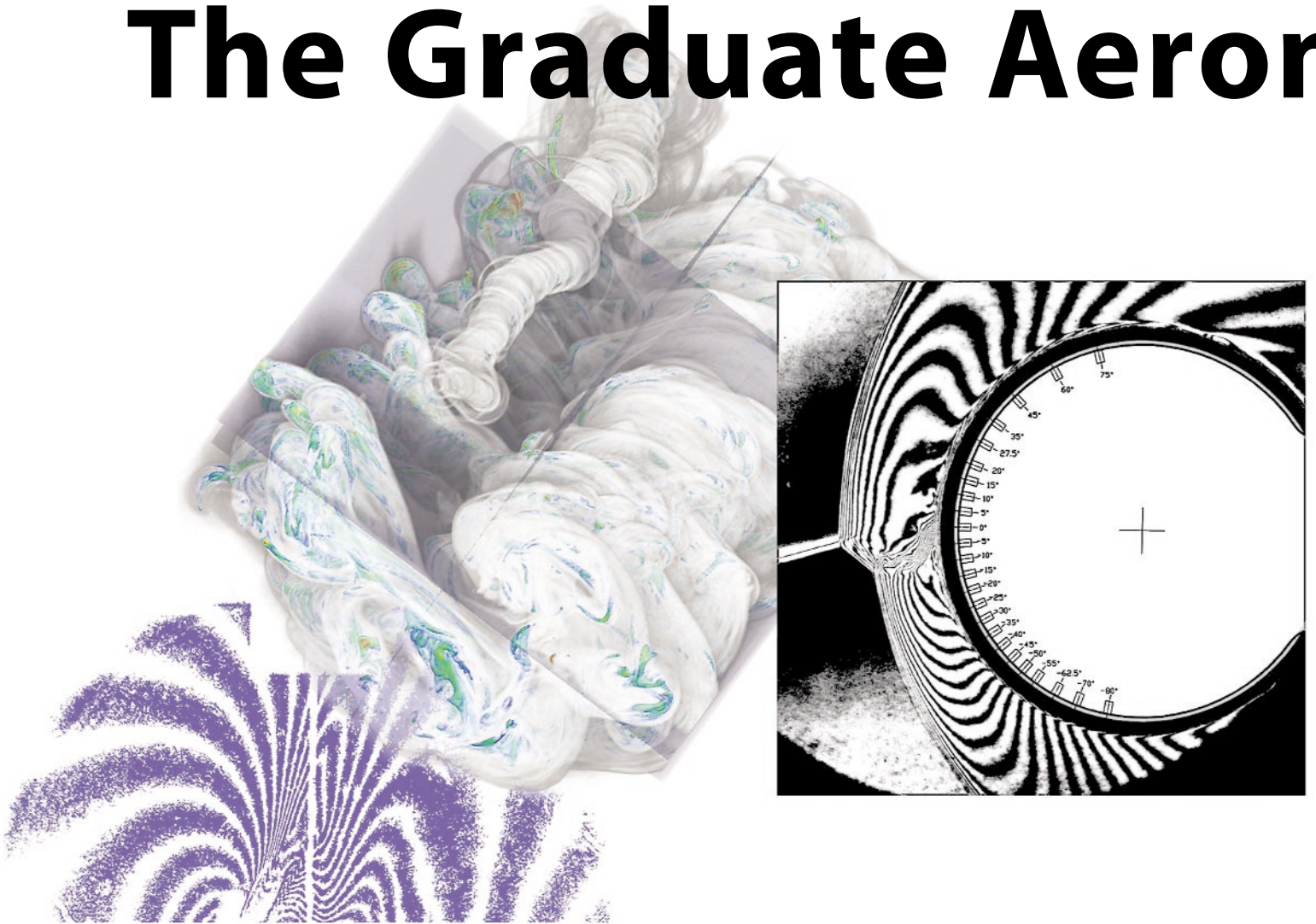


The Graduate Aeron



On the occasion of the 75th Anniversary of the founding of the Graduate Aeronautical Laboratories of the California Institute of Technology—GALCIT, that is—we took the liberty of talking with each of the faculty members about the current direction of this world-renowned research group and the factors that have led to its unique—some say unparalleled—position in the world of fluid mechanics, solid mechanics, and combustion research. It is well known in the scientific community that GALCIT is the birthplace of a large number of ideas, new theories, innovations, and scientific discoveries. It has established a long tradition of leadership in its chosen fields. However, GALCIT's ongoing obsession with the scientific foundations of fluid and solid mechanics has ensured that this 75-year old intellectual powerhouse shows no signs of advanced age.

aeronautical Laboratories

Celebrating 75 Years of Experimental, Theoretical, and Computational Innovation

As Professor Mory Gharib deftly explains, “the same principle that guided GALCIT’s early research efforts still governs today—find the most challenging unsolved problems, the *show stoppers*, and attack them before the rest of the scientific community even has them on their radar screen.”

Each generation has its own mix of show stoppers, and the original areas in which GALCIT worked revolved around aeronautical applications. The lab was founded in 1926 as the Guggenheim Aeronautical Laboratories with a \$300,000 grant from the Daniel Guggenheim Fund for the Promotion of Aeronautics (Caltech was one of seven schools that were so funded). Hans Liepmann, the third Director of GALCIT, speaking at GALCIT’s 50th Anniversary celebration, noted:

[Daniel] Guggenheim stated clearly that his endowment was not intended to be permanent, but that he thought aeronautics, then in its infancy, would be raised to a state where support would be guaranteed from both private and government sources. [...] it would have been absolutely out of the question to raise that money for that purpose at that time from the government. Congress would have never permitted such a strange venture. The legislators would have just laughed, because at that time, flying was often barnstorming and the accident rate on the few existing airlines was something like one fatality for 1,300 miles, a number that has only been reached at times by private automobiles.

Its first director, Theodore von Kármán, a pioneer in both fluid and solid mechanics, began visiting Caltech in 1926, but made a firm landing in 1930 to direct GALCIT full time. As recorded by Clark Millikan, the second Director of GALCIT, von Kármán spent the fall of 1926 at the California institute advising its staff regarding the educational policies and experimental

facilities of the new graduate school and laboratory. During this visit the essential features that characterized their subsequent development were largely worked out under von Kármán’s leadership.

The initial focus on the applications of fluid and solid mechanics to aeronautics blossomed, and by the end of the Second World War, observed Liepmann, “GALCIT was the only school in the nation equipped to tackle the problems arising from the explosive development of aircraft and missiles to transonic and supersonic speeds and finally into spaceflight.” In fact, the burgeoning aerospace industry in Southern California was catalyzed, supported, populated, and maintained by GALCIT (and Caltech) with cutting-edge research, unique testing facilities, and top-notch graduates. Aerospace companies were founded by Caltech and GALCIT alumni, led by our alumni, and served as

origins

home to creative thinkers, inventors, and engineers who succeeded in transforming society by breathtaking advances in communications and transportation. A particularly unique institution “spun-off” from GALCIT is the Jet Propulsion Laboratory (JPL), which put the first U.S. satellite into space and continues to this day leading the country’s unmanned space program. Von Kármán was JPL’s first director.

