THE WRIGHT BROTHERS, BERNOULLI, AND A SURPRISE FROM UPPER EAST TENNESSEE

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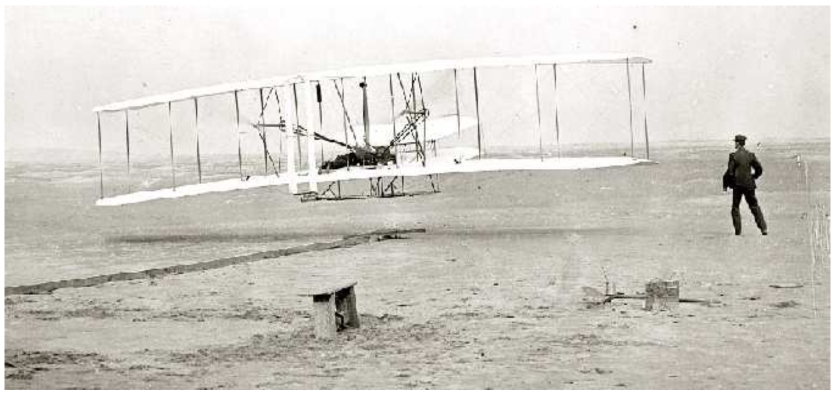
ABSTRACT

In commemoration of the centennial of the Wright Brothers' first powered flight (December 17, 1903), this presentation will give an introduction to Bernoulli's Principle and its application in the theory of airfoils to explain the lift of a wing. Bernoulli's Principle will be derived from the "Work-Energy Theorem" and illustrated with hands-on exhibits.

During the presentation, a **surprise will be revealed** concerning Upper East Tennessee's involvement in the Wright Brothers' flight!!!

INTRODUCTION

On December 17, 1903 Orville and Wilbur Wright successfully attained controlled, powered manned flight.

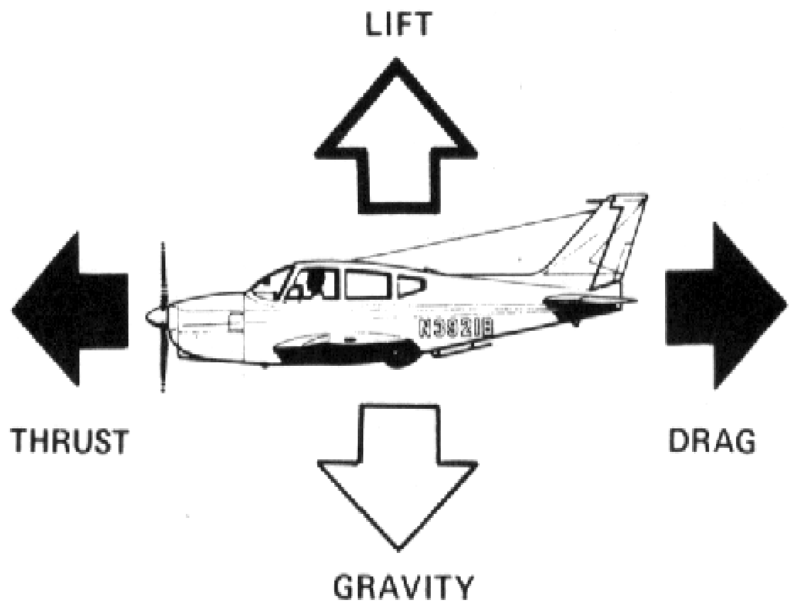


This photograph shows Orville Wright at the controls of the 1903 Wright Flyer (which is now on display in the Smithsonian Air and Space Museum). This famous picture was taken by John Daniels of the Kill Devil Life Saving Station at 10:35 a.m. December 17, 1903. This first flight was 12 seconds, in which the plane traveled 120 feet and reached a maximum altitude of 10 feet. This first flight was witnessed by Daniels, Wilbur Wright (in the photo), and four other local residents of Kitty Hawk, North Carolina.

The purpose of this presentation is to discuss *how* an airplane overcomes the pull of gravity to stay in the air, and *who* first scientifically described the relevant principles explaining this force.

THE FORCES ON AN AIRPLANE

There are four forces which act on an airplane in flight: thrust, drag, weight, and lift.

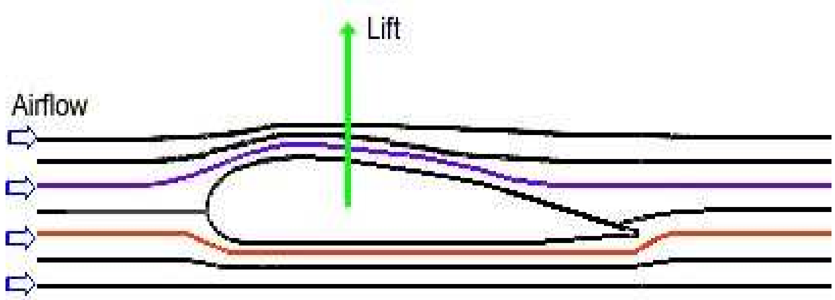


From *Aeroscience*, Second Edition, T. Misenhimer, p. 25.

The thrust is provided by the engine of the plane and the drag is produced by air resistance. The weight is due, of course, to gravity. Lift is produced by the wing... but how? To explain this, we must explore Bernoulli's Principle.

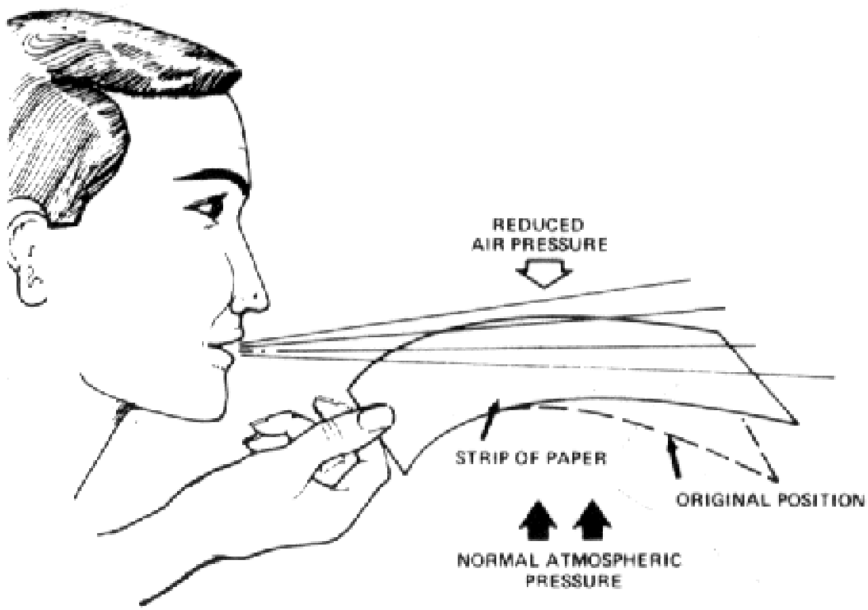
BERNOULLI'S PRINCIPLE — AN INTRODUCTION AND ILLUSTRATIONS

Note. Simply put, Bernoulli's Principle says that a fast moving fluid (such as air) exerts less pressure than the same fluid when moving slowly. This observation alone explains how an airplane generates lift. The wing is shaped in such a way that the air above the wing must move faster than the air below the wing:



Therefore the force on top of the wing is less than the force on the bottom of the wing. Hence, the *resultant* force is a net force in the upward direction called *lift*.

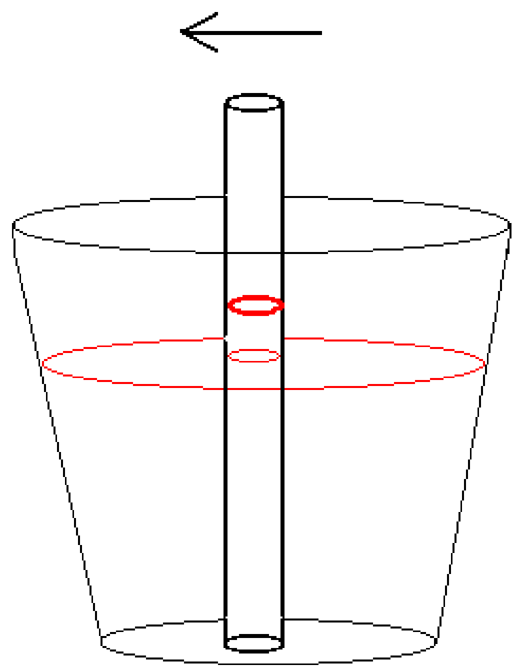
Example. This can be illustrated simply by blowing over the surface of a piece of paper. If we hold the paper up and blow horizontally over the top of it, it rises a little:



From *Aeroscience*, Second Edition, T. Misenhimer, p. 25.

