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Magnet Falling Through Superconducting Loop

<https://gemini.google.com/share/8dcc8f11ced8>

An immovable shorted ideal loop without resistance is in an environment where the magnetic flux density is zero. The current flowing in the loop is zero. The plane of the loop is horizontal in a gravitational field. Suddenly a change is made and a permanent magnet is dropped into the loop. The magnet's OD is smaller than the loop's ID and the magnet is sufficiently heavy to penetrate the loop. Calculate the function of the force vs. vertical distance $F(x)$ where positive values of $F(x)$ indicate an upward force between the magnet and the loop and negative values of $F(x)$ indicate a downward force. Gravity always generates a constant downward force (so negative). Generate a linear SVG plot of $F(x)$ if you can. Describe the direction of forces between the magnet and the loop, before, during and after exiting the loop. Describe the kinetic energy evolution of the magnet, before, during and after exiting the loop. Compare the kinetic energy of the magnet to a situation in which the loop is completely absent. Especially long after exiting the loop.

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The interaction between a falling magnet and an ideal superconducting loop (zero resistance) is a classic problem of electrodynamics and conservation of energy. Because the loop has no resistance, there is no energy dissipation (no heat loss). The system acts as a conservative system where kinetic energy is temporarily stored in the magnetic field and then returned to the magnet.

1. Force Analysis

In a normal resistive loop, the induced current creates a drag force that always opposes motion (Lenz's Law with dissipation). However, in a superconducting loop, the current is determined by the conservation of magnetic flux, not the rate of change of flux ($\frac{d\Phi}{dt}$).

- Flux Conservation: The total magnetic flux through the superconducting loop must remain constant. Since the initial flux was zero, the loop generates a current I to create a "cancellation flux" equal and opposite to the magnet's flux (Φ_{magnet}).
- $LI + \Phi_{magnet}(x) = 0 \implies I(x) = -\frac{\Phi_{magnet}(x)}{L}$
- Since the flux Φ_{magnet} from the magnet is symmetric (it rises to a peak at the center and falls off), the current $I(x)$ is also symmetric and does not change direction as the magnet passes through the center. It simply ramps up to a maximum and ramps back down.

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- The Force $F(x)$: The force is the product of the current and the gradient of the magnetic field ($F \propto I \cdot \frac{dB}{dx}$).
 - Approaching ($x > 0$): The magnet pushes flux into the loop. The loop generates a repulsive field (North facing North). The force is Upward (Positive), opposing gravity.
 - At the Center ($x = 0$): The flux is at a maximum ($\frac{d\Phi}{dx} = 0$). The force is Zero.
 - Exiting ($x < 0$): The magnet pulls flux away. To maintain the trapped "zero flux" condition, the loop effectively tries to keep the field lines there, creating an attractive field (South facing North). The force is Downward (Negative), accelerating the magnet faster than gravity.

2. Force vs. Distance Plot

The plot below shows the magnetic interaction force $F(x)$ as the magnet falls from positive x (top) to negative x (bottom).

- Green Line (F_{mag}): The magnetic force. It is a repulsive "hill" on approach and an attractive "well" on exit.
- Red Dashed Line ($F_{gravity}$): The constant downward force of gravity.
- Blue Line (F_{net}): The sum of forces.

3. Evolution of Forces and Kinetic Energy

Phase 1: Approaching the Loop ($x > 0$)

- Force: The magnet experiences a strong upward repulsive force. This opposes gravity, reducing the net acceleration (or even decelerating the magnet if the interaction is strong enough).
- Kinetic Energy: The magnet's kinetic energy increases slower than it would in free fall. Some of the gravitational potential energy is being diverted to create the magnetic field energy stored in the loop ($\frac{1}{2}LI^2$).

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Phase 2: Inside the Loop ($x \approx 0$)

- Force: As the magnet crosses the plane of the loop, the magnetic force momentarily drops to zero.
- Kinetic Energy: The magnet has its maximum "energy deficit" here. The energy stored in the superconducting loop's magnetic field is at its peak.

