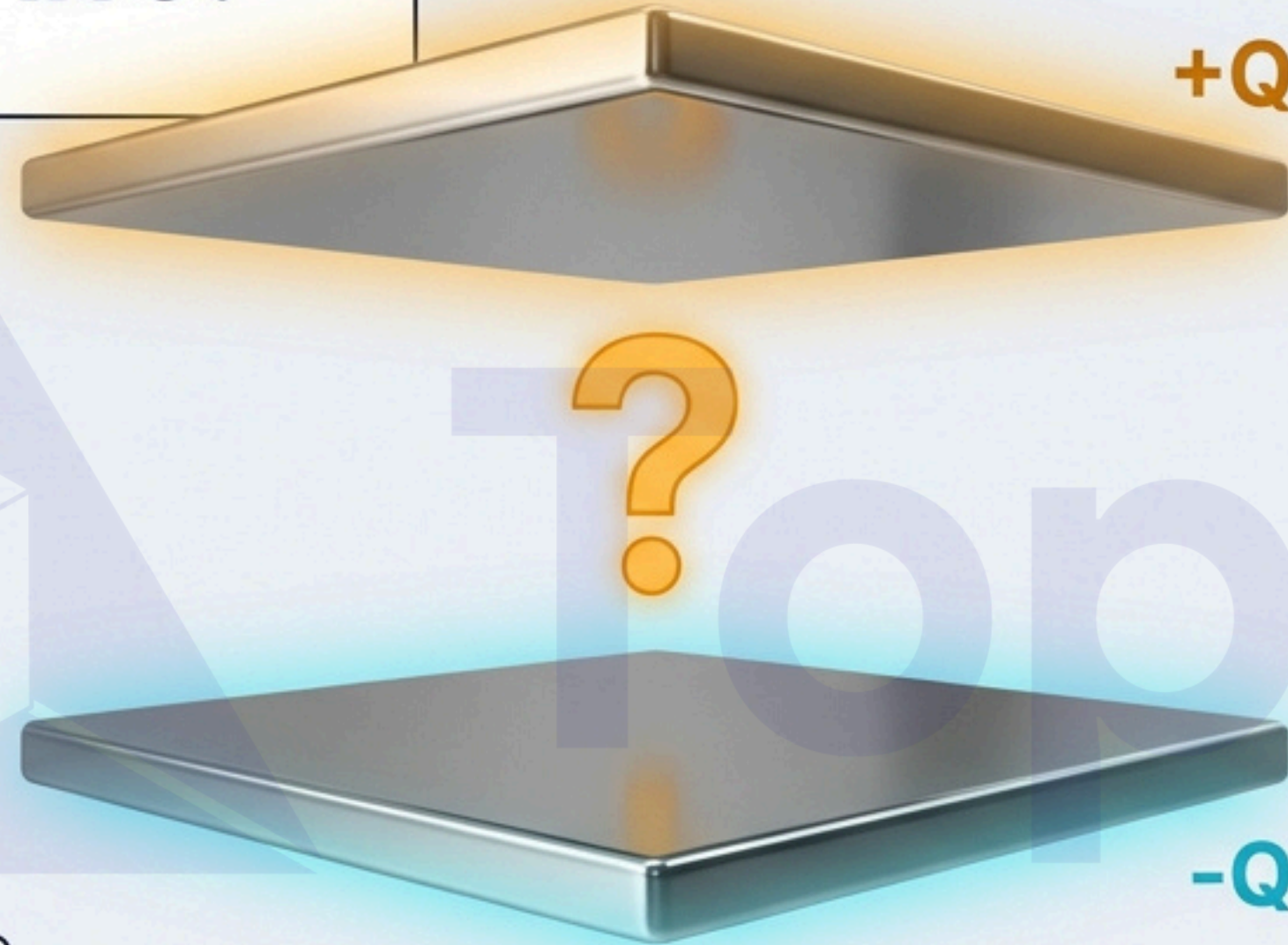


Where does capacitor energy actually live?

We know a capacitor stores electrical energy. But if you look closely at a charged capacitor, it is just two metal plates and empty space (or an insulator).

Is the energy in the metal? In the charges? Or somewhere completely invisible?



