



Ninth Edition

# Introduction to FLIGHT

John D. Anderson, Jr.  
Mary L. Bowden



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Hill**

# Introduction to Flight

**Ninth Edition**

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## INTRODUCTION TO FLIGHT

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*Courtesy of John Anderson*

**John D. Anderson, Jr.**, was born in Lancaster, Pennsylvania, on October 1, 1937. He attended the University of Florida, graduating in 1959 with high honors and a Bachelor of Aeronautical Engineering degree. From 1959 to 1962 he was a lieutenant and task scientist at the Aerospace Research Laboratory at Wright-Patterson Air Force Base. From 1962 to 1966 he attended The Ohio State University under National Science Foundation and NASA Fellowships, graduating with a PhD in Aeronautical and Astronautical Engineering. In 1966 he joined the U.S. Naval Ordnance Laboratory as Chief of the Hypersonic Group. In 1973 he became Chairman of the Department of Aerospace Engineering at the University of Maryland, and from 1980 to his retirement in 1999 he was Professor of Aerospace Engineering at Maryland. In 1982 he was designated a Distinguished Scholar/Teacher by the university. During 1986–1987, while on sabbatical from the university, Dr. Anderson occupied the Charles Lindbergh Chair at the National Air and Space Museum of the Smithsonian Institution. In addition to his appointment in aerospace engineering, in 1993 he was elected to the faculty of the Committee on the History and Philosophy of Science at Maryland, and an affiliate faculty member in the Department of History. Since 1999, he is Professor Emeritus of Aerospace Engineering, and Glenn L. Martin Institute Professor of Engineering at Maryland. Also since 1999, he is the Curator of Aerodynamics at the National Air and Space

Museum of the Smithsonian Institution.

Dr. Anderson has published eleven books: *Gasdynamic Lasers: An Introduction*, Academic Press (1976), *A History of Aerodynamics and Its Impact on Flying Machines*, Cambridge University Press (1997), *The Airplane: A History of Its Technology*, American Institute of Aeronautics and Astronautics (2003), *Inventing Flight*, Johns Hopkins University Press (2004), *X-15: The World's Fastest Rocket Plane and the Pilots Who Ushered in the Space Age* (with Richard Passman), Zenith Press (2014), and with McGraw-Hill, *Introduction to Flight*, 8th edition (2016), *Modern Compressible Flow*, 3rd Edition (2003), *Fundamentals of Aerodynamics*, 5th edition (2011), *Hypersonic and High Temperature Gas Dynamics* (1989), *Computational Fluid Dynamics: The Basics with Applications* (1995), and *Aircraft Performance and Design* (1999). He is the author of more than 120 papers on radiative gas dynamics, entry aerothermodynamics, gas dynamic and chemical lasers, computational fluid dynamics, applied aerodynamics, hypersonic flow, and the history of aerodynamics. Dr. Anderson is in *Who's Who in America* and is a member of the National Academy of Engineering, an Honorary Fellow of the American Institute of Aeronautics and Astronautics, and Fellow of the Royal Aeronautical Society. He is also a Fellow of the Washington Academy of Sciences and a member of Tau Beta Pi, Sigma Tau, Phi Kappa Phi, Phi Eta Sigma, The American Society for Engineering Education (ASEE), the Society for the History of Technology, and the History of Science Society. He has received the Lee Atwood Award for excellence in Aerospace Engineering Education from the AIAA and the ASEE, the Pendray Award for Aerospace Literature from the AIAA, the von Karman Lectureship from the AIAA, the Gardner-Lasser History Book Award from the AIAA, and the Hypersonic Systems Award from the AIAA.



Courtesy of Mary Bowden

**Mary L. Bowden** grew up in New York City where she attended a page iv French school, the Lycée Français de New York, graduating after the first year of the French Baccalaureat degree. She received a Bachelor of Arts

degree in Mathematics from Cornell University in 1978. Then, thanks to an Amelia Earhart Scholarship from Zonta International, she enrolled at MIT and obtained first a Master of Science degree in 1980 and then a Doctor of Science degree in Aeronautics and Astronautics in 1988. Her graduate degrees focused on human factors for space construction and dynamics of large space structures. After graduation, Dr. Bowden spent 8 years working in the aerospace industry for a number of different companies, including American Composites Technology, a small company in Massachusetts focused on pultrusion technology; American Rocket Company in California developing a hybrid launch vehicle; and most notably AEC-Able Engineering, also in California, a small aerospace mechanisms company designing, building, and testing the deployable masts for the International Space Station solar arrays.

In 1996, Dr. Bowden joined the faculty of the Aerospace Engineering Department at the University of Maryland College Park (UMD) as a Visiting Professor. She served as the Associate Graduate Director in Aerospace for 10 years, and later served as the Acting Director of the Women in Engineering Program for the Clark School of Engineering at UMD from 2017 to 2020. She is now a Senior Lecturer in Aerospace Engineering and a Keystone Instructor for the Clark School, where she specializes in teaching introductory Mechanics courses and an Aerospace Systems course, as well as upper-level Aerospace Structures and Space Systems Design courses. Dr. Bowden received the Women In Aerospace (WIA) Aerospace Educator Award in 2016.

Dr. Bowden is also the Director of the Balloon Payload Program at UMD, which was started in 2004, sponsored by the Maryland Space Grant Consortium, with the goal of giving aerospace students the opportunity to fly experiments in the near-space environment. The program just carried out its 95th tracked flight of a helium-filled weather balloon, and is continuing with roughly three balloon launches each semester. Over the years, these flights have lifted scores of payloads for hundreds of students from half a dozen different schools in Maryland. The Balloon Payload Team has achieved a number of accomplishments, including flying a few successful payloads on NASA-sponsored High Altitude Balloon flights (through the HASP program) and launching a micro-gravity experiment on a sounding rocket from NASA Wallops Flight Facility (through the RockSatX program). Dr. Bowden received the A. James Clark Student Competition Advisor of the

Year Award in 2017 for supervising numerous award-winning teams along with her husband, Dr. David Akin.



**To Sarah-Allen, Katherine, and Elizabeth Anderson For all their love  
and understanding, and to my two lovely granddaughters, Keegan and  
Tierney Glabus**

---

JOHN D.  
ANDERSON  
J<sub>R</sub>.

**To David, Kaitlyn, and Ellen Akin For their love, support, and  
inspiration**

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MARY L.  
BOWDEN

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This book is an introduction to aerospace engineering from both the technological and historical points of view. It is written to appeal to several groups of people: (1) students of aerospace engineering in their freshman or sophomore years in college who are looking for a comprehensive introduction to their profession; (2) advanced high school seniors who want to learn what aerospace engineering is all about; (3) college undergraduate and graduate students who want to obtain a wider perspective on the glories, the intellectual demands, and the technical maturity of aerospace engineering; and (4) working engineers who simply want to obtain a firmer grasp on the fundamental concepts and historical traditions that underlie their profession.

As an introduction to aerospace engineering, this book is unique in at least three ways. First, the vast majority of aerospace engineering professionals and students have little knowledge or appreciation of the historical traditions and background associated with the technology that they use almost every day. To fill this vacuum, the present book marbles some history of aerospace engineering into the parallel technical discussions. For example, such questions as who Bernoulli was, where the Pitot tube originated, how wind tunnels evolved, who the first true aeronautical engineers were, and how wings and airfoils developed are answered. The present author feels strongly that such material should be an integral part of the background of all aerospace engineers.

Second, this book incorporates both the SI and the English engineering system of units. Modern students of aerospace engineering must be bilingual—on the one hand, they must fully understand and feel comfortable with the SI units—because most modern and all future literature will deal with the SI system; on the other hand, they must be able to read and feel comfortable with the vast bulk of existing literature, which is predominantly in English engineering units. In this book, the SI system is emphasized, but an honest effort is made to give the reader a feeling for and understanding of both systems. To this end, some example problems are worked out in the SI

system and others in the English system.

## **NEW TO THE NINTH EDITION**

The purpose of the present edition is the same as that of the first eight: to present the basic fundamentals of aerospace engineering at the introductory level in the clearest, simplest, and most motivating way possible. Because the book is meant to be enjoyed as well as understood, we have made every effort to ensure a clear and readable text. The choice of subject matter and its organization, the order in which topics are introduced, and how these ideas are explained have been carefully planned with the uninitiated reader in mind. We have simply put ourselves in the shoes of the reader who has no knowledge of the subject matter, have asked ourselves how we would want to hear about the subject, and then start “talking” to the reader. Because the book is intended as a self-contained text at the first- and second-year levels, we avoid tedious details and massive “handbook” data. Instead, we introduce and discuss fundamental concepts in a manner that is as straightforward and clear-cut as possible, knowing that the book has also found favor with those who wish to learn something about this subject outside the classroom.

