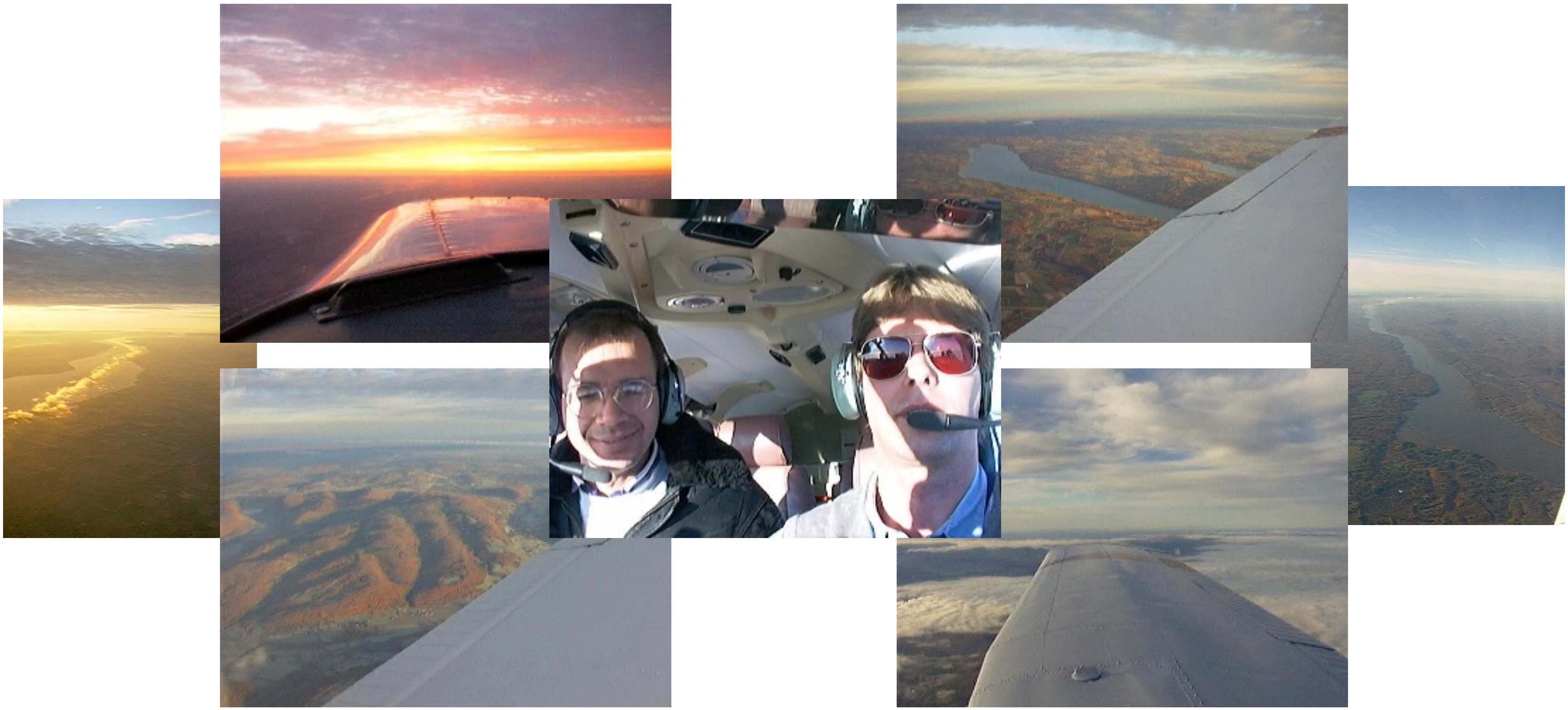
The Physics of Flying!
Lecture 25.



Views of New York State from 9000'.

Frank L. H. Wolfs

Department of Physics and Astronomy, University of Rochester

December 5th.
An important day in the Netherlands.

Course Information

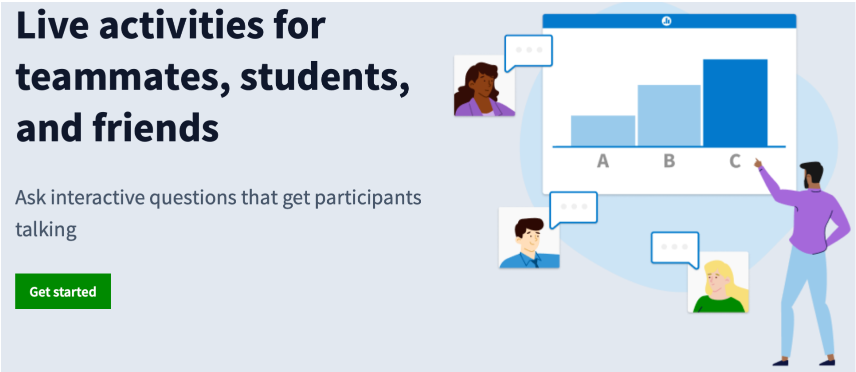
- Homework set # 10 is due on Friday 12/6.
- Optional homework set # 11 is due on Friday 12/13.

- The final exam is scheduled for Monday 12/16 between 4 pm and 7 pm.
- The final exam will cover all material discussed evenly. Error analysis is not covered on the final exam.

- There will be no recitations next week since classes end on 12/9.
- There will be normal office hours next week to answer all your exam-related questions.

Quiz lecture 25.
PollEv.com/frankwolfs050

- The quiz today will have four questions.
- I will collect your answers electronically using the Poll Everywhere system.
- You have 60 seconds to answer each question.



And now for something completely different:

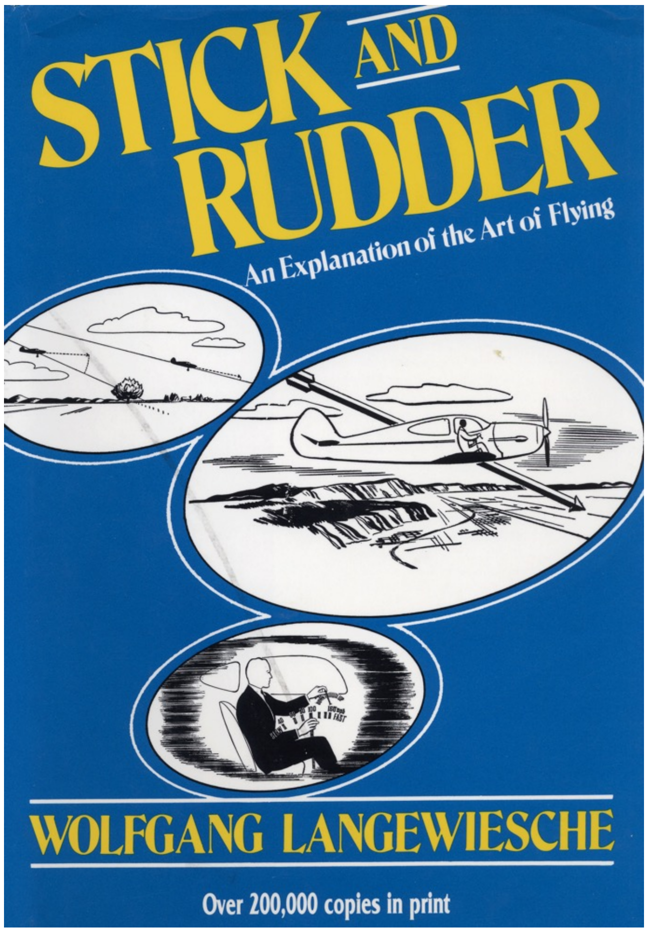
The Physics of Flying

The Physics of Flying!
Outline.

- What makes an airplane fly?
  - Weight and balance.
  - Airplane control and stability.
  - Lift and Bernoulli.
  - Take off and landing.
- What is the physics behind our instruments, and why should we trust them?
  - Forces of flight.
  - The grave-yard spiral.
  - The gyro system.
- Summary

12/17/1903

Where did I learn everything I know about flying?



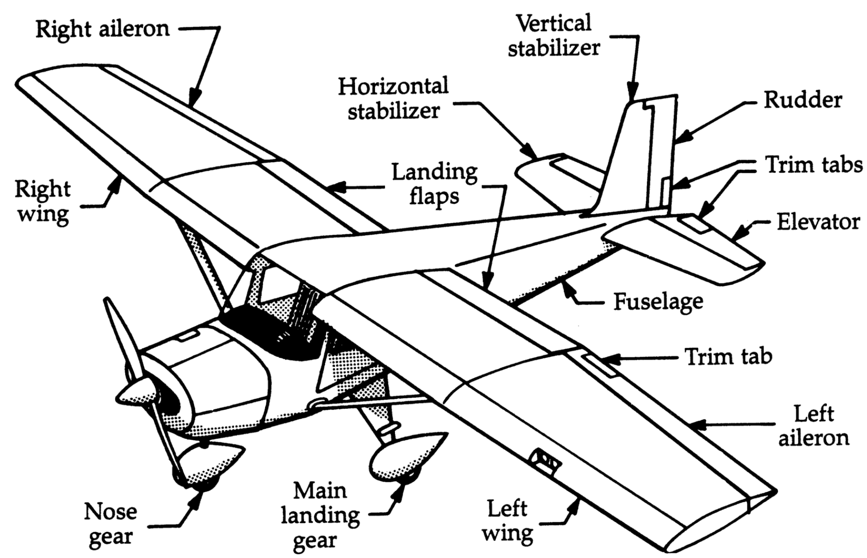
Joe d'Arpino, World's best flight instructor.