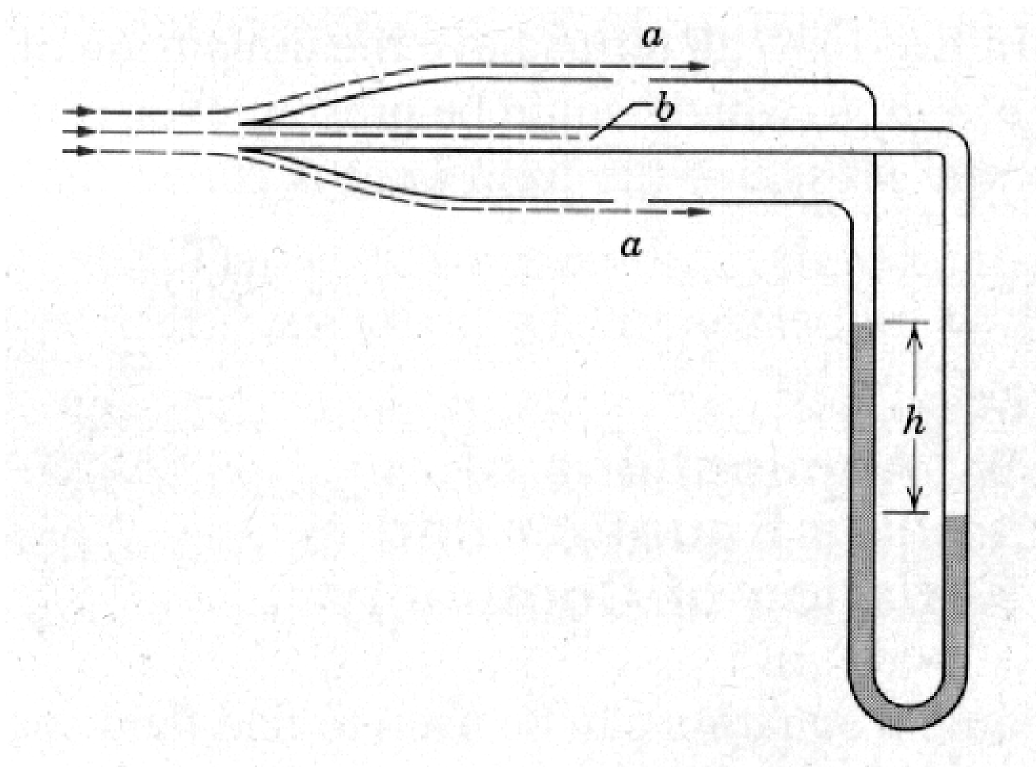
Demonstration

Example. We can also illustrate Bernoulli's Principle with a straw and cup of liquid. When the straw is sitting in the liquid, the level in the straw is the same as the level in the cup. However, if we blow over the top of the straw, the level of the fluid in the straw rises since there is less pressure in the straw due to the air moving over its top:



Demonstration

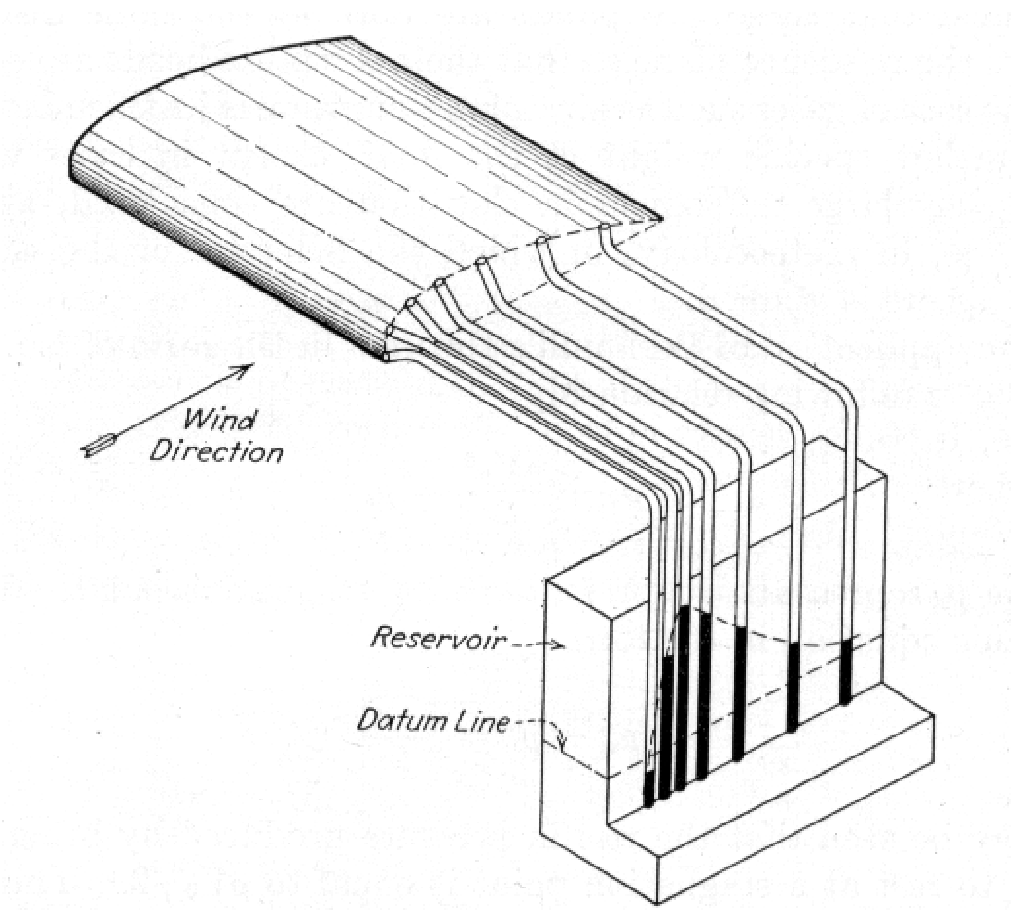
Example. This is the idea behind the *Pitot tube*:



From *Fundamentals of Physics*, Second Edition, D. Halliday and R. Resnick, p. 283.

In fact, the Pitot tube is used as air-speed indicators and can be found in airplanes.

Note. We can also use the straw idea to measure the pressure distribution over the surface of a wing:

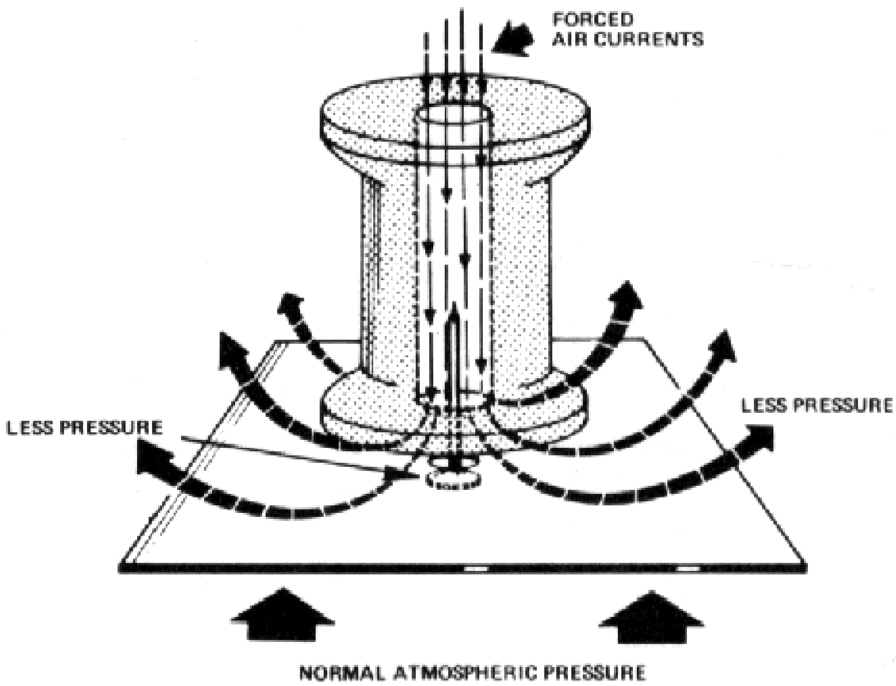


From *Fluid Mechanics*, R. Dodge and M. Thompson, p. 88.