The overwhelmingly favorable response to the earlier editions page xiii from students, teachers, and practicing professionals both here and abroad is a source of gratification. Particularly pleasing is the fact that those using the book have enjoyed reading its treatment of the fascinating, challenging, and sometimes awesome discipline of aerospace engineering.

Thanks to this response, much of the content of the eighth edition has been carried over into the ninth edition. A hallmark of this book is the use of specially designed devices to enhance the readers’ understanding of the material. In particular, these features are carried over from the eighth edition:

1. *Road maps* placed at the beginning of each chapter help guide the reader through the logical flow of the material.
2. *Design boxes* discuss interesting and important applications of the fundamental material; these are literally set apart in boxes.
3. *Preview boxes* at the chapter beginnings give the reader insight into what each chapter is about and why the material is important. These preview boxes are intended to be motivational, and to make the reader interested and curious enough to pay close attention to the content of

the chapter. They are written in an informal manner to hopefully attempt to turn the reader on to the content. In these preview boxes, we are unabashedly admitting to providing fun for the readers.

4. *Summary and Review sections* at the end of the chapters contain the important ideas and concepts presented in each chapter, first without equations, to remind readers about the physical aspects of the material and to provide a focused intellectual background for the equations that are then summarized at the end of the section.

In the same spirit, the ninth edition contains new material intended to enhance the education and interest of the reader:

1. Many of the changes in this edition of the textbook are updates to the sections on spacecraft design and space travel. For example, there is a new discussion in Chapter 2 on the “Anatomy of a Space Vehicle” and in Chapter 8 on “The Space Environment.” These sections have been added to give the reader a qualitative sense, at least, of what it takes to venture into space.
2. Further additions to Chapter 8 then provide the quantitative fundamentals that govern space travel: from the basics of orbital mechanics to the calculations necessary for orbital maneuvering; these are the tools that allow preliminary space mission design and feasibility studies.
3. In Chapter 9, the changes and new material have focused on page xiv space propulsion with a simpler derivation of the rocket equation and a top-level discussion of launch vehicle staging including the introduction of nondimensional parameters and a number of examples. Emphasis is on the key equations necessary for preliminary design of launch vehicles and the sizing of orbital vehicles.
4. New illustrative examples have been worked out in both Chapters 8 and 9, and a number of new homework problems have been appended at the end of each of these chapters.
5. Since current events very quickly become historical events especially in the space business, it has also been necessary to update and add a couple of new Historical Notes to the ends of Chapters 8 and 9. In particular, Section 8.14 covers human spaceflight up through the



Shuttle era, and Section 9.17 is a discussion of the development of the Saturn V, one of the largest and most significant launch vehicles that allowed the United States to put men on the Moon.

6. Additionally, a new Historical Note has been added to Chapter 6 about the design of “Sleeker and Faster Airplanes.” This describes the “Drag Cleanup” program that was undertaken in the NACA Langley Full Scale Wind Tunnel and led to a much more detailed understanding of the sources of drag on any aerodynamic vehicle.

To allow room for this new material, much of the discussion of atmospheric entry has been moved to the web, including ballistic entry, entry heating, and lifting entry. In addition, the website for this textbook now includes sections on Conceptual Airplane Design, the Quest for Engine Efficiency, and Advanced Orbital Maneuvering.

All told, the new material represents a meaningful enhancement of *Introduction to Flight*.

At the University of Maryland (UMD), this text is used in an introductory course for sophomores in aerospace engineering. It leads directly into a second book, *Fundamentals of Aerodynamics*, which is used in a two-semester junior–senior aerodynamics course. This, in turn, feeds into a third text, *Modern Compressible Flow: With Historical Perspective*, used in a course for advanced undergraduates and first-year graduate students. The complete triad is intended to give students a reasonable technical and historical perspective on aerospace engineering in general and aerodynamics in particular.

John Anderson wishes to give special appreciation to his wife of 60 years, Sarah-Allen, who has lived through his untold amount of time in writing textbooks for McGraw-Hill, and who has helped in the formation of ideas that are reflected throughout these books. Without her patience and indulgence, these books would have never been written. Special thanks is given to Dr. Norman Wereley, Chairman of the Department of Aerospace Engineering at the University of Maryland for his help and support of this project, and to John’s many colleagues in the Aeronautics Department at the National Air and Space Museum for their many helpful conversations on the history of aeronautical technology. He also wishes to thank Dr. Mary Bowden, who joins him as the second author of this new edition. She brings much needed and appreciated expertise in the area of space flight and is

responsible for the completely revised Chapter 8 and much of Chapter 9, as well as the addition of many new end-of-chapter problems. Her addition to this book is welcomed and much appreciated.

Mary Bowden has taught the Introduction to Aerospace Systems page xv course to sophomores at the University of Maryland for over 10 years. She has an appreciation for the capabilities and interests of this very talented set of students and thus welcomed the opportunity to contribute to this textbook. She would especially like to thank her husband of only 38 years, Dr. David Akin, a faculty member in the Aerospace Engineering department at UMD and the Director of the Space Systems Lab. His constructive criticism and historical perspective enhanced considerably the new material added to this edition. Mary would also like to thank Shikha Redhal, a doctoral student in the Aerospace Engineering department at UMD, for her skilled and patient help on the many diagrams of Chapters 8 and 9.

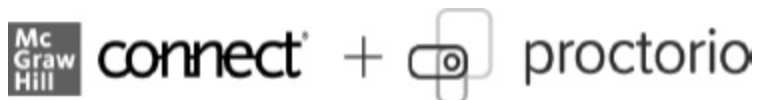
Both authors wish to thank those that offered their insights and suggestions in order to help shape the ninth edition revision: Amir Elzaway (Vaughn College); David Brian Landrum (University of Alabama, Huntsville); Robert Liebeck (University of California, Irvine); Andrew Meade (Rice University); Iskender Sahin (New York University Tandon School of Engineering); and Kamran Turkoglu (San Jose State University).

Finally, emphasizing that the study, understanding, and practice of the profession of aerospace engineering is one of the most gratifying of human endeavors and that our purpose is to instill a sense of enthusiasm, dedication, and love of the subject, let us simply say to the reader: read, learn, and enjoy.

**John D. Anderson, Jr.**

**Mary L. Bowden**

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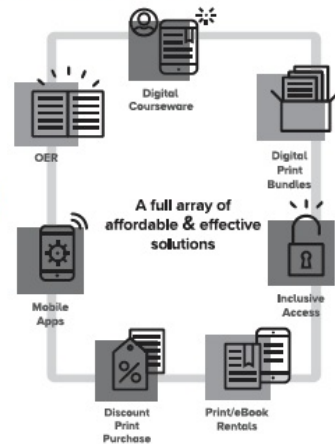
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# CHAPTER 1

## The First Aeronautical Engineers

Nobody will fly for a thousand years!