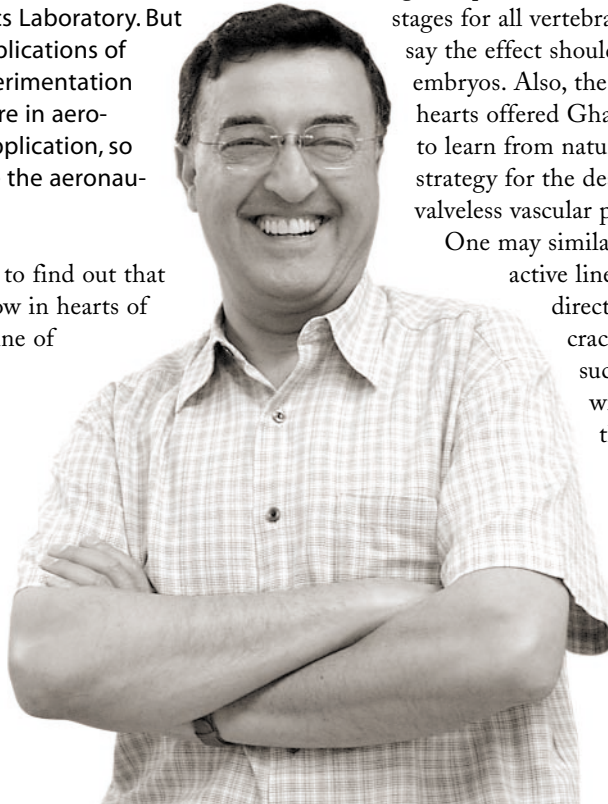
breadth

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ven as early as the '30s, '40s, and '50s, the pioneering research undertaken by GALCIT faculty and colleagues spanned a wide range of interests outside of the aeronautical envelope.

A. Rosakis: As a matter of fact I have been told that von Kármán himself was arguing about calling GALCIT basically a center of applied mechanics—the Graduate Applied Mechanics Laboratory. But at that time, the biggest applications of mechanics, theory, and experimentation in both solids and fluids were in aeronautics. That was the star application, so it made sense to emphasize the aeronautics part.

Today, one may be surprised to find out that investigation of the blood flow in hearts of embryonic zebrafish is one line of research in GALCIT. Mory Gharib is carrying out this extraordinary work with colleagues Scott Fraser, who is Rosen Professor of Biology, senior research fellow Jay Hove, and post-doctoral scholar Reinhardt Köster. By surgically blocking the flow of blood through the hearts—these tiny beating hearts are less than the diameter of a human hair—the researchers were able to



demonstrate that a reduction in “shear stress,” or the friction imposed by a flowing fluid on adjacent cells, caused the growing heart to develop abnormally. The results demonstrate for the first time that the very action of high-velocity blood flowing over cardiac tissue is an important factor in the proper development of the heart. Because the early development of an embryonic heart is thought to proceed through several nearly identical stages for all vertebrates, Gharib and his colleagues say the effect should also hold true for human embryos. Also, the studies of embryonic zebrafish hearts offered Gharib’s team a unique opportunity to learn from nature how to develop a proper strategy for the design of an optimal artificial valveless vascular pump for medical applications.

One may similarly be surprised to learn that an active line of inquiry in GALCIT is directed toward exploring dynamic crack formation in geomaterials such as the Earth’s crust—otherwise known as earthquakes—and that this research has shown that cracks can propagate at supersonic speeds.

Rosakis: I remember my second year in GALCIT. I was asked to give a talk in geophysics by Professor Hiroo Kanamori [John E. and Hazel S. Smits Professor of Geophysics], and I spoke about dynamic fracture of

Morteza Gharib (PhD '83)

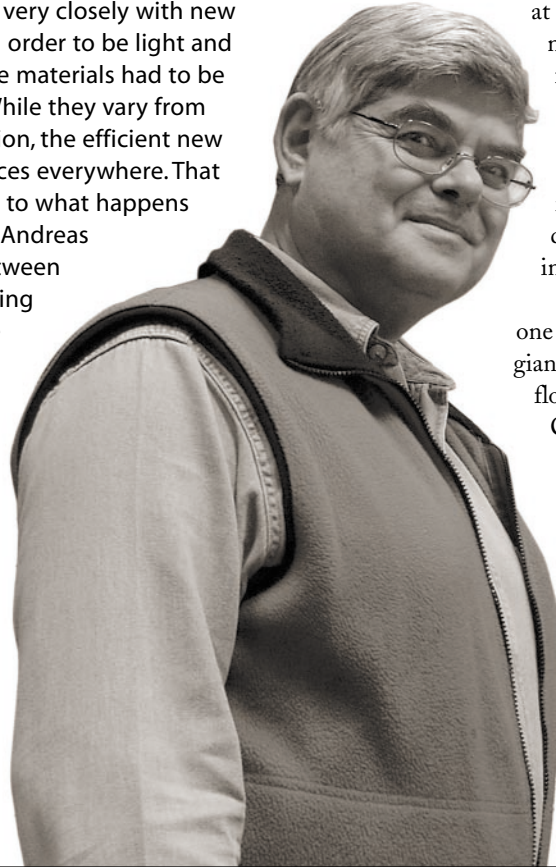
Hans W. Liepmann Professor of Aeronautics and Bioengineering

Professor Gharib’s principal research interests are vortex flows, biofluid dynamics, wake flows, free-surface turbulence, bioengineering, and quantitative visualization.

If I see that the boxfish can do better control than a 747, I drop all this rigid stuff! One of the experiments we are doing aims at understanding how a boxfish stays next to a coral reef, the sharpest object you can imagine, in high turbulence, but keeps a distance of one millimeter. And doing it by having seven fins that are flapping and creating vortices here and there, keeping the fish right there, dead accurate. This problem is a combination of fluid mechanics, flexible compliant structures, and control. The future GALCIT will be tied to these new areas, and I think the next wave of smart propulsion devices will be based on the biomechanics of flying and swimming. But we need to learn how nature engineers these things.

Another area I am working in is free surface flow. My group is studying problems associated with the wakes of big ships. Last May we went on a ten-day field trip with a Naval research vessel. We have a Caltech camera under the boat to see what the propeller is doing. How is the propeller generating bubbles? How do the bubbles end up in the wake? The Navy spends \$200 million per ship. These ships are radar-proof and stealth, but the wakes are not: you know exactly where they are. You don’t see the ship—you see the bubbles. That’s why we are helping them understand the mechanisms of wave breaking. Is it possible to remove an observable wake? It’s possible.

engineering materials. He said to me: have you ever thought about applying these same principles to different problems with different length scales, that is, earthquakes? It took me about ten years to follow his suggestion, but I finally did. And it has been a very, very interesting ride. During this same period, engineers starting working very closely with new composite materials. In order to be light and efficient and strong, the materials had to be made of composites. While they vary from application to application, the efficient new structures have interfaces everywhere. That situation is very similar to what happens in geophysics. The San Andreas fault is an interface between two plates that are sliding against each other. The engineering application is mimicking part of the geophysical application. Also the San Andreas fault separates two pieces of material that have been sliding for centuries. So they are not exactly the same material anymore to the right and left. All mature faults, for example, are composed of different properties on one side



compared to the other, like a composite is. So here are applications that are very similar.

The high-speed cameras used in Rosakis's lab show that shear cracks in interfaces propagate as fast as 7 kilometers per second. One of these cameras operates at 50 million frames per second, which is necessary since these shear cracks are faster than the fastest supersonic jet planes. This work has practical applications not only for materials engineering, but also for geophysics, because there is reason to believe that certain large earthquakes feature rupture that propagates intersonically along the geological fault.

Considering even larger scales, one may think that the dynamics of galaxies, giant whorls of matter, and other cosmological flows may be a concern only to those in Caltech's astrophysics corridors. Think again. The computational theoretical fluid dynamics work of Tony Leonard and Dale Pullin has application here, as well as in more down-to-earth applications such as climate studies and ocean dynamics problems.

D. Pullin: I am presently interested in turbulence, and although fluid dynamical flows can be simulated on a computer, there are limitations. One limitation is that turbulence involves a very vast range of

Paul Dimotakis

(BS '68, MS '69, PhD '73)

John K. Northrop Professor of Aeronautics and Professor of Applied Physics

Professor Dimotakis's principal research interests are fluid physics, the dynamics of turbulence, and high-speed propulsion.

