UNITY IN THE SCIENCE OF PHYSICS

It has many sources: mathematics as a common language, the scientific method as a common approach and paradigms as a common view of nature.

James A. Krumhansl

This article is based on the retiring presidential address delivered on 17 April 1990 at the APS Washington meeting, in a special session celebrating the unity of physics.

I hope that this special celebratory session will become an annual custom at our large conferences—to take time out to survey both the diversity and unity of physics in a common meeting that is undiluted by the multiplicity of parallel sessions that have become the hallmark of our gatherings. Our research endeavors span a wide spectrum of physics, but at the core of every effort is a common creed: to push to the frontiers our understanding of natural phenomena, by measurement and theoretical analysis. In this article, in addition to giving the retiring president's report, I want to address the idea of whether one can identify sources of unity in the science of physics. My remarks may complement those of one of my predecessors and colleagues, Robert R. Wilson, in his 1985 retiring presidential address, "The Sentiment of the Unity of Physics" (PHYSICS TODAY, July 1986, page 26).

Victor Weisskopf, in the title of his recent book, expressed our belief that it is a privilege to live the life of a physicist.[1] I think that way down deep, we all do really feel that—even if these days there seem to be many difficulties distracting us from our scholarly pursuits. It is a particular privilege to serve as president of The American Physical Society, and I am grateful to have had that opportunity. Those who have had this chance find that it is an inspiring experience to have the unstinting volunteer assistance and personal advice of so many members at large, on the council and on committees. But in addition, as my predecessors have also found, our headquarters staff, modest in size but large in capability, has been constantly supportive.

In fact, I want to take special notice of a milestone in the history of our organization: the retirement, at the end of 1990, of APS Executive Secretary W. W. Havens. Over the years Bill has given more to the society than can be appreciated in words. Today we want to promote the theme of unity in physics; Bill, more than anyone else I can think of, understands and believes in this unity. He has been a major force, an adviser, a "keeper of the grail," when centrifugal forces might have divided the society.

Building unity

Upon addressing the theme of unity in physics, one is struck by its many facets, at least three of which are the sentiment of the unity of physics, professional unity among physicists and, more abstract in nature, unity in the science of physics. I want to examine the last of these. Our colleague Gerald Holton, in the 1990 Andrew Gemant Lecture, puts it this way: "We are very good at making, and talking about, the bricks of the temple of science, but most of us are shy about the mortar, or about the speculative blueprint of the whole design." My thoughts here are directed at the mortar. Is there any in physics today? My answer is a strong yes—it exists in shared scientific concepts, if we would only take the time to see them. In particular, from my own recent research experience, I can point to the development of soliton physics as an example of that mortar in action, successful-

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ly joining many subfields, as I will discuss later in this article.

In his 1985 retiring address, Wilson noted that "we discuss the unity of physics with a kind of nostalgia, for our field today is so patently diverse," and that "we Americans are sentimental about Jefferson's dictum 'All men are created equal.' Yet from almost any point of view this statement is not true.... But behind the sentiment lies a great truth, for the meaning and idealism behind the sentiment constitute much of the moral underpinning of our nation, and of the kind of nation we aspire to become." As we think about APS today we can see parallels to that sentiment in the development over the past two decades of a multiplicity of subfields, of divisions, topical groups, multiple *Physical Reviews* and so forth. Now, during my tenure five years later, when many of our members are beset with funding problems and the promotion of the Supercollider has caused much internal divisiveness, one worries whether "unity in physics" can be anything more than hopeful idealism.

I would argue that there is in fact real commonality in our science and our profession, in spite of the appearance of diverse purposes. Our daily pressures leave us too little time for concern for either the edifice of physics or for our cousins in physics. Yet we may find, if we look, that we still could have a strong sense of unity in our affairs if we chose to recognize it. Just as it applies to our nation, the motto "*e pluribus unum*"—"out of many, one"—can apply to physicists and physics. Cultivating the unity of physics can, in Wilson's words, make us "one with our progenitors, one with our living colleagues, one with those who will create the future of physics."

