Newtons laws explain how frisbees fly.

Mr. Nicholas Landell-Mills   MA CFA ACA

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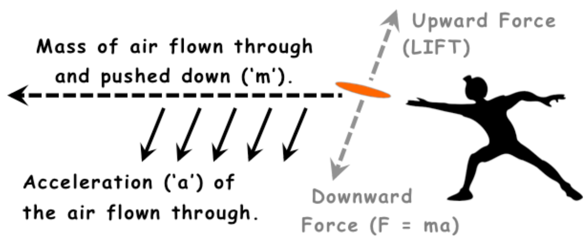
Abstract

Newtons laws of motion explain the physics for how frisbees fly. Specifically, a frisbee in horizontal flight with a positive angle of attack (AOA), will accelerate ('a') the mass of air flown through ('m') downwards to generate a downward force; due to Newtons 2nd law of motion (Force = ma). The 'equal & opposite' upward force created due to according to Newtons 3rd law of motion, provides vertical lift. The underside of the frisbees pushes air down. While the curved topside of the frisbee boosts the amount of air displaced downwards due to the Coanda effect. Air goes down and the frisbee goes up. It's that simple.



The spin on a frisbee enhances the stability of flight due to the gyroscopic effects. In turn, stability of flight allows the frisbee to generate laminar (smooth) airflows and thus better lift. Any spin itself does not directly enhance vertical lift. Airflow vortices account for trick throws, where the frisbee appears to defy normal physics.

So what? The nest performing frisbee will be one that maximises the Coanda effect on the topside of the disc; to increase the amount of air displaced down. Newtons laws can explain why a frisbee thrown flat (small AOA) generates better lift and will fly further than a frisbee thrown high, on a parabolic type of path. This explanation has not been provided previously.

I. Introduction

A. The physics of lift are debated.

Strangely, the physics of lift remain debated due to the lack of any conclusive evidence and realistic experiment to support any one theory. Broadly, there are two competing theories for lift. One camp claims that fluid flow over the topside of the frisbee sucks (pulls) it upwards. This is usually based on Bernoulli's principles of fluid dynamics, Navier-Stokes or similar complex equations. The other camp claims that lift is the equal and opposite force resulting from the frisbee pushing air downwards, based on Newtons laws of motion. This is similar to how almost every object generates forward motion.

It is noteworthy that NASA [1] sits on the fence in this debate, and supports both explanations of lift. But both theories cannot both be correct, as the physics involved are completely different.

Worse, there is no universal theory of flight that easily explains how all animals and objects fly.

This Newtonian explanation for frisbee flight fits best with what is observed in reality as well as the standard equations for lift and kinetic energy. It should not be surprising that Newtons laws of motion can explain the physics of how frisbees fly. Nor that frisbees achieve buoyancy to 'float' in the air

II. NEWTONIAN EXPLANATION OF LIFT

A. Lift explained by Newtons laws of motion.

The theory of lift based on Newtons laws of motion provides a simple and easy to understand explanation of what is observed in reality. In summary, the frisbee with a positive angle of attack (AOA) pushes air down, the equal & opposite force pushes the frisbee up. Note that the frisbees also pushes the air slightly forwards.

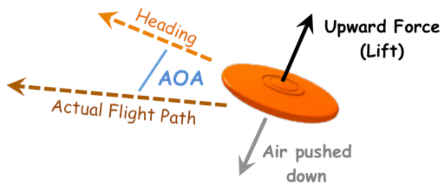


Fig 2a. Physics of frisbee flight.

Frisbees have two separate airflows. The underside of the wing PUSHES the air down. The curved topside of the frisbee PULLS air downwards, due to the Coanda effect. See Fig 3b.

According to Newtons 2nd law of motion (F = ma), this downward force can be measured; based on a mass of static air ('m') flown through that is accelerated ('a') downwards. See Fig 2b.

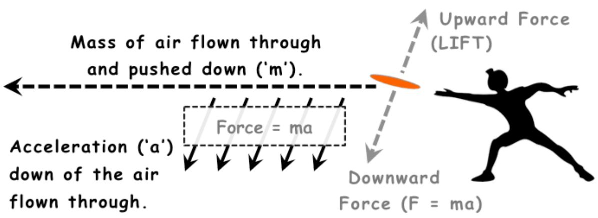


Fig 2b. Newtonian forces on a frisbee.

