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Stephen H. Davis (1939–2021)

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Interfacial Dynamics Pioneer Stephen H. Davis (1939–2021)

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Abstract

Stephen H. Davis (1939–2021) was an applied mathematician, fluid dynamicist, and materials scientist who lead the field in his contributions to interfacial dynamics, thermal convection, thin films, and solidification for over 50 years. Here, we briefly review his personal and professional life and some of his most significant contributions to the field.

1. INTRODUCTION

Stephen Howard Davis, Walter P. Murphy Professor Emeritus of Engineering Sciences and Applied Mathematics at Northwestern University, passed away on November 12, 2021, from post-surgical complications following triple bypass surgery. Steve had an illustrious career spanning more than 58 years and was regarded as one of the world's experts in the fields of fluid mechanics, particularly in hydrodynamic stability and solidification, where he greatly expanded our knowledge of the influence of flow phenomena on the freezing process. Here, we review Steve's origins, his career, and his contributions to the field.

1.1. Background and Beginnings

Steve was born in New York City on September 9, 1939. His mother, the former Eva Axelrod, although a musical "granddaughter" of the great pianist Frédéric Chopin, decided that a career as a performing pianist was not for her and instead pursued a career teaching piano. Steve's father, Harry, installed dental equipment early in his career, transitioning to cabinet making in later years. Steve had one sibling—a younger brother named Jeffrey. When Steve was three years old, the family moved to the city of Long Beach on Long Island. A precocious student, Steve began his university education at age 16 at Rensselaer Polytechnic Institute (RPI) in upstate New York. He decided to forego a full scholarship opportunity from Polytechnic Institute of Brooklyn to do this so that he could have a fuller college experience, which was a difficult decision that took him away from his beloved New York Yankees baseball team. Steve's undergraduate degree was in electrical engineering (the reason behind which most who knew him never did figure out), but for his graduate education he transitioned to mathematics.

The mathematics department at RPI at that time was a true hotbed for applied mathematics and continuum mechanics, with the likes of Richard DiPrima, George Handelman, and Lee Segel on the faculty. It was with Segel that Steve conducted his doctoral research, resulting in a dissertation entitled "Effects of Free Boundaries and Property Variations in Thermal Convection," for which he was awarded the PhD in 1964. Stories abound regarding the collegiality of the RPI applied mathematics faculty in this period, some of which are summarized by one of us in a *Journal of Fluid Mechanics* (JFM) article (Neitzel 2010) written for a special volume to commemorate Steve's seventieth birthday. Steve took that informality with him wherever he ventured thereafter and, given his infectious personality, succeeded in inculcating it within his new colleagues—faculty and students alike.

Steve's first job following the receipt of his doctorate was at the Rand Corporation, a think tank in Santa Monica, California, taking him even further from the Yankees. He worked there from 1964 to 1966, during which time he met his future partner in life, the former Suellen Lewis, at a party one evening in Beverly Hills. Their first date was dinner and live theatre, two activities that they both continued to enjoy for their 56 years of marriage together.

1.2. Transition to Academic Life

In 1966, Steve received an offer of a lectureship in Mathematics at Imperial College London (now Imperial College of Science, Technology and Medicine), and asked Suellen to accompany him there as his wife in a hastily arranged proposal, sans engagement ring, substituting a college fraternity pin instead—he must have had to search hard for this before leaving the apartment that evening! They were married shortly thereafter in Carmel, California, close to the site of a conference held in Monterey in 1999 to commemorate Steve's sixtieth birthday (Smith et al. 2002) (see **Figure 1**). Suellen, who was from Dallas, Texas, and was nicknamed "Lil Darlin'" by Steve, became as well known by Steve's associates as he.

Figure 1

A conference in Monterey, California, to commemorate Steve Davis's sixtieth birthday in 1999. Pictured are (*left to right*) Ulrich Müller, Jon Dantzig, Steve, Joel Koplik, and Bob Kelly.

Imperial was a good place for Steve to begin his academic career, considering his interest in hydrodynamic stability and the presence of J. Trevor Stuart, a giant in the field, in the Department of Mathematics. Derek W. Moore, an expert in bubbles, among other things, joined the department as a senior lecturer a year after Steve. Derek was also an accomplished jazz saxophonist who played regularly in local clubs, and given Steve's love of artists such as the great jazz trumpeter Miles Davis, one must suspect that these two had some interesting conversations about music.

Sadly, for Imperial, life in London on the salary of an Imperial College lecturer became a bit too difficult to manage. So in 1968, Steve accepted an offer from the Department of Mechanics at Johns Hopkins University in Baltimore, Maryland, to which the couple moved. Being back in the United States provided Steve another advantage—the opportunity to see the Yankees play in person. Steve convinced Suellen to accompany him to a doubleheader (back-to-back games, for those not familiar with the sport) between the visiting Yankees and the Baltimore Orioles. Suellen, who was eager to please but not the baseball fan that Steve was, agreed to go. The first game extended, because of the need to break a tie, from the traditional 9 to 14 innings.

At Hopkins, Steve's career really blossomed. Mechanics as well as other departments included prominent individuals in fluid mechanics, such as Owen Phillips, Les Kovasznay, Kim Parker, Robert Long, Bill Schwartz, and Francis Bretherton. Lucien Brush and Jerry Gavis were in the Department of Geography and Environmental Engineering and Bruce Marsh, a geophysicist with interests in volcano formation that involved fluid instability, joined the Department of Earth and Planetary Sciences later. The principal relationship, however, was the one that developed between Steve and Stanley Corrsin. Stan, a world-renowned expert in turbulence, was a fixture at Hopkins prior to Steve's arrival, and the two personalities seemed to meld together almost as one. One of the most notable aspects of their friendship was the incredible, yet noncompeting, sense of humor that both possessed. Morning coffee at 10:00 a.m. in a room adjacent to Stan's wind tunnel was an institution, and one without the slightest hint of stuffiness or puffery. Discussions took place on virtually any topic one might imagine, most accompanied by large amounts of laughter. All attendees, be they faculty, visitors, staff, or students, were on a first-name basis, and stories too numerous or inappropriate to mention exist of experiences there. It was to coffee one morning that one of us (Paul Neitzel), visiting the department as a prospective PhD student, was taken by the department chair Bob Pond (a metallurgist) to meet this young faculty member, Steve Davis, with whom Bob felt Paul might be compatible as a research student. Meeting both Steve and Stan at the same time in this setting was an incredible experience that solidified Paul's decision to study

