Nine Decades of Fluid Mechanics

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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. Select 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 brief.

1 Introduction

The Hydraulics 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 forty-four years, *JFE* was led by a succession of influential editors, 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 the following sections, which discuss in turn the analytical, experimental, and numerical advances in fluid mechanics. Separate sections are devoted to flow control and micro/nano fluidics. 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 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 available.

2 Prior to 1926

The art of fluid mechanics arguably has its roots in prehistoric times when streamlined spears, sickle-shaped boomerangs, and fin-stabilized arrows evolved empirically by the sheer perseverance and instinct to survive of archaic Homo sapiens who knew nothing about air resistance or aerodynamic principles.

The Greek mathematician Archimedes (287–212 B.C.) provided an exact solution to the fluid-at-rest problem and expressions for the buoyant force on various bodies, long before calculus or the modern laws of mechanics were known. That was the original eureka moment. The science of hydrostatics was developed at about the same time the Romans were building their system of aqueducts in order to bring fresh water from distant sources into their cities.

A few centuries of scientific drought followed the collapse of the Roman Empire, only to be re-irrigated by the Renaissance's deluge of art and science. Leonardo da Vinci (1452–1519) correctly deduced the conservation of mass equation for incompressible, one-dimensional flows. Leonardo also pioneered the flow visualization genre more than five centuries ago. He provided succulent descriptions of the smooth and eddying motions of water. In there, one could discern the Renaissance genius's prophecy of some of the flow physics to be discovered centuries after his time: Reynolds decomposition; Richardson's cascade; Kolmogorov's equilibrium theory; coherent structures; and large-eddy simulations. Particularly relevant to the modern notion of coherent structures, the words eddies and eddying motions percolate throughout da Vinci's treatise on liquid flows.

Leonardo is perhaps the world first to use visualization as a scientific tool to study turbulent flows. Around 1500, da Vinci sketched a free water jet issuing from a square hole into a pool. He wrote [translated]: "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." Leonardo might have prefigured the now famous Reynolds turbulence decomposition nearly 400 years prior to Osborne Reynolds's flow visualization and analysis!

Little more than a century and half after the incomparable Newton's *Principia Mathematica* was published in 1687, the first principles of viscous fluid flows were firmed in the form of the field Navier–Stokes equations.

Even with the simplification accorded by the incompressibility assumption, the resulting system of equations is formidable and has no general solution. Usual further simplifications—applicable only to laminar flows—include geometries for which the nonlinear terms in the (instantaneous) momentum equation are identically zero; low-Reynolds-number creeping flows for which the nonlinear terms are approximately zero; and high-Reynolds-number inviscid flows for which the continuity and momentum equations could be shown to metamorphose into the linear Laplace equation.

The last assumption spawned the great advances in perfect flow theory that took place during the second half of the nineteenth century. However, neglecting viscosity gives the totally erroneous result of zero drag for moving bodies and zero lift for lifting surfaces. Moreover, none of those simplifications applies to the rotational, time-dependent, and three-dimensional turbulent flows.

Not surprisingly, hydraulic engineers of the time showed little interest in the elegant theories of hydrodynamics and relied instead on their own collection of empirical equations, charts, and tables to compute drag, lift, pressure drop, and other practically important quantities. Consistent with that pragmatic approach, engineering students then and for many decades to follow were taught the art of hydraulics. The science of hydrodynamics was relegated, if at all, to mathematics and physics curricula.

In lamenting the status of fluid mechanics at the dawn of the twentieth century, the British chemist and Nobel laureate Sir Cyril Norman Hinshelwood (1897–1967) jested that fluid dynamists were divided into hydraulic engineers who observed things that could not be explained and mathematicians who explained things that could not be observed.

In an epoch-making presentation to the 1904 Third International Congress of Mathematicians held in Heidelberg, the German engineer Ludwig Prandtl resolved, to a large extent, the above dilemma. Prandtl introduced the concept of a fluid boundary layer, adjacent to a moving body, where viscous forces are important and outside of which the flow is more or less inviscid. At sufficiently high Reynolds number, the boundary layer is thin relative to the longitudinal length scale and, as a result, velocity derivatives in the streamwise direction are small compared to normal derivatives.

That single simplification made it possible for the first time to obtain viscous flow solutions even in the presence of nonlinear terms, at least in the case of laminar flow. Both the momentum and energy equations are parabolic under such circumstances, and are therefore amenable to similarity solutions and marching numerical techniques. From that moment on, viscous flow theory was in vogue for both scientists and engineers. Practical quantities such as skin-friction drag could be computed from first principles even for non-creeping flows. Experiments in wind tunnels and their cousins provided valuable data for problems too complex to submit to analysis.

3 Theoretical Developments

3.1 Similarity Solutions

It took a number of years for the boundary layer theory mentioned in the last section to 'diffuse' outside the small circle of Prandtl and his students at Göttingen. Prandtl's paper, naturally written in German, contained a wealth of information: the concept of boundary layer; the resulting approximations; the mechanics of separation; and flow control strategies to delay flow separation. Yet, the manuscript was limited by the Congress organizers to eight pages—difficult reading indeed.

The pace, for researchers at least, picked up just prior and certainly after World War II. But engineering schools for the most part continued to teach hydraulics, with scant attention to the Navier–Stokes equations. Only when those schools, particularly in the United States, decided that a quantum shift from engineering technology to engineering science education was in order did fluid mechanics replace hydraulics in undergraduate engineering curricula. This shift was incited in part by the 1957 launching of Sputnik 1, and the resulting space race as well as the continuing Cold War between the West and East, particularly between the USA and the now defunct USSR.