The physics of flying.
What can we cover in such a short time?

- In this talk I will focus on a few examples of the physics of flying.

- I have decided to focus on those areas of the physics of flying that are in general not well understood by the members of the physics community.

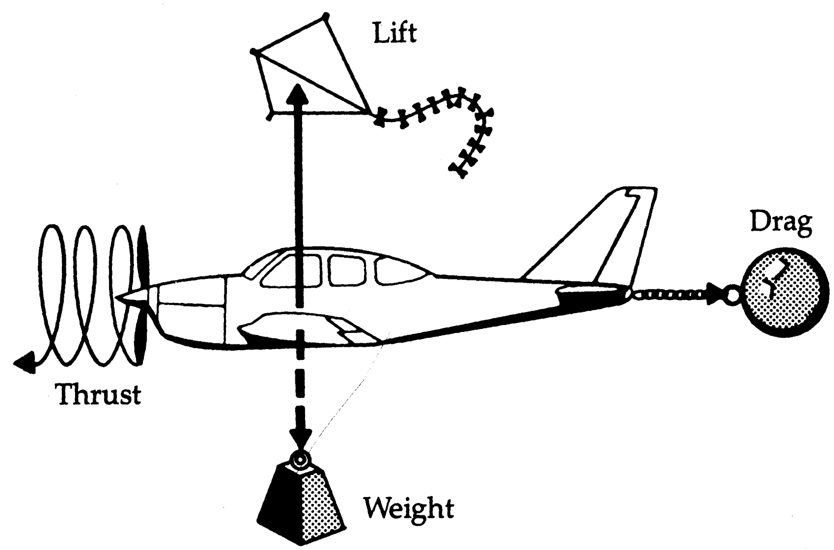
- Given the time allocated to me, this certainly will not be an "all you need to know about flying" type of talk.



The pilot's handbook of aeronautical knowledge, Paul E. Illman

The forces of flying.

- In order to understand the art of flying we need to understand the basic forces that act on an airplane:
  - Weight: the gravitational force that depends on the mass of airplane.
  - Lift: the upward force generated by the wings. The lift depends on the attitude of the airplane, its speed, and the design of the wings.
  - Thrust: the forward force generated by the engine(s). The thrust depends on engine design and operating conditions.
  - Drag: the backward force that slows the airplane down.



The pilot's handbook of aeronautical knowledge, Paul E. Illman

Airplane stability.
The tail force.

- Although the total mass of the airplane is an important factor in determining the required lift, the distribution of the mass also effects the required lift, and is a key factor in determining the stability of the airplane.
- If lift and weight are the only vertical forces acting the airplane, the plane will only be stable if the center-of-gravity coincides with the center-of-lift.
- In all other cases, a tail force is required to provide stability to the airplane.

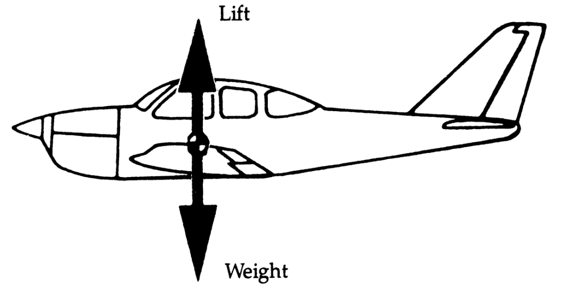


Fig. 1-27. Neutral stability.

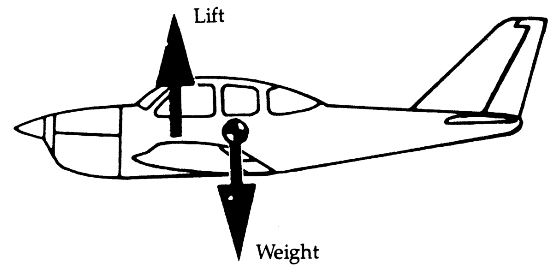


Fig. 1-28. Negative stability.

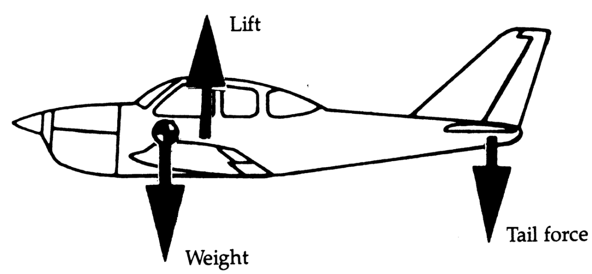
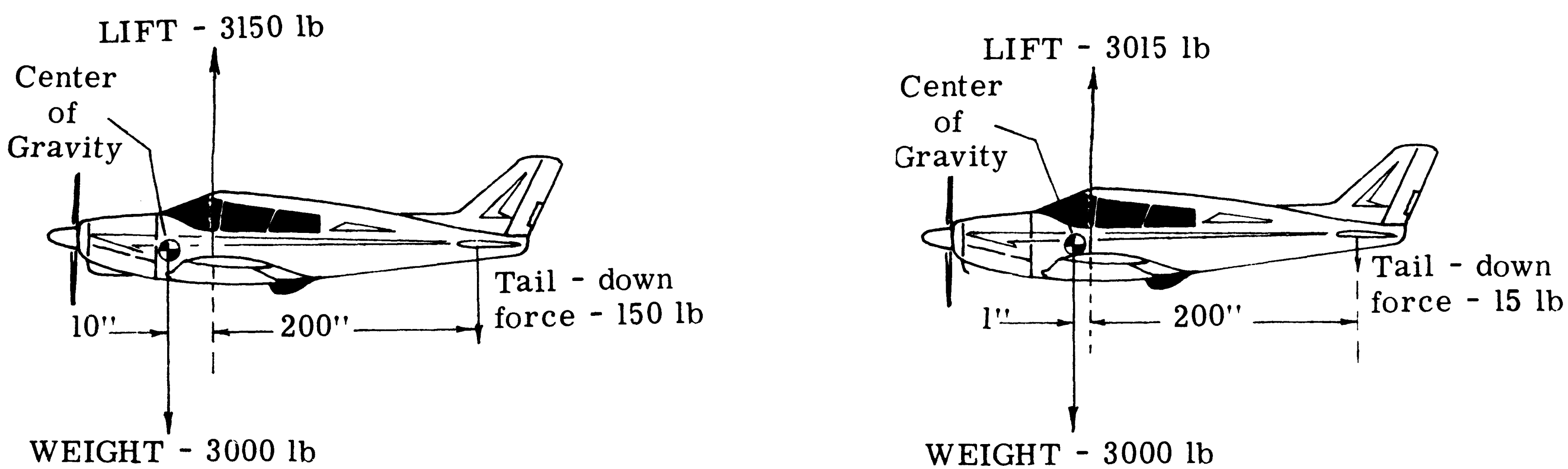


Fig. 1-29. Positive stability.

The pilot's handbook of aeronautical knowledge, Paul E. Illman

Airplane stability.
The tail force.

In this example, a 9” change in the location of the center of gravity changes the required lift by 135 lb. Changes in the location of the center of gravity occur during flight due to for example fuel consumption.