*Wilbur Wright, 1901, in a fit of despair*

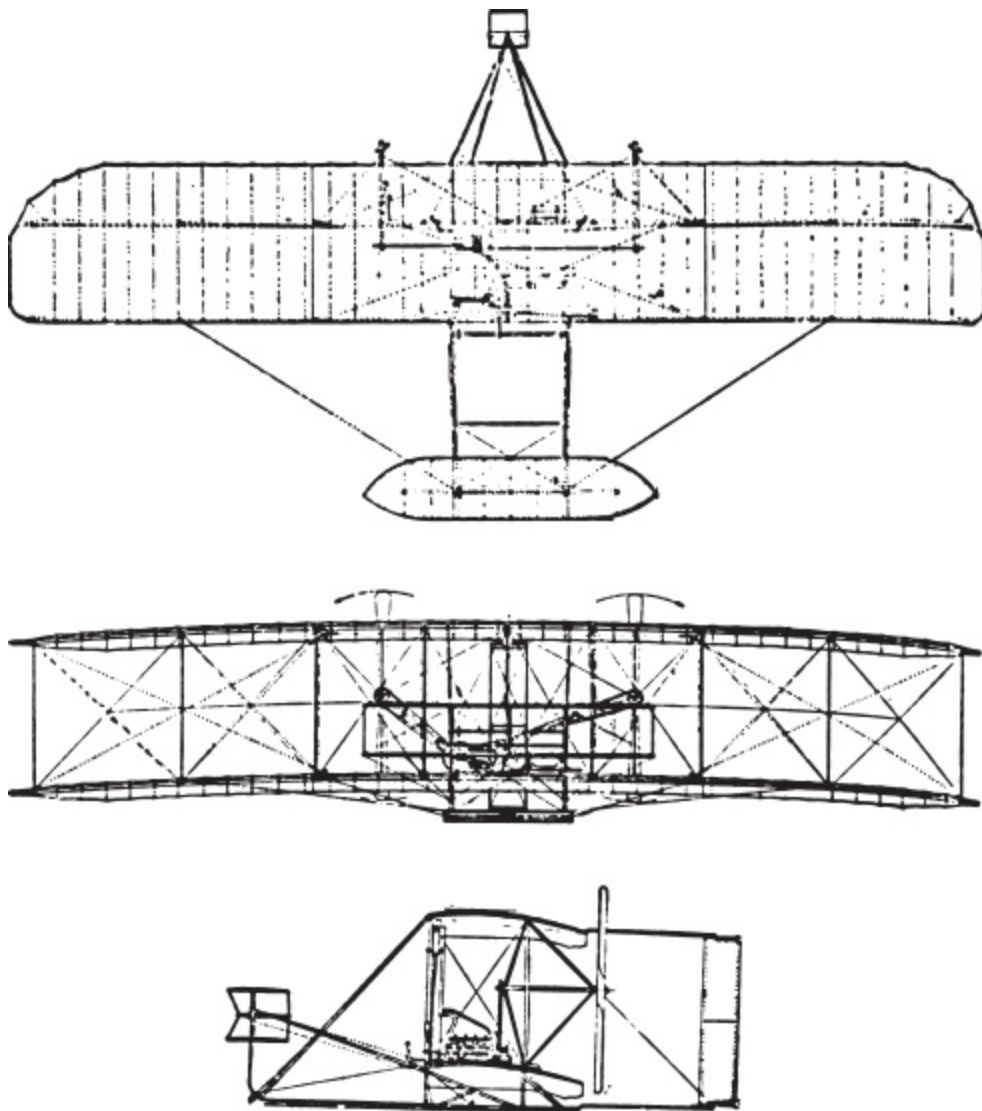
SUCCESS FOUR FLIGHTS THURSDAY MORNING ALL AGAINST TWENTY ONE MILE WIND STARTED FROM LEVEL WITH ENGINE POWER ALONE AVERAGE SPEED THROUGH AIR THIRTY ONE MILES LONGEST 57 SECONDS INFORM PRESS HOME CHRISTMAS.

*ORVILLE WRIGHT A telegram, with the original misprints, from Orville Wright to his father, December 17, 1903*

### 1.1 INTRODUCTION

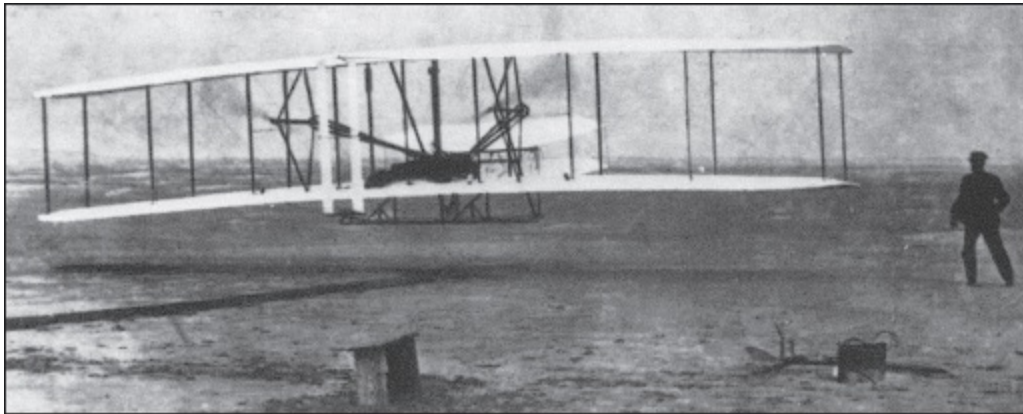
*The scene:* Windswept sand dunes of Kill Devil Hills, 4 mi south of Kitty Hawk, North Carolina. *The time:* About 10:35 AM on Thursday, December 17, 1903. *The characters:* Orville and Wilbur Wright and five local witnesses. *The action:* Poised, ready to make history, is a flimsy, odd-looking machine, made from spruce and cloth in the form of two wings, one placed above the other, a horizontal elevator mounted on struts in front of the wings, and a double vertical rudder behind the wings (see Fig. 1.1). A 12-hp engine is mounted on the top surface of the bottom wing, slightly right of center. To the left of this engine lies a man—Orville Wright—prone on the bottom wing, facing into the brisk and cold December wind. Behind him rotate two ungainly looking airscrews (propellers), driven by two chain-and-pulley arrangements connected to the same engine. The machine begins to move along a 60-ft launching rail on level ground. Wilbur Wright runs along the right side of the machine, supporting the wing tip so it will not drag the sand. Near the end of the starting rail, the machine lifts into the air; at this moment, John Daniels of the Kill Devil Life Saving Station takes a

photograph that preserves for all time the most historic moment in aviation history (see Fig. 1.2). The machine flies unevenly, rising suddenly to about 10 ft, then ducking quickly toward the ground. This type of erratic flight continues for 12 s, when the machine darts to the sand, 120 ft from the point where it lifted from the starting rail. Thus ends a flight that, in Orville Wright's own words, was "the first in the history of the world in which a machine carrying a man had raised itself by its own power into the air in full flight, had sailed forward without reduction of speed, and had finally landed at a point as high as that from which it started."



**Figure 1.1** Three views of the *Wright Flyer I*, 1903

The machine was the *Wright Flyer I*, which is shown in Figs. 1.1 and 1.2 and which is now preserved for posterity in the Air and Space Museum of the Smithsonian Institution in Washington, District of Columbia. The flight on that cold December 17 was momentous: It brought to a realization the dreams of centuries, and it gave birth to a new way of life. It was the first genuine powered flight of a heavier-than-air machine. With it, and with the further successes to come over the next five years, came the Wright brothers' clear right to be considered the premier aeronautical engineers of history.



**Figure 1.2** The first heavier-than-air flight in history: the *Wright Flyer I* with Orville Wright at the controls, December 17, 1903.

(Source: Wright Brothers Negatives, Library of Congress [LC-DIG-ppprs-00626].)

However, contrary to some popular belief, the Wright brothers did not truly *invent* the airplane; rather, they represent the fruition of a century's worth of prior aeronautical research and development. The time was ripe for the attainment of powered flight at the beginning of the 20th century. The Wright brothers' ingenuity, dedication, and persistence earned them the distinction of being first. The purpose of this chapter is to look back over the years that led up to successful powered flight and to single out an important few of those inventors and thinkers who can rightfully claim to be the first aeronautical engineers. In this manner, some of the traditions and heritage that underlie modern aerospace engineering will be more appreciated when we develop the technical concepts of flight in subsequent chapters.

## 1.2 VERY EARLY DEVELOPMENTS

Since the dawn of human intelligence, the idea of flying in the same realm as

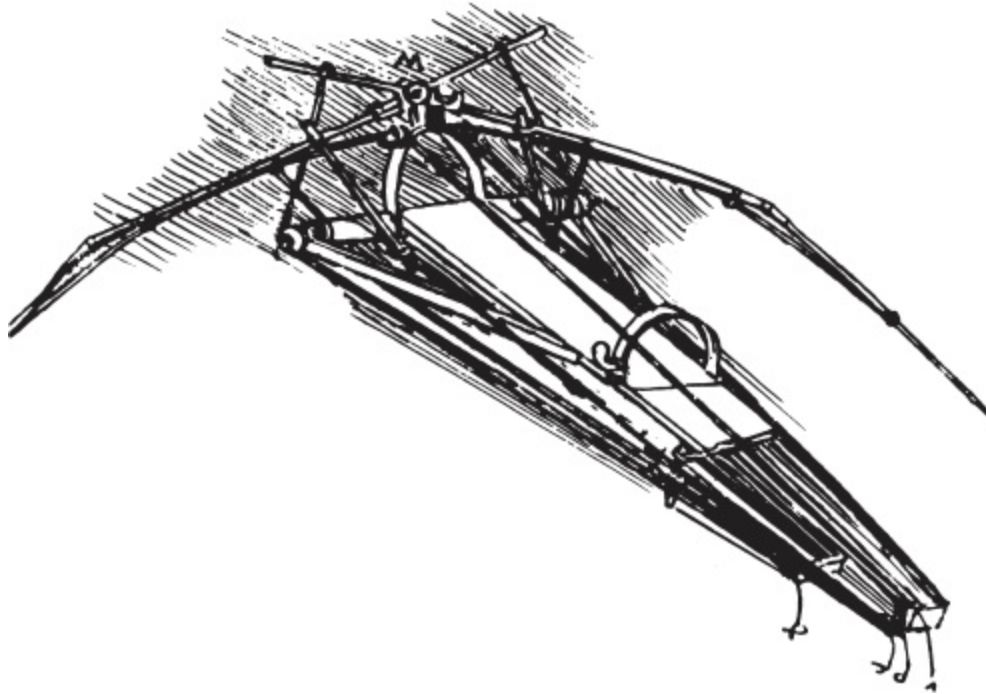


birds has possessed human minds. Witness the early Greek myth of Daedalus and his son Icarus. Imprisoned on the island of Crete in the Mediterranean Sea, Daedalus is said to have made wings fastened with wax. With these wings, they both escaped by flying through the air. However, Icarus, against his father's warnings, flew too close to the sun; the wax melted, and Icarus fell to his death in the sea.