We are still bound largely by the common language of mathematics and by a common approach in our scientific method—measure, analyze, generalize. As educators we see that physics is in some sense remarkable in that the foundation curriculum, even through the early graduate years, is pretty much the same for all, no matter what the intended later specialization; and this shared foundation provides us with a common basic language for communicating with one another. Unfortunately, though, as we have moved out of training and into our professional research careers, and as the diversity of physics (and science generally) has increased so, few of us have made the effort to try to recognize and cross the bridges to colleagues in other areas. What about "*e pluribus unum*" in the science of physics? I'd like to talk about one concept in physics that has been fertile in its unifying effects—the soliton.

Solitons

In my research over the past two decades I have been fascinated by a set of developments in physics that can be classified under the general rubric of "nonlinear" science. A particularly remarkable manifestation is the entirely counterintuitive excitation called the soliton, a form of solitary wave or transition region.[2] Whereas much of

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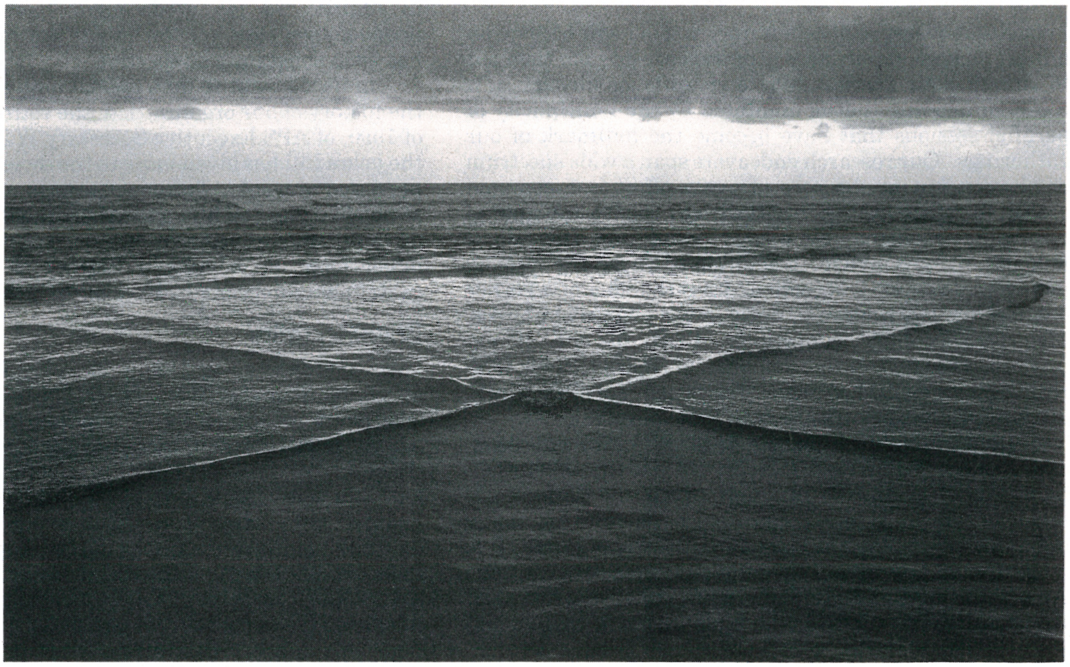
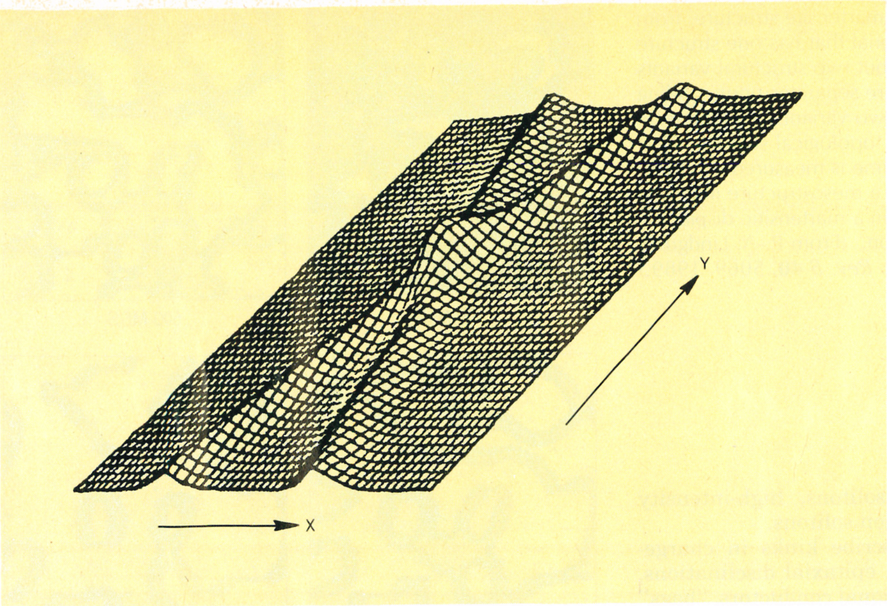