Following Blasius's pioneering similarity solution of an incompressible, steady, two-dimensional, laminar flow over a flat plate at zero incidence, numerous others trickled in, continuing even during the twenty-first century. Examples include the Falkner–Skan family of wedge flows, Kármán rotating-disk three-dimensional flow, and Illingworth–Stewartson transformation, which reduces the compressible boundary-layer equations to almost the same form as those for incompressible flows. Similarity solutions exist outside fluid mechanics and heat transfer, and cover other fields of applied mathematics where general nonlinear partial differential equations could be made parabolic via proper approximations.

3.2 Stability Theory

The linear stability of a laminar flow is governed by the Orr–Sommerfeld equation and appropriate boundary conditions. For an isothermal, incompressible flow, the equation governing small perturbations is a fourth-order, linear, ordinary differential equation. It is derived from the Navier–Stokes equations by assuming two-dimensional small disturbances superimposed upon a steady, unidirectional mean flow, $U(y)$. Though 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. The order of the Orr–Sommerfeld equation increases as forces additional to inertia and viscous ones are incorporated into the momentum balance. For example, in case of a rotating-disk flow, Coriolis and streamline-curvature terms are added leading to a sixth-order stability equation.

In the 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 real parameter α, which is the wavenumber, and the Reynolds number. The real part of c is the phase velocity of the prescribed disturbance, and the sign of the imaginary part determines whether the wave is temporary amplified ($c_i > 0$), temporary damped ($c_i < 0$), or neutrally stable ($c_i = 0$).

The more realistic spatial stability problem involves disturbances that oscillate in time but either grow or decay exponentially with downstream distance. In this case, a complex eigenvalue $\alpha = \alpha_r + i\,\alpha_i$ is determined for each pair of values of the real radian frequency $\omega = 2\pi f = \alpha_r c$ and the Reynolds number. The real part of α is the wavenumber and the sign of α_i determines whether the wave is spatially amplified ($\alpha_i < 0$) or spatially damped ($\alpha_i > 0$).

In either the temporal or spatial instability studies, the major difficulty in numerically integrating the Orr–Sommerfeld equation lies in the fact that it is highly stiff and unstable, which makes the use of conventional numerical schemes virtually impossible. Explicit numerical methods with a step size that is commensurate with the global behavior of the solution cannot be used to integrate the equation because of the numerical instabilities that characterize this ordinary differential equation.

The Reynolds number below which (linear) perturbations of all wavenumbers decay is termed the critical Reynolds number, $\Re_{\text{crit}}$, or the limit of stability. For a given velocity profile $U(y)$, the critical Reynolds number and the rate of growth of perturbations depend strongly on the shape of the velocity profile. A profile with an inflectional point ($\partial^2 U/\partial y^2 = 0$) above the wall provides a necessary and sufficient condition for inviscid instability. Such profiles must have a positive curvature at $y = 0$, since $\partial^2 U/\partial y^2$ is negative at a large distance from the wall. Even when viscous effects are included, a velocity profile becomes more stable as its second derivative near the wall becomes more negative, $[\partial^2 U/\partial y^2]_o < 0$. The profile is then said to be more full, having a smaller ratio of displacement thickness to momentum thickness than, for example, an inflectional velocity profile. In the former case, the critical Reynolds number is increased, the range of amplified frequencies is diminished, and the amplification rate of unstable waves is reduced.

Transition location depends strongly on the freestream turbulence levels and other environmental factors. Moreover, nonlinear effects that are physically significant in the transition process cannot be accounted for by procedures based on linear stability theory. Weakly nonlinear stability problems can be solved semi-analytically, but strongly nonlinear situations require numerical treatments.

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 after that when a low-noise wind tunnel was constructed at the U.S. National Bureau of Standards (now called National Institute of Standards and Technology, NIST). 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 $U(x,y)$. We now differentiate between convective and absolute instabilities. 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 has to await 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. The former assumes that at sufficiently high Reynolds number, there exists a range of wavenumbers sufficiently removed from the energy containing eddies such that 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).

The two greatest achievements of turbulence theory during the twentieth century are without a doubt the Kolmogorov's universal equilibrium theory and the Prandtl/Taylor/Kármán/Izakson/Millikan's universal logarithmic law of the wall. In fact, there is a direct analogy between the two high-Reynolds-number asymptotes, one being concerned with a hierarchy of eddies leading to an energy cascade and an inertial subrange in the spectral space, and the second with a cascade of momentum towards the viscous sink at the wall and an inertial sublayer in the physical space. At sufficiently high Reynolds number, the overall flow dynamics in both the energy spectrum subrange and the wall-bounded flow sublayer is presumed to be independent of viscosity. 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

The method of matched asymptotic expansions is a modern approach to finding an accurate approximation to the solution to an equation, or a system of equations. It is particularly used when solving singularly perturbed differential equations. It involves finding several different approximate solutions, each of which is valid (i.e., accurate) for a portion of the range of the independent variable, and then combining these different solutions together to give a single approximate solution that is valid for the whole range of values of that independent variable.

In a large class of singularly perturbed problems, the domain may be divided into two or more subdomains. In one of these, often the largest, the solution is accurately approximated by an asymptotic series found by treating the problem as a regular perturbation (i.e., by setting a relatively small parameter to zero). The other subdomains consist of one or more small areas in which that approximation is inaccurate, generally because the perturbation terms in the problem are not negligible there. These areas are referred to as transition layers, and as boundary or interior layers depending on whether they occur at the domain's boundary (as is the usual case in applications) or inside the domain.

