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Nine Decades of Fluid Mechanics

As the ASME Division of Fluids Engineering celebrates its 90th Anniversary, I make a broad-brush sweep of progress in the field of fluid mechanics during this period. Selected theoretical, numerical, and experimental advances are described. The inventions of laser and computer have profound effects on humanity, but their influence on fluid mechanics is particularly elucidated in this review. [DOI: 10.1115/1.4033961]

1 Introduction

The Hydraulic Division of the American Society of Mechanical Engineers was founded in 1926. The division's name was changed to the Fluids Engineering Division (FED) in 1962. Four score and ten years ago was arguably the midst of the fourth golden age of the broad field of fluid mechanics. Nevertheless, more golden ages followed during the period 1926–2016.

The *Journal of Basic Engineering* was established in 1959, and its name was changed to *Journal of Fluids Engineering* in 1972. For 44 years, *JFE* was led by a succession of influential editors, Robert C. Dean, Jr. (founding editor), Frank M. White, Demetri Telionis, Joseph Katz, and, currently, Malcolm J. Andrews, assisted by scores of capable associate editors.

Does the centuries-old discipline still have the audacity to gift future generations? In a recent essay searching for physical analogies between fluid mechanics and quantum mechanics, an MIT applied mathematician, John W.M. Bush, poetically wrote (*Physics Today*, August 2015, pp. 47–53): "If particle physics is the dazzling crown prince of science, fluid mechanics is the cantankerous queen mother: while her loyal subjects flatter her as being rich, mature, and insightful, many consider her to be démodé, uninteresting, and difficult. In her youth, she was more attractive. Her inconsistencies were taken as paradoxes that bestowed on her an air of depth and mystery. The resolution of her paradoxes left her less beguiling but more powerful, and marked her coming of age. She has since seen it all and has weighted in on topics ranging from cosmology to astronautics. Scientists are currently exploring whether she has any wisdom to offer on the controversial subject of quantum foundations."

Two particular inventions accelerated the progress in the art and science of fluid mechanics: the computer and the laser. Their impact will be seen in Secs. 3–5, which discuss in turn the analytical, experimental, and numerical advances in fluid mechanics. Separate sections are devoted to flow control and micro/nanofluidics. The penultimate section is addressed to the students. The coverage is rather selective and by no means is a complete historical account of this lively field. To place the progress during the past 90 years in perspective, we first start with the fluid mechanics prior to 1926.

The reader will notice that there are neither references nor figures. The lack of the latter in particular may unsettle a few, especially for a subject that is so visual. There are two rationales for the omission. One, I would have a hard time picking a reasonable number from the countless available, and two, there is not enough space in this short essay even if I am to select a tiny fraction of what is accessible.

2 Prior to 1926

Arguably, the practice of fluid mechanics began in prehistoric times when Homo sapiens used their instincts and powers of perseverance to evolve airborne weaponry—including streamlined spears, sickle-shaped boomerangs, and fin-stabilized arrows—without the knowledge of air resistance or aerodynamics.

Long before the development of calculus or modern mechanics, Archimedes (287–212 B.C.), the Greek mathematician, provided the original eureka moment by solving the fluid-at-rest problem and developing expressions for the buoyant force on various bodies. At about the same time, the Romans developed the science of hydrostatics as they built a system of aqueducts to bring fresh water into their cities.

Following the collapse of the Roman Empire, a few centuries of scientific dark ages gave way to a deluge of art and science during the Renaissance. With respect to fluid mechanics in particular, Leonardo da Vinci (1452–1519) deduced the equation for the conservation of mass of incompressible one-dimensional flows, pioneered flow visualization techniques, and provided succinct descriptions of laminar and eddy flow in water. Centuries later, these endeavors formed the basis for understanding the physics of some important flow phenomena and theory: Reynolds decomposition, Richardson's cascade, Kolmogorov's equilibrium theory, coherent structures, and large eddy simulations (LES).

It also appears that Leonardo was the world's first scientist to study turbulence. Along with a sketch of a water jet streaming from a square hole into a pool, da Vinci wrote: "Observe the motion of the surface of the water, which resembles that of hair, which has two motions, of which one is caused by the weight of the hair, the other by the direction of the curls; thus the water has eddying motions, one part of which is due to the principal current, the other to the random and reverse motion." (Translated) Thus, Leonardo's description appears to predate Osborne Reynolds's famous turbulence decomposition by nearly 400 years!

Despite these early observations, several hundred more years would pass before fluid mechanics was mathematically formulated. In fact, after the incomparable Newton published his *Principia Mathematica* in 1687, another century and a half passed before the Navier–Stokes equations established the first principles of viscous fluid flows. Unfortunately, these formidable equations have no general solution, even under the assumption of incompressible flow. Thus, further assumptions were made: (i) laminar flow; (ii) simple geometries that rendered the nonlinear terms in the (instantaneous) momentum equation to be identically zero; (iii) creeping flow (low Reynolds number), for which the nonlinear terms are approximately zero; and (iv) high-Reynolds-number inviscid flows, for which the continuity and momentum equations are transposed into the linear Laplace equation.

In the second half of the 19th century, the last assumption spawned great advances in perfect flow theory; yet, this assumption had important limits: the neglect of viscosity yields zero drag for moving bodies and zero lift for lifting surfaces. And, none of the above assumptions is applicable to turbulent flow, with its rotational, time-dependent, and three-dimensional complexities.

As a consequence of these limitations, the science of fluid mechanics was eschewed for practical purposes and instead became the domain of mathematics and physics curricula. Virtually ignoring the elegant theories of hydrodynamics, hydraulic

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engineers of the time used empirical equations, charts, and tables that they developed to compute drag, lift, pressure drop, and other practically important quantities. This pragmatic approach was taught to engineering students, both at the time and for many decades to follow. At the dawn of the 20th century, the hydraulics-versus-hydrodynamics fissure led the British chemist and Nobel laureate Sir Cyril Norman Hinshelwood (1897–1967) to quip: fluid dynamics professionals are divided into hydraulic engineers who observe things that cannot be explained and mathematicians who explain things that cannot be observed.

In 1904, the German engineer Ludwig Prandtl made an epoch-making presentation at the Third International Congress of Mathematicians in Heidelberg that, to a large extent, resolved the above dichotomy. He suggested that the viscous forces would be important only in a thin layer, a fluid boundary layer, adjacent to a moving body. Outside of this layer, the flow would be approximately inviscid. When the Reynolds number is sufficiently high, the boundary layer would be much thinner than the longitudinal length scale and, in turn, velocity derivatives in the streamwise direction would be small compared to the velocity derivatives in the normal direction.

With this single simplification, it now became possible to solve (noncreeping) viscous flow problems, at least for laminar flow, despite the presence of nonlinear terms in the governing equations. Under such circumstances, the momentum and energy equations are both parabolic, rendering them amenable to similarity solutions and marching numerical techniques. A new era ensued: both scientists and engineers embraced viscous flow theory, which enabled them to invoke first principles to calculate such practical quantities as skin-friction drag, even for noncreeping flows. Accompanying these theoretical advances, experiments were conducted in wind tunnels and related setups, providing insight into problems that were too complex for mathematical analysis.

3 Theoretical Developments

3.1 Similarity Solutions. Although the paper that Prandtl wrote (in German of course) for the aforementioned Congress contained a wealth of information—the boundary layer concept itself, the resulting approximations, the mechanics of separation, and the strategies to delay flow separation—a number of years passed before the application of the theory began to spread beyond Prandtl and his small group of students at Göttingen. As a further obstacle, the organizers of the Congress limited Prandtl's manuscript to eight pages, which made reading it difficult indeed.