All early thinking about human flight centered on the imitation of birds. Various unsung ancient and medieval people fashioned wings and met with sometimes disastrous and always unsuccessful consequences in leaping from towers or roofs, flapping vigorously. In time, the idea of strapping a pair of wings to arms fell out of favor. It was replaced by the concept of wings flapped up and down by various mechanical mechanisms, powered by some type of human arm, leg, or body movement. These machines are called *ornithopters*. Recent historical research has revealed that Leonardo da Vinci was possessed by the idea of human flight and that he designed vast numbers of ornithopters toward the end of the 15th century. In his surviving manuscripts, more than 35,000 words and 500 sketches deal with flight. One of his ornithopter designs is shown in Fig. 1.3, which is an original da Vinci sketch made sometime between 1486 and 1490. It is not known whether da Vinci ever built or tested any of his designs. However, human-powered flight by flapping wings was always doomed to failure. In this sense, da Vinci's efforts did not make important contributions to the technical advancement of flight.

Human efforts to fly literally got off the ground on November 21, 1783, when a balloon carrying Pilatre de Rozier and the Marquis d'Arlandes ascended into the air and drifted 5 mi across Paris. The balloon was inflated and buoyed up by hot air from an open fire burning in a large wicker basket underneath. The design and construction of the balloon were those of the Montgolfier brothers, Joseph and Etienne. In 1782 Joseph Montgolfier, gazing into his fireplace, conceived the idea of using the "lifting power" of hot air rising from a flame to lift a person from the surface of the earth. The brothers instantly set to work, experimenting with bags made of paper and linen, in which hot air from a fire was trapped. After several public demonstrations of flight without human passengers, including the 8-min voyage of a balloon carrying a cage containing a sheep, a rooster, and a duck, the Montgolfiers were ready for the big step. At 1:54 PM on November 21, 1783, the first flight with human passengers rose majestically into the air

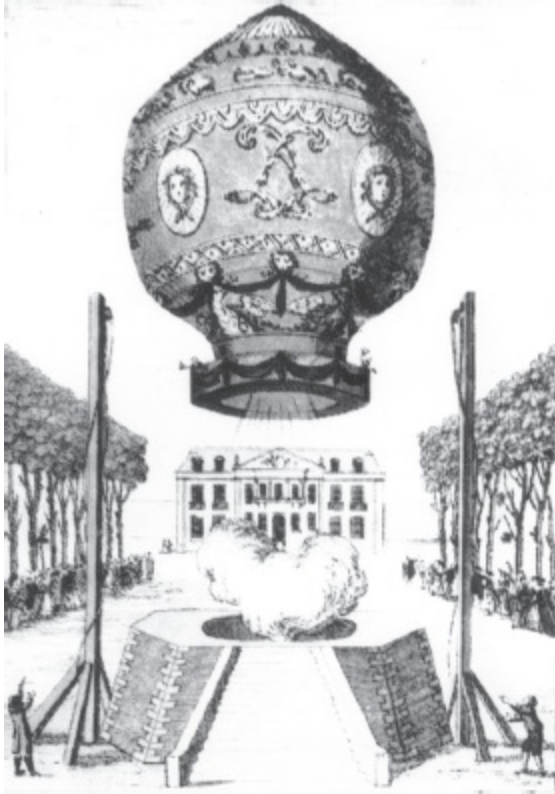
and lasted for 25 min (see Fig. 1.4). It was the first time in history that a human being had been lifted off the ground for a sustained period. Very quickly after this, the noted French physicist J. A. C. Charles (of Charles' gas law in physics) built and flew a hydrogen-filled balloon from the Tuileries Gardens in Paris on December 1, 1783.



**Figure 1.3** An ornithopter design by Leonardo da Vinci, 1486–1490.

(Source: British Science Museum by C. H. Gibbs-Smith, published by Her Majesty's Stationary Office, London: *Leonardo da Vinci's Aeronautics*, 1967.)

So people were finally off the ground! Balloons, or “aerostatic machines” as they were called by the Montgolfiers, made no real technical contributions to human heavier-than-air flight. However, they served a major purpose in triggering the public's interest in flight through the air. They were living proof that people could really leave the ground and sample the environs heretofore exclusively reserved for birds. Moreover, balloons were the only means of human flight for almost 100 years.



**Figure 1.4** The first aerial voyage in history: The Montgolfier hot-air balloon lifts from the ground near Paris on November 21, 1783.

(Source: Library of Congress Prints & Photographs Division [LC-USZ62-15243].)

### **1.3 SIR GEORGE CAYLEY (1773–1857)—THE TRUE INVENTOR OF THE AIRPLANE**

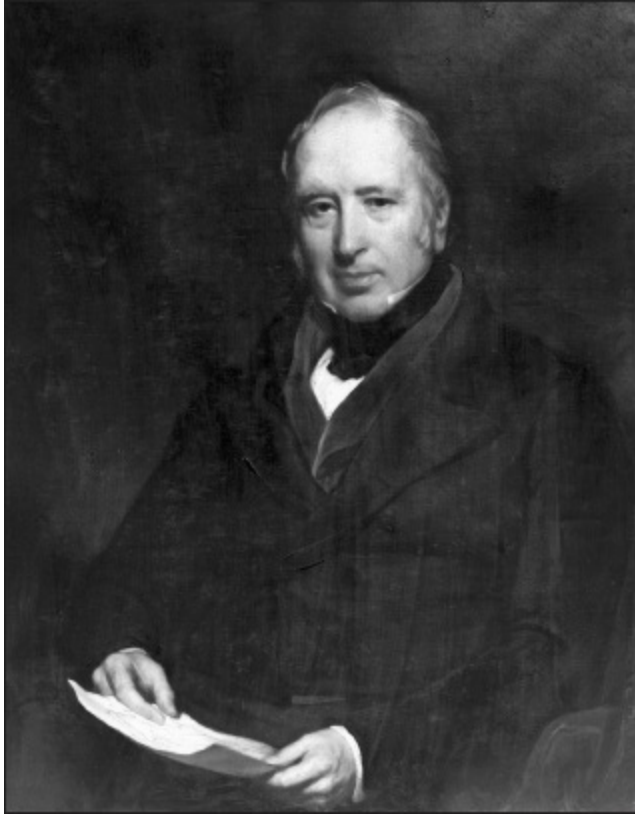
The modern airplane has its origin in a design set forth by George Cayley in 1799. It was the first concept to include a *fixed* wing for generating lift, another *separate* mechanism for propulsion (Cayley envisioned paddles), and a combined horizontal and vertical (cruciform) tail for stability. Cayley inscribed his idea on a silver disk (presumably for permanence), shown in Fig. 1.5. On the reverse side of the disk is a diagram of the lift and drag forces on an inclined plane (the wing). The disk is now preserved in the Science Museum in London. Before this time, thought of mechanical flight had been oriented toward the flapping wings of ornithopters, where the flapping motion was supposed to provide both lift and propulsion. (Da Vinci designed his ornithopter wings to flap simultaneously downward and backward for lift and propulsion.) However, Cayley is responsible for

breaking this unsuccessful line of thought; he separated the concept of lift from that of propulsion and, in so doing, set into motion a century of aeronautical development that culminated in the Wright brothers' success in 1903. George Cayley is a giant in aeronautical history: He is the parent of modern aviation and was the first to introduce the basic configuration of the modern airplane. Let us look at him more closely.



**Figure 1.5** The silver disk on which Cayley engraved his concept for a fixed-wing aircraft, the first in history, in 1799. The reverse side of the disk shows the resultant aerodynamic force on a wing resolved into lift and drag components, indicating Cayley's full understanding of the function of a fixed wing. The disk is presently in the Science Museum in London.

(Source: *Science and Society/SuperStock*.)