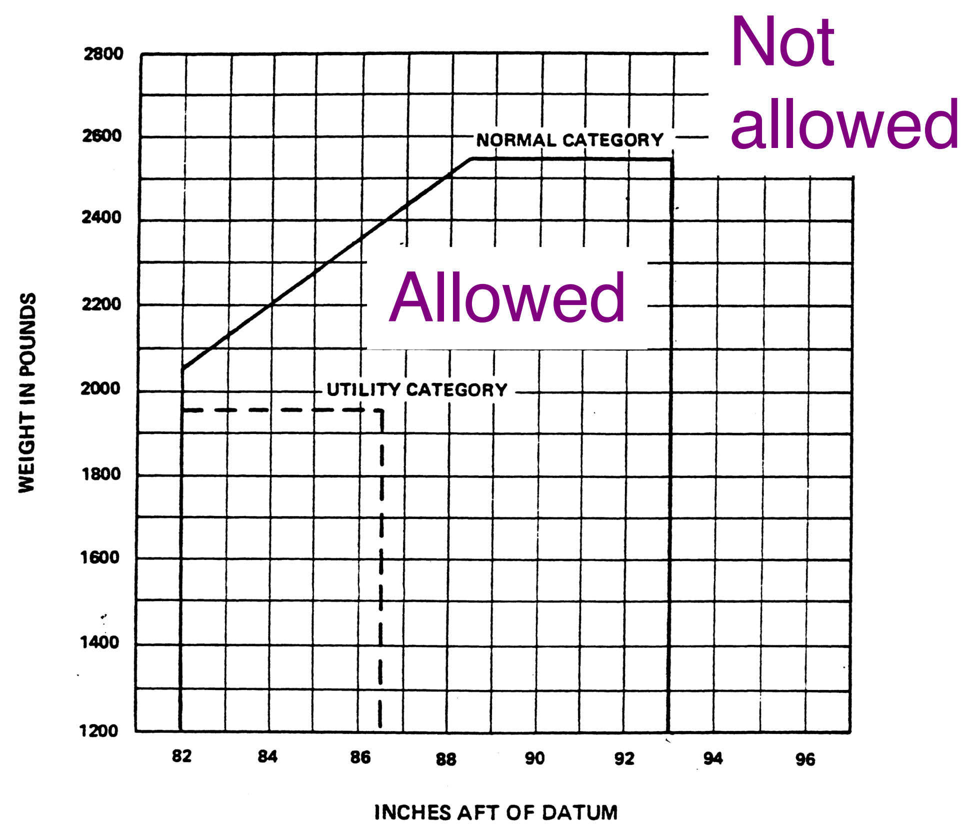
The advanced pilot’s flight manual, William K. Kershner

Airplane stability.
A serious calculation, often ignored.

- Since the location of the center of gravity has a significant impact on airplane stability, it needs to be evaluated before each flight.
- Improper loading might prevent stable operation of the airplane.

Photographer: Radomir Zaric

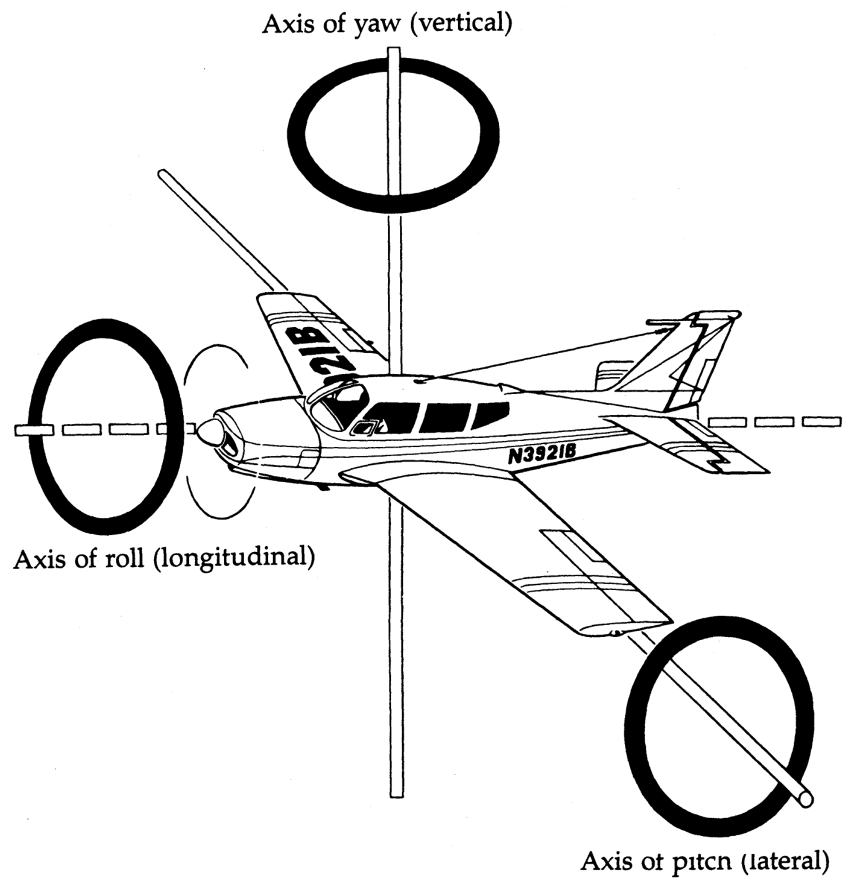
Picture from airliners.net



Weight-and-balance chart for an Archer (pilot operating hand book).

Airplane control.

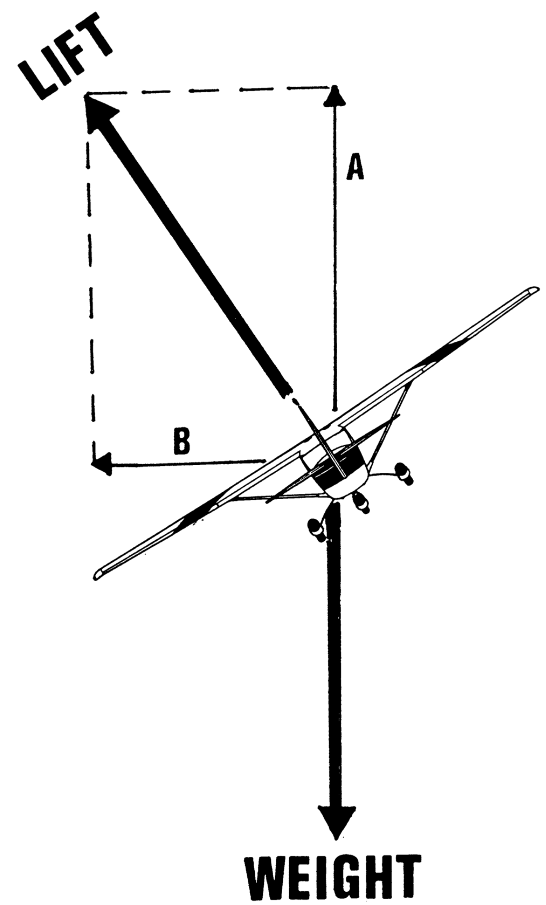
- To control an airplane requires control of its orientation with respect to the following the three axes:
  - Pitch axis: controlled with the elevator.
  - Roll axis: controlled with the ailerons.
  - Yaw axis: controlled with the rudder.
- Most airplane operations require the use of more than one control surface. For example, to turn an airplane requires simultaneous use of the rudder, the elevator, and the ailerons.



The pilot's handbook of aeronautical knowledge, Paul E. Illman

Airplane control.
An example: the constant altitude turn.

- In level flight, the magnitude of the lift is equal to the magnitude of the weight (yes, I have ignored the tail force ….).
- An airplane changes its heading by banking, and the horizontal component of the lift provides the centripetal force required for the turn.
- The vertical component of the lift is now smaller than the weight, and unless the total lift is increased, the airplane will loose altitude.

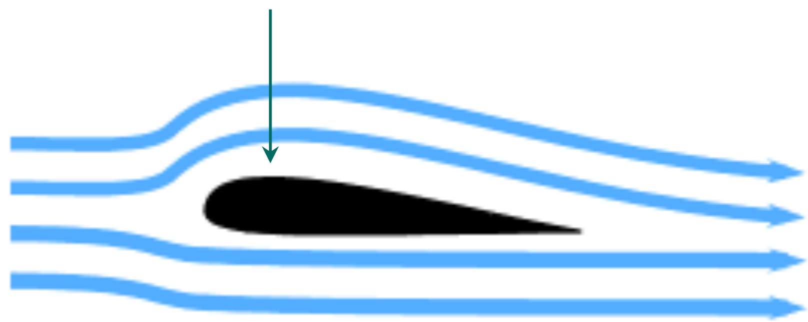


The advanced pilot's flight manual, William K. Kershner

Generating lift. Who needs Bernoulli?

- Most people who claim to understand the generation of lift, will rely on the Bernoulli effect to explain the principle of flight.
- If you are one of them, I am sorry to have to tell you that you do not understand the principle of flight.
- Although the Bernoulli effect has been used for many decades to explain the principle of flight, the Bernoulli effect can only account for a few percent of the lift generated by a wing, and it can not account for phenomena such as inverted flight.