Just before World War II, and certainly thereafter, the application of the boundary layer theory began to accelerate, at least for researchers. Nonetheless, at most engineering schools, the teaching of hydraulics persisted, and the Navier–Stokes equations received only minimal attention. However, it was not long before a quantum shift in the teaching of engineering undergraduates, especially in the U.S., began to take place: engineering science began to replace engineering technology, and, correspondingly, fluid mechanics began to replace hydraulics. This shift was prompted in part by the 1957 launch of Sputnik 1 and the resulting space race, and by the continuing Cold War between the West and East, in particular, between the U.S. and the now-defunct USSR.

In time, a series of similarity solutions began to emerge—beginning with the Blasius's pioneering work on steady, incompressible, two-dimensional, laminar flow over a flat plate at zero incidence—a trend that continues to the present day. Examples include the Falkner–Skan family of wedge flows; Kármán's three-dimensional flow generated by a rotating disk; and the Illingworth–Stewartson transformation, which reduces the equations for compressible boundary-layer flow to nearly the same form as the equations for incompressible flows. Beyond fluid mechanics, similarity solutions exist for heat transfer and other phenomena for which the governing nonlinear partial differential equations could be rendered parabolic via appropriate approximations.

3.2 Stability Theory. The Orr–Sommerfeld equation, along with suitable boundary conditions, governs the linear stability of laminar, unidirectional, isothermal, and incompressible flows, $U(y)$. Derived from the Navier–Stokes equations by superimposing small, two-dimensional disturbances on the mean flow, it is a linear, fourth-order, ordinary differential equation. Although it is linear, this equation is notoriously difficult to solve analytically.

If viscosity varies in space as a result of, for example, surface heating or cooling, additional terms containing the first and second derivatives of viscosity with respect to y result and one obtains the so-called *modified* Orr–Sommerfeld equation, which is still fourth-order. However, if additional forces (beyond inertial and viscous forces) are included in the momentum balance—for example, streamline-curvature forces and Coriolis forces in the case of a flow generated by a rotating disk—Orr–Sommerfeld can become an even higher-order equation: a sixth-order stability equation for the aforementioned rotating disk.

For Orr–Sommerfeld or similar equations, either the temporal or spatial growth of instability waves is considered as an eigenvalue problem. In the former case, a disturbance oscillates in space but either grows or decays exponentially with time. A complex eigenvalue $c = c_r + i\,c_i$ is determined for each pair of values of the wavenumber α and the Reynolds number Re (both real parameters). The real part of the eigenvalue c_r determines the disturbance's phase velocity, while the sign of the imaginary part c_i determines whether the wave is temporally amplified ($c_i > 0$), temporally damped ($c_i < 0$), or neutrally stable ($c_i = 0$).

However, a more realistic spatial stability problem would involve disturbances that are both temporal (oscillations in time) and spatial (exponential growth or decay as one moves downstream). In this case, a complex eigenvalue $\alpha = \alpha_r + i\,\alpha_i$ is determined for each pair of values of the radian frequency, $\omega = 2\,\pi f = \alpha_r\,c$, and Reynolds number—again, both real parameters. The real part α_r determines the wavenumber, and the sign of the imaginary part α_i determines whether the wave is spatially amplified ($\alpha_i < 0$) or spatially damped ($\alpha_i > 0$).

In either temporal or spatial instability studies, the numerical integration of the Orr–Sommerfeld equation is extremely difficult because the equation is very stiff and unstable; therefore, it becomes essentially impossible to use conventional numerical approaches. Explicit numerical methods with a step size on the order of the solution's global behavior cannot be used to integrate the equation, because of the numerical instabilities that characterize this ordinary differential equation.

Below a critical Reynolds number, $\Re_{\text{crit}}$, one observes a decay of the (linear) perturbations of all wavenumbers. $\Re_{\text{crit}}$, as well as the rate at which perturbations grow, is strongly dependent on the velocity profile $U(y)$. If the profile has an inflection point ($\partial^2 U/\partial y^2 = 0$), then the condition for inviscid instability is both necessary and sufficient. At the wall ($y = 0$), the curvature of such profiles must be positive, because the presence of an inflection point demands that $\partial^2 U/\partial y^2$ must be negative at some point above the wall. If viscous effects were added, the velocity profile would be more stable, because the second derivative of the velocity profile at the wall would be negative, $[\partial^2 U/\partial y^2]_o < 0$. Compared to a velocity profile with an inflection point, the ratio of displacement thickness to momentum thickness would be smaller, leading to an increase of $\Re_{\text{crit}}$, a decrease in the range of amplified frequencies, and a reduction in the amplification rate of unstable waves.

Note that the above discussion regarding the effect of viscosity is true for the inflected velocity profiles. For noninflected profiles such as the Blasius one, the introduction of viscosity is not stabilizing but rather destabilizing, due to a phase shift at the critical layer. The classically over-studied Blasius profile—for flow over a flat plate at zero angle of attack—is at a difficult border in parameter space between favorable and adverse pressure gradient since the inflection point is degenerative at the wall, and it is additionally an extremely difficult choice to study experimentally.

Transition location depends strongly on the freestream turbulence levels and other environmental factors. However, linear stability theory cannot account for any physically significant nonlinear effects in the transition process. Weakly nonlinear stability problems can be solved semi-analytically, but strongly nonlinear situations require numerical treatment.

The Orr–Sommerfeld equation has been known since 1907, and was first solved for a canonical boundary layer about two decades later, resulting in the two-dimensional Tollmien–Schlichting (TS) waves. However, the theory validation, and the existence of the TS waves, transpired two decades later, when a low-noise wind tunnel was constructed at the U.S. National Institute of Standards and Technology (NIST), known at the time as the National Bureau of Standards. The freestream in that tunnel has a very low turbulence level, less than 0.03%. Prior tunnels were too noisy, which overwhelmed the small perturbations inherent in the linear stability theory.

Several other linear and nonlinear stability problems have been solved either analytically or numerically. For example, the instability of certain inviscid, stratified, and rotating flows has been resolved. The stability of both free-shear and wall-bounded flows has been determined for slowly evolving shear layers where $U(x, y)$. Complex spatio-temporal instability problems have been tackled. Even more complex fluid–structure interaction problems (two wave-bearing media) have been approached. The stability problem continues to be an active area of research.

3.3 Energy and Momentum Cascade. Lewis Fry Richardson (1881–1953) developed the idea of an energy cascade, where the kinetic energy enters the turbulence at the largest scales of motion and is then transferred, inviscidly for the most part, to smaller and smaller scales, or eddies, until dissipated at the smallest scale allowed by viscosity. The British meteorologist established the foundation of today's weather forecasting. His methodology had to wait decades for the digital computer to be invented and for its power to increase sufficiently, in order to provide a practical and useful predictive tool.

The universal equilibrium theory of Andrey Kolmogorov (1903–1987) adds to and quantifies the intuitive picture proposed by Richardson. Kolmogorov assumes that if the Reynolds number is sufficiently high, then a range of wavenumbers sufficiently removed from the energy-containing eddies exists. For these wavenumbers, the directional biases, as well as geometry information of the large scales, are lost in the chaotic scale-reduction process. In other words, for all high-Reynolds-number turbulent flows, the small scales are statistically isotropic as well as similar (universal).

