Physics 0

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The Physical Universe

Physics describes things that are much too small to see and much too large to visit. To keep track of such a huge range, scientists use powers of ten. A power of ten tells us how many zeros are involved.

For example, $10^3 = 1000$, while $10^{-3} = 1/1000$. The prefix *milli* means 10^{-3}, *micro* means 10^{-6}, and *nano* means 10^{-9}.

> An *order of magnitude* is a change by about a factor of ten. A bacteria that is $1\,\mu$m across is about one thousand times smaller than a grain of sugar that is 1 mm across.

1.1 A map of length scales

Follow the same rule used in the presentation: every labeled step is $10^3 = 1000$ times the one before it. The two collections below use the original lesson graphics.

Figure 1. Length scales from a grain of sugar to California

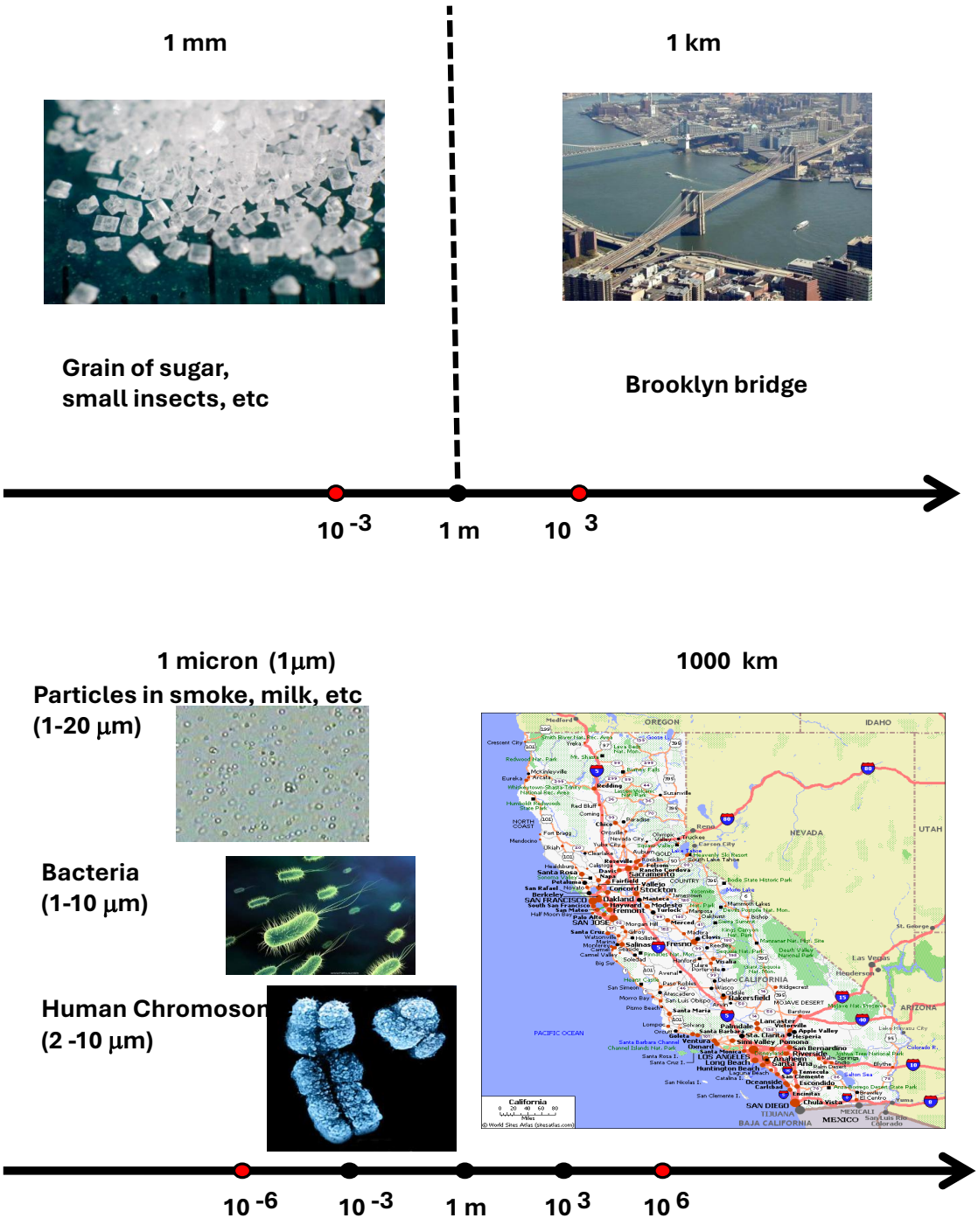
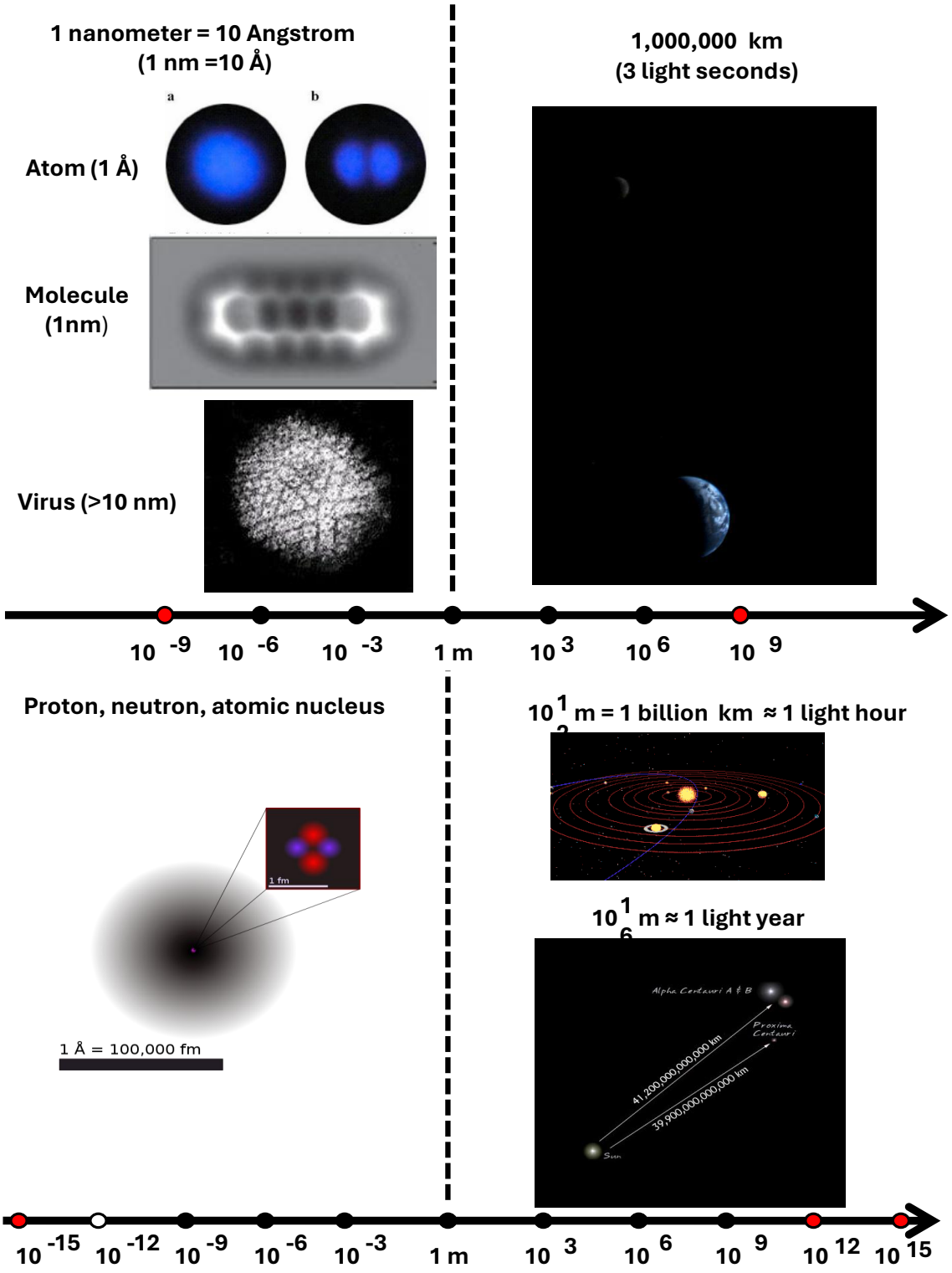


