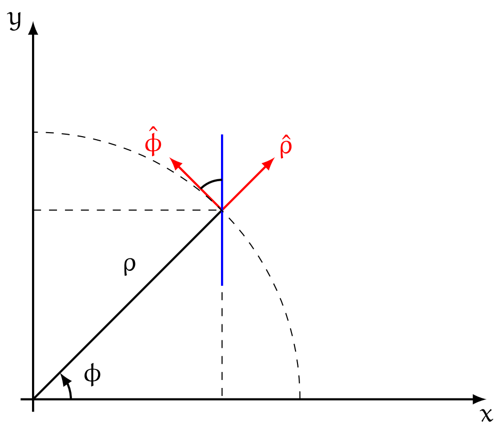
## Coordinate Systems

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

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

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, $(\rho, \phi)$.

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

To extract the input functions, we take

$$\begin{aligned} V_x &= \hat{\imath}\cdot\vec{V} \\ V_y &= \hat{\jmath}\cdot\vec{V}. \end{aligned}$$

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

$$\begin{aligned} V_\rho &= \hat{\rho}\cdot\vec{V} \\ V_\phi &= \hat{\phi}\cdot\vec{V}. \end{aligned}$$

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:

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

The main reason we avoided using the $\hat{\rho}, \hat{\phi}$ axis up until this point is that $\rho$ and $\phi$ are *position-dependent*, while the $\hat{\imath}, \hat{\jmath}$ 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 $\phi$ constant, it must be the case that any change in $\rho$ is in the $\hat{\rho}$ direction. Therefore,

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

Similarly,

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

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

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

and

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

**Example** (Velocity)**.**

$$\begin{aligned}
\mathbf{v} &= \frac{d\mathbf{s}}{dt} \\
&= \frac{d}{dt}\left(x\hat{\imath}\right) + \frac{d}{dt}\left(y\hat{\jmath}\right).
\end{aligned}$$

In the case of cartesian coordinates, $\hat{\imath}$ and $\hat{\jmath}$ are constants.

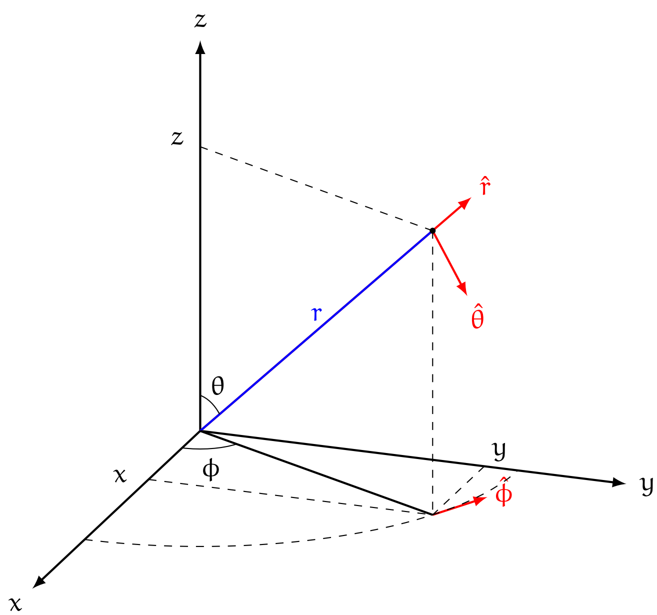
$$= v_x\hat{\imath} + v_y\hat{\jmath}$$

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

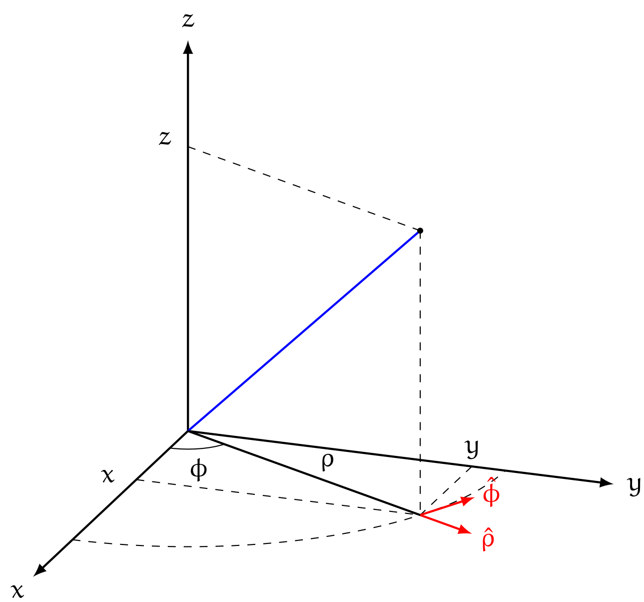
$$\begin{aligned}
\mathbf{v} &= \frac{d\mathbf{s}}{dt} \\
&= \frac{d\rho}{dt}\hat{\rho} + \rho\frac{d\hat{\rho}}{dt} \\
&= \frac{d\rho}{dt}\hat{\rho} + \rho\left(\cancelto{0}{\frac{\partial\hat{\rho}}{\partial\rho}}\frac{d\rho}{dt} + \underbrace{\frac{\partial\hat{\rho}}{\partial\phi}}_{=\hat{\phi}}\frac{d\phi}{dt}\right) \\
&= \frac{d\rho}{dt}\hat{\rho} + \rho\frac{d\phi}{dt}\hat{\phi} \\
&= \dot{\rho}\hat{\rho} + \rho\dot{\phi}\hat{\phi}.
\end{aligned}$$