Figure 2

Pre-wake dinner for Stanley Corrsin (whose portrait is in the frame) in 1986. Pictured are (*left to right*) James Grotberg, Steve Davis, Paul Neitzel, Jane Zee, Mike Karweit, Rick Buckholz, Jim Riley, and Genevieve Comte-Bellot. Grotberg, Neitzel, and Buckholz were Steve's former students.

at Hopkins, one that positively shaped the rest of Paul's career and for which he shall be forever indebted to Bob Pond (see the group picture in **Figure 2**).

Steve's arrival at Johns Hopkins in 1968 not only brought him graduate students to work with but also allowed him to expand his research interests. New research areas came quickly with graduate student help, including water waves (Liu & Davis 1977), sedimentation (Herron & Davis 1975), and lung mechanics (Grotberg & Davis 1980). Steve continued at Hopkins with his work on stability and, especially, interfacial fluid mechanics, producing outstanding results. His work with Elizabeth Dussan V. (see **Figure 3**) on contact-line dynamics is discussed below and has been recognized for its fundamental contributions to our understanding of this complex phenomenon and the role of the no-slip condition. Steve's work on the stability of time-dependent flows was prolific and noteworthy during his years at Hopkins. Toward the end of his time at Hopkins, his cosupervision of his student Jonathan Dantzig sparked his interest in the field of solidification, an area that occupied a great deal of his attention for years to come.

Figure 3

(*Left to right*) Steve Davis, Elizabeth Dussan V., and Paul Neitzel on September 23, 2018, at a restaurant in Cambridge, Massachusetts.

Steve's reputation as an advisor made him a magnet for students. Among his greatest skills was the identification of research problems that fit with a student's interests and that had clear-cut, attainable goals, as well as outcomes that resulted in publications in the best journals. He was masterful in allowing his students to work on the problems themselves, stepping in when a workaround to a proverbial brick wall was needed by providing a suggestion that pointed a way forward.

In addition to his love of baseball and his proficiency as a bowler, as noted by Neitzel (2010, 2023), Steve was a regular participant in athletic activities, especially tennis, at which he was considered to be quite accomplished. He also occasionally played basketball while at Hopkins, although the outcomes were not always positive for him. On one occasion, Steve either pivoted or was pushed by another player, twisting around while one sneaker-clad foot remained planted on the floor, resulting in a lower-leg fracture. Steve was seen by Baltimore orthopedist Charles "Chick" Silberstein, who was for a time the physician for Hopkins' lacrosse team. When Silberstein entered the room after viewing Steve's X-ray, notifying him of the fracture, Steve commented, "I'll bet the bone was broken at a 45-degree angle," to which Silberstein replied, "How could you possibly know that?" Steve's response was, "Strength of materials—that's a sophomore course." Steve taught for the rest of that semester seated, writing on transparencies on an overhead projector.

In 1978, Hopkins, which had years earlier merged its former schools of engineering and arts and sciences into a single faculty of arts and sciences, decided to form a separate school of engineering once again. Although Steve considered remaining, he was not altogether happy with the way the new school was being established and decided to leave. The University of Arizona was a strong contender for his attention, given Steve's lifelong suffering with asthma, but it was Northwestern University that won out, wooing him to the Department of Engineering Sciences and Applied Mathematics in December 1978, where Steve would spend the remainder of his career. One suspects that Tucson's lack of a regular-season major-league baseball team (teams do conduct spring training there, but these games mean little to a true aficionado) and the presence of two in Chicago may have played a small role in this decision.

To Northwestern, Steve brought the same qualities of excellence in teaching and research, coupled with an outstanding sense of humor that he had used to succeed at Hopkins. His reputation drew many visitors from around the world to campus, enhancing the already excellent reputation of the department and the McCormick School of Engineering. Working with colleagues such as Ed Olmstead, Bernie Matkowsky, Ed Reiss, Grae Worster, and Mike Miksis, as well as people in other departments such as Peter Voorhees (Materials Science and Engineering) and George Bankoff (Chemical and Biological Engineering), Steve continued his work on free-surface flows and became more deeply interested in solidification. An example of Steve's informal nature and impact on the department was the weekly fluid dynamics seminar, known as the "Lunchtime Fluids Seminar." Speakers were encouraged to speak about unfinished work, and the audience was encouraged to eat their lunch. Discussions were lively and sometimes even ended in a new approach to the problem.

One example of a materials-related interfacial flow problem to which Steve contributed while at Northwestern is the stability of thermocapillary convection, a problem motivated by its importance in float zone crystal growth processing. Steve and his student Marc Smith found (Smith & Davis 1983a,b) that thermocapillary convection could experience an instability manifesting as "hydrothermal waves." This "Smith and Davis instability," as it came to be known, spawned further research that continues to this day.

Throughout his career, Steve enjoyed visiting other academic institutions to interact with like-minded scientists and to acquaint himself with new, interesting problems. These newfound friends and collaborators would likewise visit Steve, both at Hopkins and Northwestern, opening new vistas for his students and colleagues there. A brief accounting of some of these relationships may be found in a recent obituary for Steve printed in JFM (Neitzel 2023).

The following sections provide more in-depth insight into Steve's contributions to the fluid mechanics and solidification research communities. The article ends with a brief summary of the accolades given in recognition of Steve's contributions, as well as an accounting of the ways in which Steve served these communities through other activities.