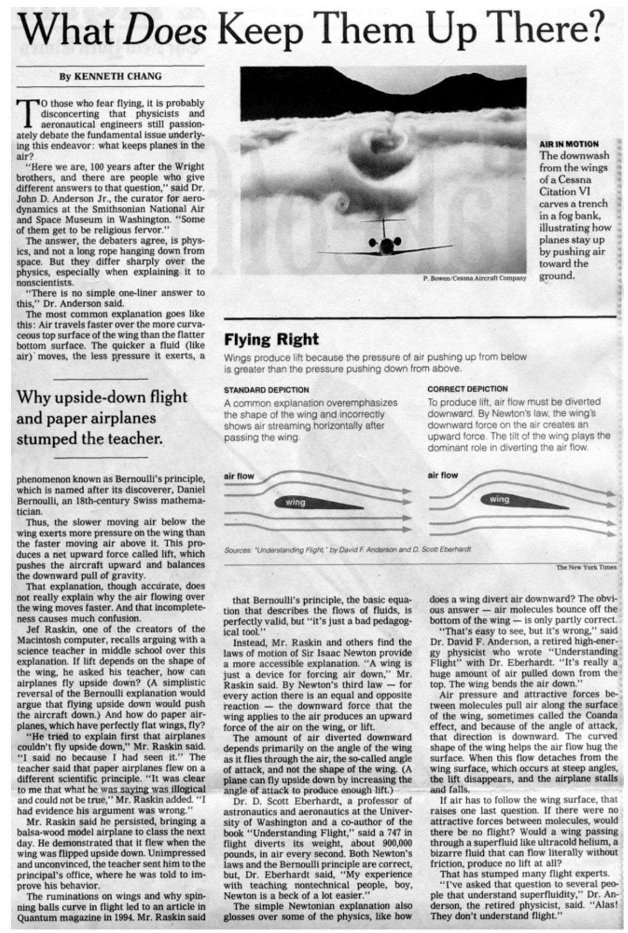
This wing does not generate lift!



http://www.aa.washington.edu/faculty/eberhardt/lift.htm

NY Times, January 2004
100 Year Anniversary of Flight

- What keeps them up there?
  - “it is disconcerting that physicists and aeronautical engineers still passionately debate the fundamental issues”
  - Jef Raskin, one of the creators of the Macintosh, was send to the principal’s office when he argued with his science teacher that the Bernoulli effect could not explain why paper airplane’s fly. According to the science teacher paper airplanes use a different scientific principle to fly.



What *Does* Keep Them Up There?

By KENNETH CHANG

TO those who fear flying, it is probably disconcerting that physicists and aeronautical engineers still passionately debate the fundamental issue underlying this endeavor: what keeps planes in the air?

"Here we are, 100 years after the Wright brothers, and there are people who give different answers to that question," said Dr. John D. Anderson Jr., the curator for aerodynamics at the Smithsonian National Air and Space Museum in Washington. "Some of them get to be religious fervor."

The answer, the debaters agree, is physics, and not a long rope hanging down from space. But they differ sharply over the physics, especially when explaining it to nonscientists.

"There is no simple one-liner answer to this," Dr. Anderson said.

The most common explanation goes like this: Air travels faster over the more curvaceous top surface of the wing than the flatter bottom surface. The quicker a fluid (like air) moves, the less pressure it exerts, a phenomenon known as Bernoulli's principle, which is named after its discoverer, Daniel Bernoulli, an 18th-century Swiss mathematician.

Why upside-down flight and paper airplanes stumped the teacher.

Thus, the slower moving air below the wing exerts more pressure on the wing than the faster moving air above it. This produces a net upward force called lift, which pushes the aircraft upward and balances the downward pull of gravity.

That explanation, though accurate, does not really explain why the air flowing over the wing moves faster. And that incompleteness causes much confusion.

Jef Raskin, one of the creators of the Macintosh computer, recalls arguing with a science teacher in middle school over this explanation. If lift depends on the shape of the wing, he asked his teacher, how can airplanes fly upside down? (A simplistic reversal of the Bernoulli explanation would argue that flying upside down would push the aircraft down.) And how do paper airplanes, which have perfectly flat wings, fly?

"He tried to explain first that airplanes couldn't fly upside down," Mr. Raskin said. "I said no because I had seen it." The teacher said that paper airplanes flew on a different scientific principle. "It was clear to me that what he was saying was illogical and could not be true," Mr. Raskin added. "I had evidence his argument was wrong."

Mr. Raskin said he persisted, bringing a balsa-wood model airplane to class the next day. He demonstrated that it flew when the wing was flipped upside down. Unimpressed and unconvinced, the teacher sent him to the principal's office, where he was told to improve his behavior.

The ruminations on wings and why spinning balls curve in flight led to an article in Quantum magazine in 1994. Mr. Raskin said that Bernoulli's principle, the basic equation that describes the flows of fluids, is perfectly valid, but "it's just a bad pedagogical tool."

Instead, Mr. Raskin and others find the laws of motion of Sir Isaac Newton provide a more accessible explanation. "A wing is just a device for forcing air down," Mr. Raskin said. By Newton's third law — for every action there is an equal and opposite reaction — the downward force that the wing applies to the air produces an upward force of the air on the wing, or lift.

The amount of air diverted downward depends primarily on the angle of the wing as it flies through the air, the so-called angle of attack, and not the shape of the wing. (A plane can fly upside down by increasing the angle of attack to produce enough lift.)

Dr. D. Scott Eberhardt, a professor of astronautics and aeronautics at the University of Washington and a co-author of the book "Understanding Flight," said a 747 in flight diverts its weight, about 900,000 pounds, in air every second. Both Newton's laws and the Bernoulli principle are correct, but, Dr. Eberhardt said, "My experience with teaching nontechnical people, boy, Newton is a heck of a lot easier."

The simple Newtonian explanation also glosses over some of the physics, like how does a wing divert air downward? The obvious answer — air molecules bounce off the bottom of the wing — is only partly correct.

"That's easy to see, but it's wrong," said Dr. David F. Anderson, a retired high-energy physicist who wrote "Understanding Flight" with Dr. Eberhardt. "It's really a huge amount of air pulled down from the top. The wing bends the air down."

Air pressure and attractive forces between molecules pull air along the surface of the wing, sometimes called the Coanda effect, and because of the angle of attack, that direction is downward. The curved shape of the wing helps the air flow hug the surface. When this flow detaches from the wing surface, which occurs at steep angles, the lift disappears, and the airplane stalls and falls.

If air has to follow the wing surface, that raises one last question. If there were no attractive forces between molecules, would there be no flight? Would a wing passing through a superfluid like ultracold helium, a bizarre fluid that can flow literally without friction, produce no lift at all?

That has stumped many flight experts.

"I've asked that question to several people that understand superfluidity," Dr. Anderson, the retired physicist, said. "Alas! They don't understand flight."

P. Bowen/Cessna Aircraft Company

AIR IN MOTION The downwash from the wings of a Cessna Citation VI carves a trench in a fog bank, illustrating how planes stay up by pushing air toward the ground.

Flying Right

Wings produce lift because the pressure of air pushing up from below is greater than the pressure pushing down from above.

STANDARD DEPICTION
A common explanation overemphasizes the shape of the wing and incorrectly shows air streaming horizontally after passing the wing.

CORRECT DEPICTION
To produce lift, air flow must be diverted downward. By Newton's law, the wing's downward force on the air creates an upward force. The tilt of the wing plays the dominant role in diverting the air flow.

Sources: "Understanding Flight," by David F. Anderson and D. Scott Eberhardt

The New York Times

Generating lift.
Who needs Bernoulli?

- In order for a wing to generate lift (producing an upward force) it must force the air down.
- The vertical component of the momentum associated with the downwash, must balanced by the vertical component associated with the lift generated by the wing.
- Thus, unless the air is forced downwards, the wing will not generate lift.

This wing does not generate lift!

This wing does generate lift!

http://www.aa.washington.edu/faculty/eberhardt/lift.htm

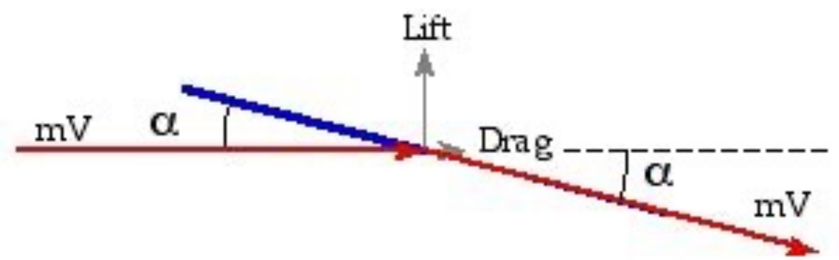
Department of Physics and Astronomy, University of Rochester

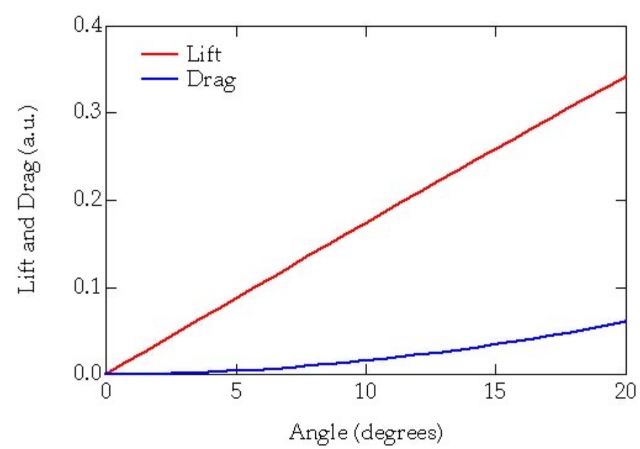
Generating lift. Who needs Bernoulli?