Without a doubt, the two greatest achievements of turbulence theory in the 20th century were: (i) the above universal equilibrium theory of Kolmogrorov, and (ii) the universal logarithmic law of the wall, developed by Prandtl, Taylor, Kármán, Izakson, and Millikan. Whereas, the former deals with a hierarchy of eddies leading to an energy cascade and an inertial subrange in the spectral space, the latter deals with a cascade of momentum toward the viscous sink at the wall and an inertial sublayer in the physical space. Yet, both of these high-Reynolds-number asymptotic descriptions are directly analogous. For both, if the Reynolds number is sufficiently high, the overall flow dynamics is presumed to be viscosity-independent. Recent findings challenge this assumption at any finite Reynolds number. Second- and higher-order corrections to the first-order results have been proposed.

3.4 Matched Asymptotic Expansions. Matched asymptotic expansion is a modern method used to find an accurate approximation to the solution of an equation, or a system of equations. Actually, several different approximate solutions, each of which is accurate for a limited range of the independent variable, are generated. Then, these different solutions are combined to obtain a single solution that is approximately accurate for the entire range. The "father" of that fascinating tool is Milton D. Van Dyke (1922–2010), although many researchers have added significant contributions in fluid mechanics as well as in a variety of other fields.

Usually, a matched asymptotic expansion is used to solve a singularly perturbed differential equation, particularly one in which the domain can be divided into multiple subdomains. In (usually) the largest of these, the solution can be approximated accurately by an asymptotic series, which can be created when the problem is treated as a regular perturbation (i.e., a relatively small parameter is set to zero). However, in the other subdomains, the same approximation is inaccurate, because the perturbation is generally non-negligible in those regions. These regions are referred to as transition layers, which may be interior layers or boundary layers depending on whether they occur inside the domain or at the domain's boundary (the most usual case). In the transition layer(s), another approximation, also in the form of an asymptotic series, is obtained by treating it as a separate perturbation problem. This approximation is called the "inner solution" to distinguish it from the solution in the largest subdomain, known as the "outer solution." Finally, the inner and outer solutions are combined through a "matching" process, thereby generating an approximate solution for the entire domain.

Numerous fluid mechanics problems—as well as aero- and hydroacoustics, heat transfer, combustion, and phase-change problems—have been solved using matched asymptotic expansions applied to the nonlinear Navier–Stokes and other laws of nature. To this day, new solutions using this powerful analytical tool are being discovered.

3.5 Nonlinear Dynamical Systems Theory. The "butterfly effect," an important tenet of dynamical systems theory, refers to the sensitivity of a nonlinear differential equation to its initial conditions. For such equations, a small change in the initial conditions can result in an exponential separation of the solution within its phase and space domains. When a nonlinear dynamical system contains at least three degrees-of-freedom, its solution may take the form of a strange attractor, which manifests a well-defined mechanism that produces chaotic behavior in the absence of any random forcing. Although chaotic behavior is deterministic, it appears to be random, in addition to being complex and aperiodic.

Given this behavior, it is natural to ask the following question: if small disturbances can grow radically within a deterministic system and generate unpredictable chaotic behavior, could a system parameter be adjusted slightly to reverse the process, thereby controlling the chaos? Recently, this question was answered in the affirmative, both theoretically and experimentally, at least for strange attractors of low-dimension. Therefore, as a first step in applying strategies of chaos control to turbulent flow, we will examine some recent attempts to represent turbulent boundary layers by constructing low-dimension dynamic-systems.

Because turbulence in a boundary layer is described by a set of nonlinear partial differential equations, it is characterized by an infinite number of degrees-of-freedom, which makes it difficult to use a dynamic systems approximation to model the turbulence. However, once one realizes that a seemingly random turbulent shear flow is dominated by quasi-periodic coherent structures, it is natural to suggest that an infinite-dimension flow can be decomposed into a number of low-dimension subunits. This implies that the low-dimension, localized dynamics can exist in a system that formally is infinite-dimensional.

By reducing the flow physics to a finite-dimensional dynamical system, the behavior of the system can be studied by examining the flow state near unstable fixed points in the low-dimensional state space. An intermittent event that produces high wall stress—a burst—can be interpreted as a jump along a heteroclinic cycle to a different unstable fixed point, which occurs when the state wanders too far from the first unstable fixed point. If this jump can be delayed by maintaining the system near the first point, momentum transport in the wall region should be reduced, leading to lower skin-friction drag. Thus, to achieve reactive control, one would sense the current local state and then apply an appropriate manipulation to keep the state close to a given unstable fixed point. In this way, the further production of turbulence could be prevented. A reduction in the bursting frequency, by say 50%, could lead to a comparable reduction in skin-friction drag.

In one significant attempt, a group at Cornell University used the proper orthogonal, or Karhunen-Loève, decomposition method to extract a low-dimension dynamic system from the experimental data of the wall region. In this attempt, the instantaneous velocity field of a turbulent boundary layer was expanded by using a set of optimally chosen, orthogonal, and divergence-free eigenfunctions (determined experimentally) in the form of streamwise rolls. Using these functions, the Navier–Stokes equations were expanded, a Galerkin projection was applied, and the infinite-dimensional representation was truncated to a finite set of ordinary differential equations (ten-dimensional). These equations, which represent the dynamic behavior of the streamwise rolls, have been shown to exhibit both a chaotic regime and an intermittency caused by a burstlike phenomenon. Unfortunately, the intermittency displayed by this system of equations is *regular*, in contrast to both: (i) the intermittency actually displayed in turbulence and (ii) the chaotic intermittency found in other nonlinear dynamic systems that exhibit stochastically distributed event durations. Despite these inconsistencies, the Cornell study concludes that, even in the absence of turbulence, the wall region can produce bursts autonomously, because the turbulent pressure signals at the wall can be triggered by the outer layer. Recently, a second Cornell group generalized the first group's approach by adding cross-stream disturbances to the streamwise disturbances and permitting both to evolve in an uncoupled fashion. Based on these results, it appears that the roots of the intermittent events exhibited in the original representation arise from deep within the dynamic phenomena near the wall, rather than solely from the incorporation of the effective-closure assumption.

Whereas, the above viewpoint is reductionist, other attempts have sought a more direct approach in determining the dimension of the attractors that underlay particular turbulent flows. As before, the central question remains: can asymptotic descriptions of turbulent solutions be found, such that a system of equations with a finite number of degrees-of-freedom can replace the Navier–Stokes equations, which has an infinite number of dimensions?

Even in wall-bounded flows, the dimension is still dauntingly high, and it appears that: (i) periodic turbulent shear flows are deterministically chaotic and (ii) a strange attractor does underlie solutions to the Navier–Stokes equations. Thus, the temporal unpredictability one finds in, say, a turbulent Poiseuille flow is due to the fact that such attractors have a tendency to spread exponentially. Although the computed dimension is finite, the idea that the global turbulence can be attributed to the interaction of a *few* degrees-of-freedom is not valid. Moreover, in a boundary layer, the flow is not periodic. Nonetheless, although the dimension of the attractor in this case is not known, it is believed to be even higher than predicted for a periodic flow.

According to one estimate, the colossal amount of data needed to measure the attractor dimension D (approximately 10^D) exceeds the capability of current computers. Although the prospects appear bleak, there are some exceptions. For turbulence near a wall or near transition, the number of modes excited is relatively small, and a dynamic system with a reasonable number of degrees-of-freedom can be used to describe the *simple* turbulence that results.

