Some Thoughts
on Science and Education

Ron Brown

This is a collection of thoughts – quotations and original essays – which are generally about science (and physics in particular) and about education and my own thoughts about those two endeavors. Most of my contributions to this enterprise have been in the form of helping students understand the nature of science and, more specifically, the principles of physics – and how we know what we know – and, in a few cases, helping them formulate their educational and career goals. I may have even occasionally helped my colleagues see a different way of looking at some problem or idea in physics or about teaching or the processes of education in general in such a way that they could more carefully formulate their own ideas and perhaps be more effective at what *they* do.

Having been at a university my entire adult life has personally been immensely rewarding – it has allowed me to indulge myself by spending that time with bright and articulate people thinking about the grandest of ideas. And this collection of quotations and essays is intended to reflect on the process – words and ideas that are loosely connected to the grand ideas of science and education.

I hope that whoever might read these thoughts will find some of them interesting and perhaps even provocative – and that they will promote their own thinking about the nature of science and of education.

Ron Brown

The formulation of a problem is often more essential than its solution.

Albert Einstein

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The aim of science is not to open the door to everlasting wisdom, but to set a limit on everlasting error.

Bertolt Brecht

It’s not what you don’t know that hurts you - it’s what you *know* that ain’t so.

Mark Twain

If we teach only the findings and products of science - no matter how useful and even inspiring they may be - without communicating its critical method, how can the average person possibly distinguish science from pseudoscience? The method of science is far more important than the findings of science.

Carl Sagan

All progress in both science and education depends on the questions asked.

Five Short Stories on Teaching

In thinking about this activity called teaching, the following has occurred to me: The best we can do - either as individuals or as a university - is create the learning environment and then offer the opportunity for an education to those who choose to acquire it. But ultimately, the emphasis has to be on learning and not on teaching.

Consider the following five short stories - personal vignettes, actually - that are loosely related to this peculiar enterprise we call education.

- In 1972, Richard Feynman was awarded the Oersted Medal for his outstanding contributions to physics teaching at a national meeting of the American Physical Society. He had been asked to talk about what makes a good teacher. He began by saying that while thinking about the talk, he decided that he didn't know how to teach. So instead of talking about teaching, he would talk about physics - the structure of the proton - to this audience of a thousand physicists. And he gave one of the best research talks I have ever heard - stripping away the details in order to focus on the essential elements of the line of reasoning. He was, as usual, exuberant and supremely clear in his presentation, developing the arguments, speculating on the outcomes of the work and on the possible implications. Although I am not an elementary particle theorist, I could follow the essential arguments and came away enriched by the insights into that discipline and his work. And the particle theorists undoubtedly saw connections or conclusions or possible future lines of inquiry they had not previously seen. It was so very clear why he was awarded the Oersted Medal.

- I saw Richard Feynman again fifteen years later - only three months before his death, and obviously very ill. The occasion was a physics teachers conference - his last professional meeting. He was a panelist in a discussion on physics teaching. What made the event so very special, however, was the discussion <u>after</u> the meeting. There were a dozen or more of us gathered around Feynman reviewing some of the day's discussion when someone handed him a long copper tube and a small object to be dropped down the tube. And once dropped, it fell ...s o s l o w l y.... not at all what one might have expected. "It must be magnetic," said Feynman of the object being dropped. Of course it was, we all knew, since that was a fairly standard lecture demonstration of how a moving magnet can stimulate eddy currents in the copper tube and hence dissipate some energy which in turn slows the magnet's fall. What was magic was the almost childlike way he played with the magnet and tube. He was clearly delighted by the interplay of physical concepts involved. Then someone asked what would have happened had the tube been one of the new superconductors instead of copper! The mood of the group suddenly changed from light to serious - a *new* physics question had just been raised - one none of us had considered before. In the animated discussion that followed a variety of speculations were offered - with supporting arguments and counter-arguments. What <u>fun</u>! Then David Goodstein, also of Caltech, made a pivotal observation – and the answer became clear. "Of course!", said Feynman - with that great excitement that comes with new insight into an interesting question.

- I had lunch with a friend and colleague just prior to the birth of his first child. He told me he was very excited about the prospect of becoming a father but that he hoped that he would not "do a number" on his kid. I said that *of course* he would do a number on his kid (*all* parents do) - it's just a question of which number.

- When my son was about five, we were walking along the cliffs overlooking the ocean. "Dad, can you tell me what makes the waves?", he asked. I told him I didn't know if I could explain it to him - that it was quite complicated. "But will you try?", he responded - as if the limitation were mine and not his.

- Finally, during a physics class last year in which I was describing the motion of some object (a projectile, if I recall correctly) by first demonstrating the motion, then drawing the force diagram, writing the equations of motion - and their solution, and sketching the graphs of the position as a function of time and of the trajectory, a student asked what would have happened if the problem were changed in some way (maybe by including air resistance, or something). I proceeded to show the effect of the change in the problem - in the diagram, in the equations and the solution, and in the graphs of the motion. I looked around and the class was both attentive and very anxious! I think my students were rather concerned that they were expected to be able to quickly go from problem statement to description, solution, graphs, and interpretation just as I had done. So I stopped and asked how many of them enjoyed music. They all raised their hands (but had no idea why I asked). I then followed by asking how many played musical instruments...fewer hands. Then how many could read music ... still fewer hands. And how many could sight read the music and play it on their instrument ... fewer still. Finally, I asked how many could read a musical score and *hear* the music. One hand remained. Interpreting physics problems and reading music are very much alike in that they are both learned skills - and you can learn anything you want to learn. What you learn depends ultimately on you.

There are a number of lessons in these stories: You teach best what you understand deeply – and are passionate about. You should teach the principles and the lines of reasoning, the goals and the possible outcomes and implications. Don't underestimate your audience. Expect a lot from your students - the best of them deserve to be challenged – and each can learn anything he or she *wants* to learn. Expect a lot from yourself as well. Teaching excellence requires that you remain a student - learning, stretching, questioning and remaining "childlike" in your curiosity and enthusiasm for learning. Learning about one's universe is a lifelong endeavor – and there will continue to be surprises and new insights for teacher and student alike. We as teachers are very much like parents in that we have influence on our students ... the only question being what kind of influence that will be. Finally, all knowledge, like all education, is ultimately driven by the questions asked. Our task is to pose the right questions – and help our students learn to ask the right questions.

