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INTERNATIONAL EDITION

Aerodynamics for Engineers

SIXTH EDITION

Bertin Cummings

PEARSON

INTERNATIONAL EDITION

Aerodynamics for Engineers

SIXTH EDITION

John J. Bertin • Russell M. Cummings

ALWAYS LEARNING

PEARSON

AERODYNAMICS FOR ENGINEERS

Sixth Edition

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and

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This edition of Aerodynamics for Engineers is dedicated to the memory of John J. Bertin

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Preface

A great deal has happened since the preface to the fifth edition of *Aerodynamics for Engineers* was written early in 2008. During the spring and early summer of 2008, John Bertin and I were busy checking chapter proofs for "The Book" (as he liked to call it). John was at home in Houston and teaching at his beloved Rice University (you may have noticed that covers of the various editions of *Aerodynamics for Engineers* were usually blue and light gray, the colors of Rice University). I was a visiting researcher at the Institute of Aerodynamics and Flow Technology at The German Aerospace Center (DLR) in Braunschweig. John had two major struggles in his life at the time: he was working through the last stages of the illness that would take his wife, Ruth, from him. He had also been diagnosed with pancreatic cancer, and was dealing with doctors, treatments, and hospitals. We spoke on the phone often about the various challenges he was facing, both with his wife's and his own health. Through the support of his family, as well as his desire to finish the fifth edition, he made it through the summer of 2008 in reasonably good shape. Copies of the book were shipped to us in July 2008, and he was very glad that we had finished the undertaking we had started so many years earlier.

Unfortunately, John's pancreatic cancer took a turn for the worse in late summer of 2008, and he passed away on October 11, 2008. A large number of former co-workers from NASA and various universities, as well as his family and friends, attended his funeral later that month, and we all knew that a very special person had passed from our ranks.

One of the things that John and I talked about during his last months of life was his desire for *Aerodynamics for Engineers* to continue to grow and evolve, even if he was not around to help with that task. I cannot help but think that he asked me to be his co-author for the fifth edition for this purpose. So, in spite of the fact that John is no longer with us, his spirit and excitement for learning will continue to live.

So, there were many goals for writing the sixth edition of *Aerodynamics for Engineers*: (1) to continue the legacy of Professor Bertin; (2) to rewrite many of the sections that provide readers with a motivation for studying aerodynamics in a more casual, enjoyable, and readable manner; (3) to update the technical innovations and advancements that have taken place in aerodynamics since the writing of the previous edition; and (4) to add aerodynamics concept boxes throughout the book to enhance the interest of readers.

To help achieve these goals, I provided readers with new sections, listed under What's New to This Edition on the next page. In addition, there are numerous new figures containing updated information, as well as numerous, additional up-to-date references throughout the book. Finally, numerous new example problems have been added throughout the book to enhance the learning of aerodynamics by the reader, and answers to selected problems have been added to help students know when they have done the problems correctly. Users of the fifth edition of the book will find that all material included in that edition is still included in the sixth edition, with the new material added throughout the book to bring a real-world flavor to the concepts being developed. I hope that readers will find the inclusion of all of this additional material helpful and informative.

Finally, no major revision of a book like *Aerodynamics for Engineers* can take place without the help of many people. I am especially indebted to everyone who aided in collecting new

materials for the sixth edition. I want to especially thank Preston A. Henne and Robert van't Riet of McDonnell Douglas; Eli Reshotko of Case Western Reserve University; David W. Hall of DHC Engineering; Stuart Rogers of NASA Ames Research Center; David McDaniel of the University of Alabama, Birmingham; Hans Hornung of Caltech; Andreas Schütte, Thomas Streit, and Martin Hepperle of DLR; Patrick Champigny of ONERA; Aaron Byerley of the U.S. Air Force Academy; John McMasters of The Boeing Company; and William H. Mason of Virginia Tech. In addition, I am very grateful for the excellent suggestions and comments made by the reviewers of the sixth edition: Roger L. Simpson of Virginia Tech, Tej R. Gupta of Embry-Riddle Aeronautical University, Serhat Hosder of Missouri University of Science and Technology, and Lisa Grega of The College of New Jersey. The editorial and production staff at Pearson has been outstanding in their support of this new edition: I greatly appreciate their efforts. I am also extremely grateful to the many students at the U.S. Air Force Academy who have pointed out errors that they found in the previous edition. I hope that everyone who reads this book will find it useful and educational.