An approximation in the form of an asymptotic series is obtained in the transition layer(s) by treating that part of the domain as a separate perturbation problem. This approximation is called the "inner solution", and the other is termed the "outer solution", named for their relationship to the transition layer(s). The outer and inner solutions are then combined through a process called 'matching' in such a way that an approximate solution for the whole domain is obtained.

Numerous fluid mechanics, 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

In the theory of dynamical systems, the so-called butterfly effect denotes sensitive dependence of nonlinear differential equations on initial conditions, with phase-space solutions initially very close together separating exponentially. The solution of nonlinear dynamical systems of three or more degrees of freedom may be in the form of a strange attractor whose intrinsic structure contains a well-defined mechanism to produce a chaotic behavior without requiring random forcing. Chaotic behavior is complex, aperiodic, and, though deterministic, appears to be random.

A question arises naturally: just as small disturbances can radically grow within a deterministic system to yield rich, unpredictable behavior, can minute adjustments to a system parameter be used to reverse the process and control, i.e., regularize, the behavior of a chaotic system? Recently, that question was answered in the affirmative theoretically as well as experimentally, at least for system orbits that reside on low-dimensional strange attractors.

We first summarize the recent attempts to construct a low-dimensional dynamical systems representation of turbulent boundary layers. Such construction is a necessary first step to be able to use chaos control strategies for turbulent flows. Additionally, a low-dimensional dynamical model of the near-wall region used in a Kalman filter can make the most of the partial information assembled from a finite number of wall sensors. Such filter minimizes in a least square sense the errors caused by incomplete information, and thus globally optimizes the performance of the control system.

Boundary layer turbulence is described by a set of nonlinear partial differential equations and is therefore characterized by an infinite number of degrees of freedom. This makes it rather difficult to model the turbulence using a dynamical systems approximation. The notion that a complex, infinite-dimensional flow can be decomposed into several low-dimensional subunits is, however, a natural consequence of the realization that quasi-periodic coherent structures dominate the dynamics of seemingly random turbulent shear flows. This implies that low-dimensional, localized dynamics can exist in formally infinite-dimensional extended systems—such as open turbulent flows.

Reducing the flow physics to finite-dimensional dynamical systems enables a study of its behavior through an examination of the fixed points and the topology of their stable and unstable manifolds. From the dynamical systems theory's viewpoint, the meandering of low-speed streaks is interpreted as hovering of the flow state near an unstable fixed point in the low-dimensional state space. An intermittent event that produces high wall stress—a burst—is interpreted as a jump along a heteroclinic cycle to different unstable fixed point that occurs when the state has wandered too far from the first unstable fixed point. Delaying this jump by holding the system near the first fixed point should lead to lower momentum transport in the wall region and, therefore, to lower skin-friction drag. Reactive control means sensing the current local state and through appropriate manipulation keeping the state close to a given unstable fixed point, thereby preventing further production of turbulence. Reducing the bursting frequency by say 50%, may lead to a comparable reduction in skin-friction drag. For a jet, relaminarization may lead to a quiet flow and very significant noise reduction.

In one significant attempt, the proper orthogonal, or Karhunen-Loève, decomposition method has been used to extract a low-dimensional dynamical system from experimental data of the wall region. A group at Cornell University expanded the instantaneous velocity field of a turbulent boundary layer using experimentally determined eigenfunctions, which are in the form of streamwise rolls. They expanded the Navier–Stokes equations using these optimally chosen, divergence-free, orthogonal functions, applied a Galerkin projection, and then truncated the infinite-dimensional representation to obtain a ten-dimensional set of ordinary differential equations. These equations represent the dynamical behavior of the rolls, and are shown to exhibit a chaotic regime as well as an intermittency due to a burst-like phenomenon. However, the ten-mode dynamical system displays a *regular* intermittency, in contrast both to that in actual turbulence as well as to the chaotic intermittency encountered in other nonlinear dynamical systems in which event durations are distributed stochastically. Nevertheless, the major conclusion of the Cornell study is that the bursts appear to be produced autonomously by the wall region even without turbulence, but are triggered by turbulent pressure signals from the outer layer. More recently, a second Cornell's team generalized the class of wall-layer models to permit uncoupled evolution of streamwise and cross-stream disturbances. The newer results suggest that the intermittent events observed in the original representation do not arise solely because of the effective closure assumption incorporated, but are rather rooted deeper in the dynamical phenomena of the wall region.

In addition to the reductionist viewpoint exemplified above, attempts have been made to determine directly the dimension of the attractors underlying specific turbulent flows. Again, the central issue here is whether or not turbulent solutions to the infinite-dimensional Navier–Stokes equations can be asymptotically described by a finite number of degrees of freedom.

The corresponding dimension in wall-bounded flows appears to be dauntingly high. This suggests that periodic turbulent shear flows are deterministic chaos and that a strange attractor does underlie solutions to the Navier–Stokes equations. Temporal unpredictability in, say, a turbulent Poiseuille flow is thus due to the exponential spreading property of such attractors. Although finite, the computed dimension invalidates the notion that the global turbulence can be attributed to the interaction of a *few* degrees of freedom. Moreover, in a physical channel or boundary layer, the flow is not periodic and is open. The attractor dimension in such case is not known but is believed to be even higher than the estimate provided thus far for the periodic *(quasi-closed)* flow.

In contrast to closed, absolutely unstable flows, such as Taylor–Couette systems, where the number of degrees of freedom can be small, local measurements in open, convectively unstable flows, such as boundary layers, do not express the global dynamics, and the attractor dimension in that case may inevitably be too large to be determined experimentally. According to one estimate, the colossal data required (about 10^D, where D is the attractor dimension) for measuring the dimension simply exceeds current computer capabilities. Turbulence near transition or near a wall is an exception to that bleak picture. In those special cases, a relatively small number of modes are excited and the resulting *simple* turbulence can therefore be described by a dynamical system of a reasonable number of degrees of freedom.