The Newtonian explanation of lift is consistent with the key principles in physics of the conservation of momentum, mass and energy. There is no net gain or loss of momentum, mass or energy. Momentum and energy are transferred from the frisbee to the air, to generate lift, by pushing the air down.

B. Inverted flight & hammer throws.

According to this Newtonian explanation of frisbee flight; A frisbee can fly inverted as long as it has a positive AOA to the direction of flight. Albeit, it won't fly as well as the curved side of the frisbee will be facing down, which will reverse the Coanda effect. This will push air up instead of down.

For example, a 'hammer' throw (inverted on a high parabolic type of path, See Fig 1c), the Coanda effect will accelerate the downward speed of a frisbee. Which is why it really can hurts to catch a hammer throw; the frisbees is descending a lot faster than normal because the Coanda effect is pushing it downwards (and gravity is pulling the frisbee down from a big height too).

C. Mass and acceleration of the air displaced.

Newtons laws of motion (F = ma) are consistent with the standard equation for lift: [1]

Lift = 0.5 x Velocity^2 x Air Density x Wing Area x Lift Cf.

All the parameters of the standard equation for lift (Velocity, Air Density, Wing Area , & Lift Coefficient) affect the mass of air displaced and/or the velocity to which this air is accelerated downwards. This is explained in more detail in another paper; 'Newtons laws explain the equation for lift..' [6]

D. Vortices.

The airflows around frisbees include vortices, which this paper does not consider to be a fundamental cause for lift. Although vortices can help explain many 'trick' frisbee throws. See Fig 2c.

Fig 2c Frisbee airflows.

Vortices are complicated. For example, birds and delta wing jets are thought to use leading edge vortices to allow for flight at unusually high angles of attack. Vortices can work both ways, either boosting lift or detracting from lift, depending on the circumstances.

E. Newtons laws explain frisbee trajectories.

In particular, Newtons laws explain why frisbees fly better when thrown fast and almost flat (parallel to the ground).

(i) Frisbee flight is effective at low angles-of-attack (AOA) to the direction of flight. Here the Coanda effect is greatest and laminar (smooth) airflow is best; displacing a lot of air downwards. In addition, at a low AOA there's the smallest amount of frisbee facing the direction of flight. This minimize the drag and air resistance to flight. See Fig 2d and 2e.

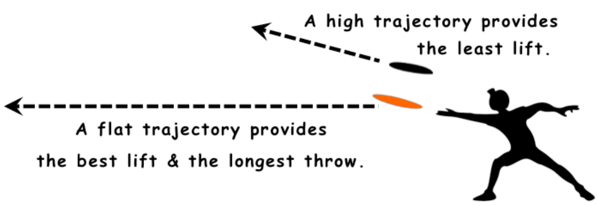


Fig 2d. Frisbee trajectories and lift.

Conversely, a frisbee thrown high, on a parabolic type of path provides a high AOA. Here the Coanda effect is weakest and airflow around the frisbee tends to be more turbulent. These two effects reduce the amount of air displaced downwards and thus reduce the lift generated.

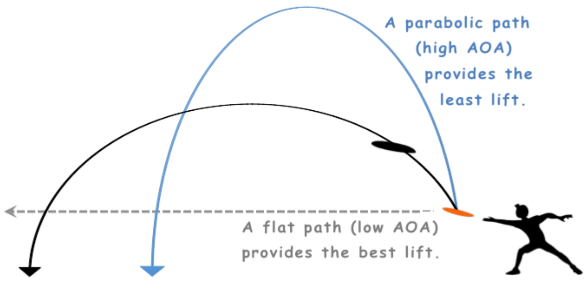


Fig 2e. Different frisbee trajectories.