Excellence in teaching ultimately has little to do with the mechanics of the process or the number of students we have or whether we hand out course syllabi or how many tests we give or how we grade. It has to do with creating the desire to learn and then establishing the environment in which the learning can flourish.

[Written in the Fall of 1995 after receiving the University's Distinguished Teaching Award.]

Truth

For every complex problem, there is a straightforward solution that is clear, concise, and incorrect.

- George Bernard Shaw

In a lecture in which Neils Bohr was presenting his famous principle of complementarity - a somewhat more general and philosophical version of Heisenberg's uncertainty principle which was expressed in purely mathematical terms - Bohr stated that for every measurable quantity there exists another measurable quantity which is complementary to the first such that the more precisely the one quantity is measured the less precisely the other can be known.

Following his talk, someone asked, "Then tell me, what is complementary to 'Truth'?"

Bohr's immediate response was, "Clarity".

It is useful to think of that in the context of what we do as teachers. Although we claim we teach "Truth" - in fact what we do is parcel out the truth in tiny increments - increments, often incomplete and only approximate, that can be understood by our audience. We often, in fact, strip away what is real and true for the purpose of simplifying the discussion so that it can be understood. And we ourselves may only understand a somewhat simplified version of the truth. In the sciences, that is what we call model building. The attempt is to create a conceptual or even a mathematical model of a system or problem that contains the essential ideas of what is being modeled, but without the myriad of complications that make it real - albeit intractable. For example, we might talk about the motion of a projectile in the absence of air resistance or of a block sliding down a frictionless inclined plane. The reason, of course, is that for idealized problems, the effects of air resistance (as well as buoyancy or friction or the variation of the gravitational field with changes in distance from earth's center) are negligibly small compared to the other forces that act, and the essence of the problem can be understood by simplifying it – that is, we can often avoid the more difficult (indeed, perhaps even impossible) solution that including the complications (*i.e.*, the realities) would require. Or we consider a system to obey the laws of classical physics – developed before the intellectual revolutions of the early twentieth century – when doing so yields results that are not significantly different from what we observe experimentally even though we know that a much more complete description of our universe requires the quantum theory and Einstein's relativity – which might render the problem at hand too difficult to solve.

And toward what end do we do that? ..... *Clarity.*

[Written following a wonderful conversation over lunch with Dr. William Little, a language professor, who brought the Neils Bohr quote to my attention, saying: "We have to talk about this!"]

Physicists spend a large part of their lives in a state of confusion. It's an occupational hazard. To excel in physics is to embrace doubt while walking the winding road to clarity. The tantalizing discomfort of perplexity is what inspires otherwise ordinary men and women to extraordinary feats of ingenuity and creativity. … Nature does not give up her secrets lightly.

Brian Greene

You see, I can live with doubt, and uncertainty, and not knowing. I think it is much more interesting to live not knowing than to have answers which might be wrong. I have approximate answers which might be wrong. I have approximate answers, and possible beliefs, and different degrees of uncertainty about different things, but I am not absolutely sure of anything. I don't have to know an answer, I don't feel frightened by not knowing things, by being lost in a mysterious universe without having any purpose.

Richard Feynman

Thoughts on Educational Quality

Education is what remains after you have forgotten what you have learned.

- B. F. Skinner

As the university attempts to define *quality* - it is important that we decide whether we are trying to define a *quality university* or a *quality education*. The distinction, I believe, is whether we want to discuss the environment or the process. I think the discussion of educational quality is about *process*. If we focus on what we are trying to accomplish for our students - and what we expect them to accomplish on their own - as they progress through their academic programs, we will also identify what the university must do to assist in those goals. A quality university can then be defined as an institution that offers a quality education. Notice the word choice: Education is not something that is *delivered*, but rather something one *acquires*. The most a university can do is *offer* a quality education to those who choose to acquire it.

Ultimately, the quality of the education the university offers depends on the quality of its faculty. It is, after all, the faculty that teach classes, work with students, do research, write books, and develop the curricula that become the basis for our students' academic experiences. To be effective in the classroom - and in our offices, studios, and laboratories - we need to be able to speak with a level of understanding and expertise that goes far beyond simply mastering the material of our courses. That requires having the time to reflect on the significance of the ideas and the time to maintain an appropriate level of currency in the field. The depth of our understanding and the excitement we have for our disciplines are felt by the students in the classroom. The quality of our students' education depends on much more than the amount of material they are exposed to - or even the amount that they are required to master. It also depends on their contact with faculty who are involved in the learning process as participants.

The university should then create the environment that supports the faculty in what it is trying to accomplish. That will, of course, lead to important discussions about the various university facilities and resources including the library, laboratories, land use, information systems, etc., as well as its support for innovation and ongoing improvement in both teaching and other scholarships, and a commitment to making the decision making processes on campus be closely tied to the educational goals of the institution.

I do not believe that the quality of the education the university offers depends on such things as the calendar it chooses for the courses it teaches. Some courses, of course, would benefit from a longer exposure to the material and some from a shorter, more intense, exposure. But in every case, it is the faculty involvement with the course that makes it successful or not. Nor do I believe it depends on the number of units a student takes or even what courses are required for graduation. To be sure, we want our graduates to be knowledgeable and skillful in each of their chosen disciplines. And graduation, of course, is a certification that the basic knowledge and skills of the discipline have been acquired. But it is not the specific knowledge or skills that are the essential measures of the quality of the education offered, but rather that our graduates have sufficient breadth and depth in their respective fields as well as the confidence, understanding, historical perspective, sense of integrity and of tolerance, and the self-reliance to succeed in their chosen fields and in life. Our graduates should have choices - and that, of course, requires preparation in their own disciplines for entry into the work environment. But it also requires the breadth and intellectual sophistication to continue their education and/or make career changes which they did not anticipate while they were students. They should leave the university excited about their experiences here as well as about the challenges they face. And they should know how to become engaged in their own pursuits of knowledge and no longer need the nurturing of the university.

[Written during 1994 – as a member of a Taskforce on Educational Quality – part of the university's attempt to define and establish the metrics of "quality ", all part of its exploration of the concept of a "charter university".]

Teaching is most effective in those happy circumstances where it is least needed.