I came to Caltech from Greece as an undergraduate freshman. The plan was to study nuclear engineering and return to Greece to build a nuclear reactor. But I fell in love with physics and the Feynman lectures. So I thought well, whatever I am going to do professionally, I am going to study physics first and answer some of my questions. So I got my first degree in Physics. I then got my Masters in Nuclear Engineering, per plan. By then, I had met Hans Liepmann and was enchanted by his intellect and enthusiasm for science. So then I said, well, it doesn't really matter what your degree says, so I switched to Aeronautics to study with Hans Liepmann. I did my thesis research in low-temperature physics and superfluidity. The Applied Physics option got started in the meantime, so my PhD is actually in Applied Physics, which better described my research.

I now work in fluid mechanics, turbulence and turbulent mixing, combustion, chemical reactions, and high-speed propulsion, among other things. But I only took one course in fluid mechanics as a student. The feeling at the time, and to a large extent this is still the case, is that you come here to be educated, not to be trained. You are educated when you understand how nature works, how the world works, and how to think; and if you learn these things, you can actually do anything. And that is the same sense I try to transmit to students that I work with. I like to think that GALCIT graduates can do anything.

eddies. Turbulence is about eddies. And there is not just one eddy in a turbulent flow, there are billions of them, and they're all of different length scales. Further, turbulence occurs everywhere: in the intergalactic medium, in the interior of stars, probably in star formation processes; it occurs in environmental fluid mechanics, on the scale of climatology; it occurs locally in environmental flows over mountains, it occurs at the interface between the ocean and the waves, it occurs inside the ocean; it occurs in turbulent combustion, inside a jet engine, in the boundary layers on 747s. It's a very important problem.

It would be nice to have a simulation tool that could deal with these problems, for obvious reasons. But unfortunately, because of the huge range of length scales, even with the world's biggest computers, we can't really do it in a faithful way. So one of the areas that I am interested in is called large-eddy simulation. This is an attempt to try and compute turbulent flows without resolving *all* of the length scales. Maybe in 20 years, because Moore's Law is working out pretty well, we will have the computational capability.

Dealing with turbulence in the presence of a wall has turned out to be a very, very difficult problem. It's actually a bit of a bottleneck at the moment. Take the computation of a very simple flow, the flow past a sphere, at large Reynolds numbers. The very best we can do at the moment, resolving all the scales, is probably flow at a Reynolds number of 10,000. And that's pushing it a bit.

Let's take an example. A golf ball flies at a Reynolds number of 50,000 – 100,000. So we are not even close. The roughness of a golf ball means that the turbulent boundary layer near the surface of the golf ball is very complicated. And it is also spinning, which is a further significant complication. You can't hit a smooth golf ball much more than about 100 yards. Tiger Woods couldn't hit a smooth golf ball out of the backyard. But he can hit a dimpled one 300 yards. That's an example of how

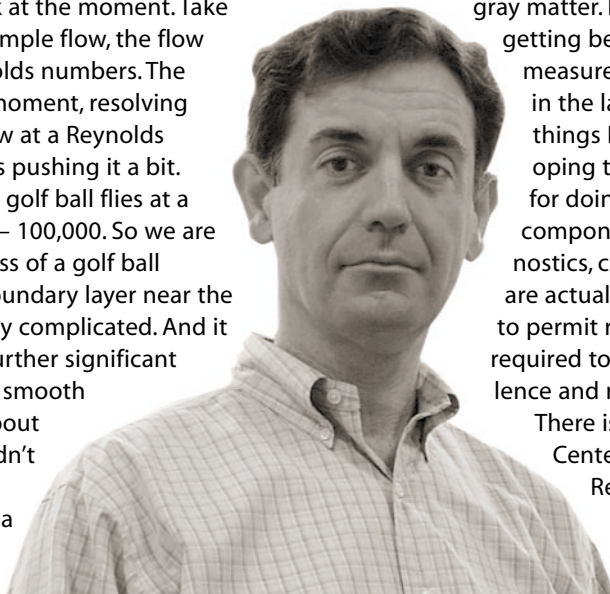
the behavior of the turbulent boundary layer profoundly affects behavior. If, in the next 10 years, I can do a faithful numerical simulation of the flow past a sphere, even a smooth sphere at a Reynolds number of 100,000 or a million, I'd be reasonably happy.

Professor Dimotakis, who also considers turbulence in his work, concurs and adds more to the mix:

P. Dimotakis: What is different about what is coming? There are two things. To "solve" the turbulence problem, we must appreciate what it is that makes it a problem, and a difficult one at that. And in the case of turbulence and turbulent mixing, what makes it difficult is that this is an unsteady, three-dimensional, non-linear phenomenon. And I need to add one more element: it is all those things but it also encompasses an enormous range of space and time scales. If it weren't for the latter, we would just put it on a computer since we understand the equations. The combination puts it out of reach of traditional analysis.

What is new and different is that we have computers that are getting larger and will eventually be large enough to handle this problem, with some help from gray matter. In addition, experiments are getting better. We are now able to measure in three and four dimensions in the laboratory. That is one of the things I've been involved in: developing the methods and technology for doing this. So that's the other component: experimental tools, diagnostics, coupled with computers that are actually getting powerful enough to permit recording of the kinds of data required to describe and analyze turbulence and mixing.

There is joint project with Caltech's Center for Advanced Computing Research (CACR) that we have been working on for three years. We will soon have the means of acquiring up to



Michael Ortiz

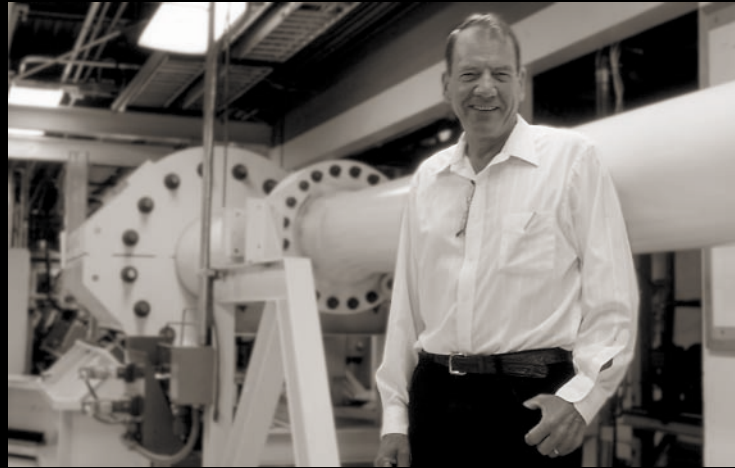
Professor of Aeronautics and Mechanical Engineering

Professor Ortiz's research interests are in computational solid mechanics.

I don't do experiments. I draw the line there. That's the one thing I don't do. But, you know, you asked me why I came to Caltech. One of the real attractions of Caltech is that it has maintained strength in experimental mechanics and experimental sciences in general, which is becoming more and more unusual at other institutions because it's expensive. There's an economic incentive for emphasizing cheaper things like computers and computation. But Caltech has done a very good job actually in maintaining strength in the experimental area. That is really unusual and really unique. And I have colleagues like Ravichandran, Knauss, and Rosakis who have devoted all their careers to experimental science. I'm in very good company. We have very good working relations where they do the experiments. Of course they are capable of doing modeling and theory themselves and they do. But often we collaborate and we combine efforts.

Hans Hornung, Director

One of the unique aspects of GALCIT has been the position of Director. There have been four Directors in the last 75 years: Theodore von Kármán, Clark Millikan, Hans Liepmann, and most recently, Hans Hornung. Hans Hornung was director from 1987 until this year when he stepped down to return to research full time. During Hans's tenure as Director there were many changes to the faculty and physical plant. Five new faculty members were hired within the first eight years of his arrival at Caltech. The lower floors of the Guggenheim building were



twenty *terabytes* of data in a short time. This will allow recording of three-dimensional data from flow that occupies about one cubic foot. We will be recording up to 10^9 measurements per second. And that is roughly what it takes to capture such phenomena. If you have not been able to see what the phenomenon is that you are trying to describe, well, you are not likely to do a good job describing it. So this is what is changing and what will be different in the next few years.