Water-wave solitons. The photograph shows two intersecting nontopological solitons in shallow water. When they collide they form a single disturbance of larger amplitude, which then separates into two reemerging waves that are parallel to but delayed from the originals.



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Two-soliton solution of the Kadomtsev–Fetviashvili equation for the situation in the photo on page 34. This contour map plots water depth as a function of position at a particular time. *X* and *Y* are directions normal and parallel to the shoreline, respectively.

nonlinear science addresses chaos out of order,[3] the soliton is a form of order out of potential chaos. I cannot convey a true appreciation of the importance of this new area of physical science and engineering without going into detailed mathematics and citing many experimental results. However, I hope that by means of a brief qualitative description and a look at the path of the soliton concept through the past 150 years of physics I can convey a sense of why many scientists today see nonlinear science as the most deeply important frontier for the fundamental understanding of nature.

Before going into the history of the soliton let me say briefly what is difficult about nonlinearity. In physical problems, say with waves, we are accustomed to believing that if we double the intensity of the source we will get the same kind of response simply doubled in strength—a linear relationship. For excitations, however, that turns out to be an idealization. We are all familiar with distortion in audio systems as a manifestation of overloading. What is happening is that as the source intensity gets greater, the result is not only sums of responses but also products of responses (and products of sums, and so on, *ad infinitum*!)—thus *nonlinearity*. Up until the past few decades most physicists threw up their hands and gave up when trying to deal descriptively with nonlinear problems. Fourier transforms, mode superposition, spectral analysis—none of the best-loved tools of the tradition work. In some cases the result of nonlinearity is chaotic behavior, awareness of which has spread beyond the physics community through popular articles and books.[3] However, and truly remarkably, there is another limiting phenomenon that often occurs in nonlinear systems, namely the development (asymptotically) of limiting forms of orderly behavior out of chaotic conditions. The soliton is one such, and in a deep sense may give a clue to why we find ourselves in a structured universe rather than a homogeneous, unstructured soup.

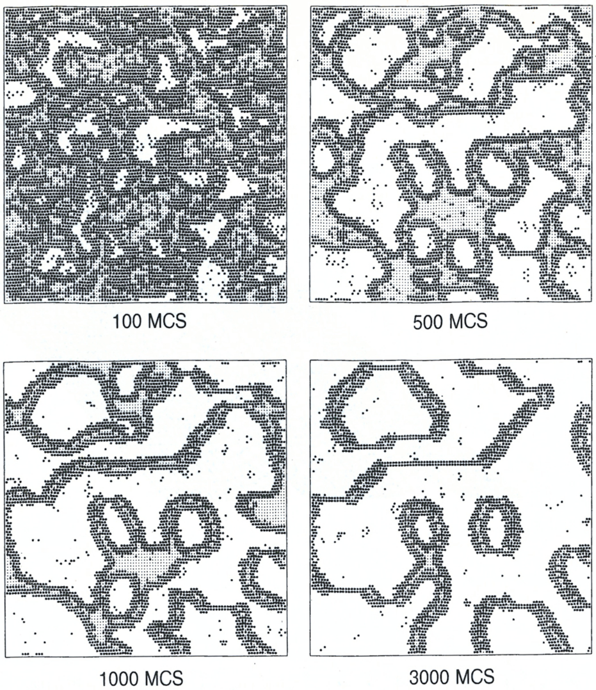
The observation of solitary waves goes back at least as far as 1838, when J. Scott Russell first observed in a narrow barge canal "a large solitary elevation, a rounded, smooth and well-defined heap of water which continued its course along the channel, apparently without change of form or diminution of speed."[4] Remarkably, this beautiful coherent wave formed itself out of all the turbulence resulting from the stopping of a canal boat. Russell followed this solitary wave on horseback for one or two miles, eventually losing it in a winding channel. He derived an expression for the velocity of solitary waves in a channel of uniform depth and proposed that the wave does not damp out under idealized conditions. In contrast, the authority on hydrodynamics, George Biddell Airy, insisted that permanent solitary waves did not exist. That controversy went on for half a century, until 1895, when D. J. Korteweg and G. deVries derived, from Leonhard Euler's (nonlinear) hydrodynamic equations, waves of great stability—waves that are, in fact, permanent—that move with velocities proportional to their amplitudes, in agreement with observations.[5]