4 Experiments

4.1 Coherent Structures. The recognition of coherent structures during the last few decades brought us back a full circle to the time of Leonardo: (i) visualization emerged once again as the method of choice for major discoveries and (ii) the importance of eddying motions and the co-presence of large, organized motions and small, random motions were reaffirmed. In the face of apparent disorder, our desire to find order is embodied by the search for coherent events.

Despite this search, as evidenced by extensive research efforts in the field of turbulence, no definition of coherent motion has been universally accepted. In physics generally, we speak of coherence when talking about a phase relationship that is well defined. However, with respect to turbulence, our view of coherence—that, essentially, turbulence is a statistical phenomenon in which a well-defined average flow has random fluctuations superimposed upon it—is changing. We now realize that the turbulent shear flows are characterized by transport properties dominated by vortex motions that are both large in scale and quasi-periodic.

We provide here two rather different views of coherence, the first is general and the second is more restrictive:

(1) General: within a three-dimensional flow, a coherent motion is one in which: (i) at least one fundamental parameter (velocity, density, temperature, etc.) correlates significantly with either itself or another parameter and (ii) the scale of space and/or time over which this correlation occurs is much greater than the smallest local flow scales.
(2) More restrictive: a coherent structure is an interrelated mass of turbulent fluid with an instantaneous vorticity that is phase-correlated over its spatial extent. In other words, a component of large-scale vorticity: (i) underlies the random, smaller-scale, and three-dimensional vorticity that is known to characterize turbulence and (ii) is coherent instantaneously over its spatial extent. For the most part, the flow's apparent randomness is caused by randomness in the size and strength of various types of organized structures that comprise the flow.

Several other definitions have been catalogued, providing a cook-book-style approach to the identification of coherent structures, using a variety of classical and modern strategies. For example, proper orthogonal decomposition is one of the tools used to identify coherent structures. Here, it is challenging to find a coherent structure that is hidden within a random background, especially when that structure is present within either a visual representation of the flow or an instantaneous signal (of velocity, temperature, or pressure). This is of course not a trivial task, and the ancient Hindu fable—in which six blind men, each from his own limited perspective, attempt to identify what an elephant looks like—immediately comes to mind. The issue is complicated by the fact that coherent structures change, depending on the type of flow; even when the type of flow is the same, coherent structures depend on the initial conditions and the boundary conditions. Because the largest eddies have scales that are the same size as that of the flow, the use of proper orthogonal decomposition for identifying coherent structures cannot be universal.

Identifying a coherent structure based on certain dynamical properties is more likely to succeed, but is quite involved. On the other hand, a kinematic detector based on its creator's perception of the dynamic behavior of the organized motion is simpler to employ but runs the risk of detecting the presence of nonexistent objects. Quadrant analysis (QA) and variable-interval time-averaging algorithm are two examples of effective kinematic detectors.

4.2 Hot-Wire Anemometry. Although the governing heat transfer law, King's law, was known since 1914, the tool to measure velocity, temperature, or concentration fluctuations in a turbulent flow did not become sufficiently accurate, wide-spread, affordable, and practical for decades to come. Hot-wire anemometers (HWA) use fine (several micrometers) metallic wires, often tungsten, that are heated electrically above ambient temperature. The wire cools as fluid flows past it. Because the electrical resistance of the metal wire depends on its temperature, a relationship exists between the wire's resistance and the velocity of the fluid. The signal is also sensitive to temperature and species concentration, and attempts must be made to separate the effects.

Advances in feedback electronic circuitry during the 1950s—essentially removing the inherent instability of the feedback system—allowed hot-wire anemometry to progress from constant-current to constant-temperature operation mode. Today, hot-wires with as much as 12 sensors are used to measure all three of the velocity and vorticity components. That complex task requires a powerful computer to acquire as well as analyze the data. Rakes of hot-wires are used for the simultaneous measurements of entire velocity profiles. Turbulence in liquid, high-speed, and two-phase flows could be accurately measured, if the physics involved are adequately understood. Regions of reverse flow or high turbulence level require specialized arrangements as conventional HWA is incapable of discerning flow direction. Temperature and species concentration fluctuations could also be discerned with careful manipulation of the hot-wire data.

4.3 Flow Visualization. Flow visualization, the most dominant tool used to address complex fluid flows, is responsible for many of the most exciting discoveries. By enabling the global behavior of the flow to be perceived visually, in a manner that is relatively quick and simple, flow visualization has the potential to provide invaluable qualitative and quantitative information regarding the flow dynamics. Prior to the invention of the laser, food-color dye or smoke were used in, respectively, liquid or gas flows to observe the outer shell of a flow field. Flood lights were the typical tool used for illumination.

Flows with density variations—for example, nonisothermal or high-speed flows—can benefit from the use of different types of optical techniques. Because interferometers respond to differences in the length of the optical path, the fluid density at various places in the flow can be determined (because the index of refraction varies directly with density). Other systems respond to the first or second derivative of the index of refraction (and thus the density): (i) when the light beam of a Schlieren system is normal to the flow, the system responds to the first derivative and (ii) when the light beam is normal to the optical path, a shadowgraph responds to the second derivative. (Essentially, the shadowgraph image displays the Laplacian of the fluid density along the line-of-sight.) However, as these techniques result in the projection of a three-dimensional field onto a two-dimensional plane, it is not possible to recover spatial structures from a single image; thus multiple views are often compiled, along with the use of tomographic reconstruction methods.

4.4 Laser-Induced Fluorescence. The acronym "LASER" stands for light amplification by stimulated emission of radiation. Although its theoretical foundation was established by Albert Einstein in 1917, it was not until 1960 that the first visible-light laser was actually constructed. Numerous industrial, medical, and scientific applications have been successfully demonstrated since then. Three in particular are relevant to fluid mechanics: flow visualization, laser Doppler, and particle tracking.

The laser-induced fluorescence (LIF) flow visualization technique was introduced about two decades after the invention of the laser. At that point, such light source had become quite affordable. LIF is now routinely used in numerous laboratories around the world, for both gas and liquid flows. The novelty lies in the ability to generate a very thin sheet of laser light in order to be able to see one plane at a time, and the use of extremely small amounts of fluorescent dye so not to make the fluid's interior opaque, except of course in the excited plane. Among the technique's advantages are its high signal-to-noise ratio and its ability to dissect the flow field, as a CAT scan would for solid or opaque objects. Different fluorescent dyes could lead to multicolor visualizations. Dye mists make the LIF technique accessible to gas flows.

A laser sheet can be generated readily from a beam of light using either a cylindrical lens or a rapidly oscillating mirror. The latter choice is more expensive but provides a better-quality sheet of light. Optical arrangements could readily make light sheets a few micrometers in thickness. Multiple sheets could be generated either simultaneously or in rapid succession.

4.5 Laser Doppler Velocimetry. Laser Doppler velocimetry (LDV), known also as laser Doppler anemometry, represents another important application of the laser to fluid mechanics. In LDV, moving particles within a fluid cause a Doppler shift in the laser beam, which can be used to measure the velocity in fluids that are transparent or semi-transparent. It also can be used to measure linear or vibratory motion on the surface of reflecting bodies of liquid. These measurements require sufficiently small particles to be seeded in the flow, in order to follow the fast-changing small eddies associated with turbulence. When the size of the particles is greater than the wavelength of the light, Mie scattering of light occurs.