The publishers would like to thank Ramesh Kolluru of BMS College of Engineering, Bangalore for reviewing the content of the International Edition.

WHAT'S NEW TO THIS EDITION?

- Aerodynamics concept boxes added throughout the book to bring real-world examples and applications to light as new material is being learned
- Chapter objectives to give readers a better understanding of the goal of each chapter and what concepts they should understand after reading through the chapter
- Significant re-writing of material and derivations from previous editions to improve clarity and usefulness
- Extra example problems to improve understanding of how to apply concepts to useful applications
- Significant new sections added on the topics of: importance of aerodynamics to aircraft performance, a description of the airplane, the irrotational flow condition, applications of potential flow theory to aerodynamics, expanded description of airfoil geometry and nomenclature, high lift military airfoils, the effect of taper ratio on wing efficiency, induced drag estimation, converging-diverging nozzles, shock/shock interactions, subsonic compressible transformations, additional compressibility corrections, critical Mach number, drag divergence Mach number, base drag, and the distinguishing characteristics of hypersonic flow
- Updated figures and photographs to help readers see concepts from real examples and on real aircraft
- Answers to selected problems

Enjoy your study of aerodynamics!

INSTRUCTORS RESOURCES

Resources to accompany the text are located on the Instructor Resource Center website at www.pearsoninternationaleditions.com/cummings. If you are in need of a login and password for this site, please contact your local Pearson representative. Resources include; Instructor Solutions Manual, Matlab files for several example problems and lecture slides for most chapters.

RUSSELL M. CUMMINGS
Larkspur, Colorado

1 WHY STUDY AERODYNAMICS?

Chapter Objectives

- Learn why aerodynamics is important in determining the performance characteristics of airplanes
- Develop a basic understanding of fluid properties such as density, temperature, pressure, and viscosity and know how to calculate these properties for a perfect gas
- Learn about the atmosphere and why we use a "standard atmosphere" model to perform aerodynamic calculations; learn how to perform calculations of fluid properties in the atmosphere
- Learn the basic components of an airplane and what they are used for

The study of aerodynamics is a challenging and rewarding discipline within aeronautics since the ability of an airplane to perform (how high, how fast, and how far an airplane will fly, such as the F-15E shown in Fig. 1.1) is determined largely by the aerodynamics of the vehicle. However, determining the aerodynamics of a vehicle (finding the lift and drag) is one of the most difficult things you will ever do in engineering, requiring complex theories, experiments in wind tunnels, and simulations using modern high-speed computers. Doing any of these things is a challenge, but a challenge well worth the effort for those wanting to better understand aircraft flight.

Figure 1.1 Aerodynamics is required for all components of the F-15E in flight, including the wing, fuselage, horizontal and vertical tails, stores, and how they interact with each other (U.S. Air Force photo by Staff Sgt. Samuel Rogers).

In order to prepare you for the challenge of learning about aerodynamics, we will first look at some interesting aspects of aircraft performance, and how we could determine if one airplane will outperform another airplane in a dog fight. Hopefully this will lead us to the point where we realize that aerodynamics is one of the prime characteristics of an airplane, which will determine the performance of the vehicle.

Of course, aerodynamics also requires that we understand some basic information about fluid dynamics, since physical materials known as fluids are made up of both liquids and gasses, and air is a gas. So some basic concepts about fluid properties and how we can describe a fluid will also be necessary. Since airplanes fly in the atmosphere, we will also develop a standard way to describe the properties of air in the atmosphere. And finally, we will discuss some of the basic geometry of an airplane, so we will have a common nomenclature for discussing how airplanes fly and for the aerodynamics of the various parts of an airplane. All of these pieces of background information will help us get started on the path to understanding aerodynamics, which is the goal of this book.