Phase 3: Exiting the Loop ($x < 0$)

- Force: As the magnet drops below the loop, the interaction becomes attractive. The loop pulls the magnet down, exerting a downward force (in the same direction as gravity).
- Kinetic Energy: The stored magnetic energy is returned to the magnet. The magnet accelerates faster than g . The "borrowed" energy is converted back into kinetic energy.

4. Comparison to Loop Absence (Free Fall)

- During the fall: The magnet passing through the loop is slower than a free-falling magnet at the same height. It has less kinetic energy because $\frac{1}{2}mv^2 + \frac{1}{2}LI^2 = \text{Constant}$.
- Long after exiting: Because the system is lossless (no resistance), all the energy stored in the magnetic field is returned to the magnet by the attractive force on the way out.
 - Kinetic Energy: The final kinetic energy is identical to the case where the loop is completely absent. ($KE_{final} = KE_{free_fall}$).
 - Position/Time: Although the final velocity is the same, the magnet through the loop will have been delayed. It arrives at the bottom later than the free-falling magnet.

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SVG Plot of Force $F(x)$:

XML



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  <text x="120" y="320" font-family="Arial" fill="green" font-size="12">Attraction</text>
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```

Would you like me to calculate the exact maximum current induced in the loop based on specific dimensions for the magnet and loop?

... [Superconducting levitation and interaction](#) ...

This video provides a visual demonstration of the interaction forces between magnets and superconductors, which helps illustrate the "locking" and conservative nature of the forces described above

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You wrote the following illogical statement:

"Phase 3: Exiting the Loop ($x < 0$)

Force: As the magnet drops below the loop, the interaction becomes attractive. The loop pulls the magnet down, exerting a downward force (in the same direction as gravity)."

The statement is illogical because the loop cannot pull the magnet down since in Phase 3 the loop is above the magnet, thus the loop can only push the magnet down.



You are absolutely right. I apologize for that confusion. You correctly identified a logical contradiction in my description.

If the loop is above the magnet (which it is in Phase 3) and it exerts a downward force, it must be pushing the magnet away. This means the interaction is repulsive, not attractive.

Here is the corrected explanation of the physics and the force evolution.

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The Correction: Repulsion, Not Attraction

Your intuition caught a critical distinction between a normal resistive loop and a superconducting loop.

- In a Normal (Resistive) Loop: The current is proportional to the *rate of change* of flux ($d\Phi/dt$). The current direction flips as the magnet passes the center. This creates drag (repulsion on approach, attraction on exit).
- In Your Superconducting Loop: The current is proportional to the *total* flux (Φ), to maintain the "trapped flux" at zero. Since the flux from the magnet does not change sign (it just rises and falls), the induced current does not change direction.

Because the current direction remains constant, the loop acts like a fixed "mirror magnet" that always opposes the falling magnet.

Revised Phases of Motion

Phase 1: Approaching ($x > 0$)

- Geometry: Loop is below the magnet.
- Interaction: The loop generates a magnetic field to block the incoming flux.
- Force: Repulsive. The loop pushes the magnet Up ($F > 0$).
- Result: The magnet falls slower than gravity.

Phase 2: Inside the Loop ($x = 0$)

- Force: Zero (The gradient of the field is zero at the center).

Phase 3: Exiting ($x < 0$)

- Geometry: Loop is now above the magnet.
- Interaction: The loop maintains the same current direction as before (trying to keep the flux at zero). It effectively "refuses" to let the magnet's field leave, but in terms of forces, since the current hasn't flipped, the polarity hasn't flipped. It continues to repel the magnet.
- Force: Repulsive. Because the loop is now *above* the magnet, a repulsive force pushes the magnet Down ($F < 0$).
- Result: The magnet is "shot" out of the loop, accelerating faster than gravity. This returns the potential energy stored during the approach.

Corrected Visualization

I have generated a corrected plot description. The shape of the graph remains the same (Positive then Negative), but the physical interpretation of the negative region is now consistent: it is a downward repulsive push, not an attractive pull.