Edward Gibbon

On Honor Codes – and Honor

I have found the response to the term "honor code" quite interesting. Once, while serving on a "visioning" committee – a group asked to explore what we might want the university to be like, say, ten years hence if we were given the freedom to make changes in fundamental ways, I proposed that perhaps it could become an "honor code university". That's it – no further elaboration than that. And a fellow committee member simply exploded – "It *never* works! Every time it has been tried at any university, it has been a failure! Honor codes simply don't work – there is always cheating!" The response was so immediate and absolute that we were never able to discuss what might even be meant by the term. I never found out what the experiences had been that led to that response. In retrospect, the response was really simply saying, "we can't expect people to behave honestly!" The problem, I think, is that the focus is too often on the word *code* rather than the word *honor*. An honor code should simply be a statement of principles and values – not a set of rules and sanctions. It should articulate expectations that coincide with what ought to exist without the honor code. The educational enterprise functions on trust – it cannot work otherwise. So an honor code should just be a reminder of those expectations and values that lead to mutual trust.

The real issue here is: How do we create the environment - the culture - of integrity, where the expectation is of absolute honesty so that every member of the community feels that they own that cultural responsibility. How can we build into the program the sense that we all benefit from that culture and hence act in our own best interests when we are absolutely honest in our dealings with all members of the community?

The university cannot make a person ethical, but can create an environment – a "free and ordered space" in the words of the late Bart Giamatti – that fosters open and honest exchanges among all its inhabitants. The real question, of course, is *how* can it do that? What, specifically, can the institution do to foster and support and encourage a sense of integrity in *all* members of the community and create the environment in which it flourishes? *That* is the hard question.

I recently dealt with two students who had submitted identical take-home diagnostic pre-tests which were to have been worked independently. In talking with them, I asked why it had happened. The student who had copied replied that he didn't want me to think he was incapable of doing the work of the course. In trying to hide what he didn't want me to know, he revealed himself in ways he surely didn't intend. Both were football players, as it turns out – defensive linemen. I asked whether, while playing in a game, if they were getting away with some infraction without drawing a penalty from the referee would their coach pull them aside and say they could not continue doing that even though they were not being caught. They both laughed uncomfortably. The most important thing in the lives of those two young men was to be successful in their athletic endeavors and they were living in a culture where getting away with violating a rule is an acceptable pathway to that success. What are the lessons being learned in that environment? And is that environment unique to athletics? What about other environments in business, the sciences – where we have become so aware of huge ethical lapses in recent years, engineering, labor/management issues, the law, and…dare I say…politics and government? Are they immune to those problems? How can the university address the larger question here – the fundamental responsibility to do what is right?

In the President's Seminar course a few years ago, the topic of honor code was raised – as a way to promote a discussion about the role of a university education in building character and producing citizens in addition to building expertise and producing professionals in its diverse disciplines. The discussion, not atypically, turned quickly to trying to define cheating, establish sanctions for doing so, identifying what would constitute a code violation and who decides. And there was such a strong sense of moral relativism coming from the group. The discussion became a purely academic exercise looking for the boundaries between what was ethical and what was not.

But most ethical lapses simply have to do with the failure to be completely honest. *All* "cheating" issues, whether on tests or papers or resumes or golf scores or fishing stories, are about trying to appear better than reality warrants. Students who cheat on tests do so not because of a pressure to succeed - but because of an unwillingness to be judged as is – an attempt to hide some inadequacy or failure in their approach to the course. People who falsify resumes or progress reports are also trying to hide their inadequacies and exaggerate their strengths and accomplishments – or worse, create those that do not exist. But the educational process depends fundamentally on the expectation of honesty. It will not work otherwise. Students have the absolute right to trust their faculty – that their faculty will be honest with them. Always. And the faculty should be able to have that same expectation – in their interactions with students, their colleagues, and their administration. Those are the fundamental underpinnings – the basic tenets, the values – of the entire enterprise. And in this microcosm of life we call the university, I suspect that most people are *not* moral relativists on that point.

So now, the real question is this: How do we create the environment of integrity that fosters that honesty? How do we create a culture that all members of the community internalize as their own? How do we get that "buy in" that always being honest *is*, ultimately, in each of our individual best interests – because of the great sense of freedom that accompanies mutual trust? What do we fear about articulating those expectations? What can be done at *this* university to cultivate that environment - to create a culture that promotes openness and honesty as well as inquiry and the pursuit of knowledge? If it already exists – and *is* a part of our culture – why don't we call it an "honor code"? If it does not, how can we create it – or are we constrained to simply assume that it will never work?

> *[Honor codes, of course, are not new to colleges and universities. But to function well, they must be accompanied by a sense of ownership. At Caltech, the entire honor code is one simple statement: "No member of the Caltech community shall take unfair advantage of any other member of the Caltech community." When I taught at Harvey Mudd College in Claremont, the honor code was part of the fabric of the institution. Most tests were take-home – some even with time limits. And students took the responsibility and privilege seriously. (I even had students stop in the middle of a problem they were working correctly and say "I just ran out of time"). Take home tests in my department here at Cal Poly are often worked in the student lounge in the presence of other students – without any hint of test related discussion or cooperation. It has become an inviolate part of the student culture and they work to preserve that privilege.]*

October 4, 1957

I remember it well - the day that I believe became the defining moment in science education in this half century. I was in high school. I had a date, of sorts, which in itself was a very rare event. While waiting for her to appear, I heard the announcement. The news was on the television in her parents' living room - and yes, I had heard it correctly: The Russians had successfully launched an artificial satellite. Tracking stations monitored its passing every ninety minutes. It was in orbit. I was in shock - excited, enthralled, fascinated - and yes, in shock. It is hard to find the words that come even close to expressing the feelings. For the first time in history, man had just broken free of earth's gravity. (That was not really true, of course, but I did not know it at the time.) Just as Isaac Newton had conceived it nearly three centuries previously, if an object was given a high enough initial speed and the proper trajectory, it could be in a continual state of freefall - with the arc of its motion being mirrored by the curvature of the earth. But why was it the *Russians*? Where were *we*?