What is so counterintuitive about this is that we all expect water waves to spread out and die away over relatively short distances. That a coherent hump can assemble itself out of turbulence and have the stability to maintain itself for some miles is nothing short of astounding! In fact, however, we can now understand that analogous behavior occurs in the turning on of lasers and in other nonlinear quantum optical systems. Indeed the soliton and its cousins are ubiquitous in many areas of physics today. Two factors have drawn our attention to this very old but new field of nonlinear science: First, over the past several decades we have pushed physical systems harder and harder, and thus beyond the limits of linear behavior. Second, modern computer simulation and graphics have given us tools for exhibiting the special coherent phenomena quickly and easily in a way that would take centuries with actual experimental tests.

There is one important subclassification of solitons into topological and nontopological solitons—those that do or do not, respectively, change the state of a system by their passage. A domain wall in a ferromagnet is a topological solitary wave: Its passage reverses the direction of magnetization. Russell's water-wave soliton is nontopological: Its passage leaves the water behind the hump as before. Recent years have seen the recognition of more and more examples of solitons in physical systems, and I can do little more than provide a partial list.

Nontopological solitons include water-wave solitons of several types, ion-plasma-wave solitons, magnetohydrodynamic solitons, nonlinear optics solitons, optical fiber

Time evolution of martensite structure, from a simulation. A material that has one structure at high temperature but two structural variants at low temperature separates upon cooling into mixtures of the two variants, separated by interfaces that are topological solitons. This sequence, in which time is measured in Monte Carlo steps, shows a mesostructure interface pattern evolving in a martensitic displacive phase transformation. (From P.-A. Lindgord, T. Castan, *Phys. Rev. B* **40**, 5069, 1989.)



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solitons, biomolecular polaron solitons, high-intensity shock solitons and nerve conduction solitons.

Topological solitons can describe kinks in charge-density waves, some dislocations, epitaxial disclinations, charge localization in low-dimensional conductors, "bags" and "lumps" in quantum gauge fields, domain walls in ferroelectrics and in ferro- and antiferromagnets, critical droplets and nucleation, instantons, "boojums" in superfluids, fractional charges, mesostructure in structural phase transformations, localized excitations and conformational structures in nucleic acids and proteins, and large-scale structures in cosmology.

It is apparent from the many subfields of physics spanned by this list that there must be deeply shared concepts in the science underlying these phenomena.

Proper solitons have the character of truly stable solutions of the differential equations of motion; in nature they survive collisions, emerging intact. However, the term "soliton" has been adopted by physicists—perhaps for the sake of brevity—also to cover a larger class of solitary excitations that are localized in space–time and, though long-lived, are only metastable.

[In an article that appeared subsequent to my speech, Andrei V. Gaponov-Grekhov and Mikhail I. Rabinovich (PHYSICS TODAY, July 1990, page 30) demonstrated that coherent structures with a high degree of spatiotemporal order exist within turbulent flow; see their figure 7. In addition, Gaponov-Grekhov and Rabinovich provided a conceptually general rationale and methodology for understanding the ubiquity of such particle-like entities. The existence of such characteristically shaped, persistent, localized structures in a uniform, or chaotic, background, which might be called "antichaos," was certainly unexpected.]