Figure 2. Length scales from nuclei to nearby stars



Watch the scale change. These short films zoom from human-sized objects toward the very small and toward the vast universe. **Classic version:** *Powers of Ten* (1977). **HD version:** Modern HD variation.

1.2 A Short History of Physics

Physics grew from people asking simple questions. Why do objects fall? How do planets move? What is light? What is matter made of? Each new answer gave people a better way to describe the world.

1.2.1 A brief timeline

Table 1.1: Some major turning points in physics.

When	What changed
Around 350 BCE	Aristotle wrote influential ideas about motion and the natural world. Many of his claims were later tested and corrected.
1600s	Johannes Kepler described the paths of planets. Galileo Galilei studied falling objects and motion. Isaac Newton combined these ideas into laws of motion and universal gravity.
1700s–1800s	The Industrial Revolution raised practical questions about machines, heat, and energy. Scientists developed optics, thermodynamics, and electromagnetism.
1905–1915	Albert Einstein developed special relativity, which changed how physicists think about space, time, and light, and general relativity, the modern theory of gravity.
1925	Modern quantum mechanics gave scientists a new language for atoms, light, and tiny particles.
1905–1975	Experiments and quantum ideas led toward the Standard Model of particle physics. Its modern form took shape mainly in the 1960s and 1970s.

1.2.2 How science moves forward

Scientists make observations and test models. A model earns trust when it correctly predicts what will happen. Newton's laws work very well for bicycles, bridges, and planets. Relativity and quantum mechanics are needed at extreme speeds, in strong gravity, or for very small objects.

Older theories remain very useful within the ranges where experiments have tested them.

1.3 Particles and Big Questions

1.3.1 The Standard Model

Everything familiar around us is made from a small set of particles. The Standard Model is the best-tested map of those particles and three of the four known fundamental interactions. Quarks build protons and neutrons. Electrons belong to another family called leptons. Photons, gluons, and the W and Z particles carry forces between particles.

The Standard Model has passed many demanding tests, but it does not include gravity and it does not answer every question.

1.3.2 Dark matter

Galaxies spin and bend light as if they contain more mass than we can see. Physicists call this missing, unseen material *dark matter*. "Dark" does not mean evil or empty. It means that it does not shine or reflect light in the usual way. We know its gravity affects stars and galaxies, but we do not yet know what dark matter is made of.

1.3.3 Dark energy

The universe is expanding. Measurements show that this expansion is speeding up. Physicists use the name *dark energy* for whatever causes this speeding up. It may be a property of empty space, a new kind of energy, or a clue that our theory of gravity needs improvement.

Two big open questions. What is dark matter? What causes the speeding-up expansion of the universe? These questions are open because scientists have strong evidence for the effects, but no final explanation yet.

Kinematics

Kinematics is the study of motion. It answers questions such as: How far did an object move? How long did the motion take? How fast did the object move, and in which direction? In this chapter, we describe motion before asking what caused it.

2.1 Distance, time, and average speed

Distance, written as d, tells us how much ground an object covers. Travel time is the change between a final time and an initial time:

$$\Delta t = t_{\text{final}} - t_{\text{initial}}.$$

The Greek letter Δ (delta) means "change." The average speed is total distance divided by travel time:

$$v_{\text{avg}} = \frac{d}{\Delta t}.$$

> Speed has no direction. A speed of 5 m/s means that, on average, an object covers 5 m every second. It does not tell us whether the object moves left, right, up, or down.