Example. As another illustration of Bernoulli's Principle, consider two flat (cardboard) planes adjacent to each other, the top one with a small hole in it and the bottom one with a pin through it which passes through the hole in the top one.

The top plane is not attached to the pin — the pin will act to stabilize the lower plane. We attach a tube to the upper plane over the hole.

Now if we hold the apparatus up by the tube and do not support the lower plane, then the lower plane simply falls down under its own weight. However, if we blow vigorously into the tube, then the lower plane will become "stuck" to the upper plane and will not fall. This is because, by blowing into the tube, we are creating a fast moving stream of air on the top of the lower plane. The air under the lower plane is stationary. Therefore there is a net upward force produced by the air on the lower plane. This upward force balances the downward force produced by the weight of the lower plane and the pin:



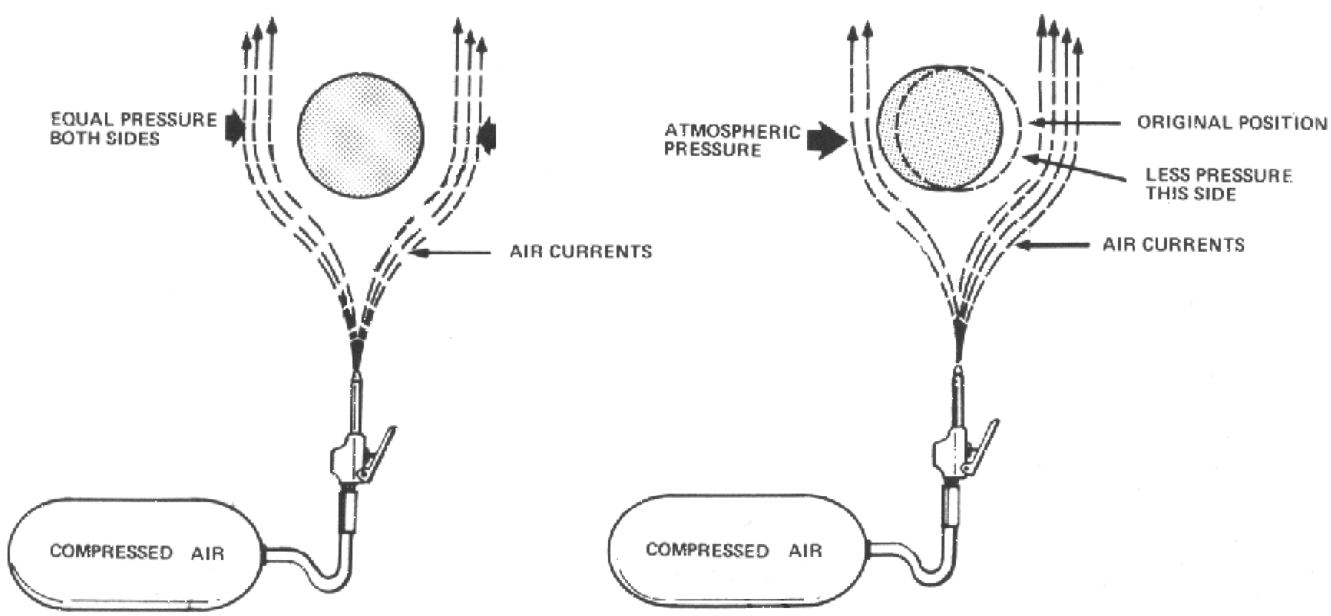
From *Aeroscience*, Second Edition, T. Misenhimer, p. 12.

Demonstration

Example. If you have been through a tornado warning, you may have heard it suggested that you open the windows of your house. This is to equalize the pressure between the fast moving air outside and the stationary air inside the house. Without this equalizing, there exists a possibility that the windows might explode outwards.

A similar, though less dramatic, situation exists when you are driving in a car. With a slight opening in the window, you can see that the smoke from a cigarette will escape through the window, since it is pulled toward the air moving past the car which produces a region of less pressure.

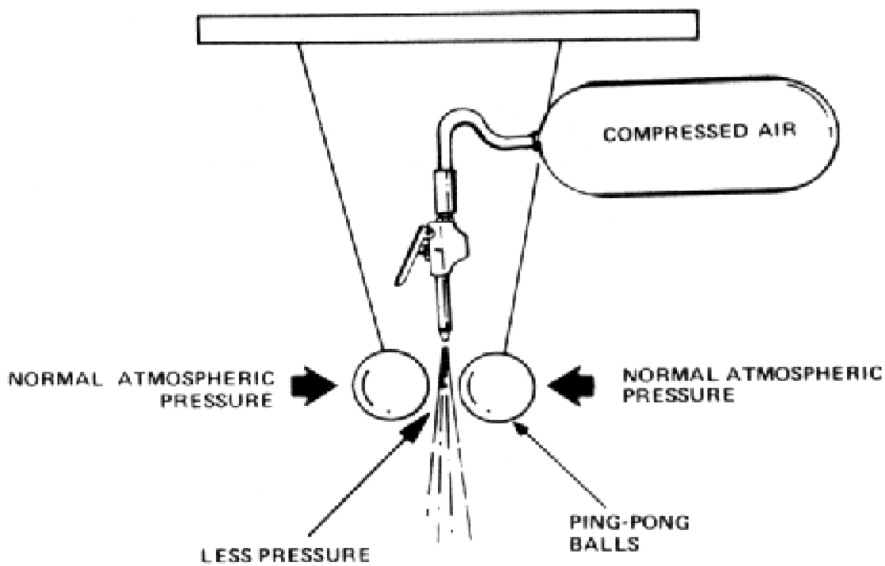
Example. We can use a column of air to support a ping pong ball. It is the pressure from the air that keeps the ball up, but it is Bernoulli's Principle that keeps the ball centered. If the ball wanders from the center of the column of air (which it will do due to the slightest turbulence), then this creates a difference in the speed at which the air passes around the ball. This difference in speed in turn produces a difference in pressure which pushes the ball back to the center of the column of air.



From *Aeroscience*, Second Edition, T. Misenhimer, p. 15.

