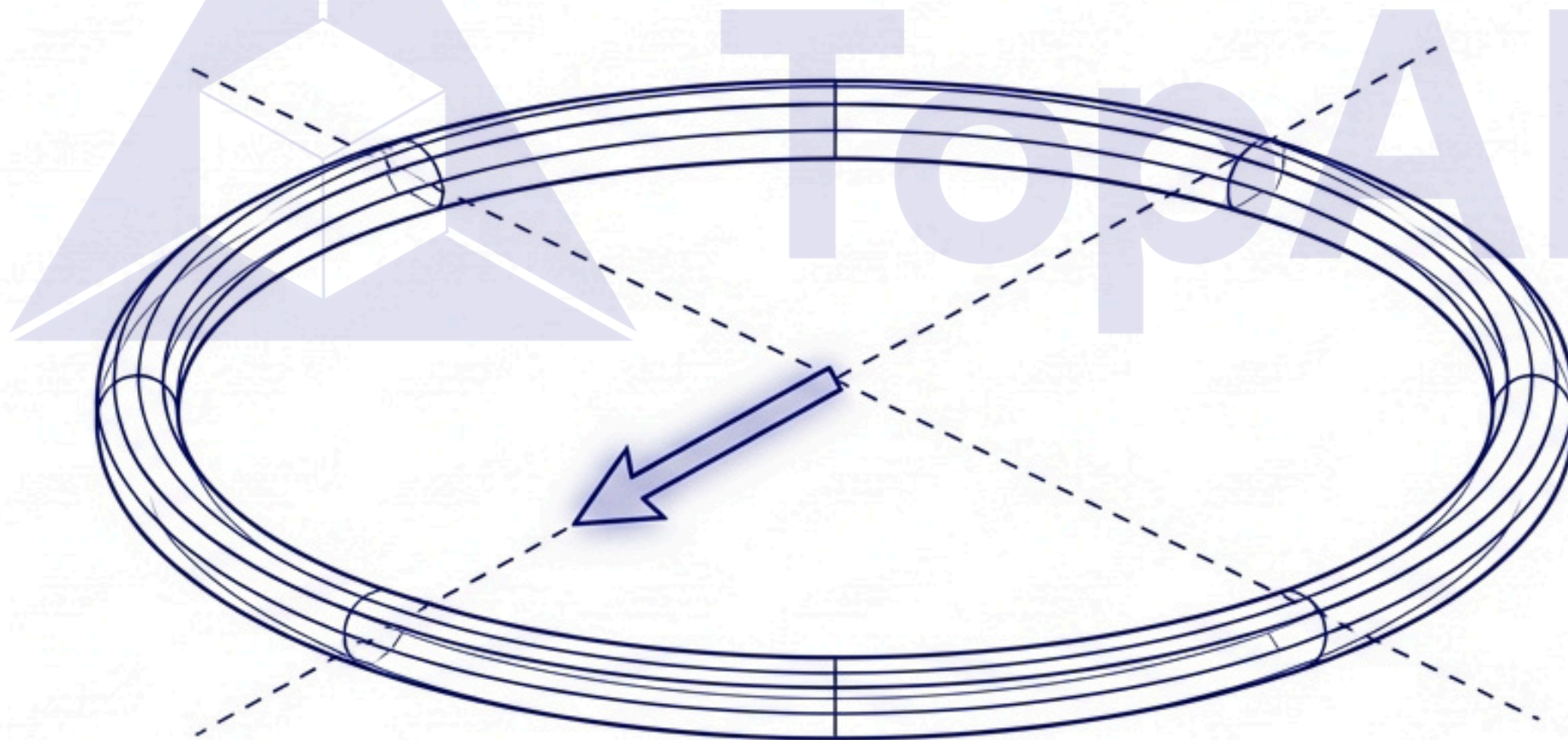