The SI unit of length is the metre (m), and the SI unit of time is the second (s). Therefore the SI unit of speed is metres per second (m/s). Other useful units include kilometres per hour (km/h) and miles per hour (mph).

Table 2.1: Common quantities and units for describing motion.

Quantity	SI unit	Other useful units
Length or distance, d	metre (m)	kilometre, centimetre, mile, foot
Time, t	second (s)	hour (h)
Speed, v	m/s	km/h, mph, cm/s
Velocity, $\vec{v}$	m/s	km/h, mph, cm/s

2.2 Position, displacement, and average velocity

In one-dimensional motion, choose a positive direction and describe the object's position with a single coordinate x. The displacement is the change in position:

$$\Delta x = x_f - x_i.$$

Average velocity is displacement divided by travel time:

$$\vec{v}_{\text{avg}} = \frac{\Delta x}{\Delta t}.$$

Distance and displacement are different. Distance counts every part of the path. Displacement compares only the final position with the initial position. Velocity includes direction, while speed does not.

For example, if a student walks 50 m east and then 50 m west, the distance travelled is 100 m, but the displacement is 0 m. The average velocity for the whole trip is therefore zero, even though the average speed is not zero.

2.3 Instantaneous velocity and speed

Average velocity describes a time interval. Instantaneous velocity describes motion at one particular moment. In symbols, we use the same ratio, $\Delta x/\Delta t$, but make the time interval very small. Instantaneous speed is the size of the instantaneous velocity.

For a small interval, calculate the slope with two nearby points:

$$\vec{v}_{\text{inst}} \approx \frac{\Delta x}{\Delta t}.$$

On a position–time graph, the slope tells us the velocity. A positive slope means motion in the positive direction. A negative slope means motion in the opposite direction. A horizontal graph means that the position does not change, so the object is at rest.

> Instantaneous speed tells how fast an object moves at one moment. Instantaneous velocity gives both the speed and the direction at that moment.

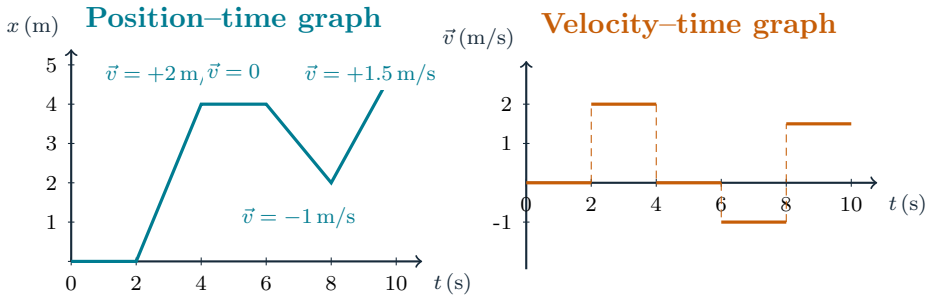


Figure 2.1: Each straight segment of the position–time graph has a constant velocity. The matching velocity–time graph shows that velocity for each interval.

The slope of each position–time segment gives the velocity for that interval. A steeper segment means a larger speed. The sharp corners in this idealized example show where the velocity changes from one interval to the next.

2.4 Acceleration

Acceleration tells us how quickly velocity changes. Average acceleration is the change in velocity divided by the time interval:

$$a_{\text{avg}} = \frac{\Delta \vec{v}}{\Delta t}.$$

Its SI unit is metres per second per second, written m/s^2. For example, if a bicycle's velocity changes from 0 to 12 m/s in 4 s, its average acceleration is $3\,\text{m/s}^2$.

Acceleration can make an object speed up, slow down, or change direction. In one-dimensional motion, choose a positive direction before using signs. For example, if up is positive, an object in free fall has acceleration $a = -g$, where near Earth

$$g \approx 9.8\,\text{m/s}^2$$

is directed downward. The value $g \approx 10\,\mathrm{m/s^2}$ is often useful for estimates.