XML



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  <line x1="300" y1="50" x2="300" y2="350" stroke="black" stroke-width="2" />
  <text x="260" y="40" font-family="Arial" font-size="14">Force F(x)</text>

  <text x="500" y="190" font-family="Arial" font-size="12" fill="gray">Top (+)
  <text x="60" y="190" font-family="Arial" font-size="12" fill="gray">Bottom (-)

  <line x1="50" y1="280" x2="550" y2="280" stroke="red" stroke-width="2" />
  <text x="310" y="275" font-family="Arial" fill="red" font-size="12">Gravity

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          T 400 50
          Q 450 200 550 200"
```

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```
<text fill="none" stroke="green" stroke-width="3" />
<text x="350" y="80" font-family="Arial" fill="green" font-size="14">Magnet

<text x="380" y="120" font-family="Arial" fill="green" font-size="12">Repu
<text x="120" y="320" font-family="Arial" fill="green" font-size="12">Repu
</svg>
```

Summary of Energy: The magnet slows down on approach (storing energy in the loop's field) and accelerates on exit (recovering that energy). Long after exiting, its kinetic energy is exactly the same as if the loop had never been there, satisfying conservation of energy.

Would you like me to derive the equation for the current $I(x)$ to prove mathematically why the direction doesn't flip?

Yes, and assume the convention that when the center of mass of the permanent bar magnet is at the center of the loop (in plane of the loop) and the magnetization axis of the magnet is parallel to the axis of the loop, then the distance $x=0$

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You are absolutely correct. My previous statement regarding the "attractive" nature of the force was logical nonsense given the geometry.

If the loop is above the falling magnet (which it is for $x < 0$) and it exerts a downward force (accelerating the magnet), it must be pushing the magnet away. This means the interaction is repulsive.

In a superconducting (or ideal zero-resistance) loop, the current direction never changes. The loop creates a magnetic field that opposes the *existence* of the magnet's flux, regardless of which side the magnet is on. It acts like a "mirror magnet" that always repels the real magnet.

1. Mathematical Proof of Repulsion

We can prove this using the principle of virtual work and energy conservation.

- Flux Conservation: Since $R = 0$, the total flux in the loop must remain constant (zero).

$$LI(x) + \Phi_{mag}(x) = 0 \implies I(x) = -\frac{\Phi_{mag}(x)}{L}$$

Because the magnet's flux $\Phi_{mag}(x)$ is a symmetric "hill" (positive values that rise and fall), the current $I(x)$ is a symmetric "valley" (always negative). The current never flips direction.

- Potential Energy (U): The energy stored in the system is purely the magnetic energy of the induced current.

$$U(x) = \frac{1}{2}LI(x)^2 = \frac{1}{2}L \left(-\frac{\Phi_{mag}(x)}{L} \right)^2 = \frac{\Phi_{mag}(x)^2}{2L}$$

- Force (F): The force is the negative gradient of the potential energy ($F = -dU/dx$).

$$F(x) = -\frac{d}{dx} \left(\frac{\Phi_{mag}(x)^2}{2L} \right) = -\frac{1}{L} \Phi_{mag}(x) \cdot \frac{d\Phi_{mag}(x)}{dx}$$

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Analyzing the Signs:

- Approaching ($x > 0$):
 - Φ_{mag} is positive.
 - As the magnet falls *towards* zero, Φ_{mag} is increasing, so the slope $\frac{d\Phi}{dx}$ (looking from positive x toward 0) is actually negative (the function value gets larger as x gets smaller, but in standard calculus terms, if you move to the *right* on the x -axis away from the center, flux decreases).
 - Let's check standard derivatives: At $x > 0$, the slope of a bell curve centered at 0 is negative.
 - $F(x) \propto -(\text{Positive}) \cdot (\text{Negative}) = \text{Positive}$.
 - Result: Upward Force (Repulsive).
- Exiting ($x < 0$):
 - Φ_{mag} is positive.
 - At $x < 0$, the slope of a bell curve is positive.
 - $F(x) \propto -(\text{Positive}) \cdot (\text{Positive}) = \text{Negative}$.
 - Result: Downward Force (Repulsive).

2. Corrected Force vs. Distance $F(x)$ Plot

This plot represents the force $F(x)$ on the vertical axis against the distance x on the horizontal axis.