Demonstration

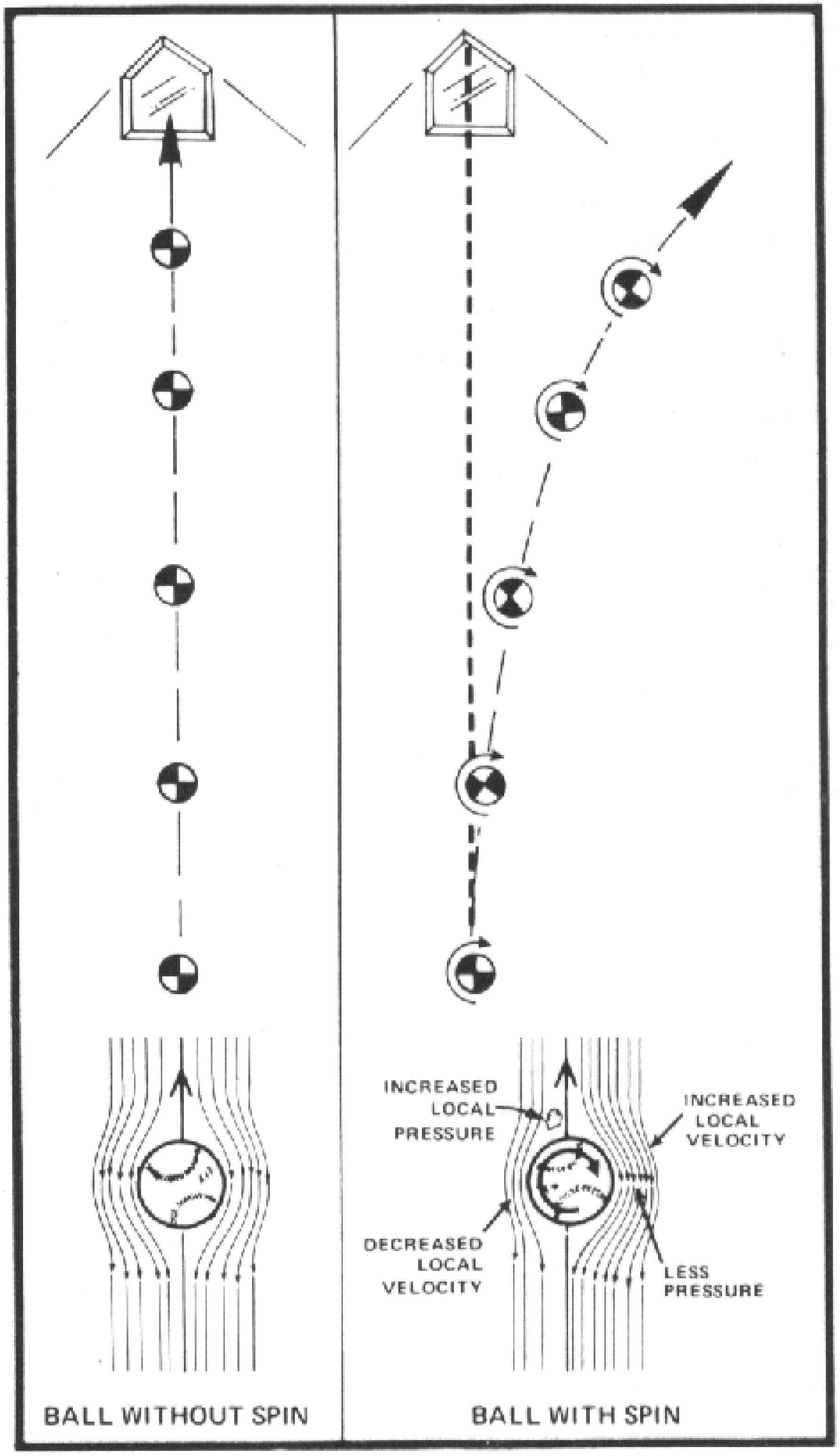
Example. We can pass a column of air between two suspended ping pong balls and they will be drawn together. This is called the "Venturi tube" concept.



From *Aeroscience*, Second Edition, T. Misenhimer, p. 13.

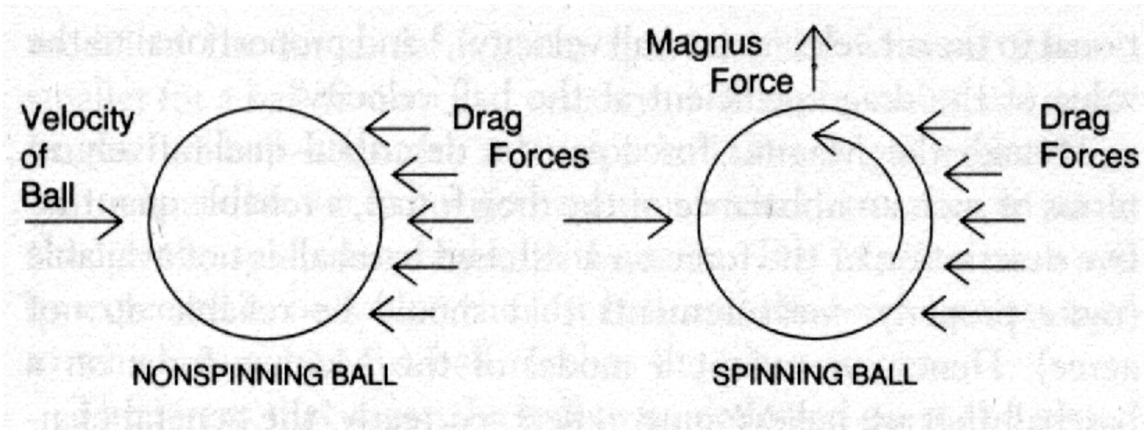
Demonstration

Example. A curveball is the result of Bernoulli's Principle.



From *Aeroscience*, Second Edition, T. Misenhimer, p. 12.

The force acting on the ball which causes it to curve is called the "Magnus force."



From *The Physics of Baseball*, Second Edition, R. Adair, p. 13.

Note. Now, let's make a more technical exploration of Bernoulli's Principle. To do so, we must first introduce the Work-Energy Theorem.

THE WORK-ENERGY THEOREM — A "CALCULUS FREE" DERIVATION

Note. We use the notation:

- t for *time* (in seconds)
- x for *position* (as a function of time) measured in meters
- v for *velocity* (as a function of time) measured in meters/second
- v_i for *initial velocity* (in meters/second)
- a for *acceleration* (in meters/second^2)

Recall. If a particle has an initial velocity v_i and undergoes a constant acceleration a for a time t, then the particle's final velocity at time t is

$$v_f = v_i + at. \tag{1}$$

Over this time period, the *average velocity* is

$$\overline{v} = \frac{v_i + v_f}{2}$$

and its displacement (i.e. its change in position from an initial position $x_i = 0$) is

$$x_f = \overline{v}t = \frac{v_i + v_f}{2}t. \tag{2}$$

Now, from (1)

$$t = \frac{v_f - v_i}{a} \tag{3}$$

and substituting (3) into (2) gives

$$x_f = \overline{v}t = \frac{v_i + v_f}{2}\left(\frac{v_f - v_i}{a}\right) = \frac{v_f^2 - v_i^2}{2a},$$

or upon rearranging

$$v_f^2 = v_i^2 + 2ax_f. \tag{4}$$

Recall. The *kinetic energy* of a mass m (kg) with velocity v (m/second) is $K = \frac{1}{2}mv^2$ (kg m^2/second^2). Also, recall that Newton's Second Law of Motion says that a force F (Newtons) applied to a mass m (kg) results in an acceleration of a (m/second^2) where $F = ma$. The *work* W (Nm) done by a force F (N) acting over a distance x (m) is (by definition) $W = Fx$.

Theorem. The Work-Energy Theorem
The work W (Nm) done on a particle by a force F (N) is equal to the change in kinetic energy K (kg m^2/second^2) of the particle: $W = \Delta K = K_f - K_i$.

Proof. Equation (4) relates position, velocities, and acceleration:

$$v_f = v_i^2 + 2ax_f. \tag{4}$$

Solving for x_f (the distance over which the particle moved) we have

$$x_f = \frac{1}{2a}(v_f^2 - v_i^2). \tag{5}$$

Multiplying the left hand side of (5) by F and the right hand side of (5) by ma (recall that $F = ma$ by Newton's Second Law) gives

$$Fx_f = \frac{m}{2}(v_f^2 - v_i^2) = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2. \tag{6}$$

Since $W = Fx$ and $K = \frac{1}{2}mv^2$, we have from (6) that $W = K_f - K_i$.
$\blacksquare$

THE WORK-ENERGY THEOREM — A CALCULUS BASED DERIVATION

Recall. The *kinetic energy* of a mass m with velocity v is $K = \frac{1}{2}mv^2$. Newton's Second Law of Motion says that a force F applied to a mass m results in an acceleration a where $F = ma$.

- Acceleration a is the rate of change of velocity v with respect to time, so

$$\begin{aligned} a &= \frac{dv}{dt} \text{ by definition} \\ &= \frac{dv}{dx}\frac{dx}{dt} \text{ by the Chain Rule} \\ &= \frac{dv}{dx}v \text{ since } v = \frac{dx}{dt} \text{ where } x \text{ is position.} \end{aligned}$$

- *Work* is force times distance. If force F is a function of position x, say force is $F(x)$, then the work done by $F(x)$ when x varies from x_i to x_f is $W = \displaystyle\int_{x_i}^{x_f} F(x)\,dx$, as seen in Calculus 2.

Theorem. The Work-Energy Theorem.

The work W done on a particle by a force F is equal to the change in kinetic energy K of the particle: $W = \Delta K = K_f - K_i$.