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. Not only was visualization once again the method of choice for the major discoveries, but also was the reaffirmation of the importance of eddying motions and the co-presence of large, organized motions and small, random ones. The search for coherent events is the embodiment of man's desire to find order in apparent disorder.

The statistical view that turbulence is essentially a stochastic phenomenon having a randomly fluctuating velocity field superimposed on a well-defined mean has been changed in the last few decades by the realization that the transport properties of all turbulent shear flows are dominated by quasi-periodic, large-scale vortex motions. Despite the extensive research work in this area, no generally accepted definition of what is meant by coherent motion has emerged. In physics, coherence stands for well-defined phase relationship. We provide here two rather different views, the first is general and the second is more restrictive. (i) A coherent motion is defined as a three-dimensional region of the flow over which at least one fundamental flow variable (velocity component, density, temperature, etc.) exhibits significant correlation with itself or with another variable over a range of space and/or time that is significantly larger than the smallest local scales of the flow. (ii) The rather restrictive definition: a coherent structure is a connected turbulent fluid mass with instantaneously phase-correlated vorticity over its spatial extent. In other words, underlying the random, three-dimensional vorticity that characterizes turbulence, there is a component of large-scale vorticity that is instantaneously coherent over the spatial extent of an organized structure. The apparent randomness of the flow field is, for the most part, due to the random size and strength of the different types of organized structures comprising that field. Several other definitions have been catalogued, providing a cook-book-style approach to coherent structure's identification using a variety of classical and modern strategies.

Proper orthogonal decomposition is one of the tools used to identify coherent structures. The challenge is to identify a coherent structure well hidden in a sea of random background, when such a structure is present either in a visual impression of the flow or in an instantaneous velocity, temperature, or pressure signal. This is of course not a trivial task, and the ancient Hindu fable about the six blind men each trying from his own limited perspective to identify how an elephant looks like immediately comes to mind. Complicating the issue is that coherent structures change from one type of flow to another, and even in the same type of flow change as initial and boundary conditions vary. The largest eddies are of the same scale as that of the flow, and consequently 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 non-existent objects.

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 a very fine metallic wire (on the order of several micrometres) electrically heated up to some temperature above the ambient. Fluid flowing past the wire has a cooling effect on the wire. As the electrical resistance of most metals (tungsten is a popular choice for hot-wires) is dependent upon the temperature of the metal, a relationship could be obtained between the resistance of the wire and the flow speed. 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 twelve 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 Visualizations

Perhaps more than any other tool available to tackle the complex problem of fluid mechanics, flow visualization is singly responsible for many of the most exciting discoveries in the field. Relatively simple, quick, and capable of giving global behavior, rendering the fluid motion accessible to visual perception could yield invaluable qualitative as well as quantitative information about the dynamics of a complex flow. 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 non-isothermal or high-speed flows, can benefit from different types of optical techniques. Interferometers respond directly to differences in optical path length, thus giving the integrated index-of-refraction (or density) field within the flow. Schlieren systems, on the other hand, are sensitive to the first derivative of the index of refraction in a direction normal to the light beam. Shadowgraphs respond to the index of refraction's second derivative normal to the optical path. In effect, a shadowgraph image displays the Laplacian of the fluid density along the line-of-sight. As a result of projecting three-dimensional space onto a plane, spatial structures cannot be recovered from a single image, unless multiple views are measured and tomographic reconstruction methods are employed.

4.4 Laser-Induced Fluorescence

The acronym 'LASER' stands for **L**igh **A**mplification by **S**timulated **E**mission of **R**adiation. Although its theoretical foundation was established by Albert Einstein in 1917, it wasn't 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 has 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 as to be able to see one plane at a time, and the use of extremely small amounts of fluorescent dye as 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 to 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 high-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

A second important application of the invention is the laser Doppler velocimetry (LDV), also known as laser Doppler anemometry (LDA). LDV is the technique of using the Doppler shift in a laser beam, scattered by moving particles, to measure the velocity in transparent or semi-transparent fluid flows, or the linear or vibratory motion of reflecting surfaces. Flow measurements with LDV require seeding particles sufficiently small to follow the fast changing small eddies in a turbulent flow. Mie scattering of light results when the particle size is larger than the light's wavelength. Backscattered light intensity is about two orders of magnitude weaker than that in the forward-scatter mode.

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, although in the case of the weaker backward scattering high-powered laser and larger receiving lens are needed to obtain an adequate signal. The technique is absolute, non-invasive, linear with velocity, and requires no pre-calibration. 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

Particle tracking is an intuitively attractive method for making spatially dense velocity measurements. Global quantitative information regarding both instantaneous velocity and vorticity could be inferred from flow images. Particle tracking is rather simple in principle: small distinct particles suspended in a fluid are illuminated, usually in a particular plane, and the resulting scattered light is imaged on a camera. In both gases and liquids, gaseous bubbles, immiscible liquid droplets, or solid particulate could be used for seeding. The particles are then imaged on a photographic film, a video array detector, or a hologram. The imaged particle-path's lengths and orientations could then be retrieved by subsequent analysis. In its most primitive form, the method has been known for about a century.