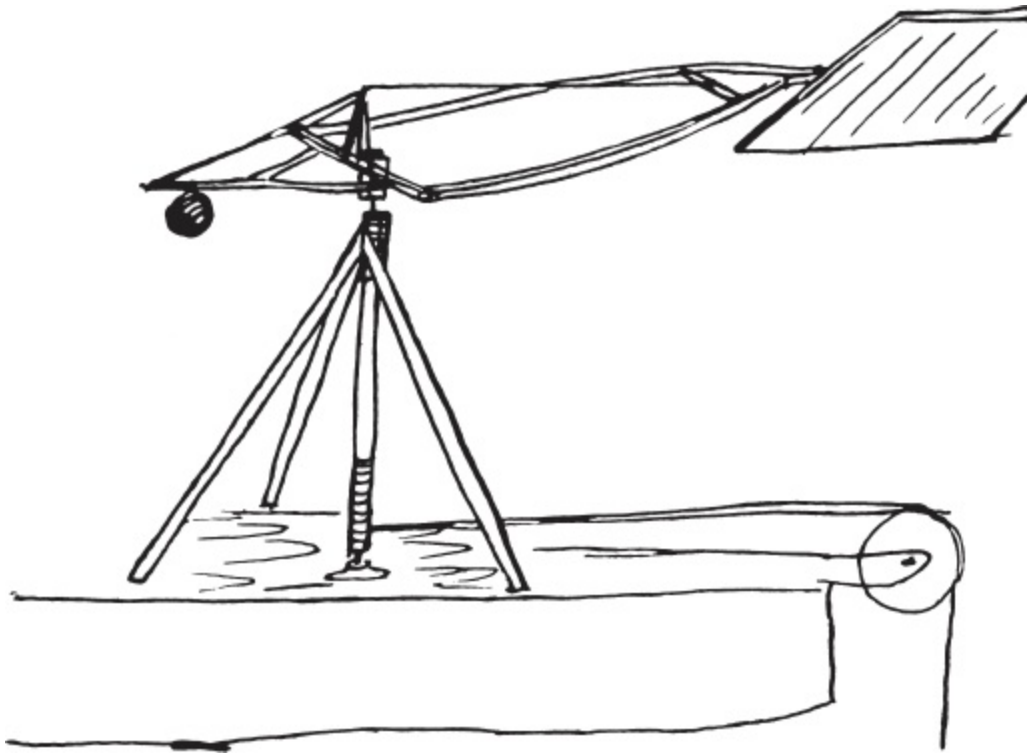


**Figure 1.6** A portrait of Sir George Cayley, painted by Henry Perronet Briggs in 1841. The portrait now hangs in the National Portrait Gallery in London.

(Source: *Science and Society/SuperStock*.)

Cayley was born at Scarborough in Yorkshire, England, on December 27, 1773. He was educated at York and Nottingham and later studied chemistry and electricity under several noted tutors. He was a scholarly man of some rank, a baronet who spent much of his time on the family estate, called Brompton. A portrait of Cayley is shown in Fig. 1.6. He was a well-preserved person, of extreme intellect and open mind, active in many pursuits over a long life of 84 years. In 1825 he invented the caterpillar tractor, forerunner of all modern tracked vehicles. In addition, he was chairman of the Whig Club of York, founded the Yorkshire Philosophical Society (1821), cofounded the British Association for the Advancement of Science (1831), was a member of Parliament, was a leading authority on land drainage, and published papers dealing with optics and railroad safety devices. Moreover, he had a social conscience: He appealed for, and donated to, the relief of industrial distress in Yorkshire.

However, by far his major and lasting contribution to humanity was in aeronautics. After experimenting with model helicopters beginning in 1796, Cayley engraved his revolutionary fixed-wing concept on the silver disk in 1799 (see Fig. 1.5). This was followed by an intensive 10-year period of aerodynamic investigation and development. In 1804 he built a whirling-arm apparatus, shown in Fig. 1.7, for testing airfoils; this was simply a lifting surface (airfoil) mounted on the end of a long rod, which was rotated at some speed to generate a flow of air over the airfoil. In modern aerospace engineering, wind tunnels now serve this function; but in Cayley's time the whirling arm was an important development that allowed the measurement of aerodynamic forces and the center of pressure on a lifting surface. Of course these measurements were not very accurate, because after a number of revolutions of the arm, the surrounding air would begin to rotate with the device. Nevertheless, it was a first step in aerodynamic testing. (Cayley did not invent the whirling arm; that honor belongs to the English military engineer Benjamin Robins in 1742.) Also in 1804, Cayley designed, built, and flew the small model glider shown in Fig. 1.8. This may seem trivial today, something that you might have done as a child; *but in 1804, it represented the first modern-configuration airplane of history*, with a fixed wing, and a horizontal and vertical tail that could be adjusted. (Cayley generally flew his glider with the tail at a positive angle of incidence, as shown in his sketch in Fig. 1.8.) A full-scale replica of this glider is on display at the Science Museum in London; the model is only about 1 m long.



**Figure 1.7** George Cayley's whirling-arm apparatus for testing airfoils.

Cayley's first outpouring of aeronautical results was documented in his momentous triple paper of 1809–1810. Titled "On Aerial Navigation" and published in the November 1809, February 1810, and March 1810 issues of Nicholson's *Journal of Natural Philosophy*, this document ranks as one of the most important aeronautical works in history. (Note that the words *natural philosophy* in history are synonymous with physical science.) Cayley was prompted to write his triple paper after hearing reports that Jacob Degen had recently flown in a mechanical machine in Vienna. In reality, Degen flew in a contraption that was lifted by a balloon. It was of no significance, but Cayley did not know the details. In an effort to let people know of his activities, Cayley documented many aspects of aerodynamics in his triple paper. It was the first published treatise on theoretical and applied aerodynamics in history. In it, Cayley elaborated on his principle of the separation of lift and propulsion and his use of a fixed wing to generate lift. He stated that the basic principle of a flying machine is "to make a surface support a given weight by the application of power to the resistance of air." He noted that a surface inclined at some angle to the direction of motion will generate lift and that a cambered (curved) surface will do this more



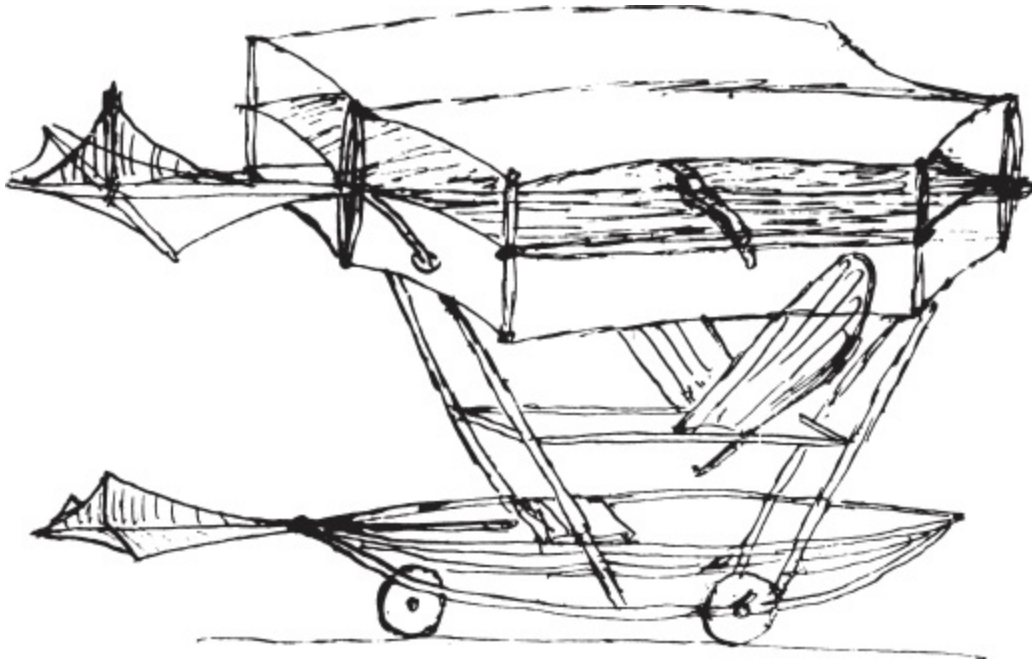
efficiently than a flat surface. He also stated for the first time in history that lift is generated by a region of low pressure on the upper surface of the wing. The modern technical aspects of these phenomena are developed and explained in Chs. 4 and 5; however, stated by Cayley in 1809–1810, these phenomena were new and unique. His triple paper also addressed the matter of flight control and was the first document to discuss the role of the horizontal and vertical tail planes in airplane stability. Interestingly enough, Cayley went off on a tangent in discussing the use of flappers for propulsion. Note that on the silver disk (see Fig. 1.5) Cayley showed some paddles just behind the wing. From 1799 until his death in 1857, Cayley was obsessed with such flappers for aeronautical propulsion. He gave little attention to the propeller (airscrew); indeed, he seemed to have an aversion to rotating machinery of any type. However, this should not detract from his numerous positive contributions. Also in his triple paper, Cayley described the first successful full-size glider of history, built and flown without passengers by him at Brompton in 1809. However, there was no clue as to its configuration.