That last question, of course, set in motion a transformation in American higher education that is with us still. The immediate reaction, however, was typical of the way we always react to the news of monumental events - especially ones that are perceived as catastrophic. Denial. Those of us that remember November 22, 1963 will forever recall the helpless feeling at the initial news reports of *that* day - surely it *could not* be true. It was the twentieth century, after all. And presidents do not get shot in the twentieth century. The reaction to the news of an orbiting Soviet satellite was similar:

> *It must be a hoax, I thought. Man has never sent anything into space before - at least not outside our atmosphere, certainly not into orbit. Our rockets are not that powerful. Surely their technology is not superior to ours. They must have made the announcement to the world to gain an enormous propaganda coup - to frighten eastern Europe into submission to the great Soviet superpower. But surely it is not true! Of course, how would we ever know? Even the Russians claim that the satellite is no larger than a grapefruit. How would we possibly know if they are telling the truth? That must be it. They claim to have orbited a satellite - and hence forever will claim to have been first even after <u>we</u> actually accomplish that task. And we will not be able to deny it. But wait - we have tracking stations picking up radio signals ....beep....beep....beep.... <u>exactly</u> as they had said. How did they do that? Could they have also tricked our tracking stations into believing they had detected a signal from an orbiting satellite?*

Those were my initial thoughts, as well as those of an entire nation - in fact, of the entire free world! Why? Because this was the very same Soviet nation that had tested megaton yield thermonuclear devices - and had only one year earlier rolled their tanks into Hungary - and whose Premier would say on the floor of the United Nations "We will bury you!" And we <u>all</u> knew that any country capable of placing an object in orbit around the earth - just as the moon is in orbit around the earth - could also launch the very same rockets laden with warheads that <u>could</u> conceivably bury us.

With all of that in mind, I still hoped that the news was true. To me, it was one of the most exciting events imaginable. I did not yet know that I wanted to be a physicist. I had not yet conceived that I would spend my entire adult life at a university. But the idea that man could not only understand *why* a satellite could orbit the earth, but could also *do* it was so intriguing that it drove science education for the next two decades. It drove students to want to participate in the adventure. It drove colleges and universities to revise their science curricula. And it drove the federal government to increase its funding for both pure and applied research as a way to regain our technological advantage over the Soviet Union. I, and probably most of this country's science and engineering faculty, can trace much of our academic and professional interests and opportunities - at least in part - to October 4, 1957.

EPILOGUE: I wrote this on my laptop while listening to Dvorak symphonies on CD. The incredible developments in micro-electronics that make that all possible is a direct consequence of the space race - our nation's need to beat the Soviet Union to the surface of the moon.

[Written on the fortieth anniversary of the orbiting of Sputnik – and included in the readings for the President's Seminar course in 1998 and 1999.]

Newton writes *F=ma* and thereby captures a whole universe of mechanical interactions. This way of expressing ideas contrasts sharply with the method of the humanities. Shakespeare cannot condense the totality of his thoughts and feelings about Lear into a sentence like "Lear is mad." Instead he must write the play in all its redundancy, ambiguity, vagueness, verbosity, and obscurity. But the comparison is misleading. Hidden behind the equation *F=ma* are the definitions of the symbols, the philosophical problems of their interpretation, the historical antecedents of the theory and its complicated, imprecise and ambiguous experimental tests, its realms of applicability and limitations, its practical consequences, its equivalent formulations - in short, its meaning. The physicist who appreciates the beautiful conciseness of the equation is aware of the vast messy world of physics in the background without which the four little symbols would be senseless. He is cheating when he pretends that *F=ma* tells the whole story, just as the scholar is cheating when he substitutes a synopsis of *Lear* for the play.

Hans Christian von Baeyer

It is the most persistent and greatest adventure in human history, this search to understand the universe, how it works and where it came from. It is difficult to imagine that a handful of residents of a small planet circling an insignificant star in a small galaxy have as their aim a complete understanding of the entire universe, a small speck of creation truly believing it is capable of comprehending the whole.

Murray Gell-Mann

I do not feel obliged to believe that the same God who has endowed us with sense, reason, and intellect has intended us to forgo their use.

Galileo Galilei

Science is an infinite regression – behind each answer lurks a question, and behind that, another.

Hans Christian von Baeyer
Rainbows, Snowflakes, and Quarks

Science at the University

"*Ricky's Dad said that each planet has one moon - but you told me Jupiter has sixteen moons.*"

"*And what do you think?*"

"*Well, I know it has at least four - because I have seen them through our telescope.*"

Most of what we claim we know is hearsay. For example, we know that a year is 365 days. How do we know that? How many of us can justify - based on our own observations - that the earth completes one orbit of the sun in what we call a year? (Or how many of us could justify *that* it orbits the sun, a much more difficult question actually, or any of the many other "known" truths about our particular planet?) Simple observations allow us to determine which direction earth spins on its axis, which way the moon travels in its orbit about the earth, and which way earth orbits about the sun - but few people ever make those observations. The absence of the ability to determine the truths of those things that are about us every day - or to even understand the process for such determinations - makes us susceptible to misconceptions and untruths and lead us to either become suspicious or totally accepting of anything that sounds like science. We live in such a technologically complex world (most of us now have the ability to retrieve information from all corners of the globe in seconds without knowing how the system works) that it is not surprising that most people assume that they cannot understand the principles that govern our universe. And when we do not understand even the nature of the human endeavor we call science, we can easily find ourselves believing anything - or worse, nothing - that we hear that sounds at all technical or "scientific". The role of science education, in the words of David Saxon, is to create the ability to distinguish *sense* from *nonsense*.

"Science at the university" has a number of meanings. We generally think of the university as an institution with the primary purpose of transmitting information. And if teaching is central to the mission of the university, it is only reasonable that teaching science would be one of its goals. But that view suggests that "science" represents a body of knowledge that one just learns - like the alphabet - and that one of the functions of the university is to merely pass that knowledge along. But science at the university is much more complex than that. Because what we call science has less to do with collections of facts that one must somehow internalize than it does the process of exploring ideas and principles and the reasons that underlie the behavior of all elements of our universe. Science at the university has at least three important roles: Teaching the principles that govern how our universe works - and the methods and thought processes associated with developing our understanding of those principles; offering access to the most sophisticated of scientific ideas and new developments - the current work that might ultimately change our lives or our perspective; and engaging in the scientific process itself. It is worth exploring each of those roles.

Much more important than what we know is how we know what we know. It is not the collective knowledge that is as important as the underlying principles that connect the uncountable number of possible observations and phenomena. Science teaching should focus on the concepts and fundamental principles and lines of reasoning. The only reason why you should study, say, incline plane problems or oscillatory motion or trajectory problems in an introductory physics course is because those problems represent a way to give meaning to the principles that relate to the motions of all objects. Knowing the solutions to such problems is not important. Understanding the principles and being able to apply those principles to problem solving in general gives both the student of engineering or technology the background necessary to become successful in his or her field of study and the humanist the ability to distinguish between explanations that are based on fundamental principles and those that are not.