Module Objective

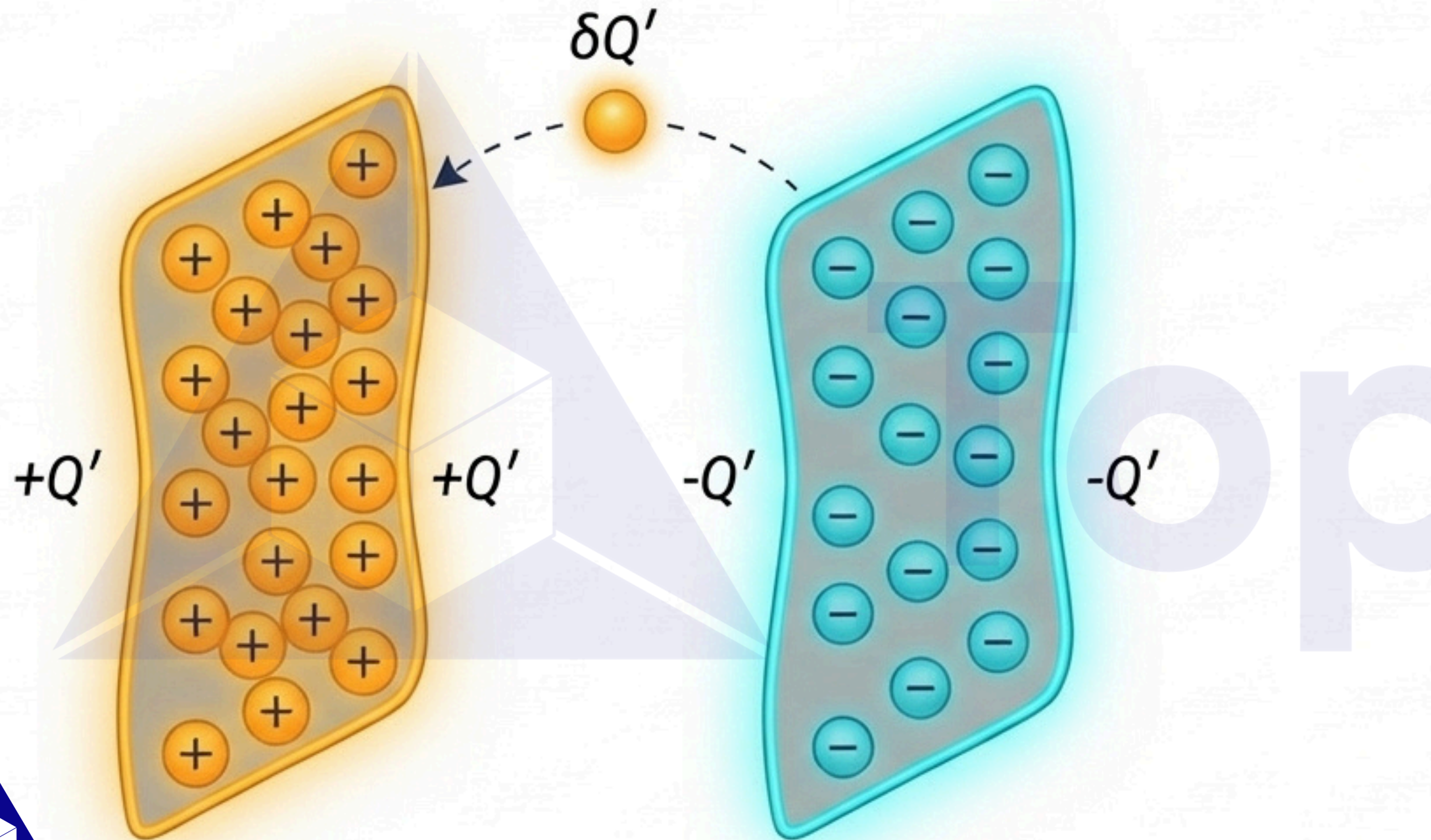
Today, we will **derive the work done to charge a capacitor** and uncover the exact physical location of its stored energy.

**Practice more,
score more**

The Process of Charging a Capacitor



Calculating the Work Done in a Small Step



The Intermediate State

Pause the charging process at an intermediate point. The charges are currently $+Q'$ and $-Q'$.

$$V' = \frac{Q'}{C}$$

The Incremental Work [Eq. 2.68]

Work done to move a vanishingly small charge from Conductor 2 to Conductor 1 against repulsion:

$$\begin{aligned}\delta W &= V' \delta Q' \\ &= \frac{Q'}{C} \delta Q'\end{aligned}$$