Proof. We have

$$
\begin{aligned}
W &= \int_{x_i}^{x_f} F(x)\,dx \text{ by definition} \\
&= \int_{x_i}^{x_f} ma\,dx \text{ by Newton's Second Law} \\
&= \int_{x_i}^{x_f} m\left(v\frac{dv}{dx}\right)\,dx \text{ since } a = v\frac{dv}{dx} \\
&= \int_{v_i}^{v_f} mu\,du \text{ using the substitution } u = v(x) \text{ and so} \\
&\qquad \frac{du}{dx} = \frac{dv}{dx} \text{ or, in differentials } du = \frac{dv}{dx}dx \text{ and} \\
&\qquad \text{when } x = x_i, u = v(x_i) = v_i \\
&\qquad \text{when } x = x_f, u = v(x_f) = v_f \\
&= \frac{1}{2}mu^2\Big|_{v_i}^{v_f} = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2 \equiv K_f - K_i = \Delta K.
\end{aligned}
$$

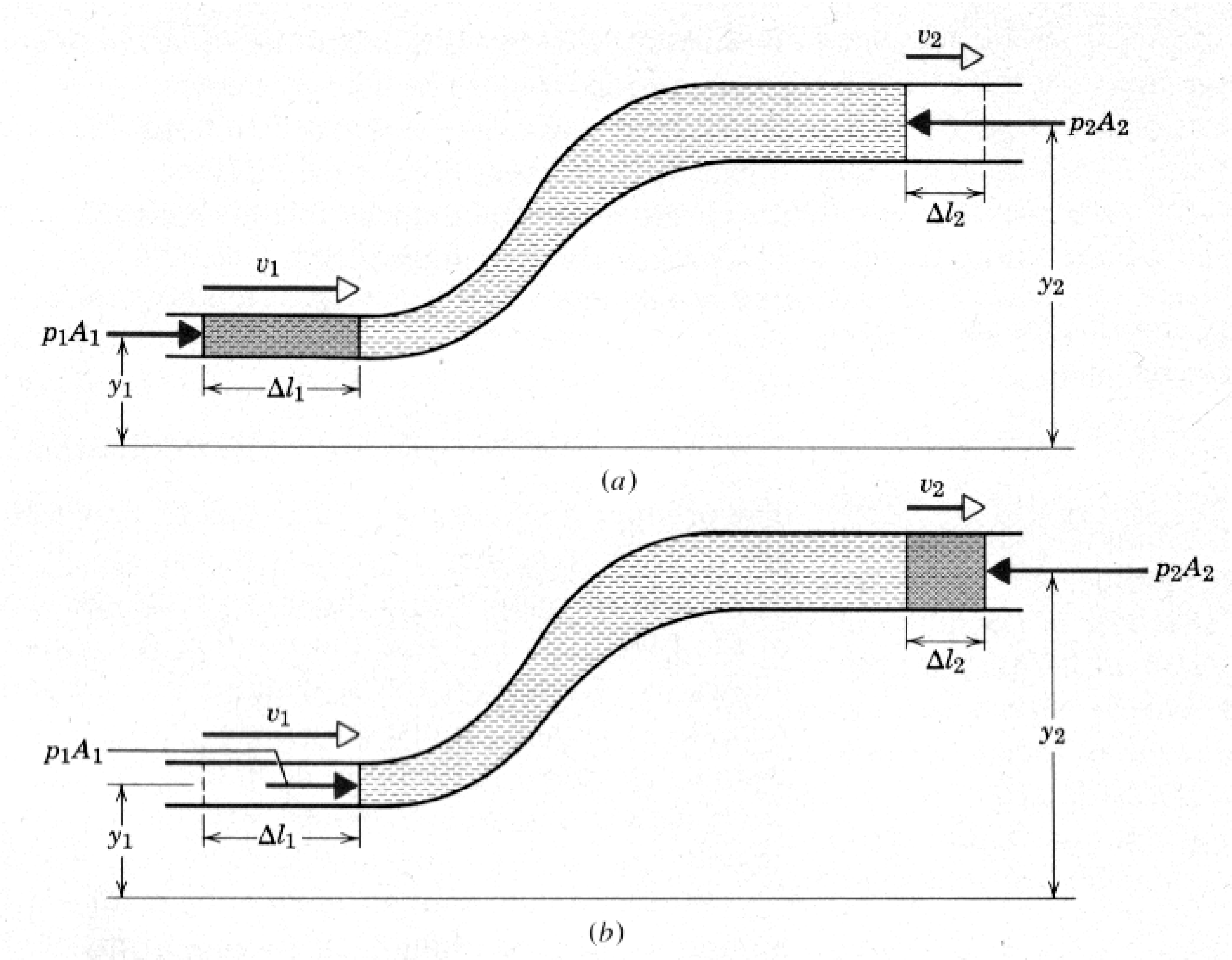
(This proof is from *Fundamentals of Physics*, Second Edition, D. Halliday and R. Resnick, p. 88.) ∎

BERNOULLI'S PRINCIPLE — A DERIVATION

Note. We now use the Work-Energy Theorem to derive Bernoulli's Principle. The fact that we can do this, indicates that Bernoulli's Principle was not really something fundamentally new to physics when introduced by Daniel Bernoulli in 1738, but is actually embedded in Newtonian mechanics.

Daniel Bernoulli (from the "Heroes of Horology" website).

We consider a nonviscous (i.e. not "sticky" — frictionless), steady (i.e. in equilibrium), incompressible fluid flow. Suppose the fluid flows through a pipeline as shown:



From *Fundamentals of Physics*, Second Edition, D. Halliday and R. Resnick, p. 280.

The shaded portions indicate a "slice" of fluid moving through the pipeline.

Theorem. Bernoulli's Principle.

A fluid of density ρ and velocity v moving through the structure above exerts a pressure p satisfying:

$$p + \frac{1}{2}\rho v^2 + \rho g y = \text{ constant}$$

where y is a measurement of height from some standard position.

Proof. The *forces* acting on the system which do work are:

1. the force on the left end $p_1 A_1$ (recall that force is pressure times area),

2. the force on the right end $p_2 A_2$, and

3. the force of gravity.

The *work* done by these forces is (respectively)

1. $p_1 A_1 \Delta l_1$,

2. $-p_2 A_2 \Delta l_2$ (the direction of motion is opposite to the direction of the force $p_2 A_2$), and

3. $-mg(y_2 - y_1)$ (again, the direction of motion is opposite to the direction of the force of gravity g).

Therefore, the total work done is

$$W = p_1 A_1 \Delta l_1 - p_2 A_2 \Delta l_2 - mg(y_2 - y_1).$$

The volume of the shaded slice of fluid does not change (the fluid is incompressible), so $A_1 \Delta l_1 = A_2 \Delta l_2$. If the mass of the slice is m and the density of the fluid is ρ, then (volume time density equals mass):

$$\rho A_1 \Delta l_1 = \rho A_2 \Delta l_2 = m,$$

or

$$A_1 \Delta l_1 = A_2 \Delta l_2 = \frac{m}{\rho}.$$

So the work is

$$\begin{aligned} W &= p_1 \frac{m}{\rho} - p_2 \frac{m}{\rho} - mg(y_2 - y_1) \\ &= (p_1 - p_2)\frac{m}{\rho} - mg(y_2 - y_1). \end{aligned}$$

The change in kinetic energy of the slice is

$$\Delta K = \frac{1}{2} m v_2^2 - \frac{1}{2} m v_1^2.$$

We know from the Work-Energy Theorem that $W = \Delta K$, so

$$W = (p_1 - p_2)\frac{m}{\rho} - mg(y_2 - y_1) = \frac{1}{2} m v_2^2 - \frac{1}{2} m v_1^2.$$

Rearranging with subscripts of 1 on the left and subscripts of 2 on the right:

$$p_1 \frac{m}{\rho} + \frac{1}{2} m v_1^2 + mgy_1 = p_2 \frac{m}{\rho} + \frac{1}{2} m v_2^2 + mgy_2.$$

Since the subscripts indicate any position along the pipe, we see that the quantity

$$p\frac{m}{\rho} + \frac{1}{2} m v^2 + mgy$$

remains unchanged as the slice moves through the pipeline. That is,

$$p\frac{m}{\rho} + \frac{1}{2}mv^2 + mgy = \text{constant}_1.$$

Multiplying through by $\dfrac{\rho}{m}$ we have

$$p + \frac{1}{2}\rho v^2 + \rho gy = \text{ constant.}$$

This is Bernoulli's Equation. ∎

Note. If the fluid is at rest and $v_1 = v_2 = 0$, then from above we have

$$p_1 + \rho g y_1 = p_2 + \rho g y_2$$

or $(p_2 - p_1) = -\rho g(y_2 - y_1)$. This means that changes in pressure are proportional to changes in vertical distance (as stated in Calculus 2, pressure is proportional to depth). The constant quantity $p + \rho gy$ is called the *static pressure* of the fluid. The other term in Bernoulli's Equation, $\frac{1}{2}\rho v^2$ is called the *dynamic pressure* of the fluid.