Part of the fascination about science and its methods is the change of viewpoint that the study offers. It *is* fascinating to peer through a telescope - or a microscope - and just see things on a different scale or to explore questions from a different perspective than that of our everyday activity. That change in viewpoint can give insight into how things work - and occasionally leads to profound conclusions - even shifts in the paradigms of human thought. (Observations in 1610 similar to those mentioned in the opening conversation with my son when he was young led Galileo to conclude that Copernicus was right - the universe cannot be geocentric - a conclusion he suffered for.) The university can offer access to those processes of discovery and to both microscopic and cosmologic viewpoints both through the laboratory experience and through the distillation of current scientific work and its integration into the classroom and the public consciousness. Current research in all areas of scientific endeavor is generally so specialized and sophisticated that only others working in similar areas can understand it fully. Yet interpreting the nature and significance of current work IS one of the important functions of a university's science faculty. And that access to the work of science can change our worldview.

Science is a process. And central to the process of science is *inquiry*. Participating in the scholarship of discovery - as university research has come to be known since the Carnegie Report on Higher Education of a few years ago - is also an important component of the intellectual life of a university. Much of the fundamental scientific research done in the world is done at universities. The reason, of course, is that the goal of research done at the university is often quite different than that done in other environments. It is ultimately driven by the interests of the individual researcher and his or her need to be a contributor to the current understanding of the discipline. At major research universities, the success of a faculty member in the institution may depend on the success of the funded research activities. At an undergraduate institution like this one, the goals of those participating in an ongoing research program are often broader and can include incorporating undergraduate students into the process to give them insight into their discipline differently than that gained in the classroom. The research activity is thus a part of the teaching activity - giving those students the important requisite tools for ultimately carrying on their own inquiries.

Science is a uniquely human endeavor - and it is inherently empirical. Model building - the development of ideas and concepts based on pure logic, of course, is an integral part of the process. But it becomes a science only when the ideas are testable. "Science is self-correcting," in the words of the late Carl Sagan. It is a process which continually examines and modifies our understanding of natural phenomena and the principles that govern them. That complex process - a dance between theory and experiment - is the way we know about our universe. And it is appropriate and important to our educational mission that the university participate in the process as well as distill, interpret, and articulate the significance of the work of others.

[This essay was written for the President's Seminar "Science, Society, and the University"- to be one of the readings for that unique seminar course in the Winter of 1997.]

Great Ideas That Have Changed Our Worldview

Although you can think of "Physics" as just a course that must be taken - or a body of knowledge that must be mastered at some level in order to proceed in some science or engineering or architecture curriculum, it is really about *ideas*. Its origins are in philosophy - or more specifically, *natural philosophy* - the quest to understand how the universe works. In that light, it is useful to see what some of those grand ideas are about and how they have changed the way humans view their universe. And even though some of those ideas are now familiar, they were not always so - and they certainly are not intuitive. These are indeed revolutions of human thought - triumphs of the human intellect.

The Copernican Revolution

We are all comfortable with the idea that the earth is one of nine planets orbiting our sun which is itself just one of more than a hundred billion similar stars in our Galaxy which is just one of perhaps hundreds of billions of galaxies. But those ideas were slow in coming - and it was only with the publication of *On the Revolutions of the Heavenly Spheres* by Nicholas Copernicus in 1543 (on the day he died) that a model of the solar system with Earth as just one of the planets was formally presented. Nearly a century later, Galileo suffered greatly for espousing that idea and was forced to recant his belief in a sun-centered solar system during the Roman Inquisition - and spent the last eight years of his life under house arrest unable to teach or publish his works.

Newton's Synthesis and the Universality of Physical Laws

Isaac Newton, who was born the year Galileo died one hundred years after the publication of Copernicus' *Revolutions*, developed the laws that govern the motion of the planets. In the process, he made an enormous intellectual leap in stating those laws apply equally well to *all* objects in the universe! That idea - that physical laws govern the universe and how it works - is a central idea in all of science. Newton articulated the relationship between forces and the changing motions of objects. But more than that, he expressed that forces are interactions between objects and determine how those objects behave. In that sense, Newton's laws are intimately related to the idea of *causality*. A consequence of Newton's synthesis is that the entire universe is a system of interacting objects - a mechanism that is governed by physical laws. The broad subject which includes those principles is called *classical mechanics*.

Energy and Entropy

These two ideas were developed over a period of about one hundred and fifty years - and can be thought of as describing the organizing principles that explain the macroscopic universe, from describing chemical processes - and hence life-processes - to describing the large scale behavior of galaxies and clusters of galaxies. The concept of *energy* is a central idea in all of science and engineering. And if the universe can be thought of as a mechanism, it can be said that energy is what drives that mechanism. And while energy can be both transferred between objects and transformed, it can always be accounted for. But even though energy is always conserved, it becomes less available for doing work - a principle expressed in the concept of *entropy*. That principle gives to natural processes a "direction" - that is, it assigns an order in time to natural processes. In that sense, the concepts of energy and entropy put limits on what can happen - and the order in which those events can occur.

The Conservation Laws

Expressing that energy can be either transferred or transformed - but can always be accounted for, is the equivalent of stating that it is a conserved quantity. The principle of energy conservation is just one of the conservation laws that are particularly useful in summarizing the laws of physics. When a quantity is invariant or unchanging, it becomes a very useful quantity to evaluate in the analysis of the behavior of objects or systems of objects. Newton himself first expressed the idea that certain quantities are conserved. He postulated, for example that mass is conserved in all processes in closed systems - ultimately, as we now know, because all matter is made up of constituent atoms - and they can always be accounted for. He also expressed the conservation of momentum in describing interacting objects or systems of objects. And energy conservation follows directly from his laws of motion. The conservation laws thus take on great importance in understanding the behavior of systems.

The Atomic Hypothesis

For well over two millennia, since the time of Democritus and Lucretius, the idea that everything is made of distinct atoms has been a part of natural philosophy, although neither understood nor even accepted even by many natural philosophers and scientists over much of the intervening time. Even as recently as the beginning of the twentieth century - within the lifetime of some humans - the existence of atoms as individual constituents of matter could not be verified without some doubt, and it had been assumed that any direct observation would be impossible. But the *atomic hypothesis* has become the *atomic fact* - and we now know that all materials are constructed of individual atoms that are distinguishable and distinct. Furthermore, the study of atoms in the first half of the last century has led to an understanding of the very structure of the atoms themselves and to the remarkable conclusion that we now know the characteristics of every type of atom that is even possible *in the entire universe* up to atomic number 118, or so, and the organizing principles for any that are heavier which are either discovered or manufactured - even in the core of some supernova in some distant unobservable galaxy. Even if the "modern physics" concepts of quantum mechanics and relativity - which changed our worldview from the classical physics of the previous centuries - are replaced by a "new" physics, it will not change what we know about the possible atoms that can exist. All that can be changed are the underlying descriptions - the mathematical formalism or interpretation that describes nature at the atomic level - but not the knowledge of the nature of the atoms themselves.