2. STEPHEN H. DAVIS AND FLUID MECHANICS

When one thinks about Steve and his place in the community, it is his association with the field of fluid dynamics that comes to mind for most people. He made contributions to convection, interfacial mechanics, rupture of films, and many other topics. Most importantly, his research related to more than just a specific application; he developed techniques that could be generalized to many other areas as well.

Outside of his research contributions in fluid mechanics, Steve was closely associated with the professional life of the fluids community. He joined the board of JFM in 1969 and was the Editor from 2000 to 2010. During those years, getting Steve's acceptance on a manuscript was considered an accomplishment, and many of us who consider themselves close colleagues of Steve learned about the high standards of JFM when receiving a rejection letter. The *Annual Review of Fluid Mechanics* (ARFM) benefited greatly from Steve's presence on the board from 1994 and his eventual editorship from 2003 to 2021 (Moin 2021). His presence at the annual Division of Fluid Dynamics meeting of the American Physical Society (APS) livened up technical discussions, and he was always willing to chat with colleagues about their recent work and provide input. Dinners usually involved many of his colleagues, as well as both former and current postdocs and students (if they could afford the restaurant).

Steve's research contributions in fluid dynamics are many. To try to describe them all would require much more space. The focus here will be on three broad topics to which we feel he is forever connected: thermal convection and stability, contact-line motion, and thin films.

2.1. Thermal Convection and Stability

Steve's dissertation research set the direction of his work for many years to follow. First, it introduced him to the subject of fluid dynamics, given that he transitioned to graduate school from electrical engineering. Second, the mathematical focus of the work was on stability, and many of the ideas in his thesis he later generalized and expanded. A quick review of Steve's publication titles shows that the word "stability" (or "instability") appears in approximately one-third of his papers.

His curriculum vitae shows but a single publication with Lee Segel (Davis & Segel 1968), although there is also a reference to a joint conference abstract (Davis & Segel 1963). The published paper focused on a nonlinear investigation of the effect of surface curvature on cellular convection and used a nonlinear-stability analysis based on previous work by Segel (1965). Given that Steve completed his thesis in 1964, wrote the manuscript while he was at the Rand Corporation, and noted in a footnote that his present address was Imperial College, he clearly was not in any rush to publish this work. Yet the ideas in the manuscript lead to several of his most well-known contributions.

For example, while at Rand, he completed one of his most cited works on convection, "Convection in a Box: Linear Theory" (Davis 1967). The novelty was that he included the impact of the sidewalls on the patterns observed in experiments. Some details are worth mentioning. A simple thermal convection experiment consists of heating from below a layer of fluid (e.g., water) that is contained in a region of finite dimensions (e.g., a finite box). The box may or may not have a top. The temperature difference between the top and the bottom is usually represented in terms of a dimensionless number, the Rayleigh number, which is proportional to the temperature jump across the layer and includes the effect of gravity and the thermal properties of the liquid. For small Rayleigh numbers, a motionless state with a linear temperature gradient can be expected. But with increasing Rayleigh number the fluid becomes dynamic and the first bifurcation past the steady state is to a state of rolls. To model the dynamics Steve used the Boussinesq approximation. The linearization process about the steady state results in a system of partial differential equations that is difficult to solve. Steve got around a direct solution by using a Galerkin procedure with approximate eigenfunctions to approximate the critical Rayleigh number. Steve's linear theory in a box compared well with the experimental prediction of a critical Rayleigh number in a box of finite dimensions. For example, he was able to predict, as a function of the geometry, the preferred observed roll directions. In a follow-up manuscript (Davis 1968), he answered the question of why experiments showed that as the Rayleigh number increased past its critical values the number of rolls decreased. This was in contradiction to theoretical predictions with an infinite layer of fluid and required a nonlinear analysis. Steve's work was the forerunner to much research by others in the early 1980s on the effect of finite domains on stability limits.

Stability continued to be a central topic in Steve's research for the rest of his career. The stability of time-periodic flows was a new area of focus for Steve after his move to Hopkins. Examples of such flows are unidirectional parallel-shear flows and thermal-convective flows, where the fluid layer is oscillated vertically so that the apparent gravitational acceleration is time periodic. The base states in these problems are time periodic; hence, a careful definition of stability and, in particular, a definition for a nonlinear theory are needed to make progress. Although stability of a state can still be described by looking for conditions under which a disturbance decays at every instant of time, the concept may be generalized to allow for growth and decay during a cycle. A basic state that allows for such transient growth, but net-zero growth over a cycle, is called transiently stable, and transiently stable states allow for situations where heat or mass transport could differ from those of the basic state. With this in mind, Steve, along with his graduate students J.D. Dudis and C. von Kerczek, developed an energy stability theory for the nonlinear-stability problem (Davis 1969; Dudis & Davis 1971a,b; von Kerczek & Davis 1972; Davis & von Kerczek 1973). They applied these ideas to study a buoyancy–surface tension instability, buoyancy and Ekman boundary layers, and oscillatory Stokes layers. This work and other approaches were summarized in an ARFM review by Davis (1976), in which he discussed several examples of the stability of time-periodic flows. One of the recommendations of the review was that additional work on the stability of time-dependent states was needed, and his recommendation was followed by many, including Steve (e.g., Neitzel & Davis 1980, 1981).