- Right Side ($x > 0$): The magnet is above the loop. The Force is Positive (Up/Repulsive).
- Left Side ($x < 0$): The magnet is below the loop. The Force is Negative (Down/Repulsive).

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XML



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</svg>
```

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3. Kinetic Energy Evolution

- Before Entering ($x \gg 0$): The magnet accelerates under gravity.
- Entering ($x > 0$): The repulsive force opposes gravity. The net acceleration decreases (it might even become negative, slowing the magnet down). Kinetic energy is converted into magnetic potential energy stored in the loop.
- At Center ($x = 0$): The force is zero. The magnet has its minimum Kinetic Energy relative to a free-fall baseline. The potential energy in the loop $\frac{1}{2}LI^2$ is at its maximum.
- Exiting ($x < 0$): The loop is now above the magnet and repels it downwards. This force acts *with* gravity. The magnet accelerates faster than g . The magnetic potential energy is returned to the magnet as kinetic energy.
- Long After Exiting ($x \ll 0$): The loop's current fades to zero as the flux disappears.
 - Comparison: The final kinetic energy is identical to the case where the loop is absent.
 - Reasoning: Since the system is conservative (no resistance/heat loss), the total energy is conserved. The magnetic "spring" compressed as the magnet entered and expanded as it left, doing zero net work over the full path. The only difference is the magnet arrives at the bottom slightly later than it would have in free fall.

... [Quantum Levitation - Why Superconductors Float](#) ...

This video is relevant because it explains the "Meissner effect" and flux pinning in superconductors, which is the physical mechanism creating the persistent, non-flipping currents and the repulsive "locking" forces described in this problem.

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Earlier you wrote:

"Summary of Energy: The magnet slows down on approach (storing energy in the loop's field) and accelerates on exit (recovering that energy). Long after exiting, its kinetic energy is exactly the same as if the loop had never been there, satisfying conservation of energy."

QUESTION: Is the Lenz Effect responsible for the slow down an approach and acceleration on exit ?



This is a subtle question that touches on the difference between "Lenz's Law" (the rule of induction) and "Magnetic Drag" (the common resistive result).

The short answer: Strictly speaking, yes, Lenz's Law is responsible for the magnetic fields that cause both the slowdown and the acceleration. However, the result (acceleration) contradicts the common "rule of thumb" that Lenz's Law always opposes motion.

Here is the breakdown of why this happens and how it differs from the standard "Lenz Drag" you might be expecting.

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1. Lenz's Law: Opposition to Flux, Not Motion

Lenz's Law states that an induced current will flow in a direction that opposes the change in magnetic flux. 

- On Approach: The magnet tries to push flux *into* the loop. To oppose this increase, the loop creates a field pointing *out*.  
 - *Result:* North faces North. Repulsion. The magnet slows down.
- On Exit: The magnet moves away, so the flux inside the loop *would* normally decrease. 
 - In a Copper Loop (Resistive): The current would flip direction to try and keep the flux there (creating an attractive South pole). This would pull the magnet back (Drag). 
 - In Your Superconducting Loop (Lossless): The current does not flip. Because the resistance is zero, the current induced during the approach simply persists to maintain the "trapped" zero-flux condition. The loop continues to act as a "North" pole, effectively "refusing" to accept the magnet's field even as the magnet leaves.
 - *Result:* The loop (now above the magnet) continues to repel the magnet (now below it). A repulsive push from *above* acts downwards.

2. The "Spring" Analogy (Conservation of Energy)

It is best to think of the superconducting loop not as a brake (like copper), but as a spring.

- Compression (Approach): As the magnet falls in, it does work against the repulsive force. Kinetic energy is converted into magnetic potential energy stored in the loop ($U = \frac{1}{2}LI^2$). The "spring" is compressed.
- Expansion (Exit): As the magnet passes the center, the "spring" unloads. The stored magnetic energy is converted back into the magnet's kinetic energy.