Underlying all of these solitary excitations is the physics of the interplay between local physical laws and long-range interactions, either or both of which may be nonlinear. An example is the domain walls—describable by Sine–Gordon solitons—separating oppositely oriented magnetic phases.

In these walls there is competition between local anisotropy energy wanting to orient a spin in one of several preferred directions and a nonlocal interspin exchange energy $J_{ij}\mathbf{S}_i \cdot \mathbf{S}_j$, both interactions being nonlinear.

A richness of physical scales and cooperative structures from metal physics to cosmology all share this concept of competing local and nonlinear physical laws. This surely is one manifestation of an intrinsic unity in physics, and there are others.

These concepts have potentially deep implications for our views of the nature of physics. Physicists commonly seek ever more fundamental laws governing the behavior of elementary systems, then from them deduce the behavior of large systems that incorporate these phenomena. These extrapolations usually have been based on essentially uniform-scaling models. Now, throughout almost all of physics, we are learning that simple scaling and reductionism does not work for large-scale nonequilibrium situations. We must deal with an intermediate, "mesoscopic" scale of structural complexity. It seems, for example, that the "dark matter" question embodies such issues.

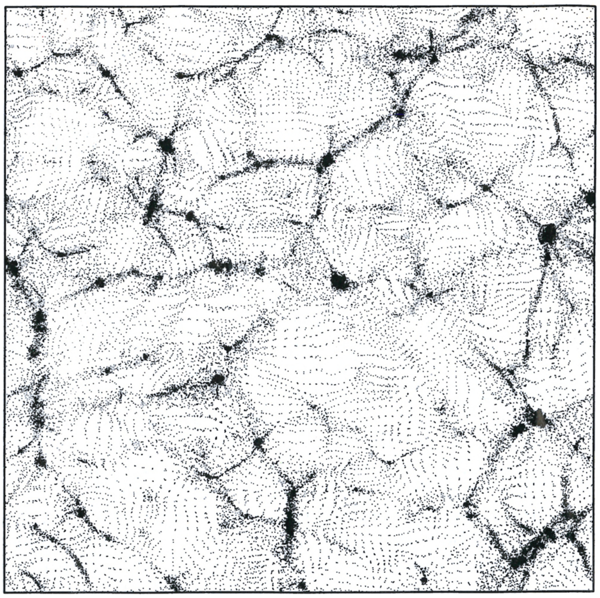
The theoretical and experimental studies of solitons have strongly stimulated an awareness of newly found states of matter that exist between the microscopic and the global. These must be considered if we are to understand nature. *E pluribus* soliton!

Our physical society

Let me now move on to news about The American Physical Society, beginning with a "health" report: Our membership continues around the 40 000 mark; our financial condition is sound under the watchful eye of Treasurer Harry Lustig; our publications continue to hold a preeminent position in the world of scientific journals thanks to Editor in Chief David Lazarus and his staff; our meetings are, on the whole, also prospering; and the guidance from Robert Park in public matters has been delightfully invaluable. In short, it appears that APS is serving the "advancement and the diffusion of the knowledge of physics" quite adequately.

Maybe so, if looked at in broad terms, and at one point in time. However, the situation is not at all that simple when one sees the dynamism in physics today and thinks about the future. Up until 25 years ago APS had no subdivisions. Then it became apparent that strongly cohesive subfields had developed, and their constituencies wanted their own subgovernance and representation on the council. So the divisions were formed. But time has churned up all sorts of new and vital areas—laser physics, computational physics, materials physics and so on. The organization of APS became increasingly strained as a

Mass distribution in the universe following the breaking of a non-Abelian global symmetry at the GUT scale, from a numerical simulation (see C.-B. Park, D. N. Spergel, N. Turok, *Astrophys. J.*, in press). If our universe underwent a phase transition as it cooled, different regions lacking causal contact would have settled into different vacuum states. This would have led to the formation of topological defects—solitons with topological charge. As the universe expanded, the coherence length would have grown and the scale of the defects would have increased. The defects, if produced at a GUT-scale symmetry breaking (10^{16} GeV), would have very large energy densities and would serve as the gravitational seeds for galaxies and large-scale structures. (The box in the figure is 500 megaparsecs on a side.)