2.2. Contact-Line Motion

For many within the fluids community, Steve's work with Dussan V. set up the fundamental principles associated with the spreading of a three-phase contact line (Dussan V. & Davis 1974). The problem is simple to state and is associated with an everyday phenomenon with which we are all familiar: the spreading of a liquid along a solid surface. Consider a drop of fluid resting along a horizontal, flat solid surface surrounded by a second fluid. This could be a drop of water in air on glass or a drop of glycerin in silicone oil on Plexiglas®. Both fluids appear to wet the solid where they meet it, and since they are immiscible, there is a three-phase line where the phases come into contact with one another. Associated with this contact line is a static contact angle given by Young's relation, which balances horizontal forces due to tension at the point of contact. Experience tells

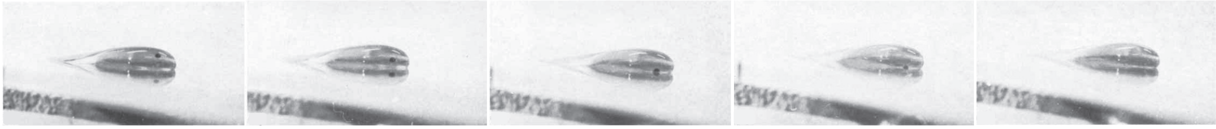

Figure 4

A drop of honey moving on a Plexiglas® surface. A dye marker indicates the existence of rolling. Figure adapted with permission from Dussan V. & Davis (1974).

us that when the solid is lifted at one end, gravity will force the drop (assuming it is more dense than the host fluid) to move downward. One then observes a moving contact line where one fluid is being displaced by the second. This simple experiment has caused difficulties in modeling and experimental verification for many fluid mechanicians. For example, using a very simple model problem where the no-slip condition is used along the solid surface, Huh & Scriven (1971) concluded that it would take infinite energy to move the contact line. This is not satisfactory and raised many questions about the validity of the no-slip hypothesis in this situation. Dussan V. and Davis revisited this problem both theoretically and experimentally (see **Figure 4**). They made several conclusions that allowed for advances within the field. In particular, they concluded that material points on the interface can move toward a contact line and reside on the solid–liquid interface or on the fluid–fluid interface (i.e., there is a rolling motion). They also noted that no-slip is kinematically compatible with a moving contact line, but that the velocity field is multivalued at the point of contact, resulting in unbounded forces. They noted that these infinite forces could be relaxed by allowing slip along the solid substrate. These observations opened the door to a host of work focused on the dynamics of contact lines [e.g., see the reviews by Dussan V. (1979), Davis (1983a), de Gennes (1985), Rosenblat & Davis (1985), Miksis (2004), and Snoeijer & Andreotti (2013)].

Steve returned to the topic of contact-line motion several times in future years. Examples include his investigation of rivulet instabilities (Davis 1980, Weiland & Davis 1981, Culkin & Davis 1984, Young & Davis 1987b), contact-angle hysteresis (Young & Davis 1987a), the origins of slip (Miksis & Davis 1994, Kirkinis & Davis 2013), and spreading on porous solids (Hocking & Davis 1999, 2000). He contributed to all aspects of the problem, from the mathematical to the physical.

The work of Ehrhard & Davis (1991) is particularly notable since it combined Steve's interest in contact-line motion with thermal effects. The problem they considered was the nonisothermal spreading of a thin liquid drop. Applying lubrication theory, they were able to derive a nonlinear evolution equation for the drop height. Although this greatly simplified the determination of the drop interface, in that it reduced it to an evolution equation, the domain is undetermined because the drop is spreading, and closing the system requires a relationship between the contact angle and the spreading velocity. Their model introduced thermocapillary forces on the interface. For this nonisothermal flow, these forces were shown to substantially retard the spreading when the plate was heated (in cases in which the liquid surface tension decreases with increasing temperature). Hence, they illustrated a mechanism for the thermal control of drop spreading. This work was later generalized to study volatile liquid drops (Anderson & Davis 1995).

2.3. Thin Films and Liquid Layers

It was observed by Osborne Reynolds that fluid flow within a narrow gap can be approximated by functions that mostly vary in the direction of flow—i.e., a complicated 3D problem can be reduced in complexity by noting the disparity of the length scales. This observation is the basis for the solution to many practical fluid dynamics problems (e.g., lubricated bearings and slider flows). It was later observed that this concept of using the disparity of scales could be directly applicable to studying the dynamics of thin films. In this context, it is sometimes referred to as a long-wave theory, which, if properly applied, may allow for the dynamics of the thin film to be reduced to an evolution equation for the thickness of the film as a function of time and the horizontal coordinates.

Steve and his student Malcolm Williams decided to ask what happens to a very thin film—so thin that van der Waals forces are on the order of the capillary forces (Williams & Davis 1982). What is the proper evolution of the film? Applying long-wave theory, they derived a first-order-in-time, fourth-order-in-space, nonlinear evolution equation for the dynamics of the interface. Prior to their work, a linear analysis by Ruckenstein & Jain (1974) predicted that thin-enough films would become unstable, leading to film rupture. Williams & Davis were able to investigate the nonlinear behavior and to estimate a rupture time. In particular, they showed that the predicted nonlinear time was smaller than what was estimated by linear theory. Their analysis has been generalized by many others in situations where the effect of a disjoining pressure is significant. This model is also the basis for studying the spreading of drops that completely wet a surface (i.e., with no contact line) (de Gennes 1985).

In 1979 Steve left Johns Hopkins for Northwestern. The department he joined was established in 1976 and was the home of nuclear engineering, biomedical engineering, and applied mathematics. The applied mathematicians there at the time were Bernie Matkowsky and Ed Olmstead. Both had a vision of growing applied mathematics within the department. In 1979, Steve was added to the group. This gave the department a firm foundation from which to grow in applied mathematics. In 1985, both nuclear and biomedical engineering found other homes at Northwestern, and from then on, applied mathematics was the focus of the department. The move to Northwestern for Steve brought new types of students (i.e., those who came to Northwestern to work in applied mathematics), and Steve was there to provide them with challenging problems along with his new focus in materials science.