1.1 AERODYNAMICS AND THE ENERGY-MANEUVERABILITY TECHNIQUE

Early in the First World War, fighter pilots (at least those good enough to survive their first engagement with the enemy) quickly developed tactics that were to serve them throughout the years. German aces, such as Oswald Boelcke and Max Immelman, realized that if they initiated combat starting from an altitude that was greater than that of their adversary, they could dive upon their foe, trading potential energy (height) for kinetic energy (velocity). Using the greater speed of his airplane to close from the rear (i.e., from the target aircraft's "six o'clock position"), the pilot of the attacking aircraft could dictate the conditions of the initial phase of the air-to-air combat. Starting from a superior altitude and converting potential energy to kinetic energy, the attacker might be able to destroy his opponent on the first pass. These tactics were refined, as the successful fighter aces gained a better understanding of the nuances of air combat by building an empirical database through successful air-to-air battles. A language grew up to codify these tactics: "Check your six."

This data base of tactics learned from successful combat provided an empirical understanding of factors that are important to aerial combat. Clearly, the sum of the potential energy plus the kinetic energy (i.e., the total energy) of the aircraft is one of the factors.

EXAMPLE 1.1: The total energy

Compare the total energy of a B-52 (shown in Fig. 1.2a) that weighs 450,000 pounds and that is cruising at a true air speed of 250 knots at an altitude of 20,000 ft with the total energy of an F-5 (shown in Fig. 1.2b) that weighs 12,000 pounds and that is cruising at a true air speed of 250 knots at an altitude of 20,000 ft. The equation for the total energy is

$$E = \frac{1}{2}mV^2 + mgh \tag{1.1}$$

Solution: To have consistent units, the units for velocity should be feet per second rather than knots. A knot is a nautical mile per hour and is equal to 1.69 ft per second, so 250 knots is equal to 422.5 ft/s. The mass is given by the equation:

$$m = \frac{W}{g} \tag{1.2}$$

(a) B-52H (b) F-5E

Figure 1.2 Aircraft used in energy-maneuverability comparison (U.S. Air Force photos; B-52H photo by Mike Cassidy).

Note that the units of mass could be grams, kilograms, lbm, slugs, or $\text{lbf}\cdot\text{s}^2/\text{ft}$. The choice of units often will reflect how mass appears in the application. The mass of the "Buff" (i.e., the B-52) is 13,986 $\text{lbf}\cdot\text{s}^2/\text{ft}$ or 13,986 slugs, while the mass for the F-5 is 373 slugs. The total energy for the B-52 is:

$$E = \frac{1}{2}\left(13{,}986\,\frac{\text{lbf}\cdot\text{s}^2}{\text{ft}}\right)\left(422.5\,\frac{\text{ft}}{\text{s}}\right)^2 + (450{,}000\text{ lbf})(20{,}000\text{ ft})$$

$$E = 1.0248 \times 10^{10}\text{ ft}\cdot\text{lbf}$$

Similarly, the total energy of the F-5 fighter is

$$E = \frac{1}{2}\left(373\,\frac{\text{lbf}\cdot\text{s}^2}{\text{ft}}\right)\left(422.5\,\frac{\text{ft}}{\text{s}}\right)^2 + (12{,}000\text{ lbf})(20{,}000\text{ ft})$$

$$E = 2.7329 \times 10^{8}\text{ ft}\cdot\text{lbf}$$

The total energy of the B-52 is 37.5 times the total energy of the F-5. Even though the total energy of the B-52 is so very much greater than that for the F-5, it just doesn't seem likely that a B-52 would have a significant advantage in air-to-air combat with an F-5. Notice that the two aircraft are cruising at the same flight conditions (velocity/altitude combination). So in this case the difference in total energy is in direct proportion to the difference in the weights of the two aircraft. Perhaps the specific energy (i.e., the energy per unit weight) is a more realistic parameter when trying to predict which aircraft would have an edge in air-to-air combat.

EXAMPLE 1.2: The energy height

Since the weight specific energy also has units of height, it will be given the symbol H_e and is called the energy height. Dividing the terms in equation (1.1) by the weight of the aircraft ($W = m\,g$)

$$H_e = \frac{E}{W} = \frac{V^2}{2\,g} + h \qquad \textbf{(1.3)}$$

Compare the energy height of a B-52 flying at 250 knots at an altitude of 20,000 ft with that of an F-5 cruising at the same altitude and at the same velocity.

Solution: The energy height of the B-52 is

$$H_e = \frac{1}{2}\frac{\left(422.5\,\frac{\text{ft}}{\text{s}}\right)^2}{32.174\,\frac{\text{ft}}{\text{s}^2}} + 20000\text{ ft}$$

$$H_e = 22774\text{ ft}$$

Since the F-5 is cruising at the same altitude and at the same true air speed as the B-52, it has the same energy height (i.e., the same weight specific energy).