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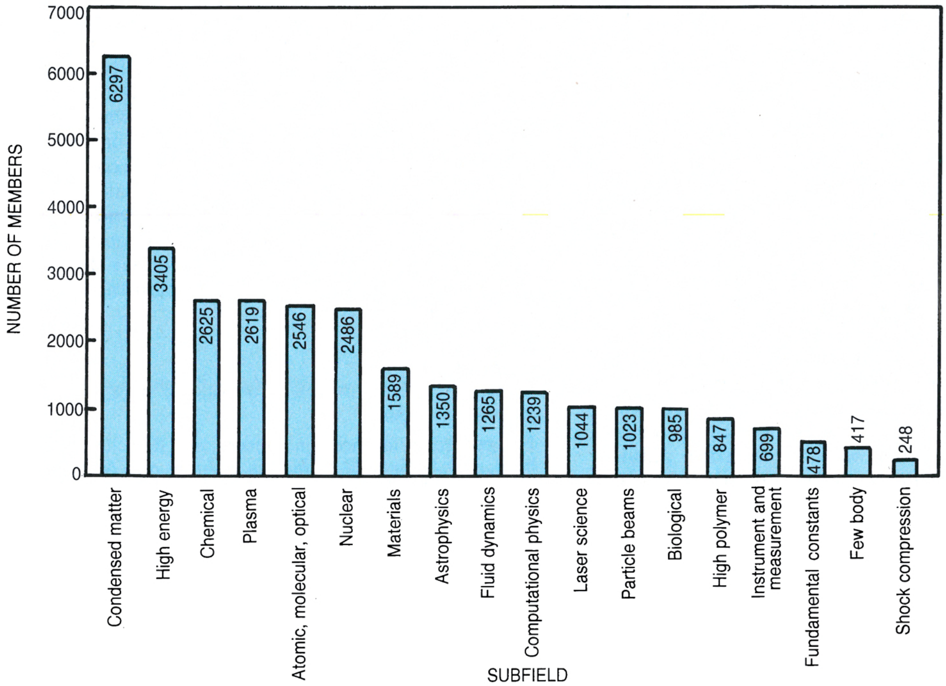
result. Thus in 1984, in response to this dynamism, the "topical group" concept was introduced, and since then these units have grown rapidly in number and size. Despite some cries of balkanization with this burgeoning diversity, this state of affairs has provided an opportunity to enrich our organization continuously by developing a more appropriate governance structure. Thus for the past two years a dedicated task force on governance, led successively by Eugen Merzbacher and Nicolaas Bloembergen, has labored, and with the advice of the council it has developed a revised constitution and governance structure. Shortly this will be circulated to the entire membership for consideration. [The revision was approved subsequent to my speech.]

Our second important function—meetings—has also come under stress. There has been a continuing shift of interest and participation from general meetings to divisional and topical meetings, so that in effect the old, great January meeting has vanished. One of the major challenges in the coming years will be to find a way to respond to the vitality of the subgroups and yet maintain in some form a coming together of the whole clan at least once a year.

Finally, in the category of the society's traditional activities, there is the topic of publications. My predecessor, Val Fitch, already recognized the challenge of the information explosion and believed that new communication and publication technology could provide the means for meeting it. The task force he established on this new technology continues, and the publication committee and the staff of the *Physical Review* have a number of projects under way. We will keep in touch with the developments in other scientific organizations while moving actively to incorporate existing software and systems into our own operations. There are serious uncertainties about what



Membership profile of The American Physical Society, January 1990.

the impact of all this will be on the finances of the society, but we must and will go forward energetically.

Social responsibilities

In years past, the above summary of the society's traditional activities—publications, meetings, finances—might have ended the president's report. But the world has changed much over the past decade, and the place of the physics enterprise in that world with it. When now we receive support for our endeavors, the institutions that provide it and the public at large expect more from us. The increased scale of investment that many areas of science now need and the present era of serious public deficits have further sharpened the competition for funding. Even if funding were not a problem, the increasing technological complexity of societal issues would demand that we think about our role as physicists. It may be that our role is still best carried out through our emphasis on basic discovery and on training toward the goal of a scientifically aware public. However, in addition to our visceral obsession with search and discovery, we should also be prepared to assume, appropriately, a wider set of responsibilities. APS is no longer able to maintain as its sole commitment its cherished scholarly dedication to the knowledge and diffusion of physics, although those must always claim the highest priority.