- Why Acceleration? To give this energy back to the magnet, the force *must* act in the direction of motion. The loop pushes the magnet down, accelerating it faster than gravity alone ($a > g$).

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3. Comparison Table

Feature	Copper Loop (Resistive)	Superconducting Loop (Ideal)
Current Direction	Flips (Sine wave)	Constant (Bell curve)
Force on Approach	Repulsive (Slows down)	Repulsive (Slows down)
Force on Exit	Attractive (Pulls back/Drag)	Repulsive (Pushes down/Boost)
Energy	Dissipated as Heat ($I^2 R$)	Stored & Returned ($\frac{1}{2} L I^2$)
Role of Lenz's Law	Creates Drag (Opposes motion)	Creates a Conservative Force (Opposes flux change)

Conclusion: Lenz's Law is responsible for creating the repulsive state that persists throughout the fall. Because this repulsion acts from *above* during the exit phase, it results in a downward push (acceleration).

... [Physics in Action: Magnet Falling Through a Conductive Pipe](#) ... *This video demonstrates the "Standard" resistive case where Lenz's Law creates drag on both entry and exit; in your superconducting scenario, the "exit drag" would effectively become a "turbo boost" due to the lack of energy loss.*

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You wrote that:

"Strictly speaking, yes, Lenz's Law is responsible for the magnetic fields that cause both the slowdown and the acceleration".

In the case of an ideal inductance (the shorted superconducting loop) does the Lenz Effect create drag on the magnet over the complete approach+departure cycle ?

:



This is a crucial distinction. The answer depends on distinguishing between "Lenz's Law" (the rule for induced field direction) and "Drag" (energy loss).

Short Answer: Yes, Lenz's Law is responsible for the forces in both phases. No, it does not create "drag" over the complete cycle.

In an ideal superconductor, the Lenz Effect acts as a perfect spring, not a brake. It stores energy on approach and returns it 100% on exit.

1. The Logical Distinction: Spring vs. Friction

Lenz's Law simply dictates that the induced currents will "oppose the change" in flux. However, the *consequence* of that opposition depends entirely on resistance. 

- In a Copper Loop (Resistive): The energy used to oppose the magnet is dissipated as heat ($I^2 R$). The energy is lost forever. The magnet feels a drag force on approach and a drag force on exit. (Like moving through molasses).

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- In a Superconducting Loop (Ideal): The energy used to oppose the magnet is stored in the magnetic field ($\frac{1}{2}LI^2$). Because there is no resistance, this energy is trapped, not lost. As the magnet leaves, the loop "unloads" this stored energy back into the magnet, pushing it downwards. (Like bouncing on a trampoline).

2. Force Comparison (The "Drag" Trap)

The graph below illustrates why the Superconducting case is not "drag" in the traditional sense.

- Drag (Resistive): The force is always Upward (opposing gravity). It tries to stop the falling magnet during both entry and exit.
- Spring (Superconducting): The force is Upward then Downward. It slows the magnet on entry, but pushes it faster on exit.

3. Detailed Breakdown of the Cycle

Phase	Resistive Loop (Standard "Drag")	Superconducting Loop (Your Scenario)
Approach	Repels (Force Up)	Repels (Force Up)
	Lenz creates a field to block flux. Energy is lost to heat.	Lenz creates a field to block flux. Energy is stored in the field.
Exit	Attracts (Force Up)	Repels (Force Down)
	Lenz creates a field to keep flux. Pulls the magnet back. Energy is lost to heat.	The "frozen" current persists. The loop pushes the magnet away. Stored energy is returned as speed.
Net Work	Negative (Energy Lost)	Zero (Energy Conserved)

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4. Conclusion

You asked: *"Does the Lenz Effect create drag on the magnet over the complete approach+departure cycle?"*

No. Over the complete cycle, the net work done by the magnetic force is zero. The "Lenz Effect" in a superconductor acts as a conservative force field (like gravity or a spring), not a dissipative drag force.

The magnet arrives at the bottom with the exact same kinetic energy as if the loop were not there (though it arrives at a different time).

Here is the visual proof of the "Spring" vs "Drag" behavior:

XML



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</svg>
```

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If the Lenz Effect is not contaminated by other phenomena, such as resistance, does it always create zero net drag ?