- The lift of a wing is generated by the downwards deflection of air.
- Consider an elastic collision between an air molecule of mass m and velocity V. The change in the vertical component of the momentum of the wing as a result of this single collision is equal to:

$$p_{lift} = mV\sin(\alpha)$$

- The lift generated will increase if V increases, if the air density increases, and/or if the angle of attack increases.





Generating lift. An example.

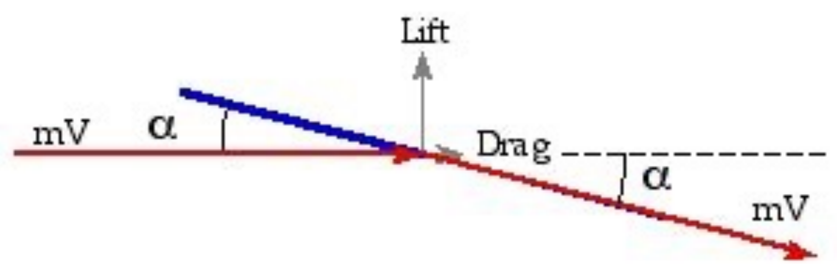
- Consider a Piper Warrior. This plane has a maximum weight of 2450 lb, and the required lift on takeoff is about 11,000 N.
- On takeoff, the airspeed is 60 knots = 31 m/s. Assume that on takeoff the angle of attack is 5°.
- To generate this lift requires that

$$Lift = \frac{dp_{lift}}{dt} = \frac{dm}{dt} V \sin(\alpha)$$

- This requires that

$$\frac{dm}{dt} = \frac{Lift}{V \sin(\alpha)} = 4100 \, \frac{\text{kg}}{\text{s}}$$

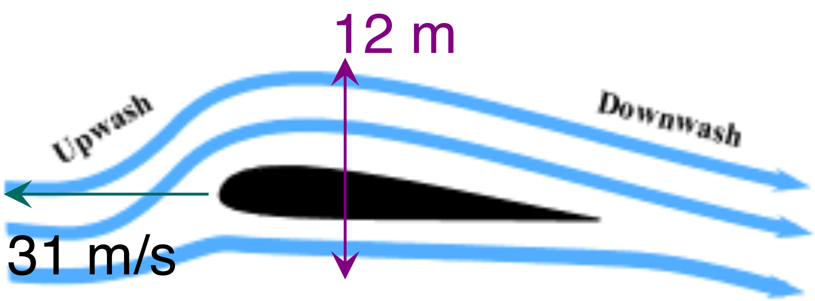
www.newpiper.com



Generating lift.
Certainly not a surface phenomenon.

- The Warrior has a wing span of 35.0 ft (10.7 m) and a wing surface area of 170 ft^2 (15.8 m^2).
- The density of air at sea level is about 1 kg/m^3.
- In order to generate an air deflection rate of 4100 kg/s, the height of the layer of air involved must be about 12 m.
- Clearly, the generation of lift is not a surface phenomenon.

The Rochester Flying Club



http://www.aa.washington.edu/faculty/eberhardt/lift.htm

Generating lift.
What does it take to lift a Boeing 737?

- At 6.02 am on 3/22/03, CO 282 took of from San Antonio (TX). For this particular flight, the weight of the plane was 106,000 pounds and the rotation speed was 131 knots (numbers provided by Mark d'Arpino, the first officer on this flight).
- For this flight:
  - dm/dt = 80,000 kg/s (80,000 m^3/s)
  - Note: (dm/dt)/M = 1.7 for this 737 compared to 3.7 for the Warrior.
  - The wingspan of this 737 is 94.9 ft, which indicates that a 41 m thick layer of air is involved in the generation of lift.

Photographer: B. Leibowitz

Photographer: M. Abbott

Pictures from airliners.net

Generating lift.

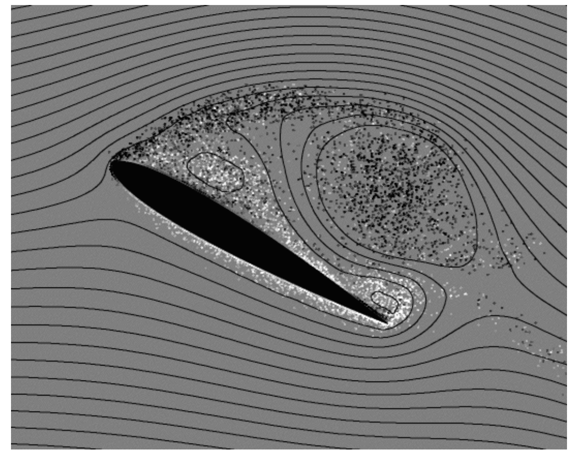
- The effect of the downwash of the wing of this citation, flying low over a fog layer, is clearly visible.

- More details about the generation of lift can be found in "*Understanding Flight*" by Anderson and Eberhardt. Note: Anderson is a retired high-energy physicists.

Photograph by Paul Bowen, courtesy of Cessna Aircraft, Co.

Generating lift.
Certainly not a surface phenomenon.

- The lift generated by the wing increases with increasing angle-of-attack.
- The increase in the lift with an increasing angle continues until the angle-of-attack exceeds a certain critical value, above which the air above the wing becomes turbulent, at which point the wing loses half of its lift.
- At this angle, the airplane stalls.

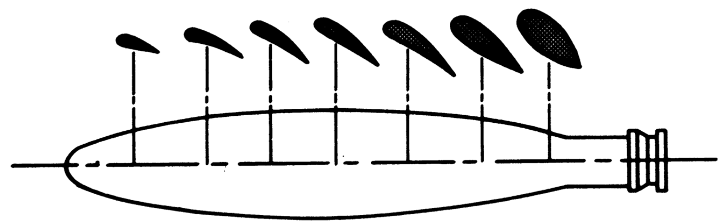


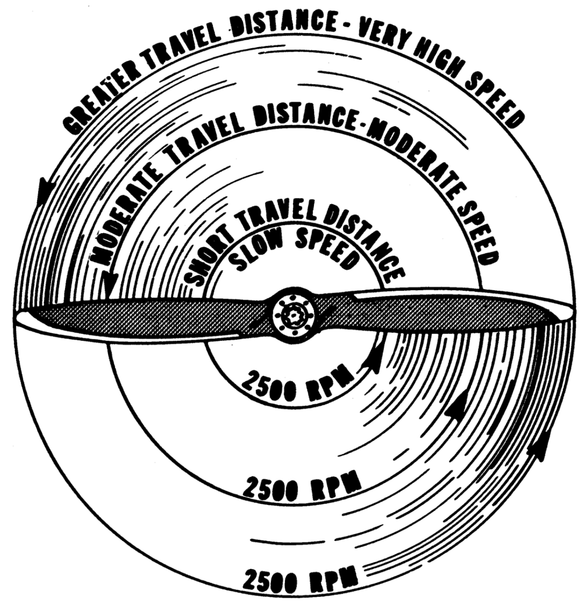
S-C Wang
FSU

Cirrus
Aircraft
Company

Generating thrust.
The physics of the propeller.

- The generation of thrust with a propeller relies on the same mechanism that allows the wing to produce lift.
- The thrust generated by a segment of the propeller relies on the angle of attack and the airspeed (which is a function of the engine rpm and the distance from the center of the propeller).
- Since the airspeed increases with increasing radius, the angle of attack must be decreasing in order to minimize the structural forces inside the propeller.





The pilot's handbook of aeronautical knowledge, Paul E. Illman

Generating thrust. The physics of the propeller.

- Consider a typical propeller installed on a Piper Warrior:
  - Diameter d = 74”
  - Maximum engine rpm = 2700
  - The velocity of the tip of the propeller is equal to

$$v_{tip} = 1.88\pi \frac{2700}{60} = 266 \frac{\mathrm{m}}{\mathrm{s}}$$

  - This velocity is close to the speed of sound in air, which is

$$v = 331 + 0.6T \frac{m}{s}$$

where T is the temperature in Celcius.