Our forum on physics and society and our panel on public affairs are already effective bodies for outreach and for raising our collective consciousness on broader societal issues relating to physics. In addition, committees for international science and for the freedom of scientists are active in APS, and we are becoming active in a variety of educational projects in which, I hope, AAPT and AIP will play major parts. Scientific societies, and APS in particular, must move to serve the broader interests of their members on a continuing basis, be those interests in public policy, technology, environment or the human condition in a world that has been so greatly affected by science. To expand in this way, we will need to develop new resources and devise new mechanisms in the operation of APS.

When scientific groups enter the public arena, they face new, difficult questions of policy and principles. In the not too distant past it was all too easy to say that APS would involve itself only in technical issues relating to public policy. That earlier and appealing privilege is no longer available to us.

There are outside forces that challenge us and that would promote disunity: The recent episode of cold fusion is an example. In addition to the compromising of the fundamental principles of open publication in science that occurred, there were elements of the lay press that tried very hard to portray the situation as a schism between chemists and physicists motivated by the same territorial instincts that have promoted the long history of wars with which our human breed seems to be cursed. Territorial chauvinism has no place in science, as all of us agree; the sciences have no owners and no national boundaries.

Unfortunately, in our times the promotion of science, both to the public and within our own community, calls increasingly on publicity. This brings us close to two areas of potential danger: one, when we deal with the public; another, whenever in our enthusiasm and conviction we become advocates for our own exciting endeavors. In the former case we risk hyperbole; in the latter we risk failing to give credit responsibly. Either can be a threat to unity within physics.

Situations involving hyperbole are indeed complex. We all sincerely believe that what we do is not only a heroic odyssey but also a public good. However, our need to obtain patronage seems to force us into extravagant claims and the hard sell. In my view, what is most dangerous in such statements is the certainty that we imply for the "benefit" of a public unable to judge the validity of claims. There is no objection to statements of hope; they are another matter. The danger, ever present, is of being drawn into events beyond our control. Even with the best of intentions, as Thomas Paine notes in *The Age of Reason* (1793), "it is with pious fraud as with bad action; it begets a calamitous necessity of going on."

The second danger is incomplete attribution. In the flush of success it is all too easy to forget the foundations, built by many, on which our present triumphs stand. The story of synchrotron radiation is only one of many that could be told for illustration: Accelerator physics, condensed matter physics and atomic physics should all be credited for bringing that phenomenon to its present wide utility.

The real strength of physics, both as a cultural resource and as a resource for technology, lies in the power a balanced use of its diversity brings to the pursuit of an overall common purpose. Any of our goals can be better advanced if we draw attention to the resources contributed by other subfields whenever we promote our own to the public.

The Hubble Space Telescope is a good example. [The flawed performance of the Hubble subsequent to my APS presentation, although a disappointment, is not material to the point of this discussion.] This instrument is "big science" indeed. Yet in spite of a funding climate that was inadequate to meet the opportunities and challenges in other fields, and in spite of the fact that the Space Telescope fell in the same budget function as NSF and the DOE general science program (and was therefore to some degree a competitor for funds), the physicists in those other fields never belittled the value of the Space Telescope or argued that the funds should be diverted their way. One may well wonder why there was virtually no outcry here to compare with the concerns about the Supercollider.

The answer, I think, is respect in the community for the way the cosmologists went about securing support for their program. They did not represent discoveries from other subfields of physics as their own by inference. They did not claim that cosmology had discovered nuclear energy or point out that previous satellites had found commercial uses, thus implying that this one would as well. They did not claim that the Hubble was essential to keeping the US number one in technology, or that spinoffs from its development would make the US competitive in world markets. They simply argued that the Hubble Space Telescope would lead to an enormous advance in our knowledge of the universe—and that was enough. And for each of us, whatever our endeavors, I believe that the time has come to tell it like it is if we are to maintain public confidence in science.

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5. D. J. Korteweg, G. deVries, Philos. Mag. **39**, 422 (1895). ■