If we consider only this weight specific energy, the B-52 and the F-5 are equivalent. This is obviously an improvement over the factor of 37.5 that the "Buff" had over the F-5, when the comparison was made based on the total energy. However, the fact that the energy height is the same for these two aircraft indicates that further effort is needed to provide a more realistic comparison for air-to-air combat.

Based on these examples, there must be some additional parameters that are relevant when comparing the one-on-one capabilities of two aircraft in air-to-air combat. Captain Oswald Boelcke developed a series of rules based on his combat experience as a forty-victory ace by October 19, 1916. Boelcke specified seven rules, or "dicta" [Werner (2005)]. The first five, which deal with tactics, are

1. Always try to secure an advantageous position before attacking. Climb before and during the approach in order to surprise the enemy from above, and dive on him swiftly from the rear when the moment to attack is at hand.
2. Try to place yourself between the sun and the enemy. This puts the glare of the sun in the enemy's eyes and makes it difficult to see you and impossible to shoot with any accuracy.
3. Do not fire the machine guns until the enemy is within range and you have him squarely within your sights.
4. Attack when the enemy least expects it or when he is preoccupied with other duties, such as observation, photography, or bombing.
5. Never turn your back and try to run away from an enemy fighter. If you are surprised by an attack on your tail, turn and face the enemy with your guns.

Although Boelcke's dicta were to guide fighter pilots for decades to come, they were experienced-based empirical rules. The first dictum deals with your total energy, the sum of the potential energy plus the kinetic energy. We learned from the first two example calculations that predicting the probable victor in one-on-one air-to-air combat is not based on energy alone.

Note that the fifth dictum deals with maneuverability. ***Energy AND Maneuverability!*** The governing equations should include maneuverability as well as the specific energy.

It wasn't until almost half a century later that a Captain in the U.S. Air Force brought the needed complement of talents to bear on the problem [Coram (2002)]. Captain John R. Boyd was an aggressive and talented fighter pilot who had an insatiable intellectual curiosity for understanding the scientific equations that had to be the basis of the "Boelcke dicta." John R. Boyd was driven to understand the physics that was the foundation of the tactics that, until that time, had been learned by experience for the fighter pilot lucky enough to survive his early air-to-air encounters with an enemy. In his role as Director of Academics at the U.S. Air Force Fighter Weapons School, it became not only his passion, but his job.

Air combat is a dynamic ballet of move and countermove that occurs over a continuum of time. Therefore, Boyd postulated that perhaps the time derivatives of the energy height are more relevant than the energy height itself. How fast can we, in the target aircraft, with an enemy on our "six." quickly dump energy and allow the foe to pass? Once the enemy has passed, how quickly can we increase our energy height and take the offensive? John R. Boyd taught these tactics in the Fighter Weapons School. Now he became obsessed with the challenge of developing the science of fighter tactics.

1.1.1 Specific Excess Power

If the pilot of the 12,000 lbf F-5 that is flying at a velocity of 250 knots (422.5 ft/s) and at an altitude of 20,000 ft is to gain the upper hand in air-to-air combat, his aircraft must have sufficient power either to out-accelerate or to outclimb his adversary. Consider the case where the F-5 is flying at a constant altitude. If the engine is capable of generating more thrust than the drag acting on the aircraft, the acceleration of the aircraft can be calculated using Newton's Law:

$$\sum F = m\,a$$

which for an aircraft accelerating at a constant altitude becomes

$$T - D = \frac{W}{g}\frac{dV}{dt} \tag{1.4}$$

Multiplying both sides of equation (1.4) by V and dividing by W gives

$$\frac{(T - D)V}{W} = \frac{V}{g}\frac{dV}{dt} \tag{1.5}$$

which is the specific excess power, P_s.

EXAMPLE 1.3: The specific excess power and acceleration

The left-hand side of equation (1.5) is excess power per unit weight, or specific excess power, P_s. Use equation (1.5) to calculate the maximum acceleration for a 12,000-lbf F-5 that is flying at 250 knots (422.5 ft/s) at 20,000 ft.