The breadth of GALCIT's work has been only hinted at. We look at a couple more examples that harken back to the "aero" in GALCIT.

F. Culick: I am working principally on unsteady chemically reacting internal flows, or combustion instabilities as this area is known. Understanding and controlling unwanted unsteady motions in liquid rockets, gas turbines, solid rockets, afterburners, and ramjets have been my areas of research, really beginning with my thesis work. The crux of the problem is that a great deal of energy is being released in a relatively small volume, with almost no losses, and this energy is being converted into unwanted, nonlinear motions of fluid. It's a tough problem. My group attacks it with both theoretical and experimental investigations. I also work in other areas, notably propulsion systems.

M. Ortiz: My particular interest is in space structures. The two main challenges there are surveillance and energy. By surveillance, I refer broadly to large-aperture optics. We want to build structures, lenses in space, which have sizes in the kilometer range. It is very difficult to deploy those structures, stabilize them in space, and then get them to work as desired. These requirements really challenge traditional concepts in structures. We are used to thinking of structures as working in gravity here on Earth and they're typically designed to *withstand* gravity. Now we're thinking of very large structures in the *absence* of gravity. These structures cannot be tested on Earth because they're too large. We cannot achieve zero gravity conditions on Earth anyway. You have to have confidence in the design and that the deployment sequence is going to work, because launching these things is very expensive. I see an important role there for modeling and simulations. It's a very exciting area. I am also interested in ideas that might allow us to capture solar energy and beam it down to Earth. This is an area where GALCIT in particular is going to play a very significant role. And there are very obvious connections to JPL with both of these projects.

J. Shepherd: We are working with companies who are building new propulsion devices based on explosions—pulse-detonation engines (PDEs). It is a very

completely renovated with the removal of the venerable 10-foot wind tunnel. The T5 Hypervelocity Shock Tube was built, as were the Ludwig Supersonic Tube, the John W. Lucas Adaptive Wind Tunnel, and the Lees-Kubota Lecture Hall. In the GALCIT tradition, Hans was a working director, managing an extensive research program in hypersonics, teaching classes, many of which he initiated, and also mentoring post-docs and students, 15 of which received PhDs working under him and several more are in progress today. Hans has carried on the tradition of excellence in research and teaching that past directors established, and like them has won many honors, including the Ludwig Prandtl Ring and election to the Royal Aeronautical Society.

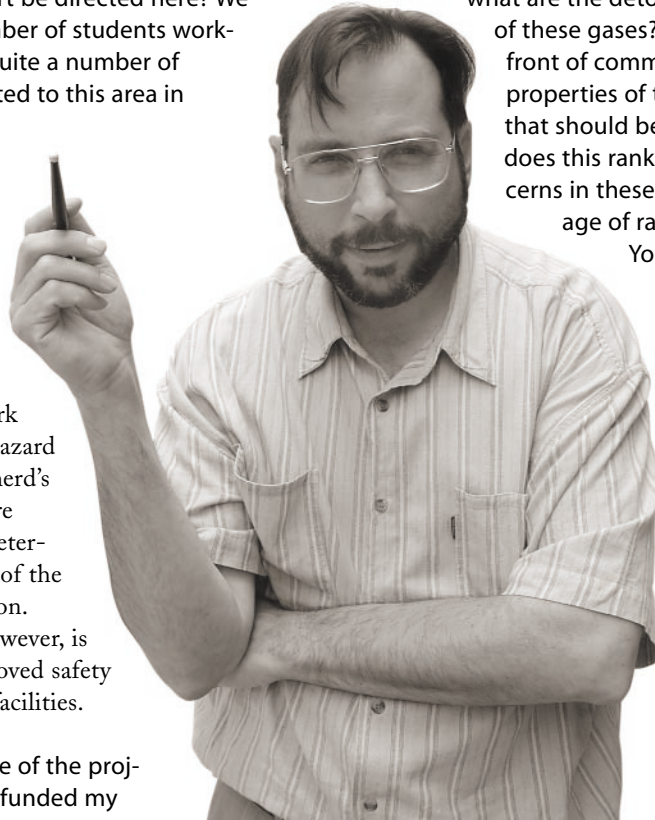
Hans's athletic abilities are known throughout the campus—he is a formidable opponent in tennis and played on the Aeronautics soccer team until it hurt too much. (Actually we hear he'll be out on the field again this season.)

In recent years, Hans has become quite interested in using computation to study fluid mechanics and has this to say about numerical simulation: "One of the developments that is extremely rapid these days is the capacity of computers. In 10 years' time, computers will be so much more powerful and things we only dream about now will be able to be simulated on the computer. At the moment three-dimensional simulations are things for which you need huge machines, powerful machines. Three-dimensional turbulence is actually four-dimensional because of time. And because you need to resolve very fine scales and very large scales at the same time, the computational problem is enormously difficult. At the same time, I think the development of diagnostics will help us measure things in much more detail and so our ability to make models of processes in nature will increase enormously. GALCIT is the place where this is going to happen."

interesting idea, but like many new ideas, it's not really clear how well this is going to work. So we are carrying out very basic research on several aspects of this concept so that we can give them some guidance. Should they be spending millions of dollars on this? We are doing the same thing for our government. We are working with the Office of Naval Research to determine if PDEs are something we should be investing the R&D budget of the country in. Should more funding and effort be directed here? We have a large number of students working on this and quite a number of publications related to this area in the last 5 years.

Shepherd and his students have been active in many areas concerned with explosions and detonations, and much of their work has centered on hazard mitigation. Shepherd's investigations were instrumental in determining the cause of the TWA800 explosion. Lesser known, however, is his work on improved safety of nuclear waste facilities.

J. Shepherd: One of the projects that initially funded my



laboratory was an interest in understanding the hazards in a nuclear waste storage facility in Hanford, Washington. Up in Hanford they have several hundred tanks that are each full of millions of gallons of toxic and radioactive waste. And it is sitting there cooking, chemically reacting. You can have releases of flammable gas, and there are mechanisms for ignition, so you can have explosions inside those tanks, which are partially full. And so one of the things we've studied is: what are the detonation and combustion properties of these gases? And then I do things like testify in front of committees about what we think the properties of these gases are. Is this something that should be of the greatest concern? Where does this rank? You have many, many types of concerns in these types of facilities. What about leakage of radioactive material into the ground?

You are also worried about contamination of workers, long-term waste storage, explosions, and so on.

There is a long list of issues that you have to evaluate, and we provide some input into that. We try to provide *scientific* input. Our goal is to give them data, and to analyze that data and apply it to their situation. The consequences of our experimentation are far-reaching.

The people in GALCIT are constantly inventing new gadgets. Measurement devices, shock tubes, image-capturing systems, the list is endless. The precision is daunting.

Joseph Shepherd (PhD '81)

Professor of Aeronautics

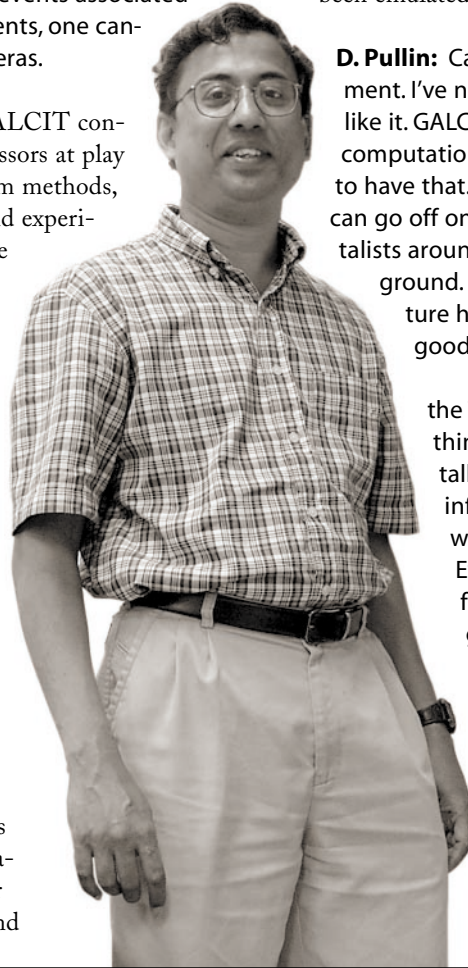
Professor Shepherd's research interests are in combustion, explosions, and shock waves with a particular interest in basic processes in flames and detonations with application to evaluating explosion hazards.