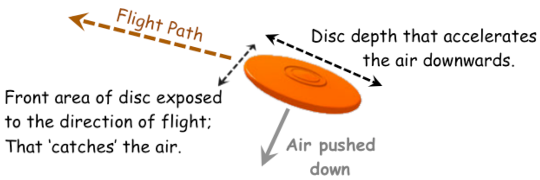
(ii) According to conventional physics and the standard equation for lift; lift is proportional to the square of the frisbee's velocity (lift ⇔ velocity^2). So a frisbee thrown twice as fast, will generate four times the lift.

The standard equation for lift: [1]
Lift = 0.5 x Velocity^2 x Air Density x Disc Area x Lift Cf.

Newtons laws of motion can explain why vertical lift is proportional to the square of horizontal frisbee velocity; (Lift => Frisbee Velocity^2). A frisbee travelling twice as fast will displace twice the mass of air (2x 'm'), and will accelerate this air to twice the velocity as before (2x 'a'), as the frisbee's momentum has also doubled. The combined effect is to quadruple the downward force (Force x4 = 2m x 2a), and thus quadruple both the upward force & lift generated. [6]

F. Wing (disc) area.

The wing (disc) area directly affects how much air mass is displaced down, and how fast this air is accelerated to. A wider wingspan (disc) and area exposed to the direction of flight increases the amount of air caught. Deeper wing (disc) area affects the velocity that the air caught is accelerated downwards. See Fig 2f.



Fig, 2f Disc area.

So, a frisbees thrown relatively flat with a small AOA, will have a constant wingspan exposed to the direction of flight that 'catches' air. But it will have relatively little wing depth (chord) and wing area exposed to the direction of flight, due to the low AOA. The means that the frisbees will have a limited ability to accelerate the air downwards.

As frisbees are round, the wingspan will equal the wing depth (chord).

G.Similar Newtonian explanations of lift.

For reference, this concept of lift based on Newtons laws of motion, is similar to that provided by the book "Understanding Flight." "In the simplest form, lift is generated by the wing diverting air down, creating the downwash." [2]. "From Newton's second law, one can state the relationship between the lift on a wing and its downwash: The lift of a wing is proportional to the amount of air diverted (down) per time times the vertical velocity of that air." [2]. ie. Lift = Downward Force = ma.

The book: "Stick and Rudder" by Wolfgang Langeweische (1944) [3], which is famous among pilots for its accurate, practical and common-sense advice on how to fly a plane well. In Chapter 1 the book states: " The main fact of heavier-than–air-flight is this: the wing keeps the plane up by pushing air down. It shoves air down with the bottom surface, and it pulls air down with the top surface. But the really important thing to understand is that the wing, in whatever fashion, makes air go down. In exerting a downward force on the air, the wing receives an upward counterforce – by the same principle, known as Newton's law of action and reaction, …. " as well as: "That's what keeps a plane up. Newton's law says that if the wing pushes the air down, the air must push the wing up."

III. The Coanda Effect

A. The Coanda effect

The Coanda effect has a significant impact on the physics of lift for frisbees. Fluid flow (airflow) naturally follows a curved surface due to the Coanda effect. Air flowing around the curved topside of a frisbee is similar to how falling water is re-directed by a spoon. See Fig 3a and 3b.

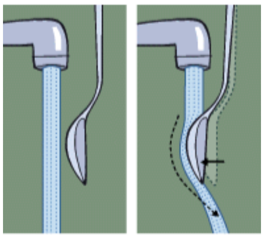


Fig 3a. Falling water being re-directed by a spoon.

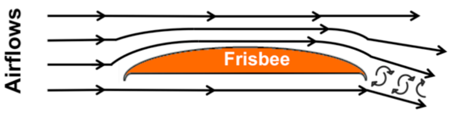


Fig 3b. Illustration of the Coanda effect on a frisbee.

The curved shape of the frisbees also creates minimal turbulence on the leeward side.

As there is a lack of appropriate data and wind tunnel experiments available for frisbees, airplane wings are used as a proxy to demonstrate the Coanda effect. See Fig 3c.

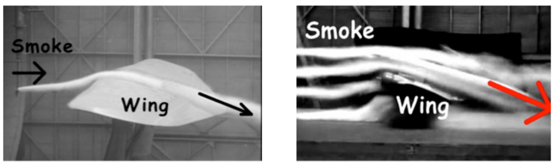


Fig. 3c. The Coanda effect on airplane wings in wind tunnels.