The Rochester Flying Club

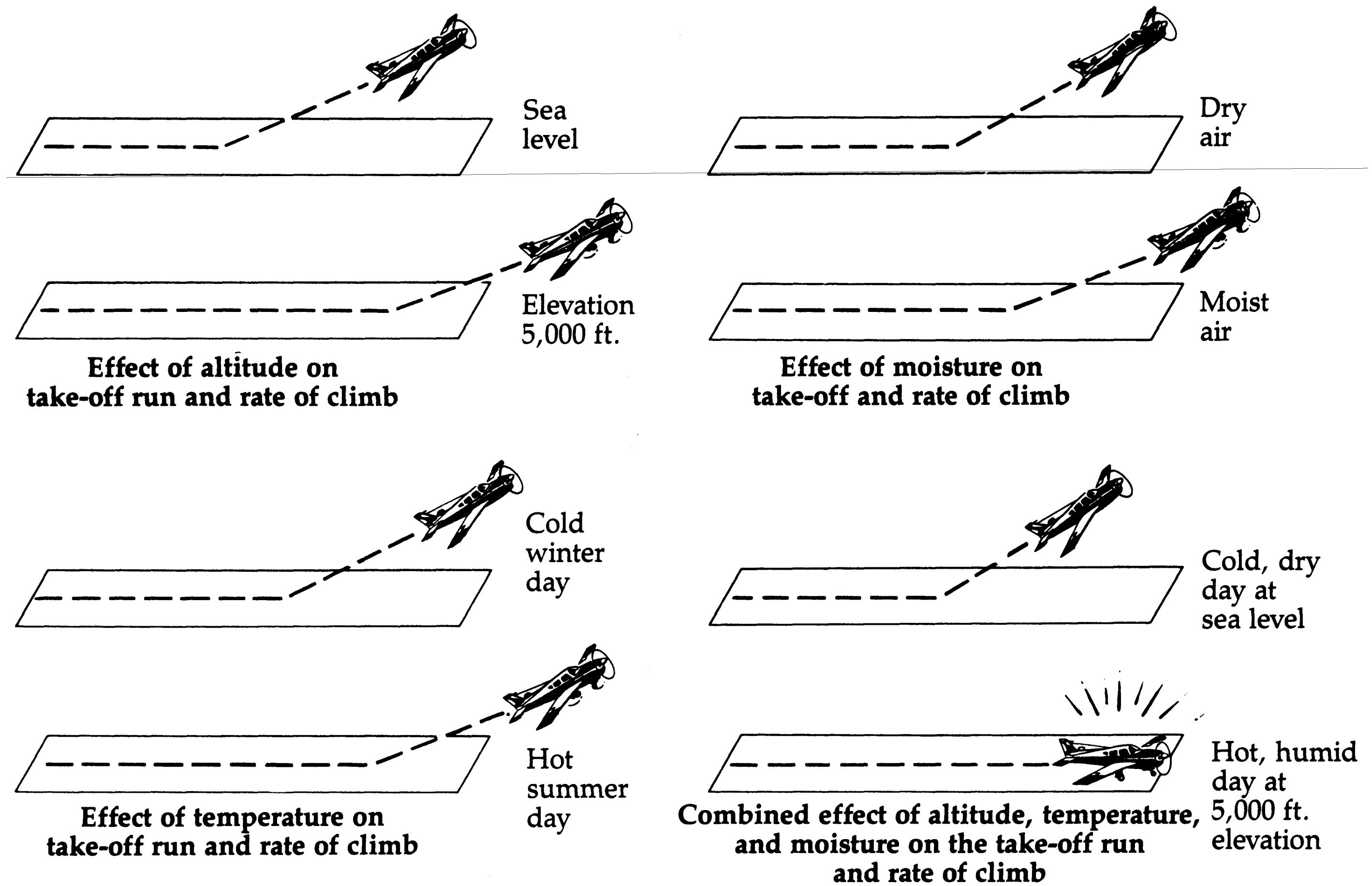
Take off.

- The airplane will take off when the lift generated by the wings exceeds the weight of the plane.

- An increase in weight impacts the required runway length:
  - The increase in weight requires an increase in lift: lift is proportional to velocity.
  - The increase in mass decreases the acceleration of the airplane (since the thrust provided by the engine(s) remains constant).

The advanced pilot's flight manual, William K. Kershner

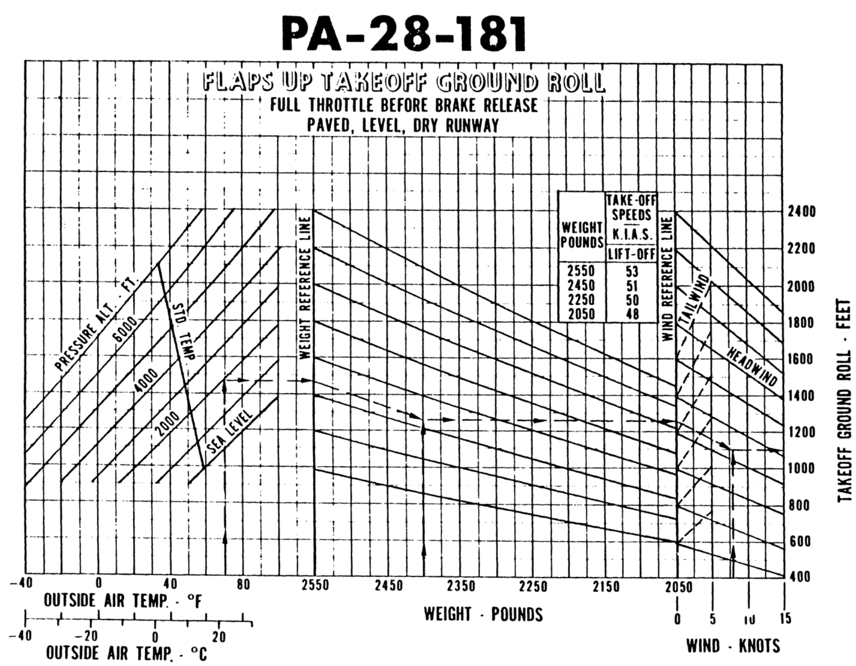
Many factors influence the length of the runway required to take off.



The pilot's handbook of aeronautical knowledge, Paul E. Illman

Many factors influence the length of the runway required to take off.

- A PA-28-181 will take off when the airspeed reaches 60 knots.
- A 15 knots head wind, requires a ground speed of 45 knots.
- A 15 knots tail wind, requires a ground speed of 75 knots.
- Assuming a constant acceleration a, the ground roll x required to achieve a velocity v is equal to $v^2/2a$.
- The difference in ground roll for the PA-282-181 in the example above is $x_{75}/x_{45} = 75^2/45^2 = 2.8$.

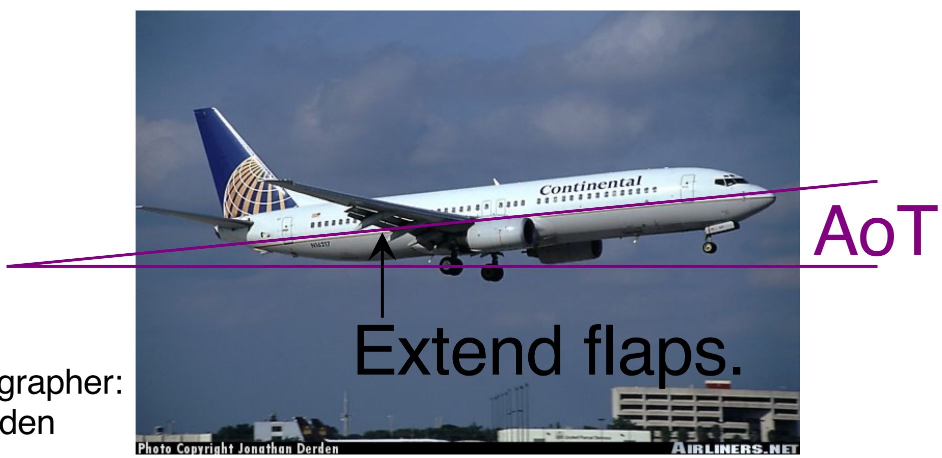


Takeoff chart for an Archer (pilot operating hand book)

Landing.

- Key issues during landing:
  - Slow the airplane down: increase the angle of attack.
  - Extend wing flaps: produce extra lift by increasing the angle of deflection of the “bottom” air.
  - Align wheels with the direction of motion.

Runway 10
KSYR



Photographer:
J. Derden

Picture from airliners.net

A Boeing 747 on final approach for 26L in Gatwick

The Physics of the North Pole. An interesting effect before getting serious again.

- The numbering of runways reflects the magnetic direction of their centerline.
- For example, to approach runway 10 in KSYR your heading will be somewhere between 95 degrees and 105 degrees.
- But ……. the magnetic North pole of the earth is moving, and as a result the orientation of runways are changing as function of time.
- KSYR recently had to renumber one of their main runways due to this effect.

Runway 10
KSYR

Instrument Flying

Joe d'Arpino, World's best flight instructor.

Instrument Flying.
You trust your gut, you die!