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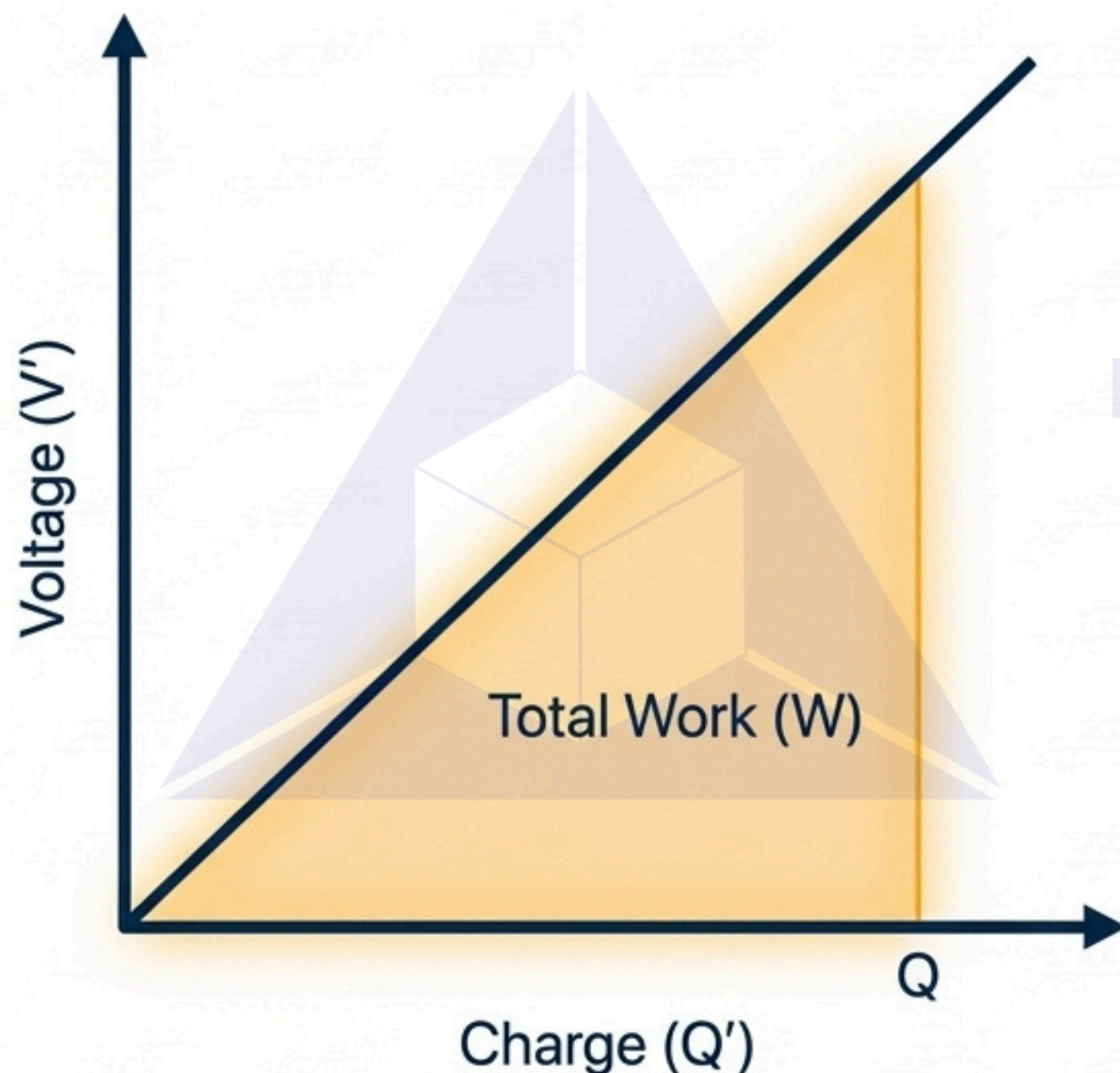


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Total Work Becomes Potential Energy



Summing the Steps

To find the total work, we integrate the micro-steps from a neutral state 0 to the final charge Q .

$$W = \int \frac{Q'}{C} \delta Q'$$

The Final Work Done

$$W = \frac{Q^2}{2C}$$



$$W = U$$

The Physics Principle

Because the electrostatic force is conservative, this total external work is completely stored as the potential energy (U) of the system. The path taken to build the charge does not matter.

The Three Faces of Stored Energy [Eq. 2.69]

By substituting $Q = CV$, we can write the stored potential energy (U) in three mathematically equivalent forms depending on the given variables:

Form 1: The Charge Form

$$U = \frac{Q^2}{2C}$$

Charge

Capacitance

Form 2: The Voltage Form

$$U = \frac{1}{2} C V^2$$

Capacitance

Voltage

Form 3: The Mixed Form

$$U = \frac{1}{2} Q V$$

Charge

Voltage

Practice more, score more

The Aha Moment: Energy Lives in the Field

Where is the energy?

It is not in the metal plates. It is physically stored in the electric field region between them!

The Volume Derivation [Eq. 2.70 - 2.72]

Substitute $C = \epsilon_0 A/d$ and $Q = \sigma A$ into the energy formula.