The experiments we do are a kind of magic act in glass, steel, and electricity. We spend weeks, months, sometimes years building these facilities so that we can have a few millionths of a second where we can very precisely control the conditions and then take an image. Then, to really understand that, we have to do it over and over again with different substances, probing the flow, and looking at it in different ways. It is a very special kind of experimentation; you can never sit and watch the flow like you can in the low-speed water channel and say "Oh, look, there's a vortex." The only way you can see anything is to use this very elaborate instrumentation. Everything has to be done in just the right order and a precise sequence of events takes place. You do that just right, and bang—you get this beautiful picture of the flow. And now you have learned something about how nature works. And that's really what we're after.

I came to Caltech as a graduate student because I was in love with physics, and everyone knew Caltech was the best place to do that. Almost by accident I wound up studying fluid mechanics under Brad Sturtevant—and have been doing it ever since. When I was offered the chance to come back as a faculty member in 1993, I jumped at it because I knew first-hand the research environment in GALCIT and how great the students are.

G. Ravichandran: One of the things we do is develop new, one-of-a-kind instruments. Recently we developed a camera that takes thermal pictures at a million frames per second. The need was related to basic experiments that we were doing to understand failure under dynamic conditions. That is, where the cracks or the shear failures propagated at very high speeds, on the order of one to several kilometers per second. In order to visualize the thermal events associated with those dynamic failure events, one cannot use ordinary thermal cameras.

The breadth of the work in GALCIT continues to expand, and the professors at play are inventing on all fronts: from methods, to tools, algorithms, devices, and experiments. They are active in all the areas that the Division of Engineering and Applied Science has identified as core intellectual thrusts for the next decade: computational science and engineering, nanotechnology, global environmental science, bioengineering, and information science and technology.



The GALCIT tradition of bringing together the best theoreticians and experimentalists, and then letting them fly in their own directions of discovery has both left a legacy and created a playground for future players that is hard to find

anywhere else in the world. GALCIT, like its sister departments in the Division of Engineering and Applied Science, strives to do a few things extraordinarily well, attracts the very best people in each chosen area, and provides them with an unparalleled environment for research. This has led to GALCIT having a visible impact out of proportion to its size, the best faculty, the best students, and a unique approach that has been emulated by others.

D. Pullin: Caltech is an unmatched research environment. I've never seen, never come across, anything like it. GALCIT has a nice balance of experimentalists, computationalists, and theoreticians. You really have to have that. A group of theoreticians, by themselves, can go off on a tangent, for years. Having experimentalists around helps you keep your feet on the ground. And of course, the intellectual temperature here is very high. The students are very good, so good they keep us on our toes.

Perhaps the best feature of the group is the Tuesday Research Conference. It's something we all contribute to, and it keeps us talking. It is intended to be a relatively informal forum for presenting unfinished work and ideas about future work. Everyone attends: students, post-docs, faculty, and visitors. And because we are generalists, we can all respond to each other's interests. That contributes to the unique environment here. It really *makes* the environment. There is a community, a very stimulating one at that.

G. Ravichandran: When I first came to GALCIT, it was a new culture for me. What particularly struck me was the camaraderie between students and

Guruswami Ravichandran

Professor of Aeronautics and Mechanical Engineering

Professor Ravichandran's research interests are in mechanics of materials, dynamic deformation and failure, wave propagation, micro mechanics, composite and active materials, and experimental mechanics.

GALCIT is a very special place, especially for the experimental side of things. This is one of the few places in the world where the experimental sciences are very strongly supported and encouraged. This is because of the historic precedents of how the wind tunnels were developed and how they supported the aerospace industry during the time of von Kármán; they were always doing large-scale experiments and really using experiments to understand the physical world around them, first in the aeronautical sciences, and later on evolving into mechanics. That provided a culture that has been built on for 75 years. This has brought forth a certain energy, a synergy to encourage experimental work, and colleagues who appreciate experimental work. And there is also close interaction with colleagues who do simulation and modeling. This is really a singular place where the experimental sciences are thriving.

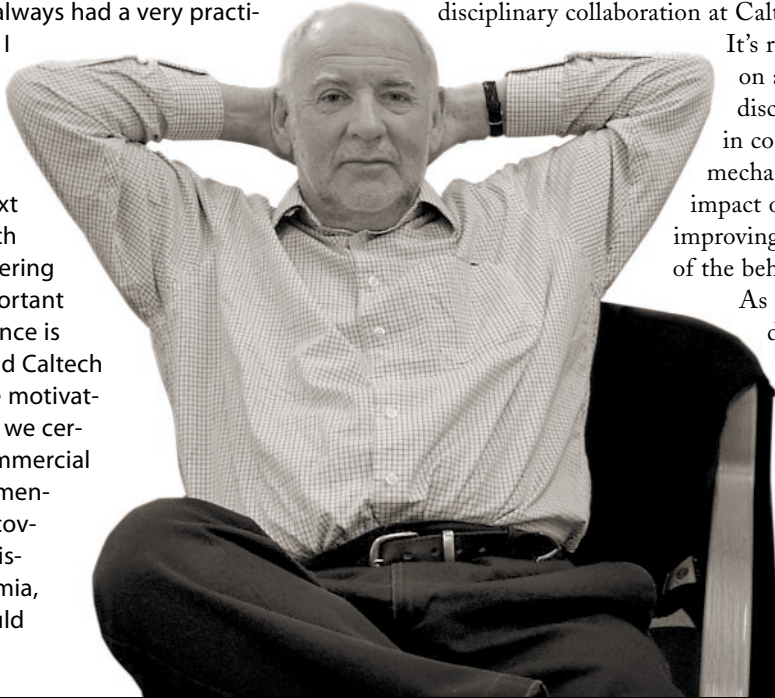
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the people here, the family atmosphere. People got along and people seemed to know everything about each other's research. Ideas were flowing freely. People were not operating in an isolated manner. And what I found particularly interesting was that it was very easy to interact with people from other parts of campus. It still is.

F. Culick: I've been here a long time. I am probably the only one still here who knew both Millikan and von Kármán. The outstanding thing from the very beginning has been the quality of the students and the quality of the faculty. It's important to realize that the entire faculty is good, not just two or three. That's always been important for GALCIT.

The other crucial element is the relation between the research we do and its application. While my work in particular has always had a very practical bent—at one point I was consulting to all the rocket companies simultaneously—it is always done in the atmosphere and context of fundamental research and science, or “engineering science.” This is an important point. Engineering science is really where GALCIT and Caltech excel. The work may be motivated by applications, but we certainly are not like a commercial lab. Without the fundamental science that we discover, develop, and then disseminate out of academia, engineering *per se* would not go far.



W. Knauss: One of Caltech's—and GALCIT's—strengths is the high caliber of its students. While my colleagues don't necessarily and uniformly want to admit it, Caltech wouldn't be so excellent if we did not have this pool of outstanding students. We can do a much greater volume of high quality work here because we need to spend relatively little time with detailed guidance of graduate students. There is also a closeness, a camaraderie among the students and advisor which derives, in good part, from the fact that we are small and that makes GALCIT unique.