✦ Yes.

In the absence of resistance (or other energy-dissipating "contaminants" like eddy currents in the magnet itself or radiation), the "pure" Lenz Effect creates zero net drag over a complete approach-and-departure cycle.

Here is the breakdown of why this is true and how it changes our understanding of Lenz's Law.

1. Lenz's Law is a "Spring," Not a "Brake"

We are often taught Lenz's Law in the context of braking (e.g., dropping a magnet down a copper tube) This creates a mental association that "Lenz = Friction "

However, Lenz's Law strictly defines the direction of the reaction: *The system reacts to oppose the change in flux.* 

- With Resistance (Contaminated): The system opposes the change by burning energy as heat. This is a "leak." You push against the field, and the energy vanishes. When you try to leave, the energy is gone, so you just feel drag again.
- Without Resistance (Pure): The system opposes the change by storing energy in the magnetic field. It is a "seal." You push against the field, and the energy is held there (like compressing a spring). When you try to leave, the system reacts by returning that energy to you.

2. The Symmetry of Work

In your scenario (the superconducting loop), the forces are perfectly symmetric in magnitude but opposite in effect regarding the motion:

1. Approach (Compression): The Lenz Effect creates a repulsive force. You do work against the loop. Kinetic Energy is converted to Magnetic Potential Energy. 
 - Result: Drag (Deceleration).

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2. Departure (Expansion): The Lenz Effect *still* creates a repulsive force (as we established). But now, the loop is behind the magnet. The force pushes the magnet forward. The Loop does work on you. Magnetic Potential Energy is converted back to Kinetic Energy.

- *Result:* Thrust (Acceleration).

Net Result:

$$\text{Work}_i + \text{Work}_t = -\Delta E + \Delta E = 0$$

The magnet leaves the loop with the exact same speed it would have had if the loop were never there (accounting for the time delay, its velocity at any specific distance x far from the loop is identical to the free-fall case).

3. Conclusion

The "Lenz Effect" is fundamentally a conservative reaction force. It acts like a magnetic elasticity. It only becomes "drag" when resistance contaminates the system and prevents the stored energy from being returned to the object.

So, in an ideal world: Lenz's Law conserves energy; it does not destroy it. 

Is a positive net drag on that magnet always associated with energy dissipation ?



Yes, in the specific context of a shorted loop, a "Positive Net Drag" implies energy dissipation.

However, in the broader context of physics, the answer is No. It is possible to have net drag (slowing the magnet down permanently) without dissipating that energy as heat.

Here is the deep dive into why, distinguishing between the specific scenario we are discussing and the general laws of physics.

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1. The Case of the Shorted Loop (Your Scenario)

If we stick strictly to the shorted loop (a simple wire connected to itself) falling in gravity:

- Conservation of Energy: $\text{Energy}_{\text{Lost by Magnet}} = \text{Energy}_{\text{Gained by Loop}}$
- Net Drag: If there is positive net drag, the magnet has less kinetic energy at the bottom than it started with. The energy had to go somewhere.
- Where can it go? In a simple shorted loop, there is no battery to charge and no spring to compress. The only mechanism available to absorb energy is Electrical Resistance.
- The Mechanism: The induced current fights the crystal lattice of the wire, generating heat ($P = I^2 R$).
- Conclusion: In this specific system, Net Drag $\equiv$ Dissipation (Heat).

2. The General Physics Case (The Exception)

If we modify the system slightly, we can create Net Drag without Dissipation.

Imagine replacing the "short" with a perfect Capacitor (an LC circuit) or a Rechargeable Battery (ideal).

- Process: As the magnet falls, it induces a voltage. This voltage drives a current that charges the capacitor or battery. 
- The Force: The loop still exerts a magnetic force opposing the magnet (Lenz's Law), causing the magnet to slow down (Drag).
- The Outcome: The magnet exits the loop slower than it entered. It has experienced Positive Net Drag.
- The Energy: The missing kinetic energy was not dissipated as heat. It was transferred and stored as potential energy in the electric field of the capacitor or the chemistry of the battery.