Solution: Performance charts for an F-5 that is flying at these conditions indicate that it is capable of generating 3550 lbf thrust (T) with the afterburner lit, while the total drag (D) acting on the aircraft is 1750 lbf. Thus, the specific excess power is

$$P_s = \frac{(T - D)V}{W} = \frac{[(3550 - 1750)\text{ lbf}]\ 422.5\text{ ft/s}}{12000\text{ lbf}} = 63.38\text{ ft/s}$$

Rearranging equation (1.5) to solve for the acceleration gives

$$\frac{dV}{dt} = P_s\frac{g}{V} = (63.38\text{ ft/s})\frac{32.174\text{ ft/s}^2}{422.5\text{ ft/s}} = 4.83\text{ ft/s}^2$$

1.1.2 Using Specific Excess Power to Change the Energy Height

Taking the derivative with respect to time of the two terms in equation (1.3), we obtain:

$$\frac{dH_e}{dt} = \frac{V}{g}\frac{dV}{dt} + \frac{dh}{dt} \tag{1.6}$$

The first term on the right-hand side of equation (1.6) represents the rate of change of kinetic energy (per unit weight). It is a function of the rate of change of the velocity as seen by the pilot $\left(\frac{dV}{dt}\right)$. The significance of the second term is even less cosmic. It is the rate of change of the potential energy (per unit weight). Note also that $\left(\frac{dh}{dt}\right)$ is the vertical component of the velocity [i.e., the rate of climb (ROC)] as seen by the pilot on his altimeter. Air speed and altitude—these are parameters that fighter pilots can take to heart.

Combining the logic that led us to equations (1.5) and (1.6) leads us to the conclusion that the specific excess power is equal to the time-rate-of-change of the energy height. So,

$$P_s = \frac{(T - D)V}{W} = \frac{dH_e}{dt} = \frac{V}{g}\frac{dV}{dt} + \frac{dh}{dt} \tag{1.7}$$

Given the specific excess power calculated in Example 1.3, we could use equation (1.7) to calculate the maximum rate-of-climb (for a constant velocity) for the 12,000 lbf F-5 as it passes through 20,000 ft at 250 knots.

$$\frac{dh}{dt} = P_s = 63.38 \text{ ft/s} = 3802.8 \text{ ft/min}$$

Clearly, to be able to generate positive values for the terms in equation (1.7), we need an aircraft with excess power (i.e., one for which the thrust exceeds the drag). Weight is another important factor, since the lighter the aircraft, the greater the benefits of the available excess power.

"Boyd, as a combat pilot in Korea and as a tactics instructor at Nellis AFB in the Nevada desert, observed, analyzed, and assimilated the relative energy states of his aircraft and those of his opponent's during air combat engagements. . . . He also noted that, when in a position of advantage, his energy was higher than that of his opponent and that he lost that advantage when he allowed his energy to decay to less than that of his opponent."

"He knew that, when turning from a steady-state flight condition, the airplane under a given power setting would either slow down, lose altitude, or both. The result meant he was losing energy (the drag exceeded the thrust available from the engine). From these observations, he concluded that maneuvering for position was basically an energy problem. Winning required the proper management of energy available at the conditions existing at any point during a combat engagement" [Hillaker (1997)].

In the mid-1960s, Boyd had gathered energy-maneuverability data on all of the fighter aircraft in the U.S. Air Force inventory and on their adversaries. He sought to understand the intricacies of maneuvering flight. What was it about the airplane that would limit or prevent him from making it to do what he wanted it to do?

1.1.3 John R. Boyd Meet Harry Hillaker

The relation between John R. Boyd and Harry Hillaker "dated from an evening in the mid-1960s when a General Dynamics (GD) engineer named Harry Hillaker was sitting in the Officer's Club at Eglin AFB, Florida, having an after dinner drink. Hillaker's host introduced him to a tall, blustery pilot named John R. Boyd, who immediately launched a frontal attack on GD's F-111 fighter. Hillaker was annoyed but bantered back" [Grier (2004)]. Hillaker countered that the F-111 was designated a fighter-bomber.

"A few days later, he (Hillaker) received a call—Boyd had been impressed by Hillaker's grasp of aircraft conceptual design and wanted to know if Hillaker was interested in more organized meetings."