One of his first graduate students at Northwestern was Marc Smith, and their work focused on instabilities of dynamic liquid layers under the influence of thermocapillarity (Smith & Davis 1983a). There were other existing investigations of surface-tension-driven convective instabilities in the literature (Gumerman & Homsy 1974), but Steve and Marc's work arose because of a specific application, in particular, the floating zone process of bulk crystal growth from a melt. This technique is a containerless method for growing low-oxygen-content materials such as silicon (due to the absence of an SiO_2 crucible in which molten Si is held) for use in electronics manufacturing. Dopant striations observed in such materials made them less desirable for increasingly smaller devices due to spatial nonuniformities, and it was originally believed that a buoyancy-driven convection instability leading to an oscillatory flow might be the culprit. Thermocapillary convection is often swamped by the existence of buoyancy-driven convection, but this is not the case in the weightless microgravity environment of space, which NASA (National Aeronautics and Space Administration) had been exploring as part of a materials-processing-in-space initiative. Steve and Marc found that thermocapillary convection could experience an instability manifesting as hydrothermal waves, which was hitherto unknown and which may be responsible for the observed dopant striations. The Smith and Davis instability, as it came to be known, spawned further research that continues to this day. We note that hydrothermal waves were later confirmed in the experiments of Riley & Neitzel (1998) (see **Figure 5**). Smith & Davis (1983b) followed up on this investigation by allowing the interface to deform, identifying a surface wave instability. These and other related works on thermocapillary instabilities were reviewed by Steve in this journal (Davis 1987).

The move to Northwestern also brought new colleagues sharing common interests. One of these was George Bankoff, who was in the Department of Chemical Engineering and focused

Figure 5

Instantaneous thermograph of hydrothermal waves on a 1.0-mm-deep layer of silicone oil, viewed from above. The hot and cold walls are at the left- and right-hand sides of the figure, respectively, and the hydrothermal waves are propagating from the lower-right to the upper-left. Figure reprinted with permission from Riley & Neitzel (1998).

on heat transfer in fluids and fluid films. Together with their student Jim Burelbach, Steve and George decided to investigate the nonlinear stability of a heated liquid film with a vapor above it (Burelbach et al. 1988). They focused on the limiting case of the two-fluid problem so as to decouple the dynamics of the vapor from the dynamics of the liquid, resulting in what they called a one-sided model of evaporation. Their model included mass loss, vapor recoil, thermocapillarity, long-range molecular forces, surface tension, and viscous forces. This resulted in a complicated moving-boundary problem to analyze. Noting that for other instances in which molecular forces are included the critical wavelength for instability was much larger than the mean thickness of the liquid layer, they used long-wave theory to develop a strongly nonlinear evolution equation for the liquid interface. Given the complexity of the problem, this was a significant achievement. Special limiting cases of the physical parameters recovered the work of Williams & Davis (1982) and of Davis (1983b). Their model allowed for the prediction of stability of the film and rupture time, including specifics of the process itself. When rupture occurred, they found a similarity form for the thickness $h(x, t)$ of the film near the rupture location of the form $h \approx k(t - t_R)^q F(x)$, where t_R is the rupture time, and the exponent q varies from unity, when mass loss is negligible, to 1/2, when it is dominant. This work and others on the long-scale evolution of thin liquid films were discussed in the review article by Oron et al. (1997). As of this writing, this is Steve's most cited publication and is the go-to article for anyone wishing to learn about the subject.

The work with Williams and the generalization with Burelbach and Bankoff resulted in a nonlinear evolution equation for the dynamics of a thin liquid layer on a solid surface. Many films exist without the presence of a substrate (e.g., the thin liquid film enclosing a gas bubble), and a reasonable question to investigate concerns the stability of these thin films in the presence of van der Waals attractions. Steve, along with his colleague Thomas Erneux, explored exactly this situation (Erneux & Davis 1993). Long-wave theory was again applied, but because of the lack of a substrate, the fluid in the membrane could flow parallel to the interfaces. Because of this, their analysis resulted in a coupled system of nonlinear evolution equations for the film thickness and the tangential flow velocity. Through a nonlinear analysis of their equations they were able to predict conditions for stability and the time to rupture. Their model was generalized and studied by other investigators (see, e.g., Ida & Miksis 1998a,b).

While it is true that the Oron et al. (1997) paper has been very influential on the field, a more recent, but less well-known, article by Steve (Davis 2017) entitled "The Importance of Being Thin" in some ways tells us more about Steve's approach to research. It describes several of Steve's prior investigations and provides a more global perspective of Steve's approach to problems in fluid mechanics. It is a fun article to read and displays the commonality between different areas when there is one small dimension.

3. STEPHEN H. DAVIS AND MATERIALS SCIENCE

Steve's interest in materials science started in the late 1970s when a Johns Hopkins graduate student, Jonathan Dantzig, approached Steve needing guidance on solidification modeling. Jon reports (private communication):

> It was just a few years after Pol Duwez made the first metallic glass by splat cooling, and I was looking into rapid solidification by melt spinning with Robert Pond Sr. I made some Cu-P eutectics that had featureless microstructures, but we really didn't have the facilities to characterize them. I started doing some theoretical modeling of solidification with kinetics, and I turned to Steve for guidance.

Materials science then became a major part of Steve's research portfolio. Materials science was a perfect new field for Steve since the evolution of interfaces in materials is a highly nonlinear process that is governed by diffusion, fluid flow, and capillarity. Steve's initial focus was on solidification processes but broadened considerably in the later stages of his career. The result is a large corpus of work that has been impactful in many ways. It is thus impossible to mention every groundbreaking paper, so we have chosen a few representative examples to illustrate the arc of Steve's work in the materials area.

3.1. Solidification

Steve's view on solidification is captured well in his book *Theory of Solidification* (Davis 2001). Steve's background in applied mathematics gives a unique perspective on the field that is captured well in the book. It provides a comprehensive picture of the evolution of interfaces during solidification. Much of the material discussed below is treated with great clarity in his book.