Relativity and Space-Time

The grand ideas surrounding Einstein's relativity have brought profound changes in the way the basic concepts of space and time are understood - and, in fact, have shown that Newton's laws are not strictly valid under all circumstances. (The conservation of mass, for example, is only approximately true since mass and energy are related through Einstein's famous equation $E=mc^2$ - but the conservation of mass and energy *together* is always true.) And as abstract (and even obscure) as the theory of relativity is, it is verifiable to a great degree of accuracy - and even plays a very important role in everyday life. The global positioning satellite technology that allows such precise determinations of positions of objects anywhere on the surface of the earth would not be possible in the absence of calculational corrections based on Einstein's general theory of relativity. And without that technology, even your cell phone - the operation of which depends on communication satellites - would not work properly.

Uncertainty and the Quantum Theory

The fundamental structure of the atom cannot be understood in terms of the classical physics of Isaac Newton. At the very core of our understanding of interactions between the constituent particles of all objects is the quantum theory - and that represents a fundamental change in our view of nature at the microscopic level. And inherent to that change in view is that nature behaves in probabilistic rather than deterministic ways. That idea - and the complex mathematics that goes with it when dealing with atomic and sub-atomic systems - calls into question the very ideas of causality. And although the quantum theory, when used to solve problems that can be experimentally tested, has never failed to achieve a high degree of accuracy, the interpretation of the theory is still developing - and could continue to evolve over a long period of time and could even be replaced by a more fundamental view of nature at the microscopic level.

Information Theory and Genetics

A fundamental change in the way we view, transfer, and store information occurred with the digital revolution. Information became data. Shannon's Law (articulated the same year the transistor was invented - a half-century ago) that information can be accurately transferred through noisy channels only if it is both digitized and redundant (thus allowing accuracy in encoding and decoding information) has led to the astonishing progress we have seen in both information technology and in molecular biology. Both computers and the replication of genes works on the same principle: Information can be faithfully reproduced if that information is in digital form and is sufficiently redundant, and mechanisms exist to decode the information - and that is the essence of molecular biology and the genetic code.

[Originally written to be included in the readings for my introductory physic course for the University Honors Program – and subsequently posted on my web page.]

> In matters of science, the authority of thousands is not worth the humble reasoning of one single person.
>
> Galileo Galilei

> It is when we take some interest in the great discoverers and their lives that science becomes endurable, and only when we begin to trace the development of ideas that it becomes fascinating.
>
> James Clerk Maxwell

All science is the search for unity in hidden likenesses. It is nothing else than the search to discover unity in the wild variety of nature. Poetry, painting, the arts are the same search.

Jacob Bronowski
(From *Science and Human Values*)

The word physics, translated literally from the Greek, means "natural things." It refers to rainbows and snowflakes, clouds and lightning, waterfalls and whirlpools, rosy dawns and brilliant sunsets, ocean surfs and ripples on puddles, to the multitude of splendid forms and ceaseless transformations that we experience as the material world.

Hans Christian von Baeyer

It is the business of physics to find unity in the diversity of natural phenomena --and to discover analogies between the inaccessible realms of the universe and the immediate world of human experience.

Hans Christian von Baeyer

On Studying and Doing Science

Science is an infinite regression - behind each answer lurks a question, and behind that, another.

Hans Christian von Baeyer

All progress in both science and education depends on the questions asked. The above quote by Hans Christian von Baeyer, perhaps more than any other that I can immediately recall, reflects how I feel about the way progress is made in science. Experimental observations raise questions that must be addressed theoretically. Theoretical models raise questions that must be tested experimentally. In both cases, it is necessary to extract from either the theory or the experiment results and conclusions - which are always answers to the questions asked. Without the carefully formulated questions, little would be gained from either theory or experiment. Progress in science ultimately involves an interplay between theory and experiment - all based on the questions asked of both.

There is a difference between *studying* science and *doing* science. The process of *doing* science is much like assembling a jigsaw puzzle - but a puzzle without the boundary "edge" pieces - or even a picture to guide you, although you may be convinced that it will make sense as you assemble it. (One of the *thema* of science, of course, is that the universe is ultimately understandable.) You proceed hoping that you can obtain all the pieces, but do not know how many pieces that will be nor do you know the size or shape of the completed puzzle. Indeed, you possibly even suspect that it may never be completed (although small parts of it may form a coherent picture), but will continue to grow and change - and reveal new surprises and insights as it develops.

To do such a puzzle, you must examine each piece carefully, learning its shape and colors and patterns and symmetries, turning it over and seeing it from different perspectives. Then you must look to see how it connects to other pieces - whether it adds to some fragmented part of the existing picture or whether it seems to open new vistas. For no matter how familiar you are with any one piece, no matter how well you know and understand it, it will still make very little real sense until it is seen in the context of other pieces that surround it. Then as pieces begin fitting together, they will create a larger more understandable pattern or picture. And even as small areas of the puzzle are completed, those areas will truly be understood only when they can be seen in relation to the surrounding areas. Each part of the picture contributes to the overall understanding of the puzzle. And sometimes, when the connections are made, your perception of the importance of any one piece may dramatically change - the piece that you thought you understood well, may play some very different role in the overall picture.

The scientific enterprise is much like the above description, except the size and complexity of the puzzle is so great that no one person can ever do more than a tiny part of the puzzle. So to work toward completing the picture requires a very large number of contributors. Of course it would never work for each person to work in complete isolation – each picking up a handful (or many handsful) of pieces and simply hoping that some fit together. Even though individuals might work independently, the work is cooperative in the sense that results are made public. Only then, as each discovery is made, can progress made in creating the picture be seen by all so that each contributor can then examine his or her own pieces of the puzzle with an expanded understanding of how they might fit. That communication between the scientists is an essential part of the enterprise.

When you *study* science, you are covering ground that others have already covered. The logical connections are already understood by others - and your study of the material involves making those connections for yourself to form a coherent picture in your own mind. You must be willing to explore - take an idea or question and examine it, see where it came from, turn it over and look underneath it, pull it apart if necessary and examine its components. Then reassemble it and see how it fits with other ideas. It too is much like doing the jigsaw puzzle described above. The difference between studying and doing science, however, is that the picture you are trying to assemble has been done by others - and hence there is a guide picture. But just looking at the guide picture is no substitute for assembling the puzzle yourself. The discovery - in fact, the *excitement* of the discovery - is still very personal. That others already understand the ideas and how they go together does not detract from the value of your own quest to understand.