"Thus was born a group that others in the Air Force dubbed the 'fighter mafia.' Their basic belief was that fighters did not need to overwhelm opponents with speed and size. Experience in Vietnam against nimble Soviet-built MiGs had convinced them that technology had not yet turned air-to-air combat into a long-range shoot-out." [Grier (2004)]

The fighter mafia knew that a small aircraft could enjoy a high thrust-to-weight ratio: small aircraft have less drag. "The original F-16 design had about one-third the drag of an F-4 in level flight and one-fifteenth the drag of an F-4 at a high angle-of-attack" [Grier (2004)].

1.1.4 The Importance of Aerodynamics to Aircraft Performance

The importance of the previous discussion is that aircraft performance is largely determined by the aerodynamic characteristics of the airplane (as well as the mass properties and thrust of the airplane). Parameters like lift and drag determine aircraft performance such as energy height. Lift and drag also determine more easy-to-understand parameters like range, rate of climb, and glide ratio (which is exactly the lift/drag ratio of the airplane). Without knowing the aerodynamics of the airplane (as well as the mass properties and thrust), we will not be able to determine how well an airplane will perform. This requires knowing the flow field around the airplane so that the pressures, shear stress, and heating on the surface of the airplane can be determined. That is why the study of aerodynamics is an essential stepping stone to gaining a fuller understanding of how an airplane will perform, and how to improve that performance to achieve flight requirements.

1.2 SOLVING FOR THE AEROTHERMODYNAMIC PARAMETERS

The fundamental problem facing the aerodynamicist is to predict the aerodynamic forces and moments and the heat-transfer rates acting on a vehicle in flight. In order to predict these aerodynamic forces and moments with suitable accuracy, it is necessary to be able to describe the pattern of flow around the vehicle. The resultant flow pattern depends on the geometry of the vehicle, its orientation with respect to the undisturbed free stream, and the altitude and speed at which the vehicle is traveling. In analyzing the various flows that an aerodynamicist may encounter, assumptions about the fluid properties may be introduced. In some applications, the temperature variations are so small that they do not affect the velocity field. In addition, for those applications where the temperature variations have a negligible effect on the flow field, it is often assumed that the density is essentially constant. However, in analyzing high-speed flows, the density variations cannot be neglected. Since density is a function of pressure and temperature, it may be expressed in terms of these two parameters. In fact, for a gas in thermodynamic equilibrium, any thermodynamic property may be expressed as a function of two other independent, thermodynamic properties. Thus, it is possible to formulate the governing equations using the enthalpy and the entropy as the flow properties instead of the pressure and the temperature.

1.2.1 Concept of a Fluid

From the point of view of fluid mechanics, matter can be in one of two states—either solid or fluid. The technical distinction between these two states lies in their response to an applied shear, or tangential, stress. A solid can resist a shear stress by a static deformation; a fluid cannot. A *fluid* is a substance that deforms continuously under the action of shearing forces. An important corollary of this definition is that there can be no shear stresses acting on fluid particles if there is no relative motion within the fluid; that is, such fluid particles are not deformed. Thus, if the fluid particles are at rest or if they are all moving at the same velocity, there are no shear stresses in the fluid. This zero shear stress condition is known as the *hydrostatic stress condition*.

A fluid can be either a liquid or a gas. A liquid is composed of relatively closely packed molecules with strong cohesive forces. As a result, a given mass of liquid will occupy a definite volume of space. If a liquid is poured into a container, it assumes the shape of the container up to the volume it occupies and will form a free surface in a gravitational field if unconfined from above. The upper (or free) surface is planar and perpendicular to the direction of gravity. Gas molecules are widely spaced with relatively small cohesive forces. Therefore, if a gas is placed in a closed container, it will expand until it fills the entire volume of the container. A gas has no definite volume. Thus, if it is unconfined, it forms an atmosphere that is essentially hydrostatic.

1.2.2 Fluid as a Continuum

There are two basic ways to develop equations that describe the motion of a system of fluid particles: we can either define the motion of each and every molecule or define the average behavior of the molecules within a given elemental volume. Our primary concern for problems in this text will not be with the motion of individual molecules, but with the general behavior of the fluid. We are concerned with describing the fluid motion in physical spaces that are very large compared to molecular dimensions (the size of molecules), so our elemental volume will contain