Note. If we set $y = 0$ and simply consider the relationship between pressure p and velocity v, we see that

$$p + \frac{1}{2}\rho v^2 = \text{ constant.}$$

Therefore, if v is large, p must be small; if v is small, then p must be large. This is **exactly** what we said earlier: a fast moving fluid (v large) exerts less pressure (p small) than the same fluid when moving slowly (v small and p large)!!!

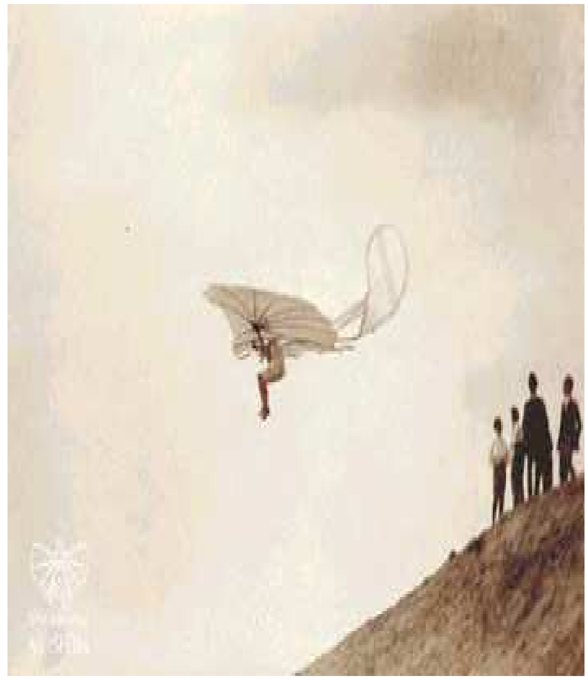
A LITTLE WRIGHT BROTHERS HISTORY

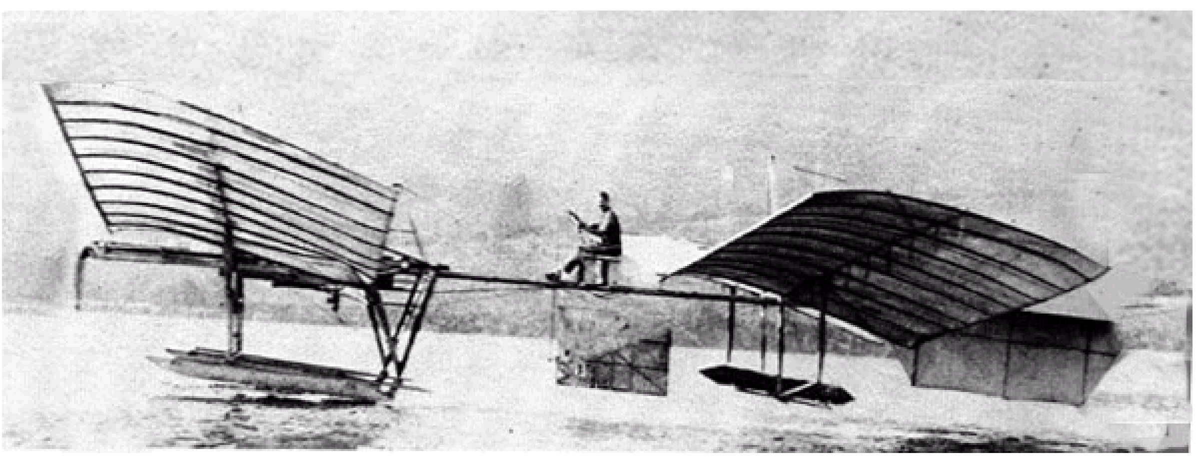
Orville and Wilbur Wright (from Dayton Metro Library)

The Wright Brothers were interested in flight from childhood. Inspired by a small flying toy given to them by their father, they tried to build a larger version, with little success. In May 1899, Wilbur Wright wrote to the Smithsonian Institute to request copies of publications dealing with heavier than air flight. He received copies of works by aviation pioneers Otto Lilienthal, S. Langley, and Octave Chanute.

Otto Lilienthal, 1896

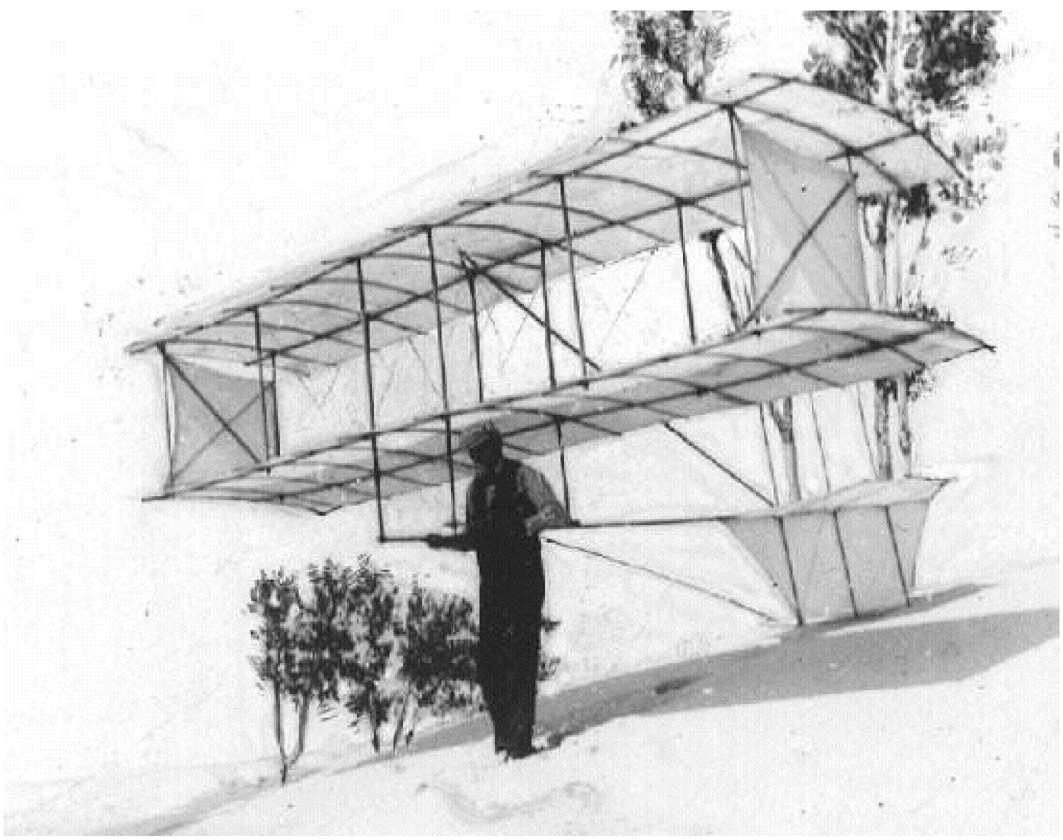


Lilienthal's glider in 1893.



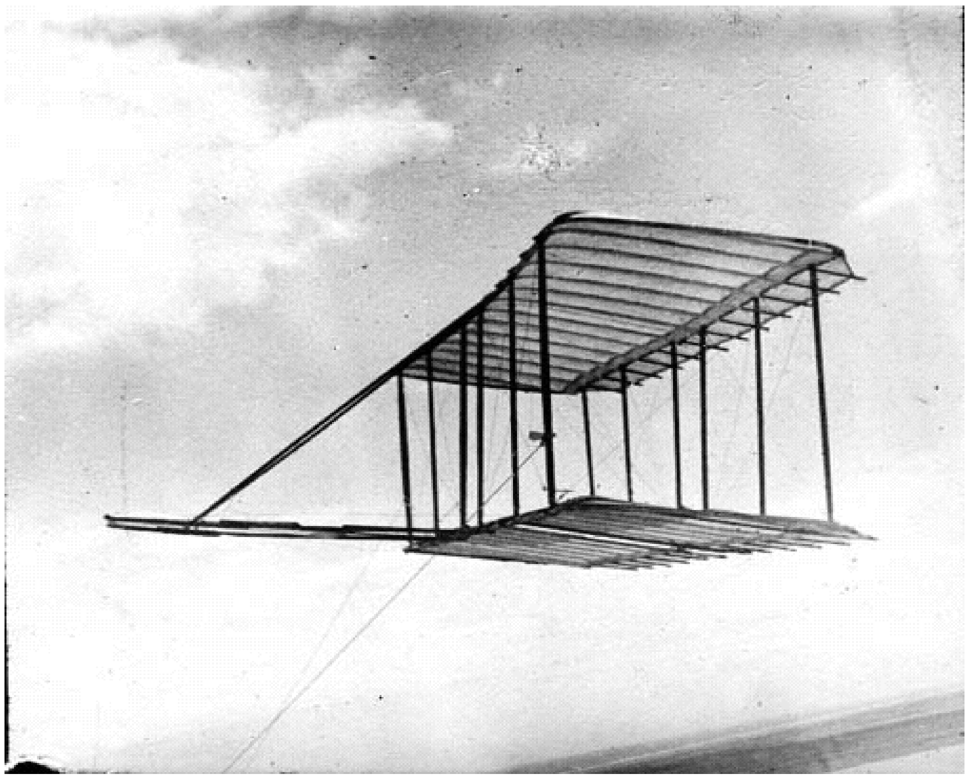
Langley in his "Aerodrome"

Octave Chanute



Octave Chanute with his 1896 glider.