[From the introduction to *Physics 131 – Supplemental Notes and Problems*, El Corral (2002), developed for the introductory physics course for the University Honors Program. The metaphor of the jigsaw puzzle came out of a marvelous conversation with one of my students – Dustin Froula – late one afternoon in my office.]

Nature uses only the longest threads to weave her patterns, so each small piece of her fabric reveals the organization of the entire tapestry.

Richard Feynman

Science is at its most creative when it can see a world in a grain of sand and a heaven in a wild flower.

Freeman Dyson

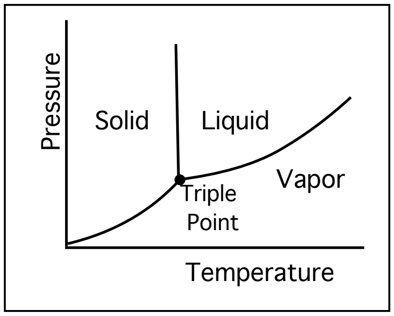
The Nature of Solids

Before embarking on a study of solid state physics, perhaps we should ask what we even mean by the "solid state"? Although the distinctions between the solid, liquid, and vapor states of matter have been a part of our common experience for a very long time, the very nature of solids has been dramatically revealed only over the last half-century in ways that were previously unimaginable and technologies have been developed that allow new structures and even new materials to be created.

At the very core of the question of the nature of solids is the atomic hypothesis. For well over two millennia, since the time of Democritus and Lucretius, the idea that everything is made of distinct atoms has been a part of natural philosophy, although neither understood nor even accepted even by many natural philosophers and scientists over much of the intervening time. Even as recently as the beginning of the twentieth century - within the lifetime of some humans - the existence of atoms as individual constituents of matter could not be verified without some doubt, and it had been assumed that any direct observation would be impossible. Einstein's explanation, in 1905, of Brownian motion as indirect evidence of the effects of individual atoms and molecules was a significant contribution to the idea that all matter, even the air we breathe, is made of atoms and combinations of atoms. And the observation of the diffraction of x-rays by crystalline solids was even stronger evidence of the microscopic structure of materials. And now, only a lifetime later, distinct materials can be identified in terms of the arrangement of their constituent atoms. In *our own* conscious lifetimes (even those of the students reading this), it has become possible to observe individual atoms using scanning tunneling microscopy and even create and study new atomic structures by placing individual atoms. The atomic *hypothesis* has become the atomic *fact* - and we now know that all materials are constructed of individual atoms that are distinguishable and distinct. Furthermore, the study of atoms in the first half of the last century has led to an understanding of the very structure of the atoms themselves and to the remarkable conclusion that we now know the characteristics of every type of atom that is even possible *in the entire universe* with atomic number less than 118 and the organizing principles for any that are either discovered or manufactured that are heavier - even in the core of some distant supernova. Even if the "modern physics" concepts of quantum mechanics and relativity - which changed our worldview from the classical physics of the previous centuries - are replaced by a "new" physics, it will not change what we know about the possible atoms that can exist. All that can be changed are the underlying descriptions - the mathematical formalism that describes nature at the atomic level - but not the knowledge of the nature of the atoms themselves.

So the discussion of the nature of solids has to be the discussion of how the individual atoms coalesce into larger structures and take on the characteristics and properties of the many possible solids. The first question, I suppose, is "Why should atoms attract each other in order to form solids?" And the answer, of course, as it is for all "why" questions, is that it is energetically preferable for them to do so. That is not a very satisfying answer, in itself, and we should only be satisfied when we know why forming solids lowers the energy of the collection of constituent atoms. To deal with such questions will require dealing with the bonding mechanisms. And the bonding mechanisms between atoms is intimately related to the very structure of the atoms themselves. For that reason, we will begin our study with a review of atomic structure - how the quantum theory predicts how the electrons fill atomic orbitals (which leads to the structure of the periodic table) and then how that in turn predicts how atoms interact with each other in order to complete their atomic shells thus forming either molecules or the larger structures which we call solids. As we will see, there are a number of different possible bonding mechanisms, and which occur will determine the atomic arrangements and the physical properties of the resulting solids.

What IS the solid state of matter? Do all substances even exist as solids? It is useful to categorize or separate matter into several states or phases - which, in general, behave quite differently from one another. The three obvious states of matter, which we all recognize in our normal experience are the solid, liquid, and vapor phases. We can use water as the common example - with the three states of water being ice, water, and steam. And our normal experience also indicates what determines the state - or phase - in which we can find that substance. Below the freezing point it is ice, above the boiling point it is steam - or vapor, and in between it is in the liquid form. And we also notice, from our own experience, that at the ice-point water and ice can exist in equilibrium just as water and steam can co-exist at boiling. But it is also true that changing the pressure can also change the temperatures at which those phase transitions occur. So the *phases* or *states* of matter for some chosen material depends both on temperature and on pressure. For that reason, absolute temperature and absolute pressure are referred to as *state variables* - that is, controlling them for some substance controls the state of the substance (liquid, solid, vapor).



A *phase diagram* is a useful way to display the states of matter for some substance. The curves which separate the phases represent the combinations of temperature and pressure for which the two phases which border that branch of the diagram are in equilibrium. There is also a triple point - a particular temperature and pressure at which all three of the phases are in equilibrium. Materials for which the triple point pressure is less than atmospheric pressure will exhibit all three phases - solid, liquid, and vapor - at atmospheric pressure depending on the temperature (again, water being an obvious example). And that is the case for most, but certainly not all, materials. Carbon dioxide, for example, has a triple point pressure well above atmospheric pressure. As a consequence, CO_2 exists in solid form (dry ice) at atmospheric pressure and as a gas, depending on the temperature, but does not have a separate liquid phase unless the pressure is raised above the triple point pressure. All of the elements will solidify at some temperature at atmospheric pressure except helium. Helium gas *liquifies* only when the temperature is lowered to within four degrees of absolute zero - the lowest boiling point of any material - and will not solidify except at high pressures with the temperature maintained at those extreme low temperatures.