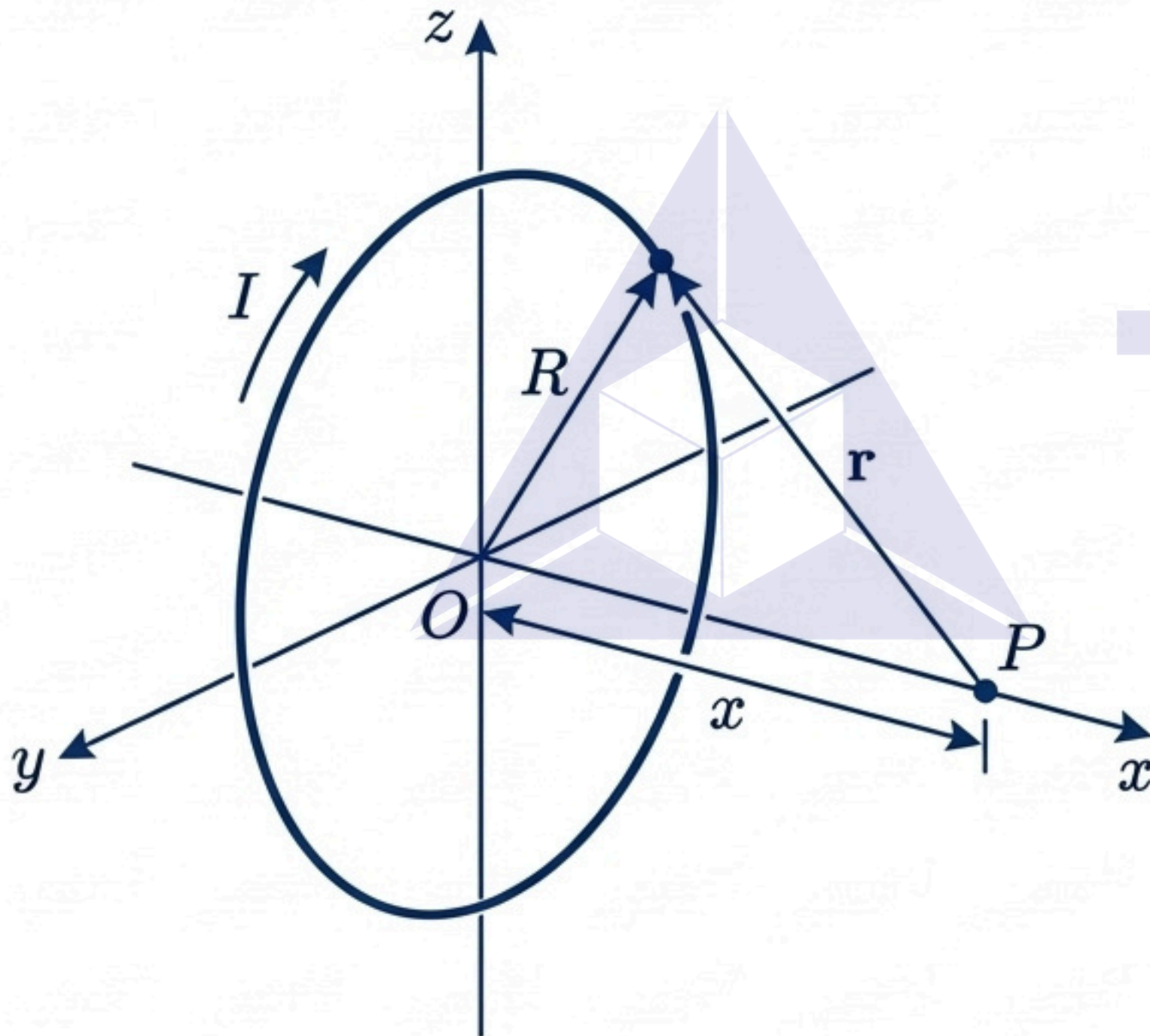