Using $E = \frac{\sigma}{\epsilon_0}$, we discover:

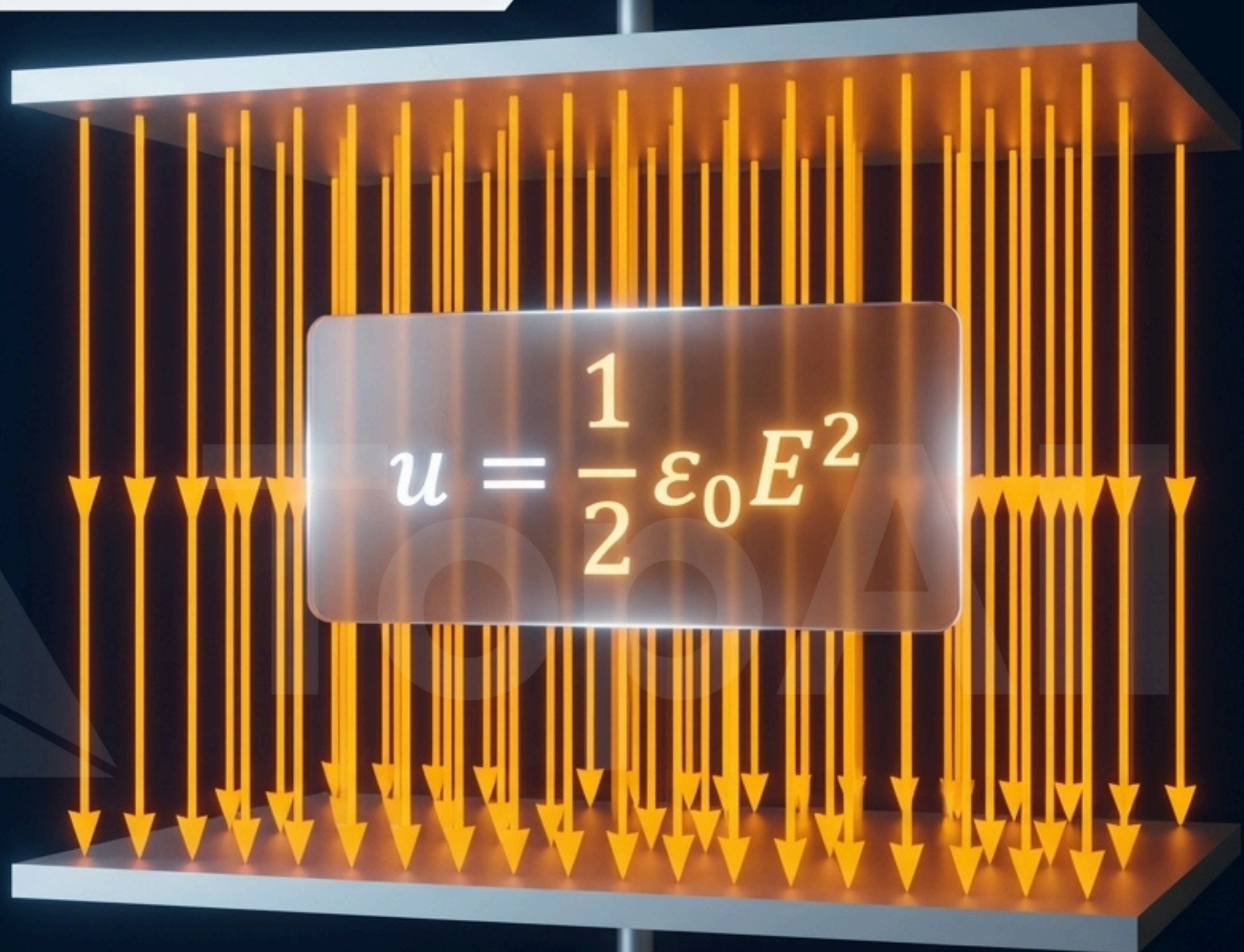
$$U = \frac{1}{2} \epsilon_0 E^2 \times (A \times d)$$

Note: $(A \times d)$ is exactly the Volume of the space!

Energy Density (u) [Eq. 2.73]

Energy per unit volume. This holds true for ANY electric field in the universe.

$$u = \frac{1}{2} \epsilon_0 E^2$$



Key Takeaways & Exam Memory Anchors

Key Takeaways

- ✓ Visualize charging as doing external work against electrostatic repulsion.
- ✓ Remember the three equivalent energy forms: $U = Q^2/2C = 1/2 CV^2 = 1/2 QV$.
- ✓ Understand that energy physically resides in the electric field region itself.
- ✓ Apply Energy Density $u = 1/2 \epsilon_0 E^2$ to any configuration of electric fields, not just capacitors.



Exam Trap

- Do not confuse **Total Energy (U)** with **Energy Density (u)**.
- Energy density is **energy per unit volume**. Always check the units requested in the exam question: **Joules (J)** versus **Joules per cubic meter (J/m³)**.



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