In July 1899, Wilbur started experiments with gliders, flying them as kites. In September 1900, Orville and Wilbur went to Kitty Hawk, North Carolina. There they flew a glider both as a kite and with a man aboard.

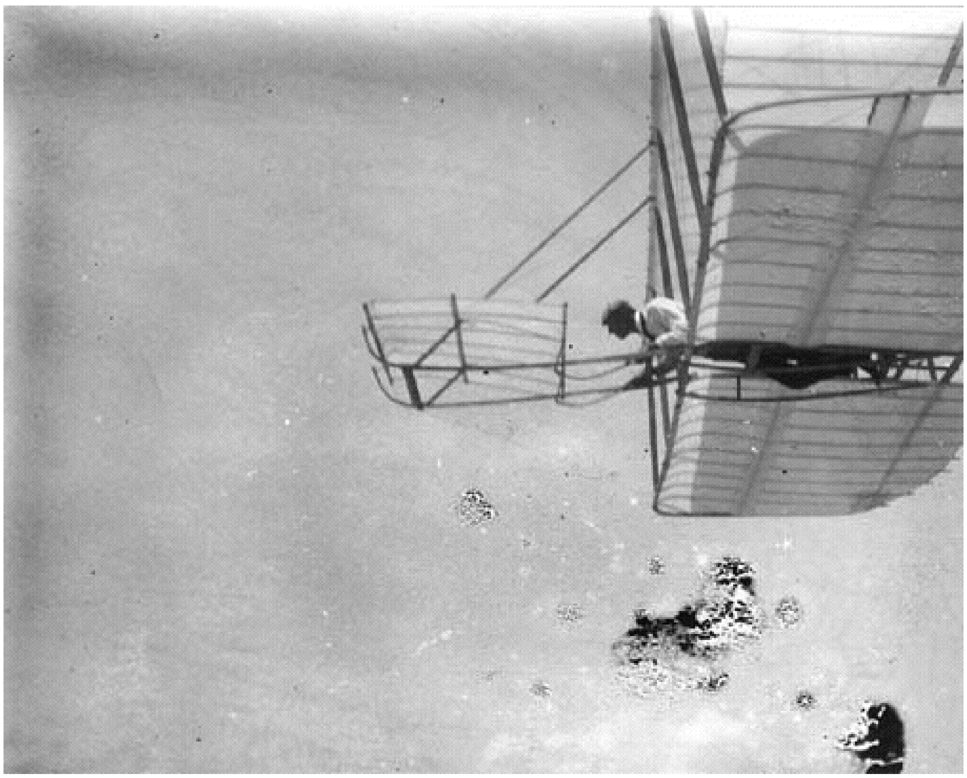


The 1900 glider (Library of Congress photo 1B2).

They had some success in the control and maneuvering of the glider, but the lift it generated was disappointing (the Wright Brothers would later find errors in lift tables published by Otto Lilienthal and produce correct tables themselves). The Wrights returned to Dayton, Ohio for the winter.

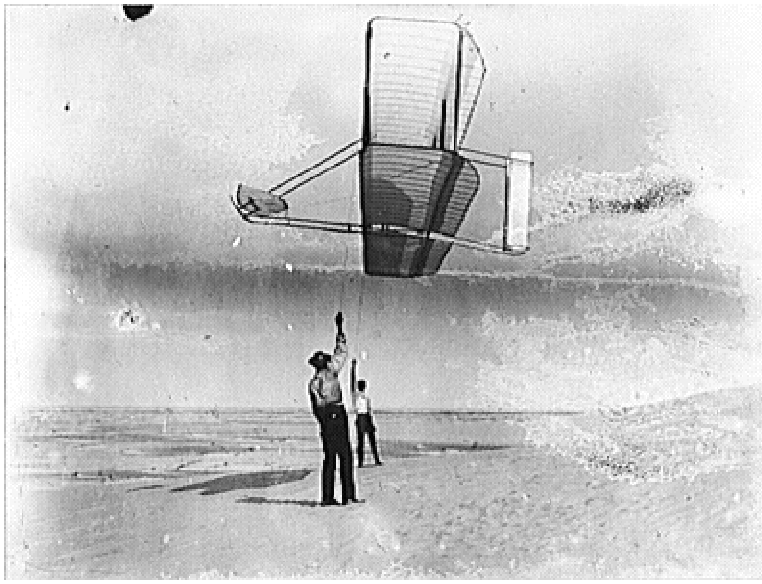
In July 1901 they again traveled to Kitty Hawk, this time with a larger glider. They made several hundred flights that year. The results were, overall, disappointing.

In late 1901, the Wright Brothers made some of their most significant progress toward understanding flight. They built the world's first wind tunnel.



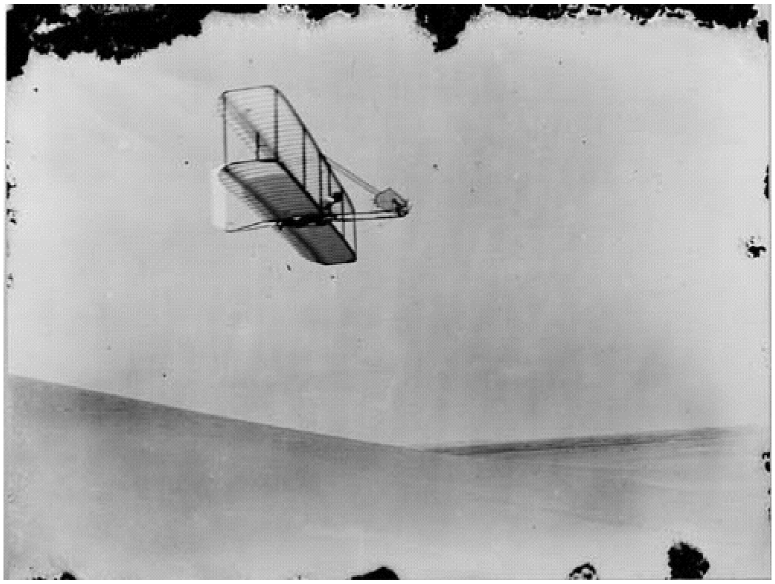
Wilbur Wright in the 1901 glider (Library of Congress photo 1A12).

They made thousands of measurements that year, and their accomplishments in this area alone would have guaranteed their fame as aviation pioneers. However, the Wright Brothers were born engineers and they desired to apply what they had learned from the wind tunnel experiments to the construction of a glider.

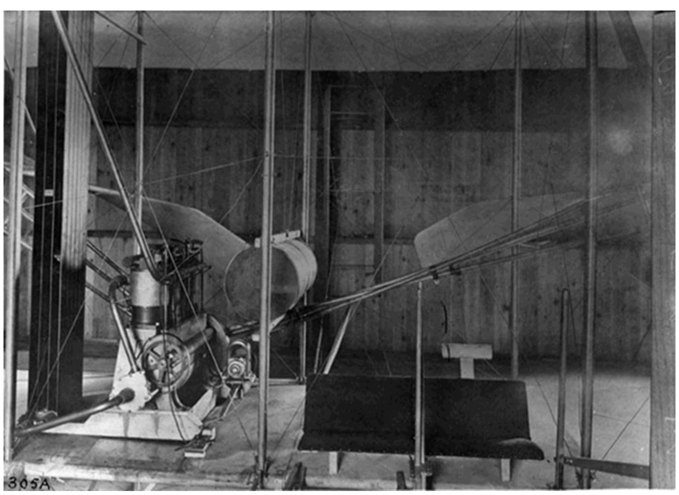


The Wright glider of 1902 flown as a kite (Library of Congress photo 1B8).