Embedded as it is in another unique institution, the California Institute of Technology, GALCIT benefits from collaborations with other academic disciplines.

Professor Ortiz puts it quite clearly: “The fact of interdisciplinary collaboration at Caltech is not just ‘talk.’

It's really true. We work on a daily basis across disciplines.” Ortiz works in computational solid mechanics. The direct impact of his work is improving our understanding of the behavior of materials.

As a necessary intermediate goal, he is improving methods in computational mechanics and computational science in general. His algorithms, for instance, seek to make more efficient uses of computers. His efforts

Dale Pullin

Professor of Aeronautics

Professor Pullin's research interests are in computational and theoretical fluid mechanics, vortex dynamics, compressible flow and shock dynamics, turbulence, and large-eddy simulation of turbulent flows.

I was actually an applicant to GALCIT—I was accepted as a student at GALCIT many years ago—I've still got the letter. But I didn't come—I went to England instead. I don't know why I went to England. L.A. had very bad press, of course, still does—remember this was in 1971, before the Internet. Much later, as a professor, I came here to visit for six months on a sabbatical. And it turned out GALCIT had a vacancy, and they wanted someone who was interested in both theory and computation. Often people do one and not the other. And L.A. was not as bad as I thought it was; it was actually quite interesting. And indeed, I always like to reinvent my life every 10 years, so an opportunity comes, you take a risk. I thought, why not? I've been here 12 years now. When you get to my age... well, let's not get into that yet.... In any case, I quickly found a superb research environment here at Caltech.

ode

in this regard have made some impact on mathematics, and with respect to his collaborators in this area he mentions, “We shouldn’t forget, I’m a

real fan of mathematics. I think it’s the grease that makes everything possible. So we interact very closely with card-carrying, hard-core mathematicians.”

The collaborations between GALCIT and various groups on campus are varied and endless. Another to note is that between Professor Ravichandran and his newest partners.

G. Ravichandran: Most recently, in collaboration with my colleagues in Mechanical Engineering, Applied Physics, and Materials Science, I have been working on *active* materials. Active materials are materials that respond to external electro/magneto mechanical or thermal mechanical loads and they can change shape. So they can be used for active control of structures. For example, for a helicopter blade, you want to deform the surface during flight to adapt to the aerodynamic conditions. This is really a dream—but I believe it will happen. So we study material behavior for actuators for novel applications.

We apply an electrical voltage on a ferroelectric material, and at the same time we subject it to mechanical loading via stress. This causes the material to change shape; as it generates strain, it is doing work against the stress, and you have work output, so it can be an active device. When we take off the voltage the

material deforms again due to the stress and you can have a cycling actuator. There is a broad range of applications one can envision. It can be used in adaptive optics for use in astronomy, and so on. My role in this project is to demonstrate the principles in such an active device.

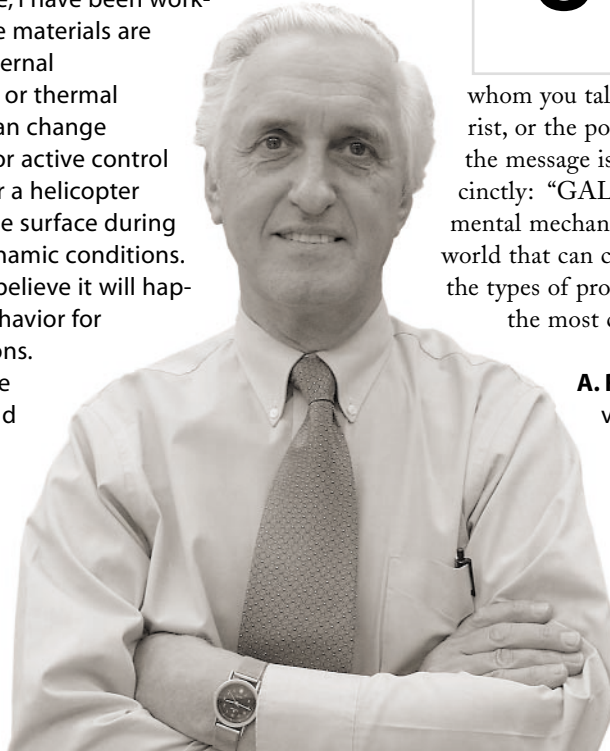
The interactions are not limited to projects between faculty members. As Professor Leonard explains, “If a student in another department happens to be interested in what you are doing, there are no barriers at all. I had a PhD student in physics; several in mechanical engineering, and one in applied mathematics. It’s great!”



ne of the particularly unique aspects of GALCIT is its strong experimental mode. No matter

whom you talk to in GALCIT, a pure theorist, or the pointedly experimental types, the message is the same. Gharib puts it succinctly: “GALCIT is the mecca of experimental mechanics. There is no place in the world that can come close. The quality and the types of problems we investigate are at the most challenging frontiers.”

A. Rosakis: At GALCIT, we are very proud of our experimental facilities. They are unique, and they are extensive. We have managed to keep them in an era where computation is taking over the world. And although the development of computer facilities is an excellent thing, in certain cases this has been at the



Wolfgang Knauss (BS '58, MS '59, PhD '63)

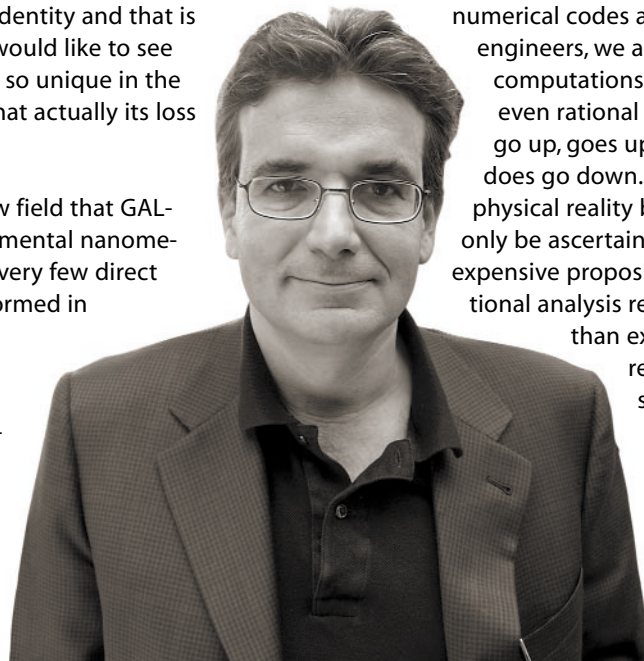
Theodore von Kármán Professor of Aeronautics and Applied Mechanics

Professor Knauss's research interests are centered in solid mechanics.

In the early 1980s, I became aware of the need to pursue materials issues at smaller and smaller size scales. It was extremely hard then to convince people of the need for this field—the phrase “nanomechanics” was to appear a decade later. I was very lucky to get \$30,000 from the National Science Foundation to build, over a two years’ time span, a Scanning Tunneling Microscope to study deformations at the nanoscale. And today this kind of research is just the accepted thing. Colleagues fight for the millions in research funds in this area. But this kind of situation has always been a problem if you pursue a view of what’s going to be needed in the future: if you’re too early, support is tough to attract. However, Caltech has been an excellent place because it fosters reaching one’s potential. If you do things well and honestly, no one interferes.

expense of the observation of reality. Computational analysts like my colleagues Michael Ortiz and Tony Leonard are developing very advanced codes that are capable of doing things that are unprecedented. However, as they would admit themselves, they are not observing reality. So advanced experimental techniques that have high fidelity and use high-resolution diagnostics are absolutely necessary. It is true that in mechanics, both in solids and fluids, the trend is to go towards theory and computation, rather than experiments, because experiments are expensive. It is a simple explanation. They are difficult, dirty, and expensive. However, at GALCIT, we have managed to preserve our experimental identity and that is one of the things that I would like to see continue. Our position is so unique in the country and the world that actually its loss would be a great crime.