Prior to the introduction of image processing techniques, the major drawback in using particle-image velocimetry (PIV) has been the enormous amount of manual work required to obtain a reasonable spatial and temporal resolutions, especially in the case of an unsteady flow field. The recent availability of powerful computers has prompted many researchers to revisit the particle tracking technique. Due to the rapid developments in the field during the 1980s, particle-image velocimetry is now capable of providing accurate, high-quality measurements of instantaneous, two-dimensional velocity fields in both slow and fast laboratory facilities. Field applications are less common but also feasible. Stereoscopic and holographic capturing allow measurements in all three dimensions.

4.7 Holographic Imaging

Holography is a complete measurement system for recording and reconstructing light waves, which makes possible the recording of color, scale, and three-dimensional images of a flow field. When a coherent light encounters a change in the refractive index of the medium, the phase of the light waves is modulated. The scattered light from a gas bubble or the like encodes all the optical properties of the object. The resulting hologram preserves the three-dimensional information by recording the wave-front phase difference as well as light intensity.

The mechanics of the holographic process is briefly as follow. A laser beam is split into two, one to illuminate an object and a reference beam to be superimposed on the light field scattered from that object. The interference pattern generated by the two beams is recorded on a transparent light-sensitive emulsion. When developed, the exposed emulsion produces a hologram composed of a series of light and dark fringes that contain the complete optical information.

To recover this information, a laser beam illuminates the hologram at the same incidence angle as the original reference beam. The incident light is diffracted by the light and dark fringes on the hologram. The resulting converging and diverging wave fronts, identical to those scattered by the original object, are therefore reconstructed. The diverging wavefronts appear to come from a virtual image behind the hologram, while the converging ones form a real image of the object on the opposite side.

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 invention of 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, wheel, printing press, and steam engine. The computer played a major role in advancing fluid mechanics, as it did in all science and engineering, and in fact in all other human endeavors.

In fluid mechanics in particular, the computer played crucial roles in acquiring the massive data resulting from the instruments described earlier, in coherent structure's identification, and, most crucially, in the numerical integration of the Navier–Stokes equations and their related, often more complicated laws of nature.

5.1 Numerical Simulations

Leaving aside for a moment less conventional, albeit just as important, problems in fluid mechanics such as those involving non-Newtonian fluids, multiphase flows, hypersonic flows, chemically reacting flows, and geophysical and astrophysical flows, in principle practically any laminar flow problem can presently be solved, at least numerically. Turbulence, in contrast, remains largely an enigma, analytically unapproachable yet practically very important. For a turbulent flow, the dependent variables are random functions of space and time, and no straightforward method exists for analytically obtaining stochastic solutions to the governing nonlinear, partial differential equations. The statistical approach to solving the Navier–Stokes equations always leads to more unknowns than equations (the closure problem), and solutions based on first principles are again not possible. The heuristic modeling used to close the Reynolds-averaged equations has to be validated case-by-case, and does not therefore offer much of an advantage over the old-fashioned empirical approach.

5.2 Turbulence Simulations

Romanticized since Leonardo da Vinci compared the motion of a water jet rapidly falling into a pool to the curls and waves of long, gorgeous hair, turbulence is a field of endeavor blessed with stunning images, elegant mathematics, intellectually fascinating physics, and vitally important applications. Its significance at the human, geologic, and cosmologic scales can only be understated. Turbulent transport in plasma sustains the nuclear fusion process that in turn keeps the stars alive; the vigorous turbulent mixing in the atmosphere keeps megacities from suffocating under their own human-produced carbon dioxide; and a turbulent boundary layer allows an airfoil to generate more lift at larger angles of attack than a corresponding laminar flow. The darker facet of turbulence is its extreme complexity, sending chills down the spines of students and professionals alike. Turbulence is also mostly responsible for the high fuel consumption of all air, land, and sea transportation systems.

Turbulence, therefore, is a conundrum that appears to yield its secrets only to physical and numerical experiments, provided that the wide band of relevant scales is fully resolved—a far-from-trivial task at high Reynolds numbers. Direct numerical simulations (DNS) of the canonical turbulent boundary layer have so far been carried out, at great cost despite a bit of improvising, up to a very modest momentum-thickness Reynolds number of a few thousands.

In a turbulent flow, the ratio of the large eddies (at which the energy maintaining the flow is inputed) to the Kolmogorov microscale (the flow smallest length-scale) is proportional to $Re^{3/4}$. Each excited eddy requires at least one grid point to describe it. Therefore, to adequately resolve, via DNS, a three-dimensional flow, the required number of modes would be proportional to $(Re^{3/4})^3$. In order to describe the motion of small eddies as they are swept around by large ones, the time step must not be larger than the ratio of the Kolmogorov lengthscale to the characteristic rms velocity. The large eddies, on the other hand, evolve on a time scale proportional to their size divided by their root-mean-square velocity. Thus, the number of time steps required is again proportional to $Re^{3/4}$. Finally, the computational work requirement is the number of modes $\times$ the number of time steps, which scales with Re^3, in other words an order of magnitude increase in computer power is needed as the Reynolds number is doubled. Since the computational resource required varies as the cube of the Reynolds number, it may not be possible to directly simulate very high-Reynolds-number turbulent flows any time soon.

Despite the bleak assessment above, one wonders whether gigantic computers combined with appropriate software will be available during the twenty-first century to routinely solve, using DNS, practical turbulent flow problems? The black box would prompt its operator for the geometry and flow conditions, and would then spit out a numerical solution to the specific engineering problem. Nobody, except the software developers, needs to know the details of what is going on inside the black box, not even which equations are being solved. This situation is not unlike using a present-day word processor or even hand calculator. A generation of users of the Navier–Stokes computers would quickly lose the aptitude and the desire to perform simple analysis based on physical considerations, much the same as the inability of some of today's users of hand calculators to manually carry out long divisions. The acumen to be able to perform rational approximations, so prevalent today in fluid mechanics teaching and practice, would gradually wither. Despite its inevitability, the present author does not look forward to such an outcome.