**Figure 1.8** The first modern-configuration airplane in history: Cayley's model glider, 1804.

Curiously, the period from 1810 to 1843 was a lull in Cayley's life in regard to aeronautics. Presumably he was busy with his myriad other interests and activities. During this period, he showed interest in airships (controlled balloons), as opposed to heavier-than-air machines. He made the prophetic statement that "balloon aerial navigation can be done readily, and will probably, in the order of things, come into use before mechanical flight can be rendered sufficiently safe and efficient for ordinary use." He was correct; the first successful airship, propelled by a steam engine, was built and flown by the French engineer Henri Giffard in Paris in 1852, some 51 years before the first successful airplane.





**Figure 1.9** Cayley’s triplane from 1849—the boy carrier. Note the vertical and horizontal tail surfaces and the flapperlike propulsive mechanism.

Cayley’s second outpouring of aeronautical results occurred in the period from 1848 to 1854. In 1849 he built and tested a full-size airplane. During some of the flight tests, a 10-year-old boy was carried along and was lifted several meters off the ground while gliding down a hill. Cayley’s own sketch of this machine, called the *boy carrier*, is shown in Fig. 1.9. Note that it is a triplane (three wings mounted on top of one another). Cayley was the first to suggest such multiplanes (i.e., biplanes and triplanes), mainly because he was concerned with the possible structural failure of a single large wing (a monoplane). Stacking smaller, more compact, wings on top of one another made more sense to him, and his concept was perpetuated into the 20th century. It was not until the late 1930s that the monoplane became the dominant airplane configuration. Also note from Fig. 1.9 that, strictly speaking, this was a “powered” airplane; that is, it was equipped with propulsive flappers.

One of Cayley’s most important papers was published in *Mechanics’ Magazine* on September 25, 1852. By this time he was 79 years old! The article was titled “Sir George Cayley’s Governable Parachutes.” It gave a full description of a large human-carrying glider that incorporated almost all the features of the modern airplane. This design is shown in Fig. 1.10, which

is a facsimile of the illustration that appeared in the original issue of *Mechanics' Magazine*. This airplane had (1) a main wing at an angle of incidence for lift, with a dihedral for lateral stability; (2) an adjustable cruciform tail for longitudinal and directional stability; (3) a pilot-operated elevator and rudder; (4) a fuselage in the form of a car, with a pilot's seat and three-wheel undercarriage; and (5) a tubular beam and box beam construction. These combined features were not to be seen again until the Wright brothers' designs at the beginning of the 20th century. Incredibly, this 1852 paper by Cayley went virtually unnoticed, even though *Mechanics' Magazine* had a large circulation. It was rediscovered by the eminent British aviation historian Charles H. Gibbs-Smith in 1960 and republished by him in the June 13, 1960, issue of *The Times*.

# Mechanics' Magazine,

MUSEUM, REGISTER, JOURNAL, AND GAZETTE.

No. 1520.]

SATURDAY, SEPTEMBER 25, 1852. [Price 3d., Stamped 4d.

Edited by J. C. Robertson, 166, Fleet-street.

## SIR GEORGE CAYLEY'S GOVERNABLE PARACHUTES.

Fig. 2.

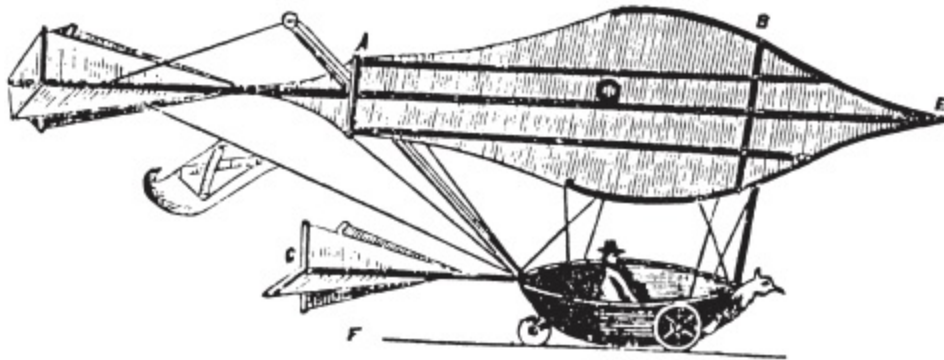
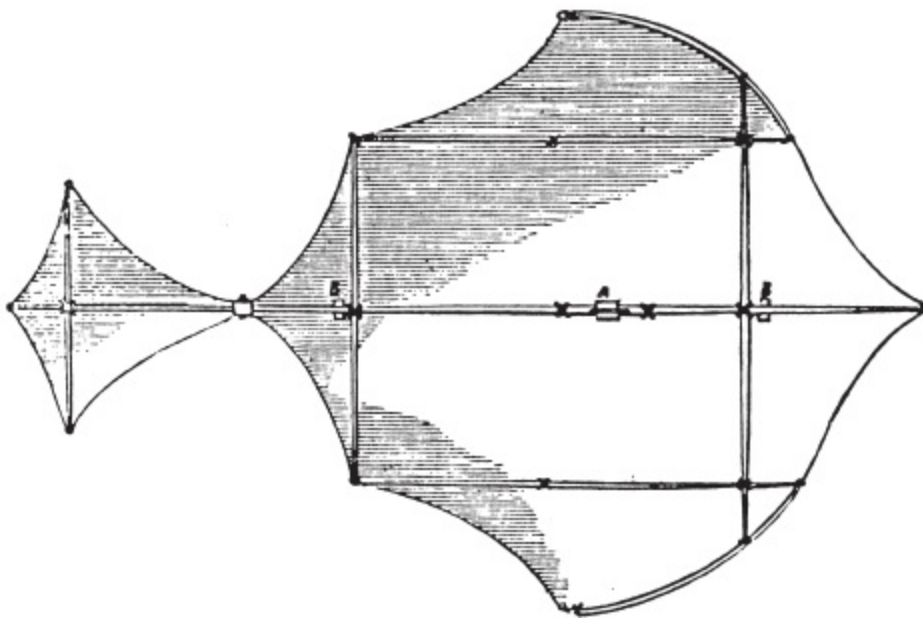


Fig. 1.



**Figure 1.10** George Cayley's human-carrying glider, from *Mechanics' Magazine*, 1852.

Sometime in 1853—the precise date is unknown—George Cayley built and flew the world’s first human-carrying glider. Its configuration is not known, but Gibbs-Smith states that it was most likely a triplane on the order of the earlier boy carrier (see Fig. 1.9) and that the planform (top view) of the wings was probably shaped much like the glider in Fig. 1.10. According to several eyewitness accounts, a gliding flight of several hundred yards was made across a dale at Brompton with Cayley’s coachman aboard. The glider landed rather abruptly; and after struggling clear of the vehicle, the shaken coachman is quoted as saying, “Please, Sir George, I wish to give notice. I was hired to drive, and not to fly.” Very recently, this flight of Cayley’s coachman was reenacted for the public in a special British Broadcasting Corporation television show about Cayley’s life. While visiting the Science Museum in London in August 1975, the present author was impressed to find the television replica of Cayley’s glider (minus the coachman) hanging in the entranceway.

George Cayley died at Brompton on December 15, 1857. During his almost 84 years of life, he laid the basis for all practical aviation. He was called the *father of aerial navigation* by William Samuel Henson in 1846. However, for reasons that are not clear, the name of George Cayley retreated to the background soon after his death. His works became obscure to virtually all later aviation enthusiasts in the latter half of the 19th century. This is incredible, indeed unforgivable, considering that his published papers were available in known journals. Obviously many subsequent inventors did not make the effort to examine the literature before forging ahead with their own ideas. (This is certainly a problem for engineers today, with the virtual explosion of written technical papers since World War II.) However, Cayley’s work has been brought to light by the research of several modern historians in the 20th century. Notable among them is C. H. Gibbs-Smith, from whose book titled *Sir George Cayley’s Aeronautics* (1962) much of the material in Sec. 1.3 has been gleaned. Gibbs-Smith states that had Cayley’s work been extended directly by other aviation pioneers, and had they digested ideas espoused in his triple paper of 1809–1810 and in his 1852 paper, successful powered flight would most likely have occurred in the 1890s. Probably so!