Figure 2.2: Galileo is often associated with dropping objects from the Leaning Tower of Pisa. The story may be a legend, but it introduces an important idea: without air resistance, objects fall with the same gravitational acceleration.

2.4.1 Motion with constant acceleration

When acceleration stays constant, velocity changes by the same amount in every equal time interval. In one dimension,

$$v_x = v_{0x} + a_x t, \qquad x = x_0 + v_{0x} t + \frac{1}{2} a_x t^2.$$

If an object starts from rest, then $v_{0x} = 0$. Its displacement from the starting point becomes

$$\Delta x = \frac{1}{2} a_x t^2.$$

For a dropped object, choosing downward as positive gives $a_x = g$, so the distance fallen is $d = \frac{1}{2} g t^2$ and its speed after time t is $v = gt$.

2.5 Vectors, trajectories, and displacement

After studying one-dimensional motion, we can extend the same ideas to motion on a map or through a room, where direction matters. A *vector* is a directed line segment: it gives both a magnitude, or size, and a direction. For example, “walk 3 km east” describes a vector. A *scalar* has magnitude only: “walk 3 km” does not tell us which way.

Displacement, velocity, acceleration, and force are vectors. Distance, speed, time, mass, and temperature are scalars. We draw a vector as an arrow; its length represents its magnitude, and the arrowhead shows its direction.

2.5.1 Adding and subtracting vectors

To add vectors graphically, slide the second arrow so that its tail touches the head of the first arrow. Do not turn or stretch either arrow. The sum is the arrow from the first tail to the final head. To subtract $\vec{b}$ from $\vec{a}$, reverse $\vec{b}$ and then add it to $\vec{a}$.

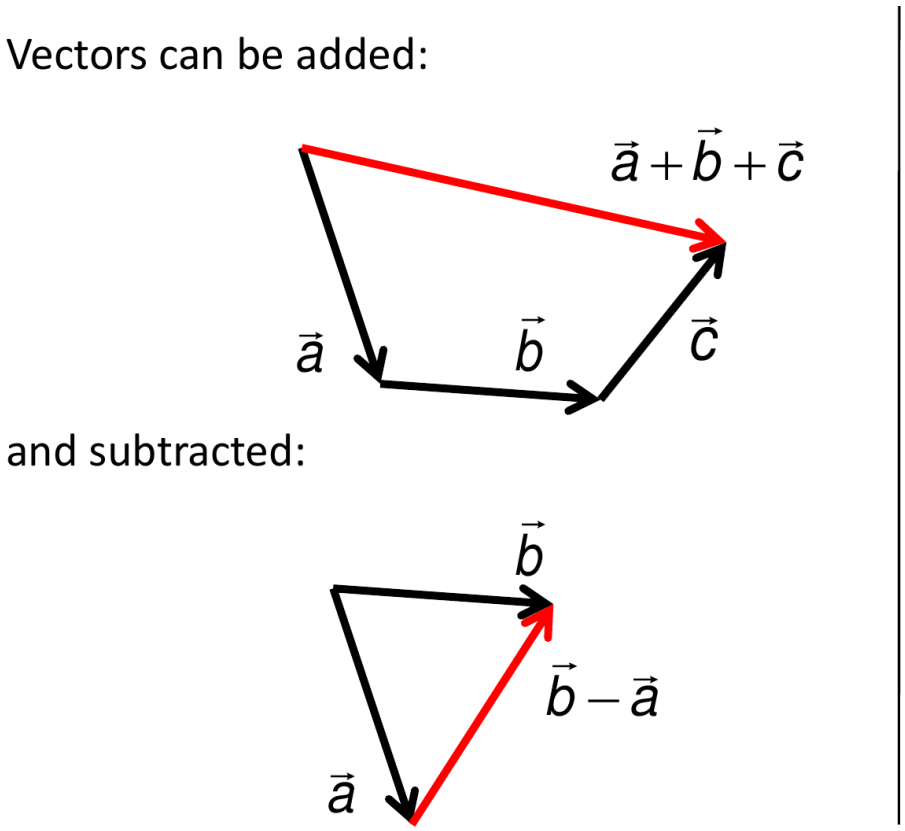


Figure 2.3: Graphical vector addition and subtraction. The red arrows show the resultant vectors.