Magnetic Field on the Axis of a Circular Current Loop

Deriving the exact axial field using the Biot-Savart law and cylindrical symmetry.



Defining the 3D System



Core System Variables

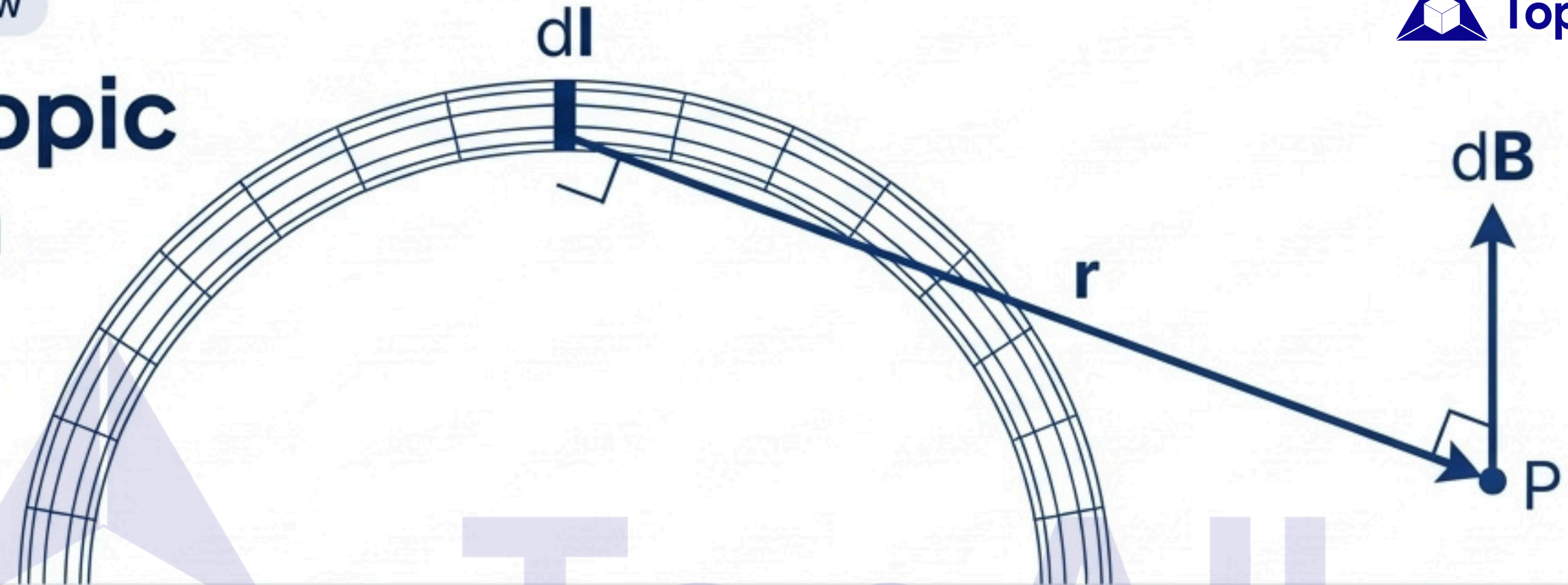
- I = Steady current flowing through the loop
- R = Radius of the circular loop
- x = Distance from the center to observation point P

The Displacement Vector

Using the Pythagorean theorem, the distance r from any point on the loop's circumference to point P is strictly defined as:

$$r = \sqrt{x^2 + R^2}$$

The Microscopic Contribution



The Cross-Product Simplification

To evaluate the field $d\mathbf{B}$ generated by the infinitesimal current element $d\mathbf{l}$, we use the Biot-Savart Law.

Because any element $d\mathbf{l}$ on the loop is perfectly perpendicular to the displacement vector $\mathbf{r}$, the cross product simplifies mathematically:

$$|d\mathbf{l} \times \mathbf{r}| = r \cdot dl \sin(90^\circ) = r \cdot dl$$

The Biot-Savart Expression:

$$d\mathbf{B} = \frac{\mu_0}{4\pi} \frac{I \cdot d\mathbf{l}}{r^2}$$

Substitute $r^2 = x^2 + R^2$:

$$d\mathbf{B} = \frac{\mu_0}{4\pi} \frac{I \cdot d\mathbf{l}}{x^2 + R^2}$$



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Key Highlights

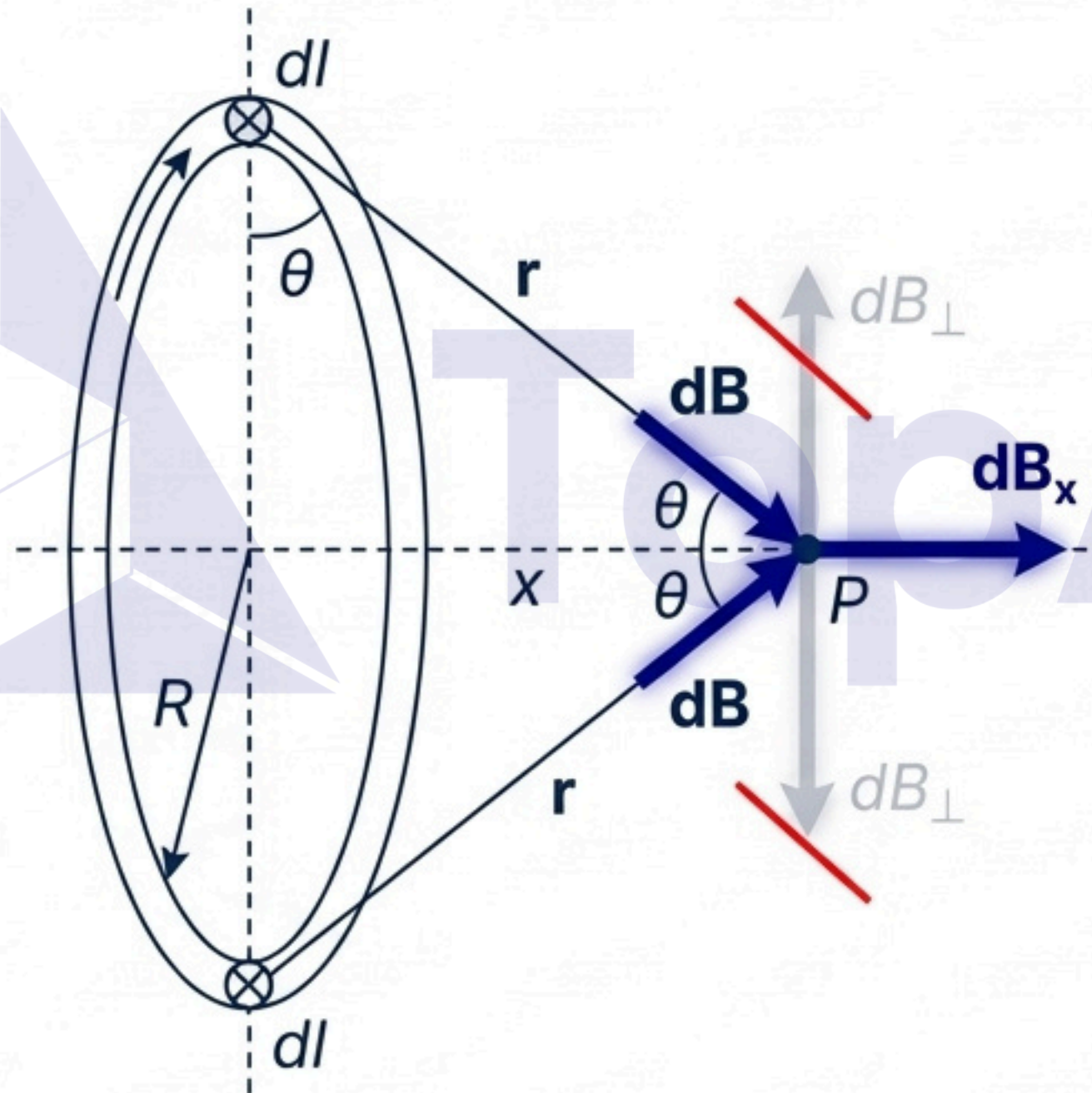
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Cancellation of Perpendicular Components

Why Symmetry Matters

When summing the field contributions from all elements around the entire loop, the components perpendicular to the axis ($dB_{\perp}$) perfectly cancel out due to diametrically opposite pairs pulling in opposing directions.



The Surviving Field

Only the axial components (x-direction) survive. The net field is purely the integral of $dB \cos \theta$.

From the geometry triangle:

$$\cos \theta = \frac{R}{\sqrt{x^2 + R^2}}$$

The Standard Formulas

GENERAL CASE

Field on the Axis

Integrating the surviving dB_x over the full circumference ($\int dl = 2\pi R$) gives the total magnetic field at any point x on the axis.

$$B = \frac{\mu_0 I R^2}{2(x^2 + R^2)^{3/2}} \hat{i}$$

N-Turns: For a tightly wound coil of N turns, multiply this result by N .

SPECIAL CASE

Field at the Center

At the exact center of the loop, the distance $x = 0$. Substituting zero into the axial formula dramatically simplifies the equation.

$$B = \frac{\mu_0 I}{2R} \hat{i}$$

(The magnetic field strength is maximum at the center and decreases as you move further along the axis).

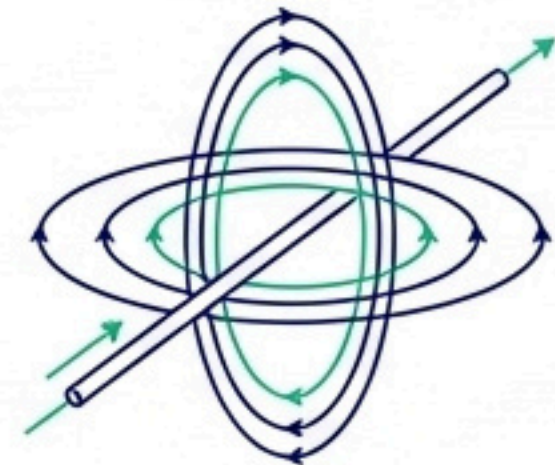
Key Takeaways

Master the Concept

- **Symmetry is Key:** The net magnetic field on the axis of a circular loop is strictly directed along the axis. All perpendicular components cancel perfectly.
- **General Axis Formula:**
$$B = \frac{\mu_0 I R^2}{2(x^2 + R^2)^{3/2}}$$
- **Center Formula:**
$$B = \frac{\mu_0 I}{2R}$$
- **Scaling:** For a coil with N turns, the total field is simply N times the single-loop field.

Right-Hand Thumb Rule

Direction of the Field: Curl the palm of your right hand around the circular wire with your fingers pointing in the direction of the current. Your extended thumb gives the exact direction of the magnetic field on the axis.





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