The Coanda effect on airplane wings shows that the amount of air re-directed depends on the maintenance of laminar (smooth) airflow. In turn this depends mostly on the AOA and shape of the wing (or frisbee). Any turbulence significantly reduces the amount of air displaced. See Fig 3d.

Fig. 3d. Airplane wings in a wind tunnel;
laminar and turbulent airflows.

In general, airplane wings will produce a stronger Coanda effect at lower AOA, at higher aircraft speeds and where the wings are deepest (widest). Conversely the Coanda effect is weakest at high AOA, slow aircraft speeds and where the wings are thinnest (eg. at wing-tips). This logic can be applied to sails.

IV. Buoyancy

A. Frisbees achieve buoyancy.

To fly, the frisbee has to generate a upward force sufficient to keep its weight in the air. As the frisbee pushes air down and slightly forwards, the upwards force is at an angle to the vertical direction. 'Lift' is simply the vertical component of the upward force. The downward force will equal the weight of the air pushed down.

But the frisbee is circulating the air. The weight (and mass) of the air pushed down with gravity, will equal the weight (and mass) of the air pushed up elsewhere against gravity. This means that the air pushed up, provides resistance to the frisbee pushing air down. This process is similar to how a swimmer treads water (by circulating the water). See Fig 4a.

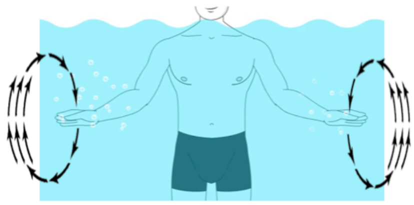


Fig 4a. Swimmer treading water.

The physics described above is shown by the equations:

$$\text{Downward Force } (F = ma) = \text{Upward Force (lift)}$$
$$\Rightarrow \text{Weight}_{\text{AIR PUSHED DOWN}} = \text{Weight}_{\text{FRISBEE PUSHED UP}}$$
$$\Rightarrow \text{Mass}_{\text{AIR DOWN}} \times \text{Gravity} = \text{Mass}_{\text{FRISBEE UP}} \times \text{Gravity}$$
$$\Rightarrow \text{Mass}_{\text{TOTAL AIR PUSHED DOWN}} = \text{Mass}_{\text{FRISBEE PUSHED UP}}$$

Note that:
- Weight = Mass x Gravity [1]
- The air directly flown through and accelerated down; indirectly displaces more air. The total mass of air displaced includes the air directly & indirectly displaced.

As the frisbee is circulating the air, gravity cancels out of the equations above, which simplify to: The mass of the air displaced down, must equal the mass of the frisbee pushed up; for the frisbee to generate a sufficient force to fly. i.e. The frisbee achieves buoyancy.

This is the same physics that explains how balloons float. Except a static balloon passively displaces air down to achieve static buoyancy and to float in the air. A frisbee actively displaces air down to achieve dynamic buoyancy and to float in the air. See Fig 4b. This is not what is taught at schools.

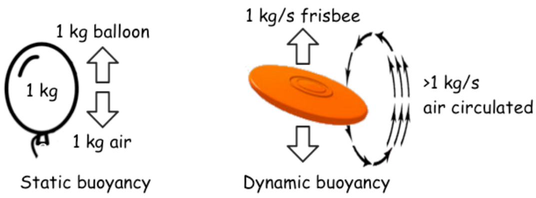


Fig 4b. Static and dynamic buoyancy.

V. Example calculation

Calculations below based on relatively conservative assumptions, show that it is feasible for a frisbee to generate a sufficient lift force to fly, based on Newtons laws of motion. Specifically, calculations assume: A frisbee that is 25 cm in diameter, and 175 g mass, is thrown at 11 m/s (40 km/hr), where all the air directly flown through (2 cm above and below the frisbee) is accelerated down at about 1.3 m/s (about 5 km/hr); to generate lift. The total mass of air displaced (directly and indirectly) down each second, equals the mass of the frisbee.