2.5.2 Components of a vector

Coordinates describe a vector in terms of its horizontal, vertical, and, when needed, depth components. A position in three dimensions can be written as $\vec{r} = (x, y, z)$. In two dimensions, write a vector as $\vec{a} = (a_x, a_y)$. Add and subtract one component at a time:

$$\vec{a} + \vec{b} = (a_x + b_x,\ a_y + b_y), \qquad \vec{a} - \vec{b} = (a_x - b_x,\ a_y - b_y).$$

The Pythagorean theorem gives the magnitude of a two-dimensional vector:

$$|\vec{a}| = \sqrt{a_x^2 + a_y^2}.$$

2.5.3 Trajectory and displacement

The *trajectory* is the path an object follows. The position vectors $\vec{r}_i$ and $\vec{r}_f$ point from the origin to the initial and final positions. The displacement vector points directly from the initial position to the final position:

$$\Delta\vec{r} = \vec{r}_f - \vec{r}_i.$$

The average velocity is displacement divided by travel time,

$$\vec{v}_{\text{avg}} = \frac{\Delta\vec{r}}{\Delta t},$$

while average speed uses the total distance d travelled along the path,

$$v_{\text{avg}} = \frac{d}{\Delta t}.$$

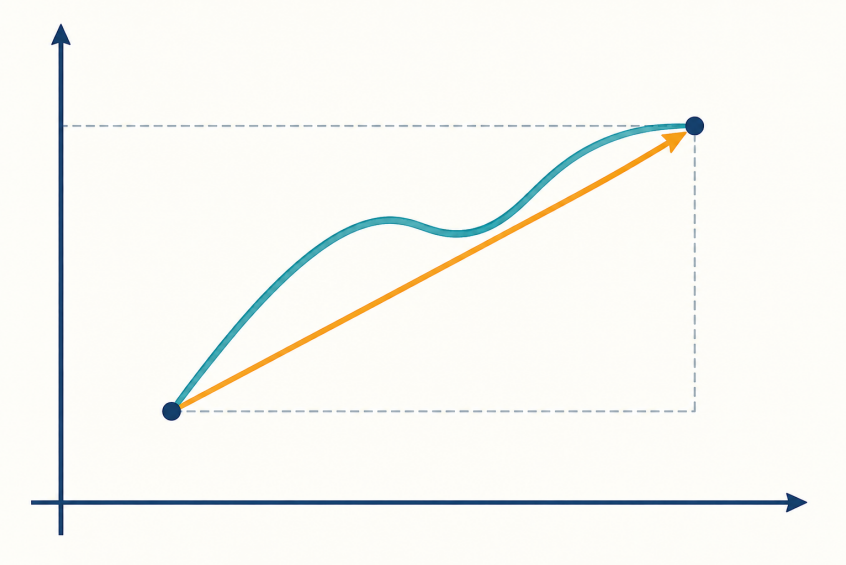


Figure 2.4: The object follows the curved teal trajectory, but its displacement $\Delta\vec{r}$ is the straight red arrow from the initial to the final position.

HOMEWORK 6

1. **Lost in the woods.** A SchoolNova student has a tracker that records the following walks: 1 km southeast, then 3 km southwest, and finally 2 km north. On quad-ruled paper, draw the three displacement vectors head-to-tail. Use your drawing to estimate how far the student is from the starting point and the compass direction the student should walk to return.

2. **Graphical vector addition.** Find the resultant of each pair of vectors shown below by drawing. Copy each pair on paper, then use the head-to-tail method. A ruler may be slid parallel to itself to copy a vector's direction and length without rotating it.