Perhaps not surprisingly, Steve's first major papers on solidification focused on the link between fluid convection and the stability of the solid–liquid interface. The fascinating question was how the presence of an interface that can change its shape due to heat and fluid flow influences the classic Bénard convection problem that Steve had studied in depth. In collaboration with Ulrich Müller and C. Dietsche (Davis et al. 1984), he examined the conditions under which rolls and hexagonal solidification patterns are observed in a single-component solid heated from below and cooled from above (see **Figure 6**). They found that the patterns are a function of the thickness of the solidified layer and were able to identify the conditions under which the

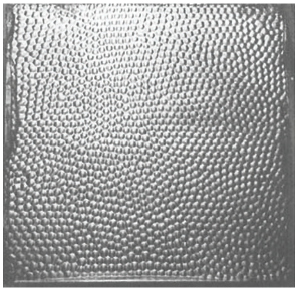

Figure 6

A corrugated solid–liquid interface in cyclohexane illustrating the hexagonal patterns resulting from convection. Figure reprinted with permission from Davis et al. (1984).

nonplanar solid–liquid interfaces and the resulting alterations in heat flow give rise to various interfacial morphologies. The mechanisms suggested, however, are general and observed in other solidification processes where buoyancy-driven convection is appreciable. Steve retained a lasting interest in the role of convection during solidification, studying long-wave equations in the small segregation limit (Young 1986), the role of convection in mushy zone evolution (Roper et al. 2008, 2011), and the effects of convection during additive manufacturing (Kowal et al. 2018).

The conditions under which a planar solid–liquid interface is stable during directional solidification are given in the classic morphological-stability theory of Mullins & Sekerka (1964). However, their theory assumes that the solidification velocity is slow enough that the interface is in local equilibrium, implying that the compositions of the solid and liquid are given by the equilibrium phase diagram, modified by capillarity. At sufficiently high interfacial velocities there is insufficient time to establish local equilibrium, and the compositions at the interface become a function of the interfacial velocity. There has been a great resurgence in interest in this topic since the interfacial velocities found during metal additive manufacturing are typically in the range where local equilibrium does not hold.

Greg Merchant and Steve (Merchant & Davis 1990) analyzed the effects of these nonequilibrium processes during directional solidification by studying the linear stability of a planar interface using a model for nonequilibrium interfaces given by Aziz & Boettinger (1994). Thus, it was possible to make experimentally testable predictions, a theme that runs through all of Steve's research. Their linear-stability analysis shows an oscillatory instability that, interestingly, has a zero-wavenumber onset. This can give rise to an experimentally observed banded structure where there are bands with increased solute content parallel to the liquid interface. Since the steady instability was also present, it was possible to investigate the parameters at which both steady and oscillatory instabilities exist. The analysis was performed in the limit where the latent heat released at the solid–liquid interface is neglected. They mentioned that latent heat can affect the critical wavenumber for the oscillatory instability, a feature investigated in depth by Huntley & Davis (1993) and seen in the simulations of Karma & Sarkissian (1992).

All of the work on solidification cited thus far assumed that the solid–liquid interfacial energy is isotropic. Through interactions with Sasha Golovin, Steve developed a long-standing interest in systems with highly anisotropic interfacial energy. In this case the interfacial energy is sufficiently anisotropic that there are missing crystallographic orientations that lead to corners on the equilibrium shape of a crystal. Studying the evolution of systems with this highly anisotropic energy is particularly challenging because, in the regions where there are missing orientations, the evolution equations for the interface shape become ill posed. Steve, Sasha, and Alex Nepomnyashchy developed a physics-based regularization to the evolution equations for a solid–liquid interface in the completely interface-reaction-controlled growth limit (Golovin et al. 1998). If the interfacial energy is curvature dependent, the corners that are present on the equilibrium Wulff shape are rounded, resulting in an evolution equation that is valid for an interface of any crystallographic orientation. They showed that in certain limits the interfacial evolution is described by a driven Cahn–Hilliard equation wherein the interface is corrugated with kinks and antikinks of a certain wavelength. A surprising result was that, due to the growth process, the range of orientations present on the growth interface is not the same as that on the equilibrium shape of the crystal. Moreover, they found that these kink and antikink patterns coarsen, resulting in an increase in wavelength, and were able to identify the temporal exponents of the coarsening process. Further work identified both power law and logarithmic coarsening kinetics and determined the importance of the convective terms due to solidification in the coarsening process (Watson et al. 2003).

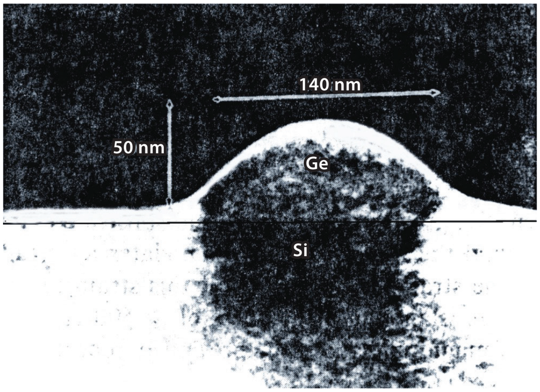

Figure 7

A coherent Ge island on an Si substrate. Figure reprinted with permission from Eaglesham & Cerullo (1990), *Physical Review Letters*, Vol. 64(16), p. 1945; copyright 1990 American Physical Society.