As a final tribute to George Cayley, we note that the French aviation historian Charles Dollfus said the following in 1923:

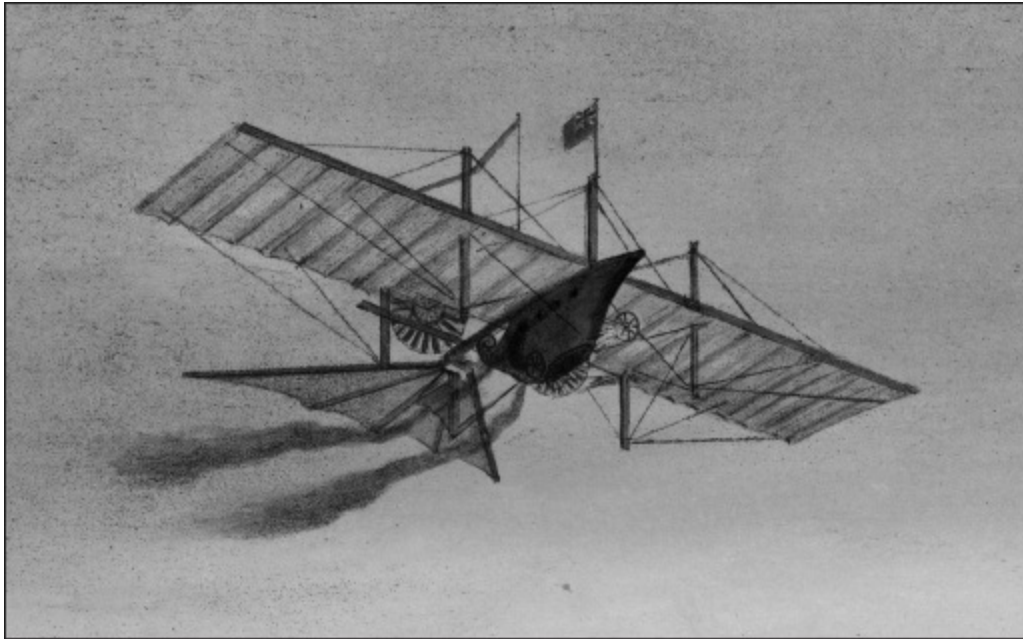
The aeroplane is a British invention: it was conceived in all essentials by George Cayley, the great English engineer who worked in the first half of last century. The name of Cayley is little known, even in his own country, and there are very few who know the work of this admirable man, the greatest genius of aviation. A study of his publications fills one with absolute admiration both for his inventiveness, and for his logic and common sense. This great engineer, during the Second Empire, did in fact not only invent the aeroplane entire, as it now exists, but he realized that the problem of aviation had to be divided between theoretical research—Cayley made the first aerodynamic experiments for aeronautical purposes—and practical tests, equally in the case of the glider as of the powered aeroplane.

## **1.4 THE INTERREGNUM—FROM 1853 TO 1891**

For the next 50 years after Cayley's success with the coachman-carrying glider, there were no major advances in aeronautical technology comparable to those of the previous 50 years. Indeed, as stated in Sec. 1.3, much of Cayley's work became obscure to all but a few dedicated investigators. However, there was considerable activity, with numerous people striking out (sometimes blindly) in various uncoordinated directions to conquer the air. Some of these efforts are noted in the following paragraphs, just to establish the flavor of the period.

William Samuel Henson (1812–1888) was a contemporary of Cayley. In April 1843 he published in England a design for a fixed-wing airplane powered by a steam engine driving two propellers. Called the *aerial steam carriage*, this design received wide publicity throughout the 19th century, owing mainly to a series of illustrative engravings that were reproduced and sold around the world. This was a publicity campaign of which Madison Avenue would have been proud; one of these pictures is shown in Fig. 1.11. Note some of the qualities of modern aircraft in Fig. 1.11: the engine inside a closed fuselage, driving two propellers; tricycle landing gear; and a single rectangular wing of relatively high aspect ratio. (We discuss the aerodynamic characteristics of such wings in Ch. 5.) Henson's design was a direct product of George Cayley's ideas and research in aeronautics. The aerial steam carriage was never built; but the design, along with its widely published pictures, served to engrave George Cayley's fixed-wing concept

on the minds of virtually all subsequent workers. Thus, even though Cayley's published papers fell into obscurity after his death, his major concepts were partly absorbed and perpetuated by subsequent generations of inventors, even though most of these inventors did not know the true source of the ideas. In this manner, Henson's aerial steam carriage was one of the most influential airplanes in history, even though it never flew.

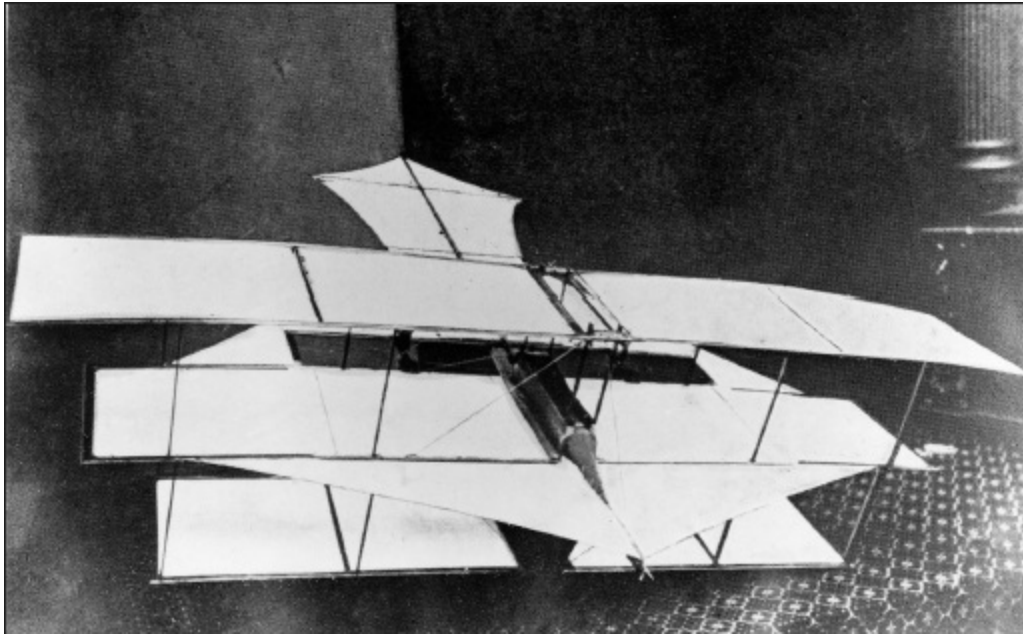


**Figure 1.11** Henson's aerial steam carriage, 1842–1843.

(Source: *Library of Congress Prints & Photographs Division [LC-DIG-ppmsca-03479].*)

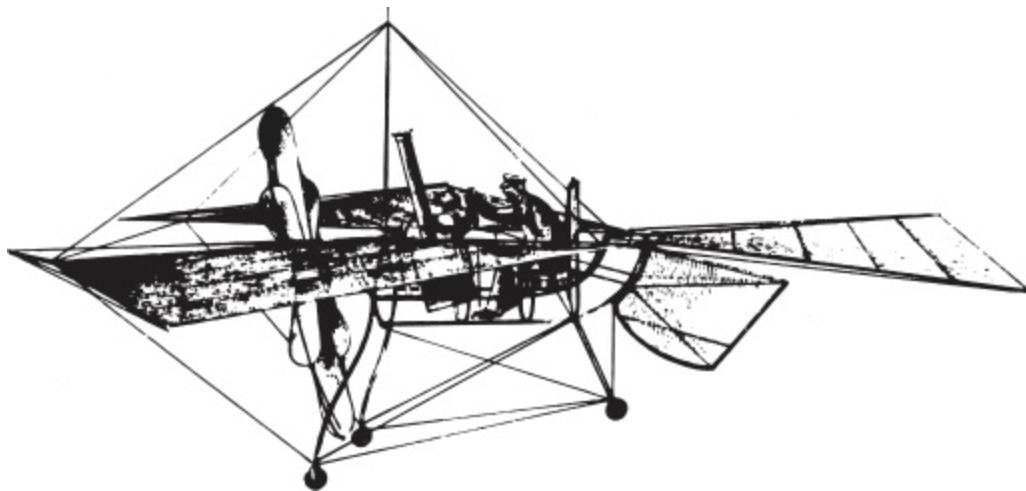
John Stringfellow, a friend of Henson, made several efforts to bring Henson's design to fruition. Stringfellow built several small steam engines and attempted to power some model monoplanes off the ground. He was close but unsuccessful. However, his most recognized work appeared in the form of a steam-powered triplane, a model of which was shown at the 1868 aeronautical exhibition sponsored by the Aeronautical Society at the Crystal Palace in London. A photograph of Stringfellow's triplane is shown in Fig. 1.12. This airplane was also unsuccessful, but again it was extremely influential because of worldwide publicity. Illustrations of this triplane appeared throughout the end of the 19th century. Gibbs-Smith, in his book *Aviation: An Historical Survey from Its Origins to the End of World War II* (1970), states that these illustrations were later a strong influence on Octave Chanute, and through him the Wright brothers, and strengthened the concept

of superimposed wings. Stringfellow's triplane was the main bridge between George Cayley's aeronautics and the modern biplane.