During the late 1990s, the supercomputer power approached the teraflop, i.e. 10^{12} floating-point operations per second. This is about right to compute a flow with a characteristic Reynolds number of 10^8, sufficient to simulate the flow around an airfoil via DNS, around a wing via large-eddy simulations, or around an entire commercial aircraft via Reynolds-averaged calculations. The petaflop (10^{15}) power was reached in 2008. An exaflop (10^{18} flops) computer is needed to carry out direct numerical simulations of the complete airplane. Exascale computing is a recent near-future goal for the United States. However, fluid mechanics is not the top priority for such computer. National security, energy, and astrophyiscal calculations take more prominent positions on the waiting list. Fluid mechanicians: take a number!

5.3 Large-Eddy Simulations

Direct numerical simulations (DNS), in which the full nonlinear, time-dependent Navier–Stokes equations are integrated without any empirical closure assumptions, are becoming feasible, at least at low Reynolds numbers, for few simple geometries. Such simulations provide a complex space–time history of a turbulent flow field, but are in practice still strongly constrained by available computer resources as well as algorithmic limitations. An alternative to DNS is the large-eddy simulations (LES), where three-dimensional, time-dependent computations of the large-scale turbulence are performed while modeling the smallest scales in any real high-Reynolds number flow.

Finite-difference, finite-element, boundary-element, and spectral methods are among the numerical methods used to integrate the governing equations. In general, spectral methods are very accurate while finite-difference algorithms are more suited for complex geometries and are more easy to set up. Typically, turbulent simulations require the ultra-high speed and enormous memory of supercomputers, but such calculations remain mostly within the realm of academic research since they are still too expensive and too time-consuming for practical engineering applications.

Once the flow field is obtained numerically, the digital data could be directly processed with any of the image processing tools available for experimental data; for example, volume rendering, motion pictures, etc. Numerical flow visualizations make possible direct as well as quick comparison between physical and numerical simulations.

6 Flow Control

The ability to manipulate a flowfield actively or passively to effect a desired change is of great technological importance, and this may account for the fact that scientists and engineers pursue the subject more than any other topic in fluid mechanics. The potential benefits of realizing efficient flow-control systems range from saving billions of dollars in annual fuel costs for land, air, and sea vehicles, to reversing or at least slowing down dangerous global warming trends, to achieving economically and environmentally more competitive industrial processes involving fluid flows. Controlling a turbulent flow is particularly difficult, and this section provides a broad overview of that subject, although in the context of the wider field of flow control.

A particular control strategy is chosen based on the kind of flow and the control goal to be achieved. Flow control goals are strongly, often adversely, interrelated; and there lies the challenge of making the tough compromises. There are several different ways for classifying control strategies to achieve a desired effect. Presence or lack of walls, Reynolds and Mach numbers, and the character of the flow instabilities all are important considerations for the type of control to be applied. All these seemingly disparate issues are what place the field of flow control in a unified framework, as exhaustively covered in the book *Flow Control* by this author.

What does the engineer want to achieve when attempting to manipulate a particular flow field? Typically she aims at reducing the drag, at enhancing the lift, at augmenting the mixing of mass, momentum, or energy, at suppressing the flow-induced noise, or at a combination thereof. To achieve any of these useful end results, for either free-shear or wall-bounded flows, transition from laminar to turbulent flow may have to be either delayed or advanced, flow separation may have to be either prevented or provoked, and finally turbulence levels may have to be either suppressed or enhanced. All those engineering goals and the corresponding flow changes intended to effect them are interrelated. None of that is particularly difficult if taken in isolation, but the challenge is in achieving a goal using a simple device, inexpensive to build as well as to operate, and, most importantly, has minimum 'side effects'. For this last hurdle, the interrelation between control goals must be elaborated, and this is what is attempted below, using, as an example, boundary-layer flows.

An external wall-bounded flow, such as that developing on the exterior surface of a wing, can be manipulated to achieve transition delay, separation postponement, lift increase, skin-friction and pressure drag reduction, turbulence augmentation, mixing enhancement, and noise suppression. These objectives are interrelated and are not necessarily mutually exclusive. If the boundary layer around the wing becomes turbulent, its resistance to separation is enhanced and more lift can be obtained at increased incidence. On the other hand, the skin-friction drag for a laminar boundary layer can be as much as an order of magnitude less than that for a turbulent one. If transition is delayed, lower skin friction and lower flow-induced noise are achieved. However, a laminar boundary layer can support only very small adverse pressure gradients without separation and, at the slightest increase in angle of attack or some other provocation, the boundary layer detaches from the wing's surface and subsequent loss of lift and increase in form drag occur. Once the laminar boundary layer separates, a free-shear layer forms, and for moderate Reynolds numbers transition to turbulence takes place. Increased entrainment of high-speed fluid due to the turbulent mixing may result in reattachment of the separated region and formation of a laminar separation bubble. At higher incidence, the bubble breaks down, either separating completely or forming a longer bubble. In either case, the form drag increases and the lift curve's slope decreases. The ultimate goal of all this is to improve the airfoil's performance by increasing the lift-to-drag ratio. However, induced drag is caused by the lift generated on a wing with a finite span. Moreover, more lift is generated at higher incidence, but form drag also increases at these angles.

All of the above point to potential conflicts as one attempts to achieve a particular control goal only to affect adversely another goal. An ideal method of control that is simple, inexpensive to build and operate, and does not have any tradeoffs does not exist, and the skilled engineer has to make continuous compromises to achieve a particular design goal.