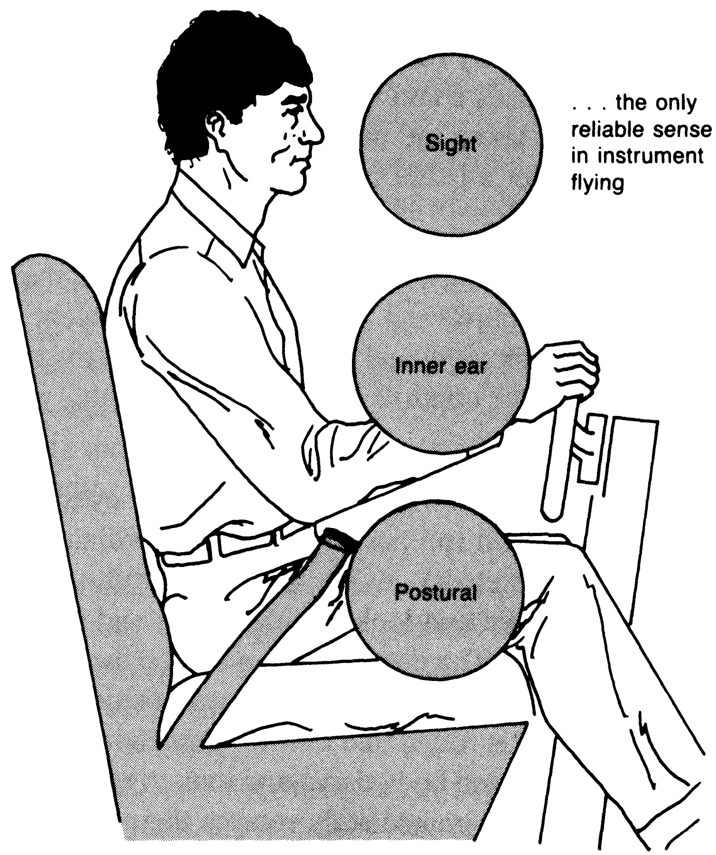
- In instrument conditions, the pilot does not have any outside visibility.
- Without being able to view the horizon or the ground, the pilot has to rely to his/her instruments to determine the attitude of the airplane.
- The pilot is also exposed to various forces which often give the impression that the airplane is in a different attitude.
- Who is right? The instruments or the pilot?

Sporty's: Volume 1, Instrument Flying Fundamentals.

Frank L. H. Wolfs
Department of Physics and Astronomy, University of Rochester

Instrument Flying.
You trust your gut, you die!

- There are three senses that are commonly used to maintain equilibrium and orientation:
  - Sight: location of horizon and ground, and instrument indications.
  - Inner ear: senses up/down motion, turning motion, and changes in orientation.
  - Postural: the “seat-of-the-pants” feeling, which senses up/down motion.



Senses Used for Maintaining Equilibrium and Orientation

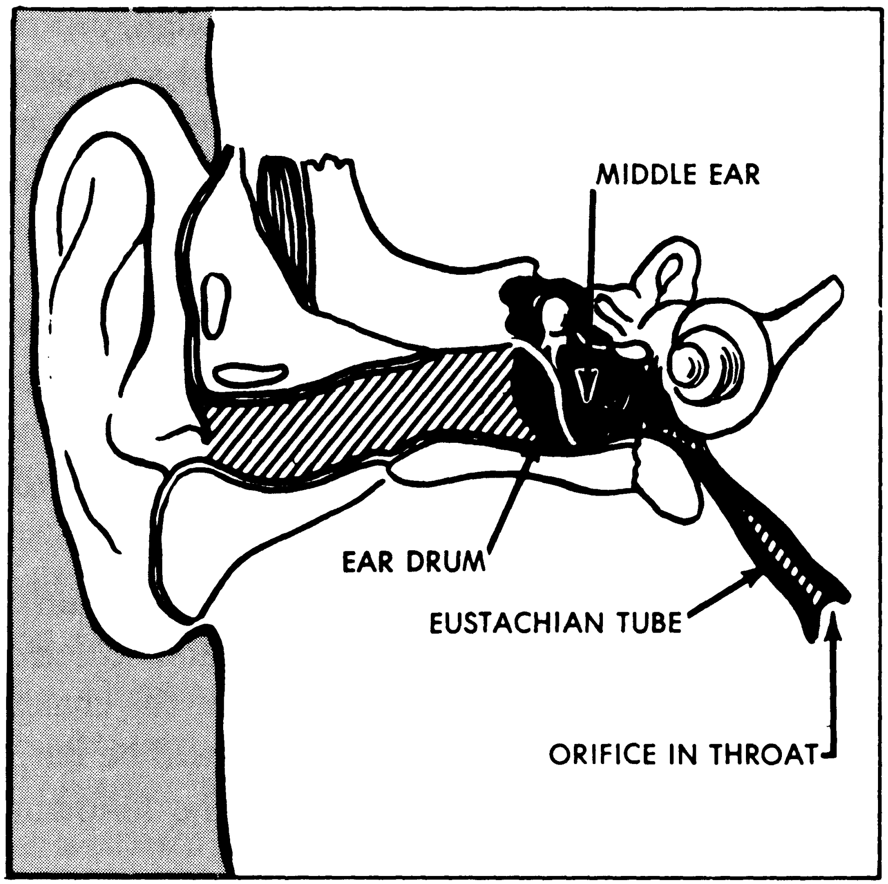
J.R. Williams, The Art of Instrument Flying

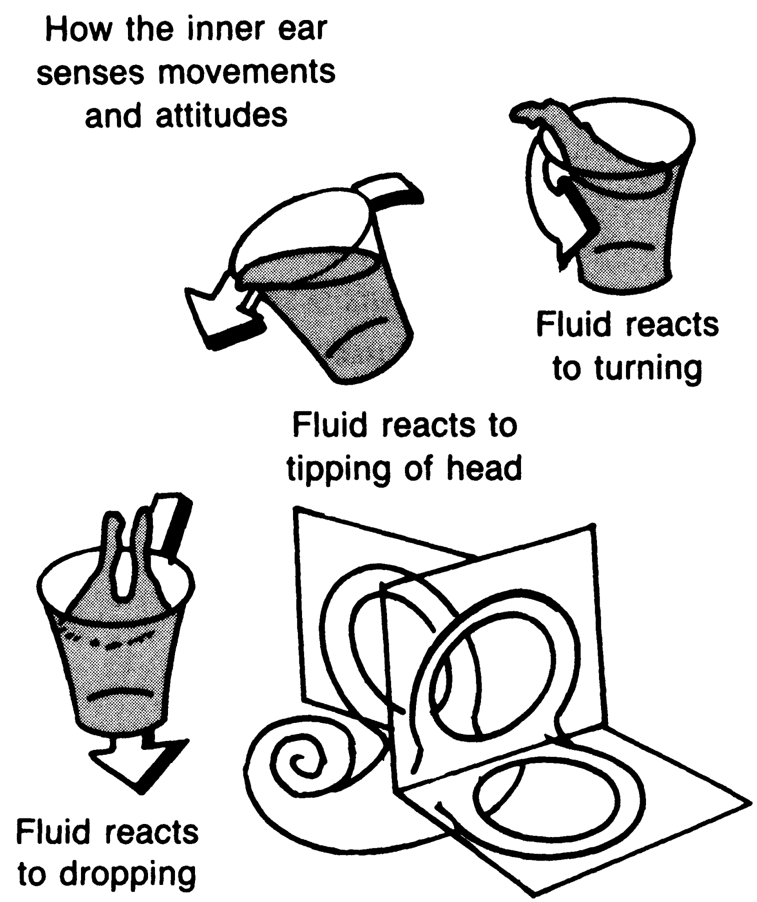
Instrument Flying.
Sight.

- In most circumstances, sight dominates the senses generated by the inner ear and the "seat-of-your-pants" (e.g. the attitude can be determined immediately on the basis of the orientation of the nose of the airplane with respect to the visible horizon).
- When an airplane enters instrument meteorological conditions, the horizon is no longer visible, and the senses generated by the inner ear and the "seat-of-your-pants" can start to dominate.

Sporty's: Volume 1, Instrument Flying Fundamentals.

Instrument Flying.
The inner ear.

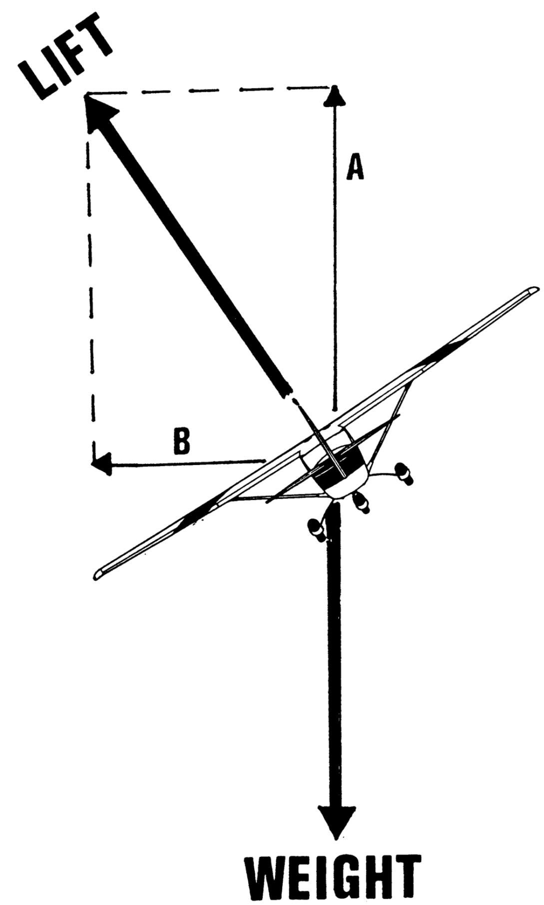




J.R. Williams, The Art of Instrument Flying

Instrument Flying.
The seat-of-your-pants force.