3.2. Nanotechnology

Steve's work in materials science and engineering was far broader than solidification and for many years involved studies in nanotechnology. One example is Steve's work on the stability of an elastically stressed thin film on a substrate. The stress is a result of the difference in lattice parameters between the film and substrate. There was intense interest in this area, since it was observed experimentally that, following deposition from the vapor, one obtains an array of isolated islands rather than the desired planar thin film. The goal was to control the size of the islands to produce quantum dots and novel optoelectronic devices. The prevailing idea was that the islands formed due to strain-induced dislocation formation. However, there were clear examples where islands form without the presence of dislocations (see, e.g., **Figure 7**). There was also previous theoretical work showing that elastic stress can lead to a morphological instability of uniaxially strained solids, now known as the Asaro–Tiller–Grinfeld instability. Using the newly developed thermodynamics of stressed solids, Steve, Brian Spencer, and Peter Voorhees studied the stability of the film–vapor interface of a misfitting film where the elastic constants of the film are different from those of the substrate (Spencer et al. 1993). The analysis showed that such a dislocation-free film can indeed be morphologically unstable. The elastic constant difference between the film and substrate affects the growth rate of the instability, and there is a critical thickness below which the film is stable for a perfectly rigid substrate. However, for all nonrigid substrates the growth rate of the instability is positive. The instability is not necessarily observable experimentally because it occurs during the growth of the thin film, and thus it is necessary to compare the growth rate of the instability to the growth rate of the planar thin film. Only when the growth rate of the instability is larger than that of the planar film will it be possible to observe the instability. Therefore, a kinetic critical thickness exists below which the film will remain nearly planar. The kinetic critical thickness has a very strong scaling with respect to the misfit strain, ϵ^8, and thus is very sensitive to the materials parameters. A weakly nonlinear analysis finds that cusp-like solutions exist that are similar to those seen experimentally (Jesson et al. 1993), but they are unstable. Later, fully numerical simulations showed that the cusp would continue to deepen until it intersected the substrate, which is related to a mechanism for crack formation by diffusion (Yang & Srolovitz 1993, Spencer & Meiron 1994).

Another important contribution of Steve's work in nanotechnology is understanding the factors controlling the growth of nanowires by the vapor-liquid-solid method. In this growth process, a catalytic liquid droplet sits atop a solid wire and leads to highly unidirectional growth of the solid

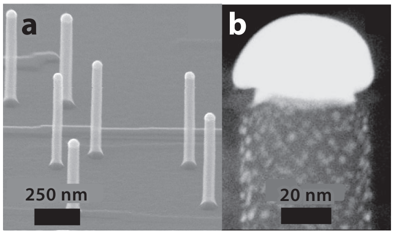

Figure 8

(*a*) An array of Si nanowires on a substrate. (*b*) A nanowire showing the formerly liquid Au catalyst on top and the Si wire below, along with Au domains along the side of the wire. Figure adapted with permission from Madras et al. (2010); copyright 2010 American Chemical Society.

wire. These nanoscale diameter wires can be used, as is the case for quantum dots, to produce novel electronic devices. For example, during the growth of silicon nanowires, a liquid gold particle is the catalyst for the decomposition of the silane (SH_4) gas that surrounds the wire (see **Figure 8**). Following the decomposition of the silane, the Si enters the droplet. The droplet then becomes supersaturated and feeds the growth of the wire at the bottom of the droplet. Highly directional growth is obtained because the solid Si sides of the wire do not promote the decomposition of silane. Under certain conditions, this process leads to the steady growth of a straight wire perpendicular to the substrate with the droplet riding atop. There is also a link between this problem and Steve's pioneering work on contact-line motion in fluids, as the dynamics of the three-phase (Si-Au-gas) contact line plays an essential role in the shape and straightness of the wire.

Working with Steve Roper and others, Steve developed a model to relate the steady growth rate of the wires to their processing conditions (Roper et al. 2007). The theory accounted for the surface energies of the three interfaces, the degree of supersaturation in the liquid catalyst, and contact-line conditions. An important assumption in the model was that the solid–liquid interface is not faceted. The model predicted the concentration profile within the droplet, the degree of supersaturation, and the modification to the shape of the solid–liquid interface due to growth, as functions of the material properties and process parameters. Interestingly, under typical experimental conditions, the interface deviation from planarity due to growth is very small. Connecting the processing conditions to the diameter is very important for applications since the electronic properties of the wire are a function of its diameter. They also examined the relationship between the diameter of the wire and its growth rate, finding that the growth rate is independent of the wire radius. This model, however, assumes that the solid–liquid interface is thermodynamically rough or not faceted. In many cases, the growth temperature is far below the roughing temperature of the interface, and thus the interface is atomistically flat or faceted. Subsequent work with Sasha Golovin (Golovin et al. 2008) investigated the rate of step migration across the surface of the solid–liquid interface and the role this step-flow process plays in setting the growth rate and diameter of the wires. Thus, Steve's work addressed two important limits of the nanowire growth problem.

One question Steve often raised during our meetings was, "Why does the liquid catalyst stay on top of the wire?" This is critical, for if the droplet rolls off, either the wire stops growing or kinks appear in the wires. A particularly interesting aspect of this problem is that when the solid–liquid interface is faceted, there is a corner at the contact line. Since the contact angle is not unique at a corner, there is a range of possible contact angles, and this plays a major role in the selection of the radius of the nanowire. The range of allowable contact angles at the corner follows from Gibbs's classic work (Gibbs 1876). Using this result, Golovin et al. (2008) showed that the radius of the wire is determined by the volume of the liquid catalyst and the ratio of the solid–liquid to vapor–liquid interfacial energies. More importantly, this suggests that the wire radius can be tuned by adjusting the value of the vapor–liquid interfacial energy via the introduction of gases with impurities that adsorb to the liquid–vapor interface. Using Gibbs's results on allowable contact angles at a sharp corner, they also related the existence of unidirectional growth to the ratios of interfacial energies. If certain values of these interfacial energies are not present, then the droplet is expected to unpin and move down along the wire. There are many possible morphologies of the liquid along the solid cylindrical wire surface. Steve and coworkers also investigated the dynamics of the depinning process. It was found to occur on the nanosecond timescale due to the large capillary forces and small size of the droplets (Schwalbach et al. 2012). This instability thus could give rise to branches and kinks in the nanowire during growth that are observed experimentally. Steve went on to examine both nonaxisymmetric droplet depinning processes (Muralidharan et al. 2013) and droplets on growing carbon nanotubes (Zhang et al. 2017).