A reference beam interferes with the Doppler-shifted beam to provide the instantaneous velocity of the seed particles. Either forward or backward scattering is used to achieve the desired signal; however, the light intensity is weaker in the backscattered mode than in the forward-scattered mode by approximately two orders of magnitude. Thus, for backscattering, a high-powered laser and a larger receiving lens are needed to obtain an adequate signal. The advantages of this technique is that it provides absolute noninvasive[1] measurement, is linear with velocity, and needs no precalibration. LDV can be used even in reverse or high-turbulence-level flow regions. These are all advantageous relative to hot-wire anemometry, although HWA is more affordable than LDV.

4.6 Particle-Image Velocimetry. In particle-image velocimetry (PIV), a light beam is projected, usually within a single plane, to illuminate small particles—either gaseous bubbles, immiscible liquid droplets, or solid particulates—seeded in a fluid. The light scattered off the particles is imaged on a photographic film, a video array detector, or a hologram. Subsequent analysis can yield the path length and orientation of the imaged particles, leading to global information regarding instantaneous velocity and vorticity.

Although PIV has been known for about a century (in rather primitive forms), its major drawback involved the huge amount of labor needed to yield adequate spatial and temporal resolution, particularly for unsteady flows. More recently, the advent of modern image processing techniques, enabled by powerful computers, encouraged many researchers to revisit PIV. Now, due to rapid developments in the 1980s, PIV can provide accurate, high-quality measurements in laboratory facilities. Field applications are less common but also feasible. Stereoscopic and holographic capturing allow measurements in all three dimensions.

4.7 Holographic Imaging. In holography, a laser beam is split into two parts: the first is used to illuminate an object and the second (a reference beam) is superimposed on the light scattered from that object. The two beams generate an interference pattern that is recorded on a transparent light-sensitive emulsion, which, when developed, produces a hologram, a series of light and dark fringes that contain the complete optical information. To recover this information, another laser beam is used to illuminate the hologram. The light from this laser beam, delivered at the same angle of incidence as the original reference beam, is diffracted by the light and dark fringes on the hologram. A pattern of diverging and converging wave fronts results, with the former appearing to come from a virtual image behind the hologram, while the latter appears to form a real image of the object on the opposite side.

[1]Note however, that the requirement for high-powered lasers when investigating slow liquid flows has been observed to heat the fluid sufficiently to add disrupting buoyancy effects.

These wave fronts are identical to those scattered by the original object.

Holography is a complete measurement system for recording and reconstructing light waves, thereby enabling the color, scale, and three-dimensional images of a flow field. The process described above is used for static holography. Dynamic holography is needed for fluid mechanics applications. Real-time holograms require a different arrangement such as phase-conjugate mirrors, image processing, and optical computing.

5 The Computer

The digital computer is arguably one of the most profound inventions in all human history. Its rate of progress and affordability are also a reminder of human's ingenuity and power to improve. The invention of the computer is perhaps up there with the discovery of fire, the wheel, the printing press, and the steam engine. While the computer has played a major role in all science and engineering disciplines, and in fact in all other human endeavors, it has been especially important in fluid mechanics, where it plays a crucial role in the acquisition of the massive data generated from the instruments described earlier. Other crucial roles involve the numerical integration of the Navier–Stokes equations and related, often more complicated, laws of nature.

5.1 Numerical Simulations. In principle, practically any laminar flow problem—with the exception of less conventional flows such as those involving non-Newtonian fluids, multiphase flows, hypersonic flows, chemically reacting flows, and geophysical and astrophysical flows—can be solved, at least numerically. In contrast, turbulent flows remain perplexing and analytically unapproachable; nonetheless they are very important in practical applications. But even for a time-dependent laminar flow, there remains the practical difficulty of completely defining the physical problem, which may include initial conditions and time-dependent boundary conditions.

For a turbulent flow, the dependent variables are random functions of space and time, and any statistical approach to solving the nonlinear, partial differential Navier–Stokes equations always leads to more unknowns than equations (the closure problem). Moreover, solutions based on first principles again are not possible. Although heuristic modeling sometimes can be used to close the equations when they are Reynolds-averaged, this approach requires validation on a case-by-case basis; as such, its advantage over old-fashioned empirical approaches is questionable.

5.2 Turbulence Simulations. From the time that Leonardo da Vinci compared the motion of a water jet streaming into a pool to the curls and waves of hair (see Sec. 2), the field of turbulence has been blessed with stunning images, intellectually fascinating physics, and elegant mathematics, not to mention the vitally important applications. Its significance at human, geologic, and cosmologic scales cannot be overstated. In a plasma, turbulent transport sustains nuclear fusion, the process that keeps the stars alive; in the atmosphere, vigorous turbulent mixing prevents megacities from suffocating from human-produced carbon dioxide; and turbulent boundary layers allow airfoils to generate more lift at larger angles of attack than a corresponding laminar flow. But turbulence has a dark side as well. Turbulence is the main culprit behind the high fuel consumption of all air, land, and sea transportation systems. Plus, its extreme complexity can be chilling for both students and professionals.

As a result, turbulence is an enigma that apparently yields its secrets only during experiments, both physical and numerical, provided that one can fully resolve the wide band of relevant scales—which, at high Reynolds numbers, is easier said than done. In fact, the direct numerical simulations (DNS) of the canonical turbulent boundary layer that have been conducted to this point, at great cost despite a bit of improvising, have been limited to flows with only a very modest momentum-thickness Reynolds numbers (a few thousand).

In a turbulent flow, the ratio of the size of large eddies (to which the energy that maintains the flow is delivered) to the Kolmogorov microscale (the smallest length-scale in a flow) is proportional to $\mathrm{Re}^{3/4}$. Because at least one grid point is required to describe each excited eddy, the required number of modes should be proportional to $(\mathrm{Re}^{3/4})^3$, in order that a three-dimensional flow can be resolved using DNS. In addition, the time step must be no greater than the ratio of the Kolmogorov lengthscale to the characteristic root-mean-square (RMS) velocity; otherwise it would not be possible to describe how small eddies move under the influence of large ones. On the other hand, because the time scale for the evolution of large eddies is proportional to their size divided by their RMS velocity, $\mathrm{Re}^{3/4}$ again represents the number of time steps needed to resolve their motion. Finally, the number of computations needed is found by multiplying the number of modes by the number of time steps, which is proportional to Re^3. The upshot of all these time-step calculations is that every doubling of the Reynolds number will require an increase in computer power of an order of magnitude. Such a huge increase in computational resources means that the direct simulation of turbulent flows at very high Reynolds numbers may not be possible in the near future.

Although the above assessment is bleak, one can image a time, perhaps during the 21st century, when gigantic computers combine with sophisticated software to routinely solve practical turbulent flow problems via DNS. In this imaginary scenario, an operator would be prompted by a black box for the geometry and flow conditions, and then the box would spit out the numerical solution to a specific engineering problem. Except for the software developers, no one would need to understand the operations inside the black box, including what equations are being solved—a situation reminiscent of today's use of word processors or even hand calculators. Analogous to the inability of many users of hand calculators to manually perform long division, a generation of users of the Navier–Stokes equations would quickly lose the aptitude and desire to apply physical considerations in performing simple analyses. Gradually, the ability to perform rational approximations, which today is so prevalent in the teaching and practice of fluid mechanics, would wither. Despite its inevitability, the author does not look forward to such an outcome.