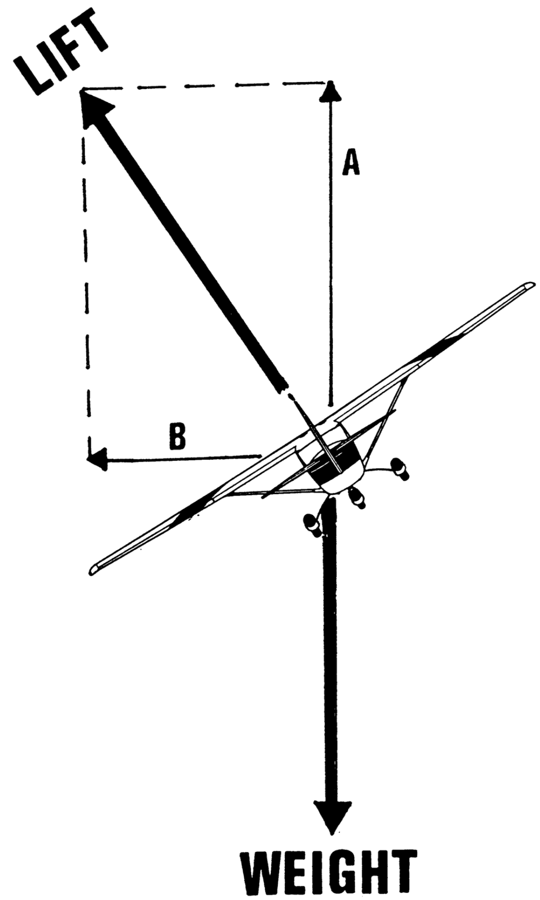
- The pilot experiences a number of different forces during a flight:
  - Examples:
    - During take-off, the pilot is pressed into his/her seat. An increase in this "seat-of-your-pants" force is frequently associated with an increase in altitude.
    - During the initiation of a descent, the "seat-of-your-pants" force decreases, and this decrease is frequently associated with a decrease in altitude.
    - However, these "seat-of-the-pants" forces can also be generated during other phases of flight when the altitude is constant.



The advanced pilot's flight manual, William K. Kershner

Instrument Flying.
The seat-of-your-pants force.

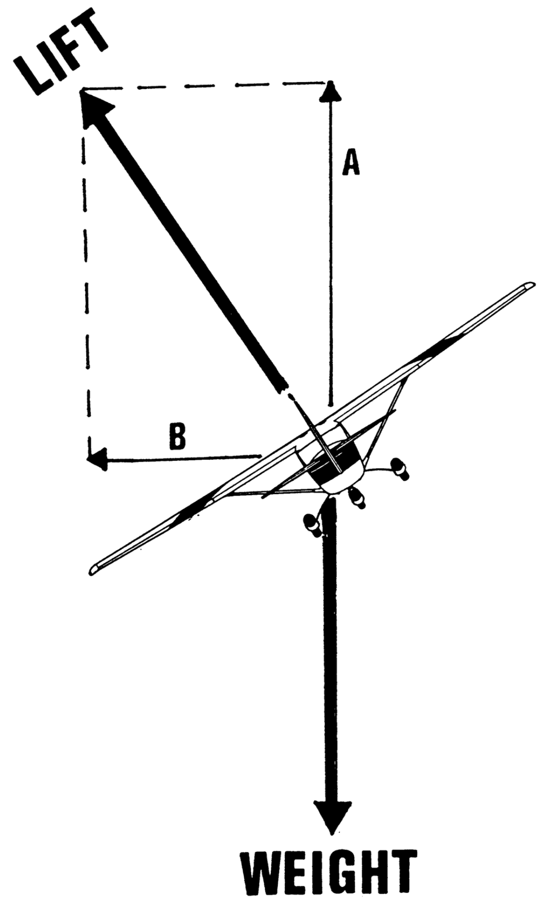
- Let us consider the constant altitude turn:
  - To maintain altitude in this turn, the lift must be increased.
  - The "seat-of-the-pants" force felt by the pilot increases.
  - If the pilot trusts his/her instruments, the airplane will maintain its altitude.



The advanced pilot's flight manual, William K. Kershner

Instrument Flying.
The seat-of-your-pants force.

- If the pilot trusts his/her "seat-of-the-pants" feeling (continued):
  - The pilot will "feel" the plane going up, and pushes the yoke forward.
  - The airplane will loose altitude and increase its speed.
  - The increase in speed results in an increase in the lift.
  - Assuming the the pilot maintains a standard-rate turn, the horizontal component of the lift will be proportional to its speed and will thus increase.
  - The pilot will "feel" the plane going up even further, and pushes the yoke further forward.
  - ....
  - **The graveyard spiral.**



The advanced pilot's flight manual, William K. Kershner

Instrument Flying.
The gyro instruments.

www.newpiper.com

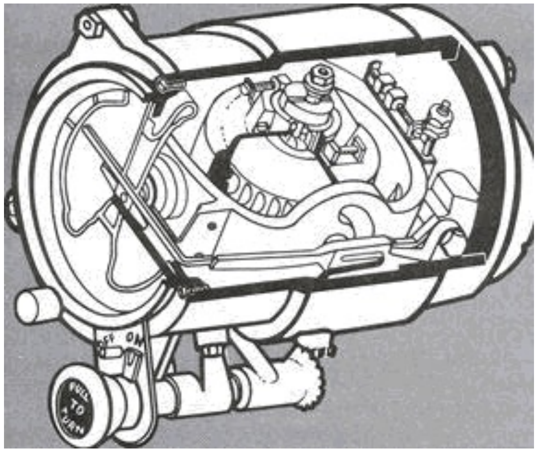
- Although the instrument panel varies greatly between different planes, the following six basic instruments can be found in almost every plane:
  - Airspeed indicator
  - Attitude indicator
  - Altitude indicator
  - Vertical speed indicator
  - Directional indicator
  - Turn indicator
- Three of these six instruments rely on gyroscopes for their operation.

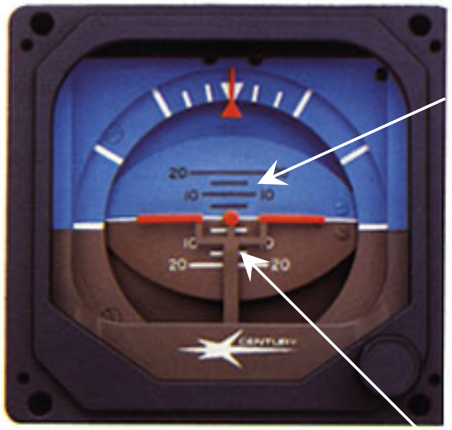
Photographer: B. Wang

KLM 747 @ 31,000' over Hudson Bay.

Instrument Flying.
The gyro instruments.

- The gyroscopes in aviation instruments are either vacuum or electrical driven.
- The gyroscope will maintain its orientation in space, independent of the orientation of the airplane.
- In the attitude indicator, the gyro axis points in the vertical direction.
- The artificial horizon is attached to the gyro axis, and it will thus remain aligned with the real horizon.





Instrument Flying.
The gyro instruments.

- By comparing the position of the airplane with respect to the position of the artificial horizon, the pilot can judge the attitude of the airplane (in this example, the airplane is nose high, and in a left turn).
- The directional gyro is used to determine the heading of the airplane, and is stable in turbulent conditions and in turns.
- The turn indicator is used to make constant rate turns (2 minutes for 360 degrees).

The Physics of Flying
Some Final Remarks

- Many of our lecture demonstrations have important ties to aviation, although quite often most of us are not aware the important ties.

- Some of the most obvious ones are:
  - The gyroscope: does not only provide the basis for our most important flight instruments, but also are the basic components of most autopilots.
  - The jumping ring: a neat demonstration in Physics 122/142, but the operation of electric fuel pumps, used as backups for the mechanical pumps, rely on this effect for their operation.
  - The simple radio: a nice demo to illustrate the properties of radio emission. The relation between the signal size and antenna orientation forms the basis of the ADF. It allows you to use WHAM 1180 to fly home from as far away as Washington DC.

The Physics of Flying.
Summary.

- Although the world of aviation has changed a lot in the last 100 years, the physics of flying has not changed.
- There is a lot of physics in flying, more than many people realize.
- If you remember one thing from this talk, please remember that the lift generated by a wing relies on the downward deflection of air, and that the Bernoulli effect does not explain why planes fly.

From: A 747 pilots-eye-view.

The end of Physics 141 Lectures!

Good luck with all your finals.

See you on Monday 12/16 in

Hoyt at 4 pm!

Physics 141.
Now you are almost free (and so am I)!

Frank L. H. Wolfs

Department of Physics and Astronomy, University of Rochester