3.3. Interface Motion by Capillarity: Another Intersection with Fluid Mechanics

Steve was long fascinated by the motion of contact lines and the role of interfacial energy in the evolution of interfaces. A perfect example of this deep interest is his work on capillary-driven dewetting of solid thin films. Not only is the physics underlying capillarity and contact-line motion, which are present in similar problems in fluids, important, but also the morphologies are strikingly similar to fluids problems, as seen in **Figure 9*a***. Unlike in fluids, the dewetting process occurs by surface diffusion along the solid film surface. While there are many interesting basic-science questions that Steve considered, the dewetting process has important technological implications. In one limit, if the goal is to produce a uniform thin film on a substrate, this dewetting process should be avoided, but in another, the instability can be useful in creating domains on a surface that may have interesting opto-electronic applications (Thompson 2012).

Inspired by the experiments of Jiran & Thompson (1992) (see **Figure 9*a***), Steve's first foray into solid-state dewetting was to consider the linear morphological stability of lines of film deposited

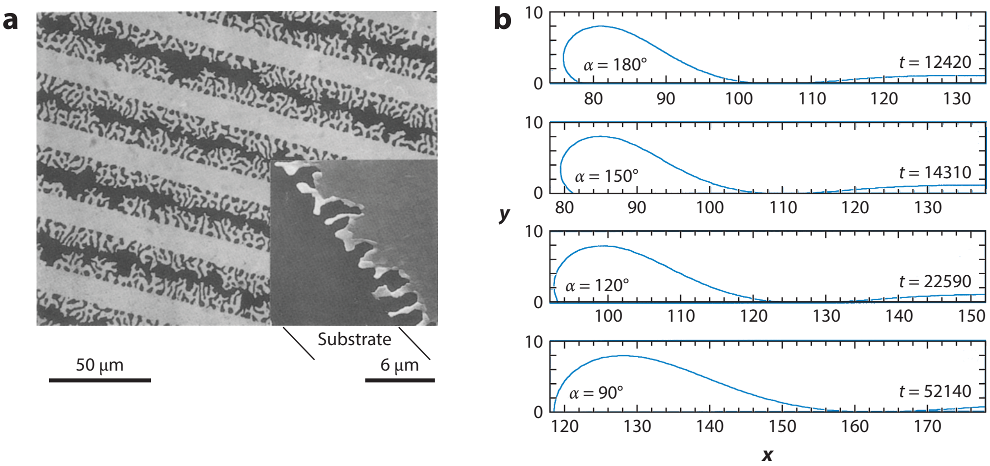

Figure 9

(*a*) Dewetting of a solid Au film patterned into lines on a fused silica substrate. The inset shows a magnification near the contact line illustrating the complex morphology and enhanced thickness of the film near the contact line. Panel adapted from Jiran & Thompson (1992, p. 1723); copyright 1992, with permission from Elsevier. (*b*) Evolution of a film wedge to the point of touchdown as a function of the contact angle α. The contact line is moving from left to right where the y- and x-axes are dimensionless and equally scaled. Panel adapted with permission from Wong et al. (2000).

on a substrate (McCallum et al. 1996). He and collaborators took the cross-section of the film as a portion of a circle with a height given by the contact angle at the film–substrate–air contact line. If the contact angle is 180°, the problem reduces to the classic Rayleigh instability, and if the contact angle is 0°, the film is planar and linearly stable. Thus, the focus of the study was to determine the effects of contact angle on the instability. While the line is always unstable to perturbations with a range of wavenumbers in the axial direction, the range of unstable wavelengths is always less than that of a cylinder of the same volume. More importantly, the maximum growth rate of the instability varies strongly with the contact angle. Despite the linear nature of the analysis, the predictions were surprisingly close to the experimentally observed wavelength and growth rates of the instability.

The linear-stability analysis, of course, cannot address the film breakup process shown in **Figure 9*a***. To address this issue, Steve and coworkers (Wong et al. 2000) developed a model for the evolution of film-step on a surface. The film–substrate–vapor contact line will move due to the nonuniform curvature along the surface. This, then, drives surface diffusion along the film, resulting in the film retracting from its initial position. The retracting film edge forms a thickened ridge followed by a valley that is observed in experiment (see **Figure 9*a***). The valley sinks with time and eventually touches the substrate, as observed in **Figure 9*b***. The ridge then detaches from the film and the new film edge retracts to form another ridge accompanied again by a valley, and the mass-shedding cycle is repeated. This periodic mass shedding was simulated numerically and the dynamics was found to depend strongly on the contact angle α, as shown in **Figure 9*b***. They also found that the long-time retraction speed and the distance traveled per cycle agreed quantitatively with experiments by Jiran & Thompson (1992).

4. CONCLUSIONS

Above we have reviewed several of Steve's most impactful contributions. The intent was to illustrate the breadth of his work, which will grow in impact in future years. The research community acknowledged his contributions through his election to the American Academy of Arts and Sciences, the National Academy of Engineering, and the National Academy of Sciences. Among his many other accolades are his receipt of the Fluid Dynamics Prize from APS and The G.I. Taylor Medal from the Society of Engineering Science. In addition to his aforementioned service on the

Figure 10

The first Stephen H. Davis Lecture. Pictured are (*left to right*) John Hinch, G.M. "Bud" Homsy, Steve, Dean Julio Ottino, Parviz Moin, and Detlef Lohse. Picture by Joel Wintermantle.

editorial boards of both JFM and ARFM, Steve's service to the profession included membership and chairmanship of advisory committees to agencies such as NASA and the National Science Foundation.

Steve will be forever remembered in the Department of Engineering Sciences and Applied Mathematics at Northwestern University and in the community through the annual Stephen H. Davis Lecture. The first lecture was held in 2019, and we were all fortunate to have Steve in attendance, as seen in **Figure 10**. Unfortunately, the COVID-19 pandemic and health issues forced Steve to miss the second lecture, and he passed away before the third. His impact, humor, and general spirit will be remembered by all of us who knew him and will be carried forward by his many graduate students, postdocs, collaborators, and friends.

DISCLOSURE STATEMENT

The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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