During the late 1990s, the number of floating-point operations per second (flops) achievable by supercomputers approached teraflop levels (10^{12} flops), approximately the right amount of power to compute fluid flows with a characteristic Re of 10^8, such as the flow around an airfoil using DNS, the flow around a wing using LES (Sec. 5.3), or the flow around an entire commercial aircraft using Reynolds-averaged calculations. Although petaflop power (10^{15} flops) was reached in 2008, exaflop power (10^{18} flops) will be needed to resolve the flow around a complete airplane using DNS. Although exascale computing has become a recent near-future goal for the U.S., fluid mechanics problems are not among the top priorities for such a computer. National security, energy, and astrophysical calculations take more prominent positions on the waiting list. Fluid mechanicians: take a number!

5.3 Large Eddy Simulations. The DNS discussed in Sec. 5.2 have limits. The feasibility of using DNS—which involve the integration of the full nonlinear, time-dependent Navier–Stokes equations, without any assumptions of empirical closure—is limited to a few simple geometries and low-Reynolds-number flow. Although DNS provide a complex space–time history of a turbulent flow field, in practice, they are strongly constrained by computer power and algorithmic limitations.

Consequently, LES have emerged as an alternative to DNS. In LES, the flow field is split: for large-scale turbulence, three-dimensional, time-dependent computations are performed; the smallest scales are modeled as high-Reynolds-number flows. A number of numerical methods are used to integrate the governing equations—including spectral, finite-difference, finite element, and boundary-element methods—each of which has its own advantages. For example, spectral methods are very accurate, while finite-difference and finite element algorithms—in boundary-fitted nonorthogonal coordinates—are more suited for complex geometries and are more easy to setup. For all of these methods, the ultra high-speed and memory of supercomputers are needed; however, such calculations are largely the province of academic research, because the expense and time requirement are too large for practical engineering applications.

After a flow field is obtained numerically, the digital data could be processed directly with the same image processing tools—e.g., volume rendering, motion pictures—now used for experimental data. Flow visualizations based on numerical simulations enable a fast and direct comparison with physical experiments. A final note, improvements in algorithm accuracy and efficiency have been as dramatic as improvements in serial-computer hardware speed. Additionally, improvements in the parallel-processing speed typically involve tradeoffs in algorithm efficiency.

6 Flow Control

The ability to manipulate a flow field to effect a desired change is of great technological and financial importance. Effective flow-control systems could save billions of dollars in annual fuel costs for land, air, and sea vehicles, reverse or slow down global warming, and achieve more efficient industrial processes involving fluid flow. Such potential benefits may account for the fact that flow control is pursued by scientists and engineers more than any other fluid mechanics subject. However, the control of a turbulent flow is particularly difficult. This section provides a broad overview of that subject, in the context of the wider field of flow control.

One chooses a particular control strategy as a function of the characteristics of the flow and the control goal that is sought. The characteristics of the flow may involve the presence or absence of walls, the size of the Reynolds and Mach numbers, and the character of the flow instabilities, all of which are important considerations for the type of control to be applied. The flow control goals—such as reducing drag or enhancing lift—are often strongly interrelated and can be conflicting; hence, tough compromises must be made. All of these seemingly disparate issues are exhaustively covered in the book *Flow Control* by this author.

When attempting to manipulate a particular flow field, an engineer typically aims to reduce drag; enhance lift; augment the mixing of mass, momentum, or energy; suppress flow-induced noise; or achieve a combination of these goals. Whether the flow is considered to free-shear or wall-bounded, the achievement of any of these end results may require: (i) that the transition from laminar to turbulent flow be delayed or advanced; (ii) that flow separation be prevented or provoked; and (iii) that turbulence levels be suppressed or enhanced. Although none of the above goals, or the flow changes intended to effect them, are particularly difficult in isolation, they are interrelated. Hence, the challenge to achieving the goal(s) is to not only to use a simple device that is inexpensive to build and operate but also, and most importantly, to minimize the consequences of "side effects." To achieve this last hurdle, it is important to understand the interrelation between control goals. In the following paragraphs, we attempt to provide this understanding, using boundary-layer flow as an example.

An external wall-bounded flow, for example, one that develops on the exterior surface of a wing, can be manipulated to achieve all of the aforementioned goals: delay of transition, postponement of separation, increase in lift, reduction in skin-friction and pressure drag, suppression of noise, enhancement of mixing, and augmentation of turbulence. These goals are not necessarily mutually exclusive: when the boundary layer becomes turbulent, its resistance to separation is enhanced and the wing can achieve more lift at increased incidence.

On the other hand, the above goals are interrelated, which can be seen by considering how lift and drag are affected by the transition to turbulence (keeping in mind that one usually seeks to improve an airfoil's performance by increasing the lift-to-drag ratio). First, we point out that the skin-friction drag for a laminar boundary layer can be as much as an order of magnitude less than that for a turbulent boundary layer. Thus, if we delay transition, we can achieve lower skin friction (with lower flow-induced noise as a bonus). However, a laminar boundary layer can support only very small adverse pressure gradients without separation; a slight increase in angle of attack, or some other provocation, can cause the boundary layer to detach from the surface of the wing, with an accompanying decrease in lift and increase in form drag. Once the laminar boundary layer separates, a free-shear layer forms, and a transition to turbulence occurs, even for moderate Reynolds numbers. Then, turbulent mixing can cause increased fluid entrainment, resulting in the reattachment of the separated region and the formation of a laminar separation bubble. At higher incidence, the bubble breaks down (either separating completely or forming a longer bubble), which causes the drag to increase and the lift to decrease.

The above discussion illustrates what can happen when an attempt to achieve a particular control goal adversely affects another goal. In fact, no ideal method of control—i.e., one that is simple, is inexpensive to build and operate, and does not have any tradeoffs—exists; hence, continuous compromises must be made and accepted, in order to achieve a particular design goal.

Once this need to compromise is understood, engineers can get down to the business of implementing flow control solutions. Flow control is most effective when applied near transition or separation points, where flow instabilities can quickly become magnified. At such points, the delay or advance of laminar-to-turbulence transition and the prevention or provoking of separation are relatively easy to accomplish. A more challenging problem would involve an attempt to reduce skin-friction drag in a nonseparating turbulent boundary layer, where the mean flow is quite stable. Nonetheless, any attempt to achieve even a modest reduction in fluid resistance is well worth pursuing. For example, a small reduction in drag on airplanes in the worldwide commercial fleet could translate into annual fuel savings of billions of dollars. Therefore, new ideas for turbulent flow control are always being sought; one new approach focuses on the targeting of coherent structures, which are quasi-periodic, organized, large-scale vortex motions embedded in a random, or incoherent, flow field.

Another factor that engineers must consider involves the different levels of "intelligence" that can be incorporated into a particular control system. Control systems can be passive, requiring no control loop or auxiliary power, or active, requiring a control loop and an expenditure of energy. Manufacturing a wing with a fixed streamlined shape is an example of passive control. Active control is further divided into predetermined control and reactive control:

(1) Predetermined control involves the application of a steady or unsteady energy input, without regard to the particular state of the system, for example, a pilot engaging the wing's flaps for takeoff. In this case, the control loop is open, and no sensor information is fed forward; i.e., this open control loop is not a feedforward control loop, a subtle point that often gets confused, thereby blurring the distinction between predetermined control and reactive, feedforward control (discussed next).
(2) Reactive, or "smart," control allows designers to pursue their ultimate goal of autonomous control (that is, without human interference). In reactive control, the control input is continuously adjusted based on some type of measurement. The control loop can be an open feedforward loop or a closed feedback loop. In feedforward control, the measured variable and the controlled variable can be different. For example, a sensor may detect the pressure at an upstream location, and the resulting signal could be used to actuate a shape change that in turn influences the shear stress (that is, skin friction) at a downstream location. On

the other hand, feedback control requires that the controlled variable be measured, fed back, and compared with a reference input. An example of reactive control is the use of distributed sensors and actuators on a wing's surface to detect certain coherent flow structures and, based on a sophisticated control law, subtly morph the wing to suppress those structures and thereby dramatically reduce skin-friction drag.