Flow control is most effective when applied near the transition or separation points, where conditions are near those of the critical flow regimes when flow instabilities magnify quickly. Therefore, delaying or advancing the laminar-to-turbulence transition and preventing or provoking separation are easier tasks to accomplish. Reducing the skin-friction drag in a non-separating turbulent boundary layer, where the mean flow is quite stable, is a more challenging problem. Yet, even a modest reduction in the fluid resistance to the motion of, for example, the worldwide commercial airplane fleet is translated into annual fuel savings estimated to be in the billions of dollars. Newer ideas for turbulent flow control focus on targeting coherent structures, which are quasi-periodic, organized, large-scale vortex motions embedded in a random, or incoherent, flow field.

Future systems for control of turbulent flows in general and turbulent boundary layers in particular could greatly benefit from the merging of the science of chaos control, the technology of microfabrication, and the newest computational tools collectively termed soft computing. Control of chaotic, nonlinear dynamical systems has been demonstrated theoretically as well as experimentally, even for multi-degree-of-freedom systems. Microfabrication is an emerging technology that has the potential for mass-producing inexpensive, programmable sensor/actuator chips, where each sensor or actuator is as small as a few micrometers. Soft computing tools include neural networks, fuzzy logic, and genetic algorithms. They have advanced and become more widely used in the last few years, and could be very useful in constructing effective adaptive controllers. Such futuristic systems are envisaged as consisting of a colossal number of intelligent, interactive, microfabricated wall sensors and actuators arranged in a checkerboard pattern and targeted toward specific organized structures that occur quasi-randomly (or quasi-periodically) within a turbulent flow. Sensors would detect oncoming coherent structures, and adaptive controllers would process the sensors' information and provide control signals to the actuators, which in turn would attempt to favorably modulate the quasi-periodic events. A finite number of wall sensors perceives only partial information about the flow field. However, a low-dimensional dynamical model of the near-wall region used in a Kalman filter can make the most of this partial information. Conceptually all of that is not too difficult, but in practice the complexity of such control systems is daunting and much research and development work remains.

Different levels of 'intelligence' can be incorporated into a particular control system. The control can be passive, requiring no auxiliary power and no control loop, or active, requiring energy expenditure. Manufacturing a wing with a fixed streamlined shape is an example of passive control. Active control requires a control loop and is further divided into predetermined or reactive. Predetermined control includes the application of 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. The control loop in this case is open, and no sensors are required. Because no sensed information is being fed forward, this open control loop is not a feedforward one. This subtle point is often confused, blurring predetermined control with reactive, feedforward control.

Reactive, or 'smart', control is a special class of active control where the control input is continuously adjusted based on measurements of some kind. The control loop in this case can be an open, feedforward one, or a closed, feedback loop. Achieving that level of autonomous control (that is, without human interference) is the ultimate goal of 'smart-wing' designers. In feedforward control, the measured variable and the controlled variable are not necessarily the same. For example, the pressure can be sensed at an upstream location, and the resulting signal is used together with an appropriate control law to actuate a shape change that in turn influences the shear stress (that is, skin friction) at a downstream position. Feedback control, on the other hand, necessitates that the controlled variable be measured, fed back, and compared with a reference input. Reactive, feedback control is further classified into four categories: adaptive, physical model-based, dynamical systems-based, and optimal control. An example of reactive control is the use of distributed sensors and actuators on the wing surface to detect certain coherent flow structures and, based on a sophisticated control law, subtly morph a wing, for example, to suppress those structures in order to dramatically reduce the skin-friction drag.

7 Micro- and Nanofluidics

With the advent of micro- and nanoelectromechanical systems (MEMS and NEMS) comes the new fluid mechanics branches of micro- and nanofluidics: how to model fluid flows at the micro- and nanoscales? Traditional fluid mechanics assumes that the flow is continuum and in a quasi-equilibrium thermodynamics state. This implies that all flow parameters such as velocity, pressure, temperature, and density are continuous, infinitely-differentiable functions of space and time. It also implies linear relations between stress and rate-of-strain, between heat flux and temperature gradients, etc. Finally, no slip and no temperature jumps can exist between a wall and fluid. Those restrictions break down for non-Newtonian fluids, for rarefied gases, and for situations when there is insufficient number of molecules in the smallest control volumes to avoid statistical chaos.

As the characteristics length scales approach the micro- and eventually the nanoscales, the original assumptions breakdown, and new modeling is called for. First to be affected is the no-slip condition, then the linear relations between a flux and its corresponding potential, then the continuum assumption. Once the last fails, one has to revert to molecular-based models using for example the computer-intensive molecular dynamics (MD) 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 DNS of the Navier–Stokes equations pale by comparison.

Another complication in micro- and nanofluidics is the possibility of having to consider the flow compressible even for extremely small Mach number. 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 micro- or nanochannel's inlet to its outlet makes the constant-density assumption difficult to justify, and the flow must be treated as compressible.

Flows in micro- and nanodevices are clearly more complicated to treat than the corresponding flows at the macroscale. The fluid mechanics subfield, which only commenced in the early 1990s, is currently an active area of research. Surprisingly, the seemingly straightforward models described in this section took quite a number of years to realize. The similarities between microflows and rarefied gas dynamics were not obvious in the beginning, and powerful computers were needed to perform MD simulations or to solve the nonlinear integrodifferential Boltzman equation.

Experiments with microdevices are notoriously difficult as well. Pressure transducers have to be built in situ as microchannels are fabricated, μPIV and μbalance systems have to be developed, and measuring flow rates in the micro- or nanolitre range is far from trivial. Scanning electron microscopes (SEM) 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 its '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.