In their 1902 experiments, this had a great deal of success! Their glider produced the lift they desired, and they were successful in controlling it (through a method called “wing warping”).

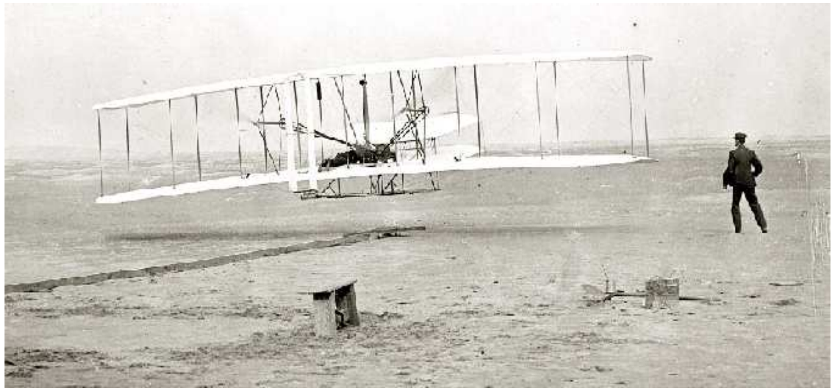


Wilbur Wright in the 1902 glider (Library of Congress photo 1B14).



The engine of the 1903 flyer (from the Dayton Metro Library).

In 1903, they added an engine and propeller. Their goal was sustained, controlled, powered flight of a manned flying machine.



The first flight, December 17, 1903.

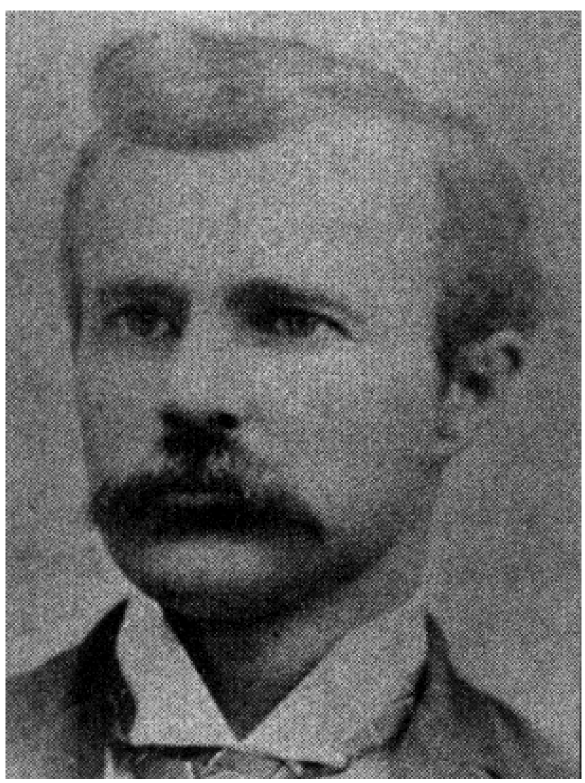
On December 17, 1903 at 10:35 a.m. they achieved success at Kitty Hawk, North Carolina with a 12 second 120 foot flight. They made two other flights of a distance of about 175 feet, and a fourth flight of 852 feet which lasted 59 seconds. They had invented the airplane.

Orville and Wilbur Wright around the turn of the century.

AN UPPER EAST TENNESSEE SURPRISE

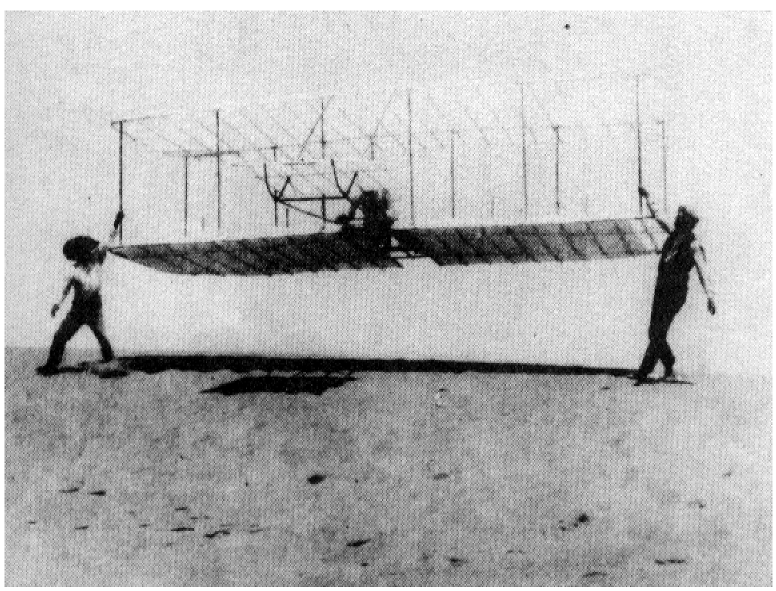
Note. As hinted at above, the Wright Brothers were extremely talented *experimentalists*. However, they were not *theoreticians* and based the shapes of their wings on observations of birds and results of their wind tunnel experiments. As we've seen, Bernoulli's Principle explains why a wing generates lift. But who first proposed this? The answer involves one of Upper East Tennessee's own native sons.

Note. Edward Chalmer Huffaker was born July 16, 1856 in Seclusion Bend (near Knoxville), Tennessee.



Edward Huffaker, from *First in Flight* by Stephen Kirk, p. 59.

He graduated from Emory and Henry College (in Emory, Virginia) in 1876 and completed a master's degree from the University of Virginia in 1883. He taught in Virginia, Kentucky, and Louisiana in the 1880's. In 1889, he moved to Chuckey, Tennessee where he did his own glider experiments in 1893. He corresponded with Langley and Octave Chanute (who visited him in Tennessee in 1894). He lived in Bristol, Tennessee in 1893 and 1894, where he wrote editorials for the Bristol *News*. He worked for the Smithsonian Institute (where Langley worked) from 1895 to mid 1896. In late 1896, he returned to Chuckey, Tennessee where he continued his glider tests. In July 1901, he visited with the Wright Brothers at Kitty Hawk.



Dan Tate and Edward Huffaker launching the 1901 Wright glider, from *First in Flight* by Stephen Kirk, p. 79.

He built a glider for Octave Chanute that was to be tested at Kitty

Hawk, but was destroyed by a storm before it could be tested. By most accounts, the Wright Brothers did not get along with Huffaker. The Wright Brothers were very formal (dressing in coats and ties even when working alone on the North Carolina outer banks), while Huffaker was . . . less formal.

He lived in Bristol, Sevierville, and Chuckey, Tennessee until he died in 1937 and was buried in Chuckey, Tennessee. Interestingly, he never flew in an airplane but his correspondence with Langley and others gives him a unique claim to fame: He appears to be the first to propose that Bernoulli's Principle explains the lift of a wing.

In 1893 in a letter to Langley, Huffaker proposed this application of Bernoulli's Principle. Langley in a reply acknowledges that Huffaker is likely the first to make this connection. Surprisingly, the aviation literature does not make this connection for almost 30 years. The first published mention of this seems to be Leonard Bairstow's *Applied Aerodynamics* in 1920. Unfortunately, Huffaker's ideas appear in his correspondence, but not in his publications. None-the-less, Huffaker has a strong claim to being the first person to explain the lift of an airplane wing using Bernoulli's Principle. This gives those of us in East Tennessee a local connection to this momentous development in theoretical aerodynamics!

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SOME WEBSITES

1. Library of Congress photos of the Wright Brothers: `http://invention.psychology.msstate.edu/i/Wrights/W_Gliders.html`
2. Otto Lilienthal Museum: `http://home.t-online.de/home/LilienthalMuseum/ehome.htm`
3. "Heroes of Horology" (where the portrait of Bernoulli can be found): `http://www.twigsdigs.com/horology/heroes/`
4. AIAA Wright Flyer Project: `http://www.wrightflyer.org/`