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

**Spherical and Cylindrical Coordinates**




[1]Note 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,[ii] $\phi$ denotes the polar angle and $\theta$ 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.

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

**Scale Factors and Jacobians**

| Coordinate System | Line Element | Area Element | Volume Element |
|---|---|---|---|
| Polar | $\mathbf{ds} = \hat{\rho}d\rho + \rho\hat{\phi}d\phi$ | $\mathbf{da} = r\,drd\phi$ | — |
| Cylindrical | $\mathbf{ds} = \hat{\rho}d\rho + \rho\hat{\phi}d\phi + \hat{k}dz$ | — | $\mathbf{dv} = r\,drd\phi dz$ |
| Spherical | $\mathbf{ds} = \hat{r}dr + r\sin\theta\hat{\phi}d\phi + r\hat{\theta}d\theta$ | $\mathbf{da} = \sin\theta d\phi d\theta$ | $\mathbf{dv} = r^2\sin\theta\,drd\phi d\theta$ |

[ii]Physicists 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 $\rho$ in the expression of $\rho\hat{\phi}d\phi$ is the *scale factor* on $\phi$.

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 $\rho$ to account for the fact that the magnitude of the area element scales with the radius.

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

Recall that the definition of an angle $\phi$ 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 $\Omega$. 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:

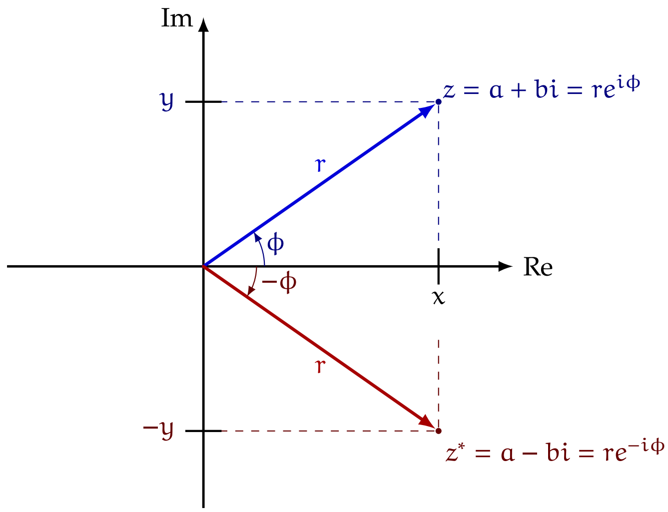
$$\begin{aligned} J &= \frac{\partial(x,y)}{\partial(u,v)} \\ &= \begin{pmatrix} \frac{\partial x}{\partial u} & \frac{\partial y}{\partial u} \\ \frac{\partial x}{\partial v} & \frac{\partial y}{\partial v} \end{pmatrix}. \end{aligned}$$

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

## 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 $\mathrm{Re}(z)$ and $\mathrm{Im}(z)$, the real and imaginary parts of $z$, by

$$\mathrm{Re}(z) = \frac{z + z^*}{2}$$
$$\mathrm{Im}(z) = \frac{z - z^*}{2i}.$$

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

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

$$z \in \mathbb{R} \Leftrightarrow z = z^*$$
$$z \in i\mathbb{R} \Leftrightarrow z = -z^*.$$

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

$$z_1 = i^i.$$

[III]This can be proven relatively easily through substitution into the Taylor series, which is allowed because $e^z$ is entire.
[IV]Physicists amirite?

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:

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

**Trigonometric Formulas with Euler's Formula**

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

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

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