

Journal of Physics Special Topics

An undergraduate physics journal

P1 9 Holding Space for Defying Gravity

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December 10, 2025

Abstract

This paper explores the physical possibility of Elphaba Thropp's flight during the song *Defying Gravity* in the musical *Wicked*. By applying fundamental physics principles, we find that aerodynamic lift would require horizontal velocities of $\sim 14 \text{ ms}^{-1}$, whereas magnetic levitation would require a field strength of 0.22 T. We conclude that, of these two models, magnetic levitation offers the most realistic explanation within the limits of known physics.

Introduction

During the song *Defying Gravity* in the musical *Wicked*, Elphaba Thropp famously declares her intent to "fly" as she rises into the air supposedly unaided. While the narrative attributes this phenomenon to a magic levitation spell, the underlying physics of such an event can be analysed. This paper investigates the question: what physical mechanisms could explain Elphaba's flight? We consider two possibilities, including aerodynamic lift and electromagnetic lift.

Lift Force

For steady vertical flight, the upward lift equals the downward gravitational force:

$$F_g = mg. \quad (1)$$

If Elphaba accelerates upwards, an additional net force, $F_{\text{net}} = ma$ must be applied. Assuming an average human mass, m , of 65 kg [1], and taking an initial upward acceleration, a , to be 1.5 ms^{-2} , the total lift is calculated using:

$$F_L = m(g + a), \quad (2)$$

giving a force of 735 N.

Aerodynamic Model

If Elphaba's cloak functions as a wing, lift can be estimated using the equation:

$$F_L = \frac{1}{2} C_L \rho A v^2, \quad (3)$$

where C_L is the lift coefficient, determined by the angle of attack and wing shape, ρ is air density, 1.225 kgm^{-3} [2], A is the wing surface area, and v is Elphaba's velocity relative to the air. Solving for v :

$$v = \sqrt{\frac{2F_L}{C_L \rho A}}, \quad (4)$$

and taking a maximum lift coefficient for an airplane wing of 1.3 [3], and assuming a cloak surface area of $\sim 5 \text{ m}^2$ (based on the costume design reports indicating that Elphaba's final dress was constructed from over 40 yards of fabric [4] and assuming only $\sim 10\%$ of this total material belongs to the cloak itself), requires Elphaba to travel at $\sim 14 \text{ ms}^{-1}$. Note that aerodynamic lift depends on the horizontal velocity component of Elphaba's cloak relative to the air, independent of the vertical acceleration considered for the lift force. Thus, the required velocity of $\sim 14 \text{ ms}^{-1}$,

is the horizontal velocity needed to generate the required lift.

Magnetic Levitation

Another explanation involves magnetic levitation, where magnetic forces counteract gravity. Magnetic pressure arises due to the magnetic energy density, and is strongest when a magnetic field exists on one side of a surface and is excluded on the other. Therefore, for a net magnetic pressure to act on Elphaba, we assume that her broom is made from a superconducting material which excludes magnetic fields, creating an effective repulsive force. Under this idealised assumption, the lift force per unit area can then be approximated by [5]:

$$\frac{F_L}{A} = \frac{B^2}{2\mu_0}, \quad (5)$$

where F_L is as calculated using Equation (2), A is the area of the broom, B is the magnetic field strength, and μ_0 is the permeability of free space, $4\pi \times 10^{-7} \text{ NA}^{-2}$. For simplicity, Elphaba's broom is modelled as a cylindrical broom handle with a radius, r , and length, L , of 1.25 cm and 1.5 m respectively. Since the broom is oriented horizontally during flight, the upward magnetic pressure acts on its projected vertical area. For a horizontal cylinder, this projected area corresponds to a rectangle of length, L , and width $2r$, giving an area of 0.0375 m^2 . Rearranging for the magnetic field strength, B :

$$B = \sqrt{2\mu_0 \frac{F_L}{A}}, \quad (6)$$

gives a required magnetic field strength of 0.22 T, which is ~ 22 times stronger than a small bar magnet [6] and ~ 4600 times stronger than Earth's average magnetic field [6].

Discussion

Although Elphaba's ascent in *Defying Gravity* is depicted as instantaneous and effortless, the physics behind the vertical lift imposes strict energetic and mechanical requirements, such as a lift force of 735 N. The aerodynamic model suggests that a cloak acting as a wing would require

Elphaba to travel at roughly 14 ms^{-1} , $\sim 31 \text{ mph}$, to produce sufficient lift. This estimate, however, is based on several simplifying assumptions, including an ideal lift coefficient usually associated with shaped aircraft wings, not a flat cloak. The estimate is further simplified by assuming a flat cloak surface area, of which we use an estimated value, and steady airflow. All of these simplifying assumptions underestimate the true velocity required for aerodynamic lift. Even under these optimistic conditions, such speed would create turbulence, noise, and visible air displacement which are not observed in the performance, making purely aerodynamic flight improbable.

Magnetic levitation provides a more subtle elevation. The calculated required magnetic field strength of 0.22 T is significantly greater than Earth's magnetic field but still within the range produced by electromagnets. If Elphaba's broom were to be superconducting and interact with a magnetic surface below of field strength 0.22 T, stable levitation could occur. However, generating and sustaining such a field would require a continuous energy supply and precise magnetic control, technologies currently limited to experimental magnetic levitation systems.

Conclusion

Through the application of classical mechanics and electromagnetism, this paper evaluates two potential explanations for Elphaba's defiance of gravity. Aerodynamic lift is shown to be an unrealistic explanation due to the excessive velocity and turbulence expected, whereas magnetic levitation offers a more physically consistent possibility, though technologically demanding.

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