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This is the principle behind Regenerative Braking in electric cars. The car feels "drag" and slows down, but the energy isn't burned up in brake pads (dissipation); it is sent back into the battery (storage).

3. Summary Diagram: Where does the energy go?

This flowchart tracks the Kinetic Energy (KE) of the magnet as it passes through different types of loops.

Key Takeaway:

- "Instantaneous Drag" (Slowing down): Does not imply dissipation. It only implies energy transfer (either to storage or to heat).
- "Net Drag" (Permanent loss of speed): Implies the energy was removed from the magnet and put somewhere else.
 - In a Resistive/Shorted Loop, it went to Heat (Dissipation).
 - In a Storage/Regenerative Loop, it went to Storage (Useful Energy).

So, for your immovable shorted loop: Yes, drag is proof of energy dissipation.

the Lenz Effect is perfectly elastic and creates zero net drag.

Gemini

In the case of a resistive loop ($R > 0$) is it the Lenz Effect that is responsible for the positive net drag or the resistance ?



This is a fantastic question that gets to the heart of causality in electrodynamics.

The short answer is: Resistance is responsible for the net drag

The Lenz Effect is merely the mechanism of interaction (the "grip"). Resistance is what turns that grip into a source of energy loss (the "friction"). Without resistance, the Lenz Effect is perfectly elastic and creates zero net drag.

Here is the breakdown of the "partnership" between the two:

1. The "Architect" vs. The "Executioner"

- The Lenz Effect (The Architect): Lenz's Law provides the rule: "Generate a force to oppose the *change*." It ensures there is an interaction between the magnet and the loop. However, Lenz's law itself is neutral regarding energy loss—it just demands a reaction. <?
- Resistance (The Executioner): Resistance dictates what happens to the energy generated by that reaction. It converts the electrical energy into heat. This removal of energy causes the asymmetry in the force that results in net drag.

2. The Critical Shift: Symmetry vs. Asymmetry

To understand why resistance is the culprit, compare the force profiles (the shape of the "push"):

- Ideal Case ($R = 0$): Perfect Symmetry
 - Behavior: The current is proportional to the Flux (\$).
 - Force: The loop pushes the magnet UP on approach and pushes it DOWN on exit.
 - Net Result: The upward push exactly cancels the downward push. Zero Net Drag.

Gemini

- Resistive Case ($R > 0$): The "Phase Shift"
 - Behavior: The current is dominated by the *rate of change* of Flux ($d\Phi/dt$).
 - Force:
 - Approach: Magnet pushes flux *in*. Loop pushes back (Repulsion/Upward).
 - Exit: Magnet pulls flux *out*. Loop pulls back (Attraction/Upward).
 - Net Result: The force is always Upward (always opposing gravity). The magnet is dragged on entry *and* dragged on exit.

3. Why Resistance Changes the Force Direction

In the superconducting loop we discussed earlier, the current never flipped direction, so the magnet was repelled on both sides (Up then Down).

In a resistive loop, the current does flip direction.

1. Entry: Current flows CW to block flux. (Repulsive North pole).
2. Exit: Current flows CCW to replace flux. (Attractive South pole).

This current flip—caused by the fact that the energy dissipates instantly rather than being stored—is what ensures the force always points UP, fighting the magnet's fall the entire way.

Summary

- Lenz's Law creates the forces.
- Resistance ensures those forces always act to steal kinetic energy (Drag), rather than borrowing and returning it (Elasticity).

If you could turn off resistance (make $R = 0$), Lenz's Law would still exist, but the net drag would instantly vanish. Therefore, Resistance is the cause.

Gemini

With that insight, do you think that the phrase "Lenz Drag" is physically consistent ? Only a short answer, please.

✦ No, strictly speaking, it is not physically consistent.

The phrase conflates two distinct phenomena:

1. Lenz's Law: A rule of direction (which can be purely elastic/conservative).
2. Drag: An outcome of energy dissipation (requiring resistance).

A more accurate term would be "Resistive Magnetic Drag" or "Inductive Braking," as the drag is a consequence of the resistance, not the law of induction itself.