In the future, the merging of a number of disciplines—the science of chaos control, the technology of microfabrication, and "soft computing" computational tools—could greatly benefit the control of turbulent flows in general and turbulent boundary layers in particular:

(1) The control of chaotic, nonlinear dynamic systems has been demonstrated, both theoretically and experimentally, even for systems with multiple degrees-of-freedom.
(2) Microfabrication is an emerging technology with a potential to mass-produce small (few micrometers) inexpensive, programmable sensor/actuator chips.
(3) In the last few years, soft computing tools—including neural networks, fuzzy logic, and genetic algorithms—have advanced and become more widely used; these tools could be very useful in the construction of effective adaptive controllers.

Futuristic control systems based on advances in the above fields are envisaged as consisting of a colossal number of microfabricated wall sensors and actuators, all intelligent and interactive, targeted toward organized structures that occur quasi-randomly (or quasi-periodically) within a turbulent flow. In operation, the sensors would detect these organized structures, adaptive controllers would process the data from the sensors, and actuators would receive control signals from the controllers and attempt to favorably modulate the quasi-periodic events. Although, by definition, a finite number of wall sensors can perceive only partial information about a flow field, the utility of this partial information can be maximized by employing a low-dimension dynamic model of the near-wall region, such as that used in a Kalman filter. While this scenario may not be too difficult to conceptualize, in practice, the complexity of such control systems is daunting, and much research and development work remains.

7 Micro- and Nano-fluidics

With the advent of micro- and nano-electromechanical systems (MEMS and NEMS) comes the new fluid mechanics branches of micro- and nano-fluidics, along with the attendant question: how should fluid flows at the micro- and nano-scales be modeled? Traditional fluid mechanics assumes that the flow is a continuum and in a quasi-equilibrium thermodynamics state. This assumption implies: (i) that all flow parameters—such as velocity, pressure, density, and temperature—are continuous, infinitely differentiable functions of space and time; (ii) that linear relationships exist between such parameters as stress and rate-of-strain, heat flux and temperature gradient, etc.; and (iii) that the no-slip and no-temperature-jump boundary conditions exist between a wall and fluid. Those restrictions break down for non-Newtonian fluids, for rarefied gases, and for flows at the microscale and nanoscale, where the number of molecules in the smallest control volumes is insufficient to avoid statistical chaos.

In such cases, one has to revert to molecular-based models using, for example, computer-intensive molecular dynamics simulations. For gases, one has to deal with the problem using statistical mechanics tools such as the unsolvable Liouville equation or, for dilute gases, the more restricted but at least approachable Boltzmann equation. For molecular dynamics simulations, a potential between molecules must be chosen, and quantum mechanics calculations may be needed to chose that potential rationally. Such calculations are extremely computer intensive, and make the DNS of the Navier–Stokes equations pale by comparison.

Another complication in micro- and nano-fluidics is the possibility of having to consider the flow compressible, even for extremely small Mach numbers. This is particularly evident in small channels where a large pressure drop is needed to drive the flow. A corresponding large change in density, from the inlet of a micro- or nano-channel to its outlet, makes it difficult to justify an assumption of constant-density, and the flow must be treated as compressible.

The subfield of micro- and nano-fluid mechanics, which commenced only in the early 1990s, is currently an active area of research. The modeling of these flows was initially difficult because the similarities between microflows and rarefied gas dynamics were not obvious in the beginning. In addition, experiments with microdevices have proven to be notoriously difficult. Pressure transducers have to be built in situ as microchannels are fabricated, and μPIV and μbalance systems have to be developed. Plus, the measurement of flow rates in the micro- or nano-liter range is far from trivial. Finally, scanning electron microscopes or similar devices are needed to even see the details of MEMS and NEMS.

8 Students Only

We are all students of the cantankerous queen mother. However, this section is for only the eyes of "real" students. It is a bit preachy, but hopefully not patronizing. The section's sole aim is to share with the younger generation a few of the lessons learned, mostly the hard way, by one of the older generation.

When encountering a new problem to solve, read all you can about that subfield. This in itself is an art. If you conduct a literature search, you will be overwhelmed by the number of available articles and books. Learn how to narrow that number to a manageable level. Boolean searches, with their "AND," "NOT," and "OR" operators, could further narrow your search to more relevant results. There is a risk here of missing an important publication, but that risk has to be managed as well. Be skeptical, but not cynical, about at least some of what you end up reading. I would recommend the students to read thoroughly a few of the original papers in one's area of speciality. Such articles, for example, the one by Lewis Fry Richardson mentioned earlier, give unique insight and perspective.

Now that you are ready to start your own research, what tools are you going to use in order to successfully complete the task? Any tool you decide to employ has its advantages, disadvantages, and limitations. So, you have to spend more time investigating the chosen tool(s). Below, I provide three examples of possible pitfalls: (i) the use of HWA; (ii) the interpretation of flow visualization results; and (iii) the numerical integration of the governing equations. Numerous other examples are available in the open literature.

When using a HWA, which is now considered a straightforward instrument, ask what the recorded signal means. Is the hot-wire measuring velocity, temperature, or concentration fluctuations? Is the length-to-diameter ratio adequate to alleviate the prongs' effects? Does heat transfer to the wall need to be taken into consideration? Is the signal resolving the smallest scales of interest; in other words, do you have sufficient temporal and spatial resolutions? What happens when a hot-wire is used in a hypersonic flow or in a microchannel? I know of a student who constructed the first μHWA. The student was very excited when the new device recorded a random signal in a microchannel flow. Unfortunately, as it turned out that signal was not even remotely related to the velocity.

The visualization of unsteady flows can be confusing, particularly with respect to the various kinds of flow lines that one can observe, including pathlines, streamlines, and streaklines:

(1) A pathline is the locus of points traversed by a particular fluid particle in the flow field as a function of time. It also is known as the particle path.
(2) A streamline is the locus of points at which the magnitude of the velocity is the same. Also, at all points in the flow field, streamlines are tangential to the instantaneous direction of the velocity.

(3) A streakline (called a filament line in some references) is the instantaneous locus of all fluid particles that have passed through a particular fixed point within the flow. (Picture a tracer introduced continuously into the flow field at a point source.) In a steady flow, all three of the above lines coincide; however, this is not the case for a time-dependent flow.

At the risk of adding even more confusion, a time line is different than all three of the above lines. It is produced by injecting a tracer, in a single instant, from a line source that is transverse to the freestream direction. At a later time, the shape and location of the time line will likely have changed. By generating a series of time lines at a given rate, several consecutive rows of tracers can be produced. Then, a velocity distribution can be determined by measuring the distance between two consecutive lines at various points in the flow. In addition to velocity distributions, timelines are used to reveal flow fluctuations.