W. Knauss: A totally new field that GALCIT is exploring is experimental nanomechanics. There are really very few direct experiments being performed in the nano range. Instead, everything is done by inference from what is measured on a considerably larger scale, and to deduce properties or behavior with the aid of those inferences, assumptions are a necessary evil. It has always



seemed terribly dangerous to make these assumptions and then apply the results without the direct experimentation background.

Let me cite a recent experience as an example. One of my students performed measurements of the (frequency dependent) volumetric compliance of a polymer. This deformation process was then simulated via a molecular dynamical computational model. Upon comparing experiment with the computations, the two differed very significantly—they were in the ballpark, but not close enough even for rough engineering purposes. Where GALCIT excels is in supplying *both* experiments and computational capability to fine-tune

numerical codes and make them accurate. As engineers, we are often asked to put faith in computations because they all *look* fine or even rational in the sense that what has to go up, goes up and what should go down, does go down. But how *close* we come to physical reality by computational means can only be ascertained via experiment. This is an expensive proposition, and because computational analysis renders “results” more quickly than experiments, the trend in

research—and funding—is on a seemingly unstable slope towards computation. My biggest worry is that the experimentalists are beginning to disappear in solid mechanics. If GALCIT has a mission it is the perpetuation of the proven syner-

Ares Rosakis

Professor of Aeronautics and Mechanical Engineering

Professor Rosakis's research interests are in the mechanics of solids, dynamic failure, impact mechanics, and the reliability of microelectronic components.

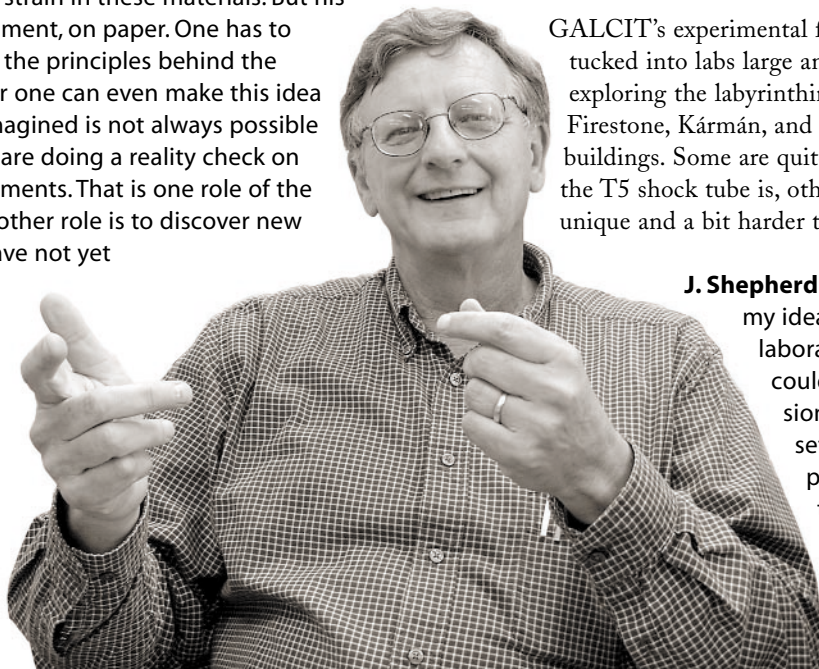
These days, in addition to aeronautics, we have space applications, which are traditional to aeronautics, but we also have the micro and the nano worlds, which are full of solid mechanics and microfluidics problems, and then we have geophysics. In my own research, I started with the engineering scale, went to the large scale with geophysical research, and recently I have been working with very small length scales, in particular microelectronic components such as thin-film structures on flat substrates, interconnects, and optoelectronics—basically things that are baked on a wafer. These become microchips in your computer. We are concerned with how small we can make these components. It turns out there is a physical limit which is dictated not by the electronic performance, but by the strength of the thin-film materials.

Through the years I have investigated materials on many orders of magnitude: from microns to hundreds of kilometers. This really reflects the philosophy of GALCIT. Mechanics—whether its fluid mechanics, solid mechanics—is continuum mechanics. There are very powerful tools that we work with at all of these length scales. One of the biggest strengths of GALCIT both in the research and in the teaching of graduate students has been to lay down the fundamentals in mechanics. And it does not matter what the application is. The application could be aeronautical, it could be space, it could be geophysical, it could be everyday engineering, it could be microelectronics. But really the fundamental principles are the same.

gisms of experiment and analysis in both solid and fluid mechanics. As a final reminder in this context it needs to be remembered that new physical phenomena are only found in the laboratory.

G. Ravichandran: I am an experimentalist—sometimes I do computations, but I am primarily interested in experiments. I always liked to build things and see things work. I am interested in physical phenomena rather than doing things on the computer or with paper and pencil. I am a hands-on person and that's what fascinates me. As part of our ferroelectrics work, we have experimentally validated a theoretical prediction. Kaushik Bhattacharya [Professor of Mechanics and Materials Science] first made the prediction of how to achieve large strain in these materials. But his was a thought experiment, on paper. One has to understand what are the principles behind the concept, and whether one can even make this idea work. What can be imagined is not always possible to implement. So we are doing a reality check on these thought experiments. That is one role of the experimentalist. The other role is to discover new phenomenon that have not yet been predicted by theory. The theory then catches up. This doesn't happen often, but there are quite a few examples. It's a very important part of the mix.

Very striking is that the thing which is



most attractive to the theorists is this practical, “down and dirty” work at which GALCIT excels.

A. Leonard: GALCIT is very strong experimentally. That is what makes it great. And that's one thing I think that we all agree on; even the computational people agree that we have to keep this going. In today's climate it's hard to do that, but we've got to, we can't just follow the crowd. The experiments that [Professor Emeritus] Don Coles was doing in the 1970s were the things that really attracted me to this place. He was doing experiments on turbulent spots in laminar boundary layers. They were really neat experiments, and I just happened to be trying to compute these same things at the time.

GALCIT's experimental facilities are tucked into labs large and small, found by exploring the labyrinthine corridors of the Firestone, Kármán, and Guggenheim buildings. Some are quite well known, as the T5 shock tube is, others are absolutely unique and a bit harder to find.

J. Shepherd: When I came, my idea was to set up a laboratory where we could study explosions in a university setting. There are people who do that around the world, but it's a fairly unique activity. Most people view

Anthony Leonard (BS '59)

Theodore von Kármán Professor of Aeronautics

Professor Leonard's research interests are centered in computational fluid dynamics.

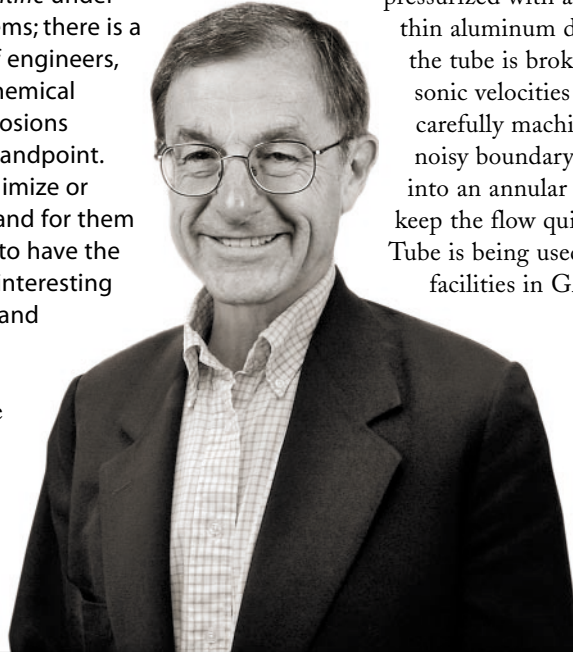
I was an undergrad here from '55 to '59 in mechanical engineering. I didn't get to know too many of the GALCIT people. I remember being sort of happy to leave, because it was really a tough four years. But then I think after awhile you start to remember the good things. So I always had a good feeling, definitely a good feeling, about Caltech. Then I went into nuclear engineering as a grad student. I worked in this field for 10 or 12 years, including being an assistant professor at Stanford. But nuclear engineering went downhill in the early '70s. However, I had started getting more and more interested in fluid mechanics and managed to land a senior post-doc position at NASA's Ames Research Center. This was really a terrific job for me. And then an interesting thing happened at Ames. They had a fairly new director, Hans Mark, who wanted to move into an essentially untouched area: computational fluid mechanics. This allowed me to really develop this new interest of mine in depth. I don't know the exact history because I wasn't here, but GALCIT decided they wanted somebody in computational fluid mechanics. They didn't have anybody; it was just too new. I came down to campus as a visiting professor in '83, and I came back in '85, full time. So it was a perfect match. The whole deal just fell into place. It was very serendipitous. It was an unusual path back to Caltech.