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 invest more time investigating the chosen tool(s). I give here three examples of possible pitfalls: (i) the use of HWA; (ii) interpreting flow visualization results; and (iii) numerical integration of the governing equations. Numerous other examples are out there.

When using a hot-wire anemometer, 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 taking 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.

Visualization of unsteady flows can be particularly confusing. While in a steady flow a streamline, a streakline, and a pathline all coincide, this is not the case for a time-dependent flow. To recall briefly, a pathline (or particle path) is the curve that a particular fluid particle traverses in the flow field as a function of time. Streamlines are the curves tangential to the instantaneous direction of the velocity at all points in the flow field. A streakline (called filament line in some references) is the instantaneous locus of all fluid particles that have passed through a particular fixed point within the flow. Typically, a tracer is introduced continuously into the flow field at a point or line and, hence, the observed patterns are, respectively, streaklines or streaksurfaces. At any instant, the visualization provides the time history of the tracer but not the local event, even in a frame frozen with the observed phenomenon.

A time line differs from all three lines above. It is produced by injecting a tracer instantaneously from a source located along a line transverse to the freestream direction, and is used to reveal velocity distributions and flow fluctuations. At a later instant of time, the shape and location of such a line will generally have altered. By repeating the process that generated a time line at a known frequency, several consecutive rows of marker are produced. The local velocity could then be readily computed by measuring the distance between two consecutive lines at several points along the evolved curves.

In 1962, Francis R. Hama provided a convincing example of the possible pitfalls in interpreting flow visualization results in an unsteady flow field. He numerically generated the streamlines, pathlines, and streaklines for a shear layer flow perturbed by a traveling sinusoidal wave of neutral stability. The resulting pattern of streamlines changed dramatically when these lines were recorded with a moving camera or with a camera at rest in the laboratory frame. Moreover, when dye was injected near the critical layer (where the flow speed equals the wave speed), the streaklines had an appearance of amplification and rolling as if to indicate that the flow had developed into discrete vortices. In fact, there was no amplification of the neutrally stable wave and no discrete vortices that existed anywhere in the flow.

Hama asserted that the rolling-up of a streakline in an unsteady flow cannot constitute a positive identification of the presence of a discrete vortex. Away from the critical layer, the streaklines appeared to show an alternating amplification and damping with the wrong wavelength and wave velocity. Hama clearly showed that information due to pathlines as obtained by tracing marked particles are equally improper in regard to the wave motion. Apparent u and v fluctuations as determined by tracing a particle had no direct bearing on the velocity fluctuations at a point.

Similar to experiments, be skeptical of all numerical results. When studying the wake flow behind a cylinder at a Reynolds number of 3,000, and assuming the flow to be steady, two-dimensional, and laminar, the computer is happy to oblige. It will generate a correct solution of the Navier–Stokes equations. but that solution does not exist in reality because it is an unstable one that is replaced by the unsteady, two-dimensional Kármán vortex street, a three-dimensional version of the same, followed by a turbulent wake, which is fully three-dimensional and time-dependent. If we start by assuming that the wake is turbulent, chances of simulating the actual flow are still limited. Once again, just because the computer is generating a random signal does not necessarily mean you are observing something related to an actual turbulent flow solution of the Navier–Stokes equations.

A final thought for the students: do not be intimidated or discouraged but rather be inspired by those who came before you, at least some of them. Scientific revolutions happen too infrequently, but they need all the scientific evolutions they can get. There are always new and wonderful things that 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 are standing on the shoulders of other giants. The metaphor *Nanos gigantum humeris insidentes* (Latin for, Dwarfs standing on the shoulders of giants) does not apply to you, a giant in his or her own way.

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, little new scientific or engineering breakthroughs are to be expected from the aging field of study. It may be worth remembering that much the same was said about physics toward the end of the nineteenth century. Self-satisfied that almost all experimental observations of the time could be fitted into either Newton's theory of mechanics or Maxwell's theory of electromagnetic, it appeared to the majority of physicists that the work of their successors *would be merely to make 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, Abraham Lincoln's commissioner of patents recommended that the commission be closed in a few years because the rate of discovery had become so great that everything that needed to be discovered would have been discovered by then. The patent commission would simply have no future business. *"Opportunity is dead! All possible inventions have been invented. All great discoveries have been made."* In 1899—before the airplane, laser, and computer were invented—the commissioner of the U.S. Office of Patents, Charles H. Duell, urged President McKinley to abolish this office because *"everything that can be invented has been invented."*

Foolish, fallacious statements like those 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, who all of course wanted only to show how ignorant and unimaginative the hapless patent officer must have been. Daniel E. Koshland Jr., the editor-in-chief of the periodical *Science*, in a 1995 editorial on the future of its subject matter; the cyberseer and mega-entrepreneur Bill Gates in the hardcover—but not the paperback—1995 edition of the instant best-seller *The Road Ahead*; and the president of the National Academy of Sciences Bruce Alberts in a fundraising letter dated April 1997, 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 by Henry L. Ellsworth, the commissioner of patents in 1843, who told the 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 a mere rhetorical flourish intended to emphasize the remarkable strides forward in inventions then current and to be expected in the future. Indeed, Commissioner Ellsworth asked the Congress to provide him with extra funds to cope with the flood 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 1,093 US 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 ninety years. The advances, in no small part due the invention of the laser and the computer, perhaps exceed all those taking place during the previous nine-hundred or even nine-thousand 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 ninety years in other branches of fluid mechanics. For example, in 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/nano fluidics.

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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