In 1962, Francis R. Hama provided a convincing example of possible pitfalls in the interpretation of flow visualization results when the flow field is unsteady. He generated pathlines, streamlines, and streaklines numerically for a shear layer flow perturbed by a traveling sinusoidal wave of neutral stability. He observed that the pattern of streamlines was dramatically different, depending on whether the lines were recorded with a moving camera or with a camera at rest in the laboratory frame. Another anomaly occurred with respect to streaklines: when dye was injected near the critical layer (where the flow speed equals the wave speed), the streaklines appeared to amplify and roll, suggesting that the flow had developed into discrete vortices. In fact, no discrete vortices existed anywhere in the flow, leading Hama to assert that the rolling-up of a streakline in an unsteady flow is not evidence for the existence of a discrete vortex. Finally, Hama showed that pathlines also can provide misleading information: apparent u and v fluctuations, as determined by tracing a particle, had no direct bearing on the velocity fluctuations at a point.

Finally, students should be skeptical of all numerical results. If one wants to study steady, two-dimensional, laminar wake flow behind a cylinder at a Reynolds number of 3000, the computer will be happy to oblige. Although it will correctly solve the Navier–Stokes equations, that solution will not exist because, in reality, the flow is unstable. The presumed steady flow is replaced by an unsteady, two-dimensional Kármán vortex street, a three-dimensional version of the same, and by a turbulent wake, which is fully three-dimensional and time-dependent. Even if we had begun by assuming that the wake was turbulent, the chances of simulating the actual flow would still be limited. Just because the computer is generating a random signal does not necessarily mean you are observing something related to an actual turbulent flow that results from solving the Navier–Stokes equations. Finally, there is an emergent recognition of the importance of verification and validation of CFD. This journal pioneered the development of accepted verification and validation definitions and methods. The preponderance of commercial software in science and engineering, which use algorithms of dubious accuracy, should be a red flag. Some vendors are notorious for not providing convincing V&V documentation.

We conclude this section with a few final thoughts for students. First, do not be intimidated or discouraged by those who came before you; rather, expect to be inspired by at least some of them. Scientific *revolutions* happen too infrequently, but they need all the scientific *evolutions* they could get. Many new and wonderful things still remain to be discovered, however, incrementally. Many giants before you—Bernard of Chartes, Isaac Newton, and Stephen Hawking, to name a few—stated that they stand on the shoulders of other giants. Do not allow the metaphor *Nanos gigantum humeris insidentes* (Latin for, Dwarfs standing on the shoulders of giants) to apply to you; you are a giant in your own right.

There are those who consider fluid mechanics to be a mature subject that led to very useful technological breakthroughs in the past, but that the pace of improvements is fast reaching the point where returns on investment in research are not sufficiently impressive. The cynics claim that little new scientific or engineering breakthroughs are to be expected from this aging field of study. However, it may be worth remembering that much the same was said about physics toward the end of the 19th century. The majority of the physicists of that time—self-satisfied that all experimental observations could be explained by either Newton's theory of mechanics or Maxwell's theory of electromagnetism—believed that their successors would be relegated to *merely making measurements to the next decimal place*. That was just before the theory of relativity and quantum mechanics were discovered!

Technology has its share of amusing anecdotes as well. In the 1860s, the commissioner of patents under Abraham Lincoln recommended the closing of the commission with a few years, arguing that the rate of discovery had advanced to the point that anything needing discovery would already have been discovered by that time, and that there would be no future business for the patent commission. *Opportunity is dead! All possible inventions have been invented. All great discoveries have been made.* Similarly, in 1899—before the airplane, laser, and computer were invented—Charles H. Duell, commissioner of the U.S. Office of Patents under President McKinley, also advocated that this office be abolished because *everything that can be invented has been invented.*

Foolish, fallacious statements like those above are frequently attributed to various myopic patent officials of the past and are perpetuated even by the most respected writers and speakers of our time. We cite here three of the most recent perpetuators, all of whom of course wanted only to show how ignorant and unimaginative the hapless patent officer must have been: (i) Daniel E. Koshland Jr., editor-in-chief of the periodical *Science*, in a 1995 editorial on the future of its subject matter; (ii) cyberseer and mega-entrepreneur Bill Gates in the 1995 hardcover—but not the paperback—edition of the instant best-seller *The Road Ahead*; and (iii) the president of the National Academy of Sciences Bruce Alberts, in a fund-raising letter dated April 1997 and widely distributed to *friends of science* in the United States.

The definitive history of the above and related apocryphal anecdotes was documented by Eber Jeffery, who in 1940 conducted an exhaustive investigation of their authenticity and origin. Jeffery traced the then widely circulated tales to a testimony delivered before the United States Congress in 1843 by commissioner of patents Henry L. Ellsworth, who told lawmakers that the rapid pace of innovation *taxes our credulity and seems to presage the arrival of that period when human improvement must end.* According to Jeffery, this statement was merely a rhetorical flourish intended to highlight the noteworthy progress being made by then current inventions and the progress that should be expected in the future. Indeed, Commissioner Ellsworth asked the Congress to provide the Office of Patents with additional funds to handle the deluge of inventions he anticipated. Jeffery concludes that no document could be found to establish the identity of the mysterious commissioner, or examiner, or clerk, who thought that all inventions were a thing of the past. This was not true then and is certainly not true now, for both science and technology have indeed an *endless frontier*.

We end this "sermon" with two quotes from the holder of 1093 U.S. patents, Thomas Alva Edison (1847–1931): "Genius is one percent inspiration, ninety-nine percent perspiration"; "To invent, you need a good imagination and a pile of junk." May your eureka moment come sooner than later.

9 Concluding Remarks

Much has progressed in the broad field of fluid mechanics during the past 90 years. The advances, in no small part due to the invention of the laser and the computer, perhaps exceed all those taking place during the previous 900 or even 9000 years. Despite her advanced age, the cantankerous queen mother still has more to offer. The best is yet to come.

To some extent, the present essay focussed on turbulence in Newtonian, incompressible flows. Similar spectacular advances took place during the past 90 years in other branches of fluid mechanics. For example, in biofluid mechanics, non-Newtonian fluids, compressible (including hypersonic) flows, rarefied gasdynamics, multiphase flows, fluid–structure interaction problems, droplets, sprays and coatings, reacting flows, aero- and hydroacoustics, and micro/nanofluidics.

The rather terse presentation herein, void of any references or figures, does not do fairness to a lively field of human endeavor. Perhaps an entire book, full of references and figures, should celebrate the centennial of the ASME Division of Fluids Engineering. I may not be here to enjoy the book, but somehow would be watching over the shoulders of the fortunate author. *Ad altiora tendo!*

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It is indeed an honor and privilege to be invited to write this article for the special issue of the *Journal of Fluids Engineering*, and to deliver a plenary lecture at the corresponding celebratory meeting, July 10–14, 2016. For the ASME Division of Fluids Engineering to award me a medal as the division celebrates its 90th Anniversary, and to be considered as contributing to the advancement of the science and practice of fluids engineering is beyond anyone's aspiration, especially for someone who practiced the field for not even half of the 90 years. My sincere gratitude to members of the FED 90th Anniversary Awards Committee, to the editors of this special issue of the journal, and to the meeting organizers. I would also like to thank Dr. Patrick J. Roache and Dr. Robert E. Berger for reading and commenting on the manuscript. The reader is encouraged to study the following references by the author for more complete details and additional information: the books *Flow Control*, Cambridge University Press, 2006, and *The MEMS Handbook*, CRC Taylor & Francis, 2006, and the articles *Prog. Aerosp. Sci.* **29**, pp. 81–123, 1992; *Int. J. Eng. Educ.* **14**, pp. 177–185, 1998; and *Acta Mech.* **218**, pp. 309–318, 2011.