**Figure 1.12** Stringfellow's model triplane exhibited at the first aeronautical exhibition in London, 1868.

(Source: *Science and Society/SuperStock*.)



**Figure 1.13** Du Temple's airplane: the first aircraft to make a powered but assisted takeoff, 1874.

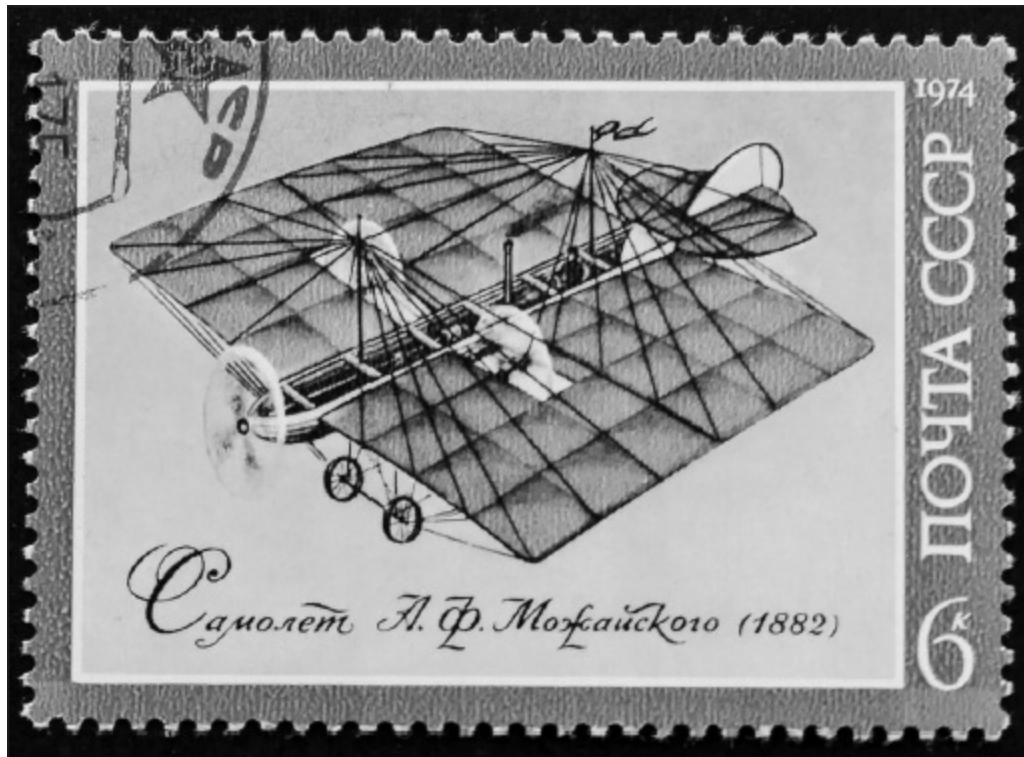
During this period, the first powered airplanes actually hopped off the



ground, but only for hops. In 1857–1858 the French naval officer and engineer Felix Du Temple flew the first successful powered model airplane in history; it was a monoplane with swept-forward wings and was powered by clockwork! Then, in 1874, Du Temple achieved the world's first powered takeoff by a piloted, full-size airplane. Again the airplane had swept-forward wings, but this time it was powered by some type of hot-air engine (the precise type is unknown). A sketch of Du Temple's full-size airplane is shown in Fig. 1.13. The machine, piloted by a young sailor, was launched down an inclined plane at Brest, France; it left the ground for a moment but did not come close to anything resembling sustained flight. In the same vein, the second powered airplane with a pilot left the ground near St. Petersburg, Russia, in July 1884. Designed by Alexander F. Mozhaiski, this machine was a steam-powered monoplane, shown in Fig. 1.14. Mozhaiski's design was a direct descendant of Henson's aerial steam carriage; it was even powered by an English steam engine. With I. N. Golubev as pilot, this airplane was launched down a ski ramp and flew for a few seconds. As with Du Temple's airplane, no sustained flight was achieved. At various times the Russians have credited Mozhaiski with the first powered flight in history, but of course it did not satisfy the necessary criteria to be called such. Du Temple and Mozhaiski achieved the first and second *assisted* powered takeoffs, respectively, in history, but neither experienced sustained flight. In his book *The World's First Aeroplane Flights* (1965), C. H. Gibbs-Smith states the following criteria used by aviation historians to judge a successful powered flight:

In order to qualify for having made a simple powered and sustained flight, a conventional aeroplane should have sustained itself freely in a horizontal or rising flight path—without loss of airspeed—beyond a point where it could be influenced by any momentum built up before it left the ground: otherwise its performance can only be rated as a powered leap, i.e., it will not have made a fully self-propelled flight, but will only have followed a ballistic trajectory modified by the thrust of its propeller and by the aerodynamic forces acting upon its aerofoils. Furthermore, it must be shown that the machine can be kept in satisfactory equilibrium. Simple sustained flight obviously need not include full controllability, but the maintenance of adequate equilibrium in flight is part and parcel of sustentation.





**Figure 1.14** The second airplane to make an assisted takeoff: Mozhaitski's aircraft, Russia, 1884.

(Source: Zenobillis/Shutterstock.)

Under these criteria, there is no doubt in the mind of any major aviation historian that the first powered flight was made by the Wright brothers in 1903. However, the assisted “hops” just described put two more rungs in the ladder of aeronautical development in the 19th century.

Of particular note during this period is the creation in London in 1866 of the Aeronautical Society of Great Britain. Before this time, work on “aerial navigation” (a phrase coined by George Cayley) was looked upon with some disdain by many scientists and engineers. It was too out of the ordinary and was not to be taken seriously. However, the Aeronautical Society soon attracted scientists of stature and vision, people who shouldered the task of solving the problems of mechanical flight in a more orderly and logical fashion. In turn, aeronautics took on a more serious and meaningful atmosphere. The society, through its regular meetings and technical journals, provided a cohesive scientific outlet for the presentation and digestion of aeronautical engineering results. The society is still flourishing today in the form of the highly respected Royal Aeronautical Society. Moreover, it

served as a model for the creation of both the American Rocket Society and the Institute of Aeronautical Sciences in the United States; both of these societies merged in 1964 to form the American Institute of Aeronautics and Astronautics (AIAA), one of the most influential channels for aerospace engineering information exchange today.

In conjunction with the Aeronautical Society of Great Britain, at its first meeting on June 27, 1866, Francis H. Wenham read a paper titled “Aerial Locomotion,” one of the classics in aeronautical engineering literature. Wenham was a marine engineer who later was to play a prominent role in the society and who later designed and built the first wind tunnel in history (see Sec. 4.24). His paper, which was also published in the first annual report of the society, was the first to point out that most of the lift of a wing was obtained from the portion near the leading edge. He also established that a wing with a high aspect ratio was the most efficient for producing lift. (We will see why in Ch. 5.)

As noted in our previous discussion about Stringfellow, the Aeronautical Society started out in style: When it was only two years old, in 1868, it put on the first aeronautical exhibition in history at the Crystal Palace. It attracted an assortment of machines and balloons and for the first time offered the general public a firsthand overview of the efforts being made to conquer the air. Stringfellow’s triplane (discussed earlier) was of particular interest. Zipping over the heads of the enthralled onlookers, the triplane moved through the air along an inclined cable strung below the roof of the exhibition hall (see Fig. 1.12). However, it did not achieve sustained flight on its own. In fact, the 1868 exhibition did nothing to advance the technical aspects of aviation; nevertheless, it was a masterstroke of good public relations.

## **1.5 OTTO LILIENTHAL (1848–1896)—THE GLIDER MAN**

With all the efforts that had been made in the past, it was still not until 1891 that a human literally jumped into the air and flew with wings in any type of controlled fashion. This person was Otto Lilienthal, one of the giants in aeronautical engineering (and in aviation in general). Lilienthal designed and flew the first successful controlled gliders in history. He was a man of aeronautical stature comparable to Cayley and the Wright brothers. Let us examine the man and his contributions more closely.