explosions as something that is hazardous and they are a little reluctant to think about setting up a lab inside a building. We built this lab in order to look at problems that are both of scientific interest, and of interest to industry. We have to pay the bills. So we have always looked to practical problems—crashing

people

airplanes, explosions in chemical plants, hazards inside of nuclear waste storage facilities. The goal, though, is to have a *scientific* understanding of these problems; there is a very large community of engineers, including those in the chemical industry, who study explosions from a very pragmatic standpoint. They simply want to minimize or eliminate the problems and for them what's interesting is *not* to have the explosion; for us, what's interesting is to have the explosion and study it.

New to GALCIT are the Lucas Adaptive Wall Wind Tunnel (AWT) and the Ludwig Tube. The Lucas AWT was made possible by a generous gift from the Richard M. Lucas



Foundation. It uses adaptive wall technology in the test section to reduce and even eliminate the need for data corrections required in straight-wall tunnel tests. While the tunnel is operating, pressure measurements are taken along the floor and ceiling of the test section; combined with the current displacement profiles, a one-step predictive algorithm determines the required wall contour for the current model configuration and adapts the walls to match. The system effectively “tricks” the air into thinking it is in an infinite flowfield, rather than confined by the walls of the tunnel.

The Ludwig Tube is a Mach 2.3 facility that provides clean supersonic flow with relative ease and low cost. It is ideal for universities as it allows students the possibility to do experimental work at supersonic regimes without a complex facility to support. The device is the ultimate in simplicity, consisting of a tube pressurized with air and an evacuated tank. When the thin aluminum diaphragm separating the tank from the tube is broken, the flow is accelerated to supersonic velocities for about one-half second inside the carefully machined nozzle at the end of the tube. The noisy boundary layer on the tube walls is diverted into an annular slot at the end of the tube in order to keep the flow quiet inside the nozzle. The Ludwig Tube is being used not only for teaching, but like many facilities in GALCIT, as a research tool as well.

The most important product that GALCIT has produced, however, is its people. Approximately 2,000 people have graduate degrees from GALCIT, and they have gone forth to all parts of the world to make their mark. The

Fred E. C. Culick

Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering and Professor of Jet Propulsion

Professor Culick's principal research interests are in combustion, active control of combustion dynamics, nonlinear acoustics, and propulsion.

In 1980 I started working in applied aerodynamics: teaching courses, doing a lot of historical research, and starting out on a project that is just now in its finishing stages. It really goes back to a day in 1977 when I took a boys' ice hockey team down to San Diego for a pair of games. In between the morning and the afternoon games, I visited the San Diego Aerospace Museum to see the *Spirit of St. Louis*, the plane Lindbergh flew solo, non-stop across the Atlantic. When I was there, I saw a replica of the 1903 Wright *Flyer*, and had an epiphany of sorts. My adventures into finding out just why that airplane looks the way it looks—it's highly unstable, and in fact what I think helped the Wright brothers the most is that they didn't know just how dangerous it was—have taken me on a ride that has lasted two decades. In that time I built a 1/6 scale model of the 1903 *Flyer* which was tested in the GALCIT 10-foot wind tunnel, and have been involved in building two full-scale replicas in conjunction with AIAA projects, one of which I hope to fly before the end of this year. I have found it a fascinating endeavor to explain an historical object with current theoretical understanding and experimental techniques. This research niche—applying modern understanding to the behavior of older airplanes—has been very enjoyable.

Brazilian, Indian, and Chinese space programs all began with significant leadership by GALCIT graduates. You will find many GALCIT graduates as professors in universities across the U.S. and throughout the world, as well as in the top echelons of government labs and industry.

P. Dimotakis: And if you ask me what is different about GALCIT, I would say it is this philosophy that what we strive to impart to the students is a very fundamental and a very broad-based understanding in mathematics and physics, as well as engineering principles and fluid mechanics and solid mechanics, and so on. There is a continuum of types of knowledge one needs so that one is productive not only at the time one graduates, but also 10, 20 years later. That is a very sobering thought. In case it is difficult to imagine 20 years out, I invite students to think back 20 or 30 years and to imagine that they had graduated then, and now they are called upon to contribute to bioengineering, to space physics, to high-energy lasers, to failure analysis—you name it. Would they have received the tools and educational background to make such contributions? Did they receive them then, and are they receiving them now? Well, GALCIT graduates did. The testimony to that is that if you look at many of the new technologies and many of the new thrusts in science and engineering that were initiated in the last 10 to 20 years, many of them have GALCIT graduates behind them. The development of the chemical laser, for instance. And, in some measure, GALCIT graduates contributed to the development of inertial-confinement fusion and laser fusion. These could well be the power sources of 50 years from now. Many of the challenges and limitations in how well one can hope to convert hydrogen and deuterium into helium and energy have to do with shockwaves and gasdynamics. The compression takes place by a converging shock that is driven by umpteen lasers ablating an outer shell. Not many people understood the gasdynamics of how to do that—but GALCIT graduates helped do that. You will find GALCIT graduates doing all kinds of things. Some of them are in the aerospace world, but probably not the majority.

A

nd so GALCIT is poised for the next 75 years, balanced on long-standing organizing principles and unbounded imagination.

F. Culick: My thesis supervisor at MIT had been a GALCIT student for a while, and he eventually earned his PhD elsewhere with H.S. Tsien [PhD '39]. So my connec-

tion with GALCIT in this respect stretches way back. When I arrived in the early 1960s, most of the then current faculty had been here a long time and constituted really the first generation of GALCIT. I have seen all the incarnations of GALCIT over the decades. In some respects, the place is still the same, still guided by the same aspirations and goals it was founded with. But we are suffering from the same problem most universities are suffering from these days—we are more and more buffeted by external influences, and this usually comes down to funding. Time spent raising money detracts from cultivating the closeness that we have always treasured.

G. Ravichandran: GALCIT has adapted in a unique way to the current and future universe of ideas in the sense that for 75 years it has evolved. You cannot be stationary and be successful. We have adapted to new ideas and generated new ideas. We also look into the

future

future and reach out. This is what keeps the place alive. This has been brought about by a culture based on fundamental science with an eye toward practical applications.

P. Dimotakis: The philosophy of von Kármán, still embraced today, guides us. If you want something that is lasting, that will be at the forefront 20 years from now: don't train people, educate them. There is a difference there that is not so subtle. This is what sets GALCIT apart.

It's important to capture people's imagination. It's important to work and contribute to frontier areas, because those capture the imagination of young people and ultimately that is what it's all about. ■ ■ ■

The GALCIT 75 Anniversary Celebration will be held on November 14 – 15, 2003.

For more information please see www.galcit.caltech.edu/galcit75