A. Volume of air flown through.

(i) First, the volume of air around a frisbee directly flown through and displaced each meter flown, is estimated. See Fig 5a.

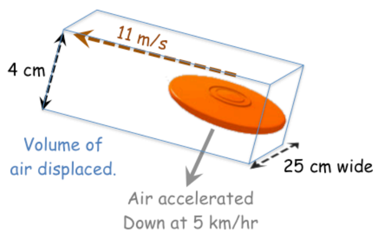


Fig 5a. Assumptions

Volume of air flown through each meter
= (distance thrown in one second x Frisbee diameter x Wing Reach) per meter
= (1100 cm/s x 25 cm x 4 cm)
= 110,000 cm^3 / s
= 0.11 m^3 / s

'Wing Reach' is the vertical distance away from the wing (disc) that the wing influences the air. A Wing Reach of 4 cm is assumed; this is 2 cm above and below the frisbee. Wing Reach depends on things like the wing shape and wing AOA.

The frisbee's velocity of 11 m/s is about 40 km/hr.

B. Mass of air flown through.

(ii) The volume of air flown through each second, is converted into mass of air flown through each second using the standard density of air [1] of 1.2 kg/m^3.

Mass = Volume x Air Density
= 0.11 m^3 /s x 1.2 kg/m^3
= 0.132 kg/s

C. Acceleration downwards of the air flown through.

(iii) The lift force that the frisbee needs to generate to fly is:

Downward Force
= ma
= mass of air directly flown through each second x acceleration of this air
= 0.132 kg/s x 1.33 m/s^2
= 0.175 kg/s

In summary, the downward force is sufficient to displace a total mass of air (directly and indirectly) down each second, that equals the mass of the frisbee Therefore, the frisbee will fly in these circumstances.

It is assumed that the frisbee has a low AOA; and all the upward force is converted into lift. To put it another way, it is assumed that the induced drag from the frisbee pushing air slightly forwards is minimal.

VI. Discussion of Results

This analysis provides significant into how frisbees fly that has not been provided previously. It should not be surprising that Newtons laws of motion can explain how a frisbees flies.

This helps to resolve the debate regarding the physics of lift. Navier-Stokes equations, Euler, Kutta effect, vortices …. may provide insight into airflows and flight, but they fail to explain the physics of the standard equation for lift.

Analysis shows that Newtons laws of motion are consistent with the standard equation for lift (Force = ma = Lift). So, Newtons laws of motion can explain why vertical lift is proportional to the square of horizontal velocity; (Lift => Velocity^2).

Calculations based on relatively conservative assumptions, show that it is feasible for a frisbee to generate a sufficient lift force to fly, based on Newtons laws of motion.

The alternative theories of flight based on fluid flow are unable to explain the standard equation for lift.

Applying Newtons laws of motion to flight allows the application of the standard equation for kinetic energy, to estimate the kinetic energy used by a frisbee to fly:

Kinetic Energy = $0.5\, mv^2$ [1]

Where:
m = Mass of air displaced.
v = Velocity of the air displaced.

The spin on a frisbee enhances the stability of flight due to the gyroscopic effects of the spin. In turn, stability of flight allows the frisbee to generate lift. Spin itself does not directly enhance vertical lift. However, spin can cause the frisbee to deviate horizontally from a straight path due to the Magnus effect. This aspect is relatively unimportant and not material to lift.

VII. Conclusions

Newtons laws of motion explain the physics of how a frisbee flies. In particular, Lift (Force = ma) is equal to the mass of air displaced ('m') and the velocity to which this air is accelerated ('a'). This Newtonian explanation for frisbee flight fits best with what is observed in reality. Frisbees float in the air when they circulate enough air to achieve buoyancy.

VIII. Additional information

Website: Short explanatory video on frisbees.

Author contact details: 75 Ch. Sous Mollards, Chamonix, 74400 France. T: 0033 638 77 39 40. Email: nicklm@gmx.com.

Affiliations: The author is a graduate of the Dept. of Humanities & Social Sciences, The University of Edinburgh, Edinburgh, UK. He was awarded a M.A. degree class 2:1.

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Corresponding authors: None.

Acknowledgments: None.

IX. References

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