How these 'factoids" are useful to us are to remind us of the nature of solids. If all materials are made of atoms, whether the material is a solid or a liquid or a vapor depends on whether the atoms form some relatively rigid bond with respect to their neighboring atoms or whether that bond is such that the atoms or molecules can move with respect to each other, yet form a surface (as in a condensed droplet), or whether they behave independently of each other and can only be contained with a closed volume. And the conditions that determine which of those states occur are temperature and pressure.

But even though atomic bonding and the structure of the resulting solids is important, we ultimately want to discuss the properties of the various types of solids that can form. Closely related to the atomic bonding are the mechanical properties of solids - how rigid or pliable the solid would be or how readily vibrations could be propagated through it. And closely related to how the atoms vibrate are the thermal properties of solids - thermal expansion, for example, or thermal conductivity and molar heat capacity. (And as we will see, the heat capacity of a solid will become an important measure of how the atoms vibrate.) But it is the electrical (or the electronic) properties of solids that will hold most of our interest. That is, depending on the bonding mechanisms that allow atoms to coalesce into solid form, there may be electrons that can migrate among the atoms or ions which then render the solid to be an electrical conductor. On the other hand, if the outer electrons of the atoms that form the solid are all participating in the bonding - in order to complete closed shells on the atoms - then the material would not be inherently conductive. These distinctions will need to be made carefully to fully understand the characteristics of metals, insulators, and semiconductors. In attempting to understand the behavior of the electrons in solids, we will find that our classical assumptions will be inadequate - that is, assuming that the electrons behave classically (like charged b-b's moving among the "bowling ball" atoms or ions) will yield behaviors that are not consistent with experiments. And resolving the inconsistencies will require applying quantum theory to the electrons and that in turn will give us a language to discuss the distinctions between metals, insulators, and semiconductors - and hence the language to deal with the properties of semiconductors and the devices that can be made from those materials. Finally, there are some "special states" that can be discussed - and a study of solid state physics would be remiss if those special states are not included. Magnetic materials and superconductors are intriguing and important types of solids that can only be understood following the discussion of normal solids.

Given that overview, it is now time to begin our study of the principles that are necessary to understand the properties of solids. We will begin with a review of the elements of quantum mechanics - the formalism that will be required throughout the study of solids.

[From the introduction to *Solid State Physics – An Introduction for Scientists and Engineers,* El Corral (2003), the textbook developed for the sequence of solid state physics courses taken by students in physics and engineering.]

> Newton’s laws tell us how matter behaves when it is acted on by forces. The only two things we need to know about the physical world that Newton’s laws don’t tell us are: What is the nature of matter? What is the nature of forces that act between bits of matter? These two questions are still the central concerns of physics.
>
> David Goodstein
> (from *Feynman’s Lost Lecture*)

Entropy and the Second Law of Thermodynamics

............How the universe works

The first law of thermodynamics is simply a statement of energy conservation. That is, it states that energy can always be accounted for, that the energy of the universe is a constant - it can be transferred between objects and can change form, but the total doesn't change. But the first law does not preclude things occurring that we know do not occur: A glass of water does not spontaneously separate into ice cubes and warm water even though the energy balance equations of calorimetry would allow it. That is, energy conservation - the first law of thermodynamics - would allow for the possibility that a system in thermal equilibrium could separate into two systems - one at a higher temperature than the other - and that temperature difference could then be used to drive a heat engine to do work. The second law of thermodynamics explains why the universe does not work that way. It articulates the underlying principle that gives the direction of heat flow in any thermal process. The result, of course, fits our everyday experience. The second law states the reason why it is true.

> *Heat naturally flows from higher temperatures to lower temperatures.*
>
> *No natural process has as its sole result the transfer of heat from a cooler to a warmer object.*
>
> *No process can convert heat absorbed from a reservoir at one temperature directly into work without also rejecting heat to a cooler reservoir. That is, no heat engine is 100% efficient.*

Carnot Cycle - Maximum Thermodynamic Efficiency in a Cyclic Process

It was observed by Sadi Carnot - a French scientist and engineer trying to improve the efficiency of steam engines in the mid-1800s - that there is always waste heat rejected by a heat engine. And that waste heat limits the efficiency of the engine since energy has to be conserved or accounted for. In trying to understand the limits of efficiency, he stated that in any heat engine in principle there would always be rejected heat (even in an ideal engine) - and the net work done would be the difference between the heat absorbed and that rejected. He then set out to determine the principles that would affect that efficiency. He stated that the most efficient heat engine possible would be one that worked reversibly - an ideal that could never be attained. This would mean that heat transferred into or out of the system (the heat engine) would only occur at constant temperatures - the high or the low temperatures between which the heat engine operated. That is, the system would stay at the temperatures of the reservoirs during those heat transfers - necessary for the process to be reversible since the heat flow could not be reversed to go from the lower to the higher temperature. And furthermore, said Carnot, the maximum conceivable efficiency would be limited by those two temperatures. The most efficient thermodynamic cycle operated between any two temperatures is therefore called a *Carnot cycle*.

The Carnot cycle is a four step process involving two isothermal processes (which are said to be ideal reversible processes) one at a high temperatures T_{high} and the other at a low temperature T_{low} and two adiabatic processes (*i.e.*, without heat transfer) which operate *between* those two temperatures. In the isothermal steps, there is no change in internal energy and the heat exchanged is equal to the work done. In the two adiabatic processes, there is no heat exchanged. No such system can ever be built - since it is an idealized process (the two isothermal steps being reversible and quasistatic which means, in effect, they occur infinitely slowly). The importance of the process is that it gives an upper limit to the efficiency of any cyclic process between the same two temperatures.

Entropy and the Second Law of Thermodynamics

In trying to synthesize the ideas of Kelvin, Joule, and Carnot - that is, that energy is conserved in thermodynamic processes and that heat always "flows downhill" in temperature - Rudolf Clausius invented the idea of *entropy* in such a way that the change in entropy is the ratio of the heat exchanged in any process and the absolute temperature at which that heat is exchanged. That is, he defined the change in entropy ΔS of an object which either absorbs or gives off heat Q at some temperature T as simply the ratio Q/T.

With this new concept, he was able to put the idea that heat will always flow from the higher to the lower temperature into a mathematical framework. If a quantity of heat Q flows naturally from a higher temperature object to a lower temperature object - something that we always observe, the entropy gained by the cooler object during the transfer is greater than the entropy lost by the warmer one since $Q/T_{low}. > |Q|/T_{high}$. So he could state that the principle that drives all natural thermodynamic processes is that the effect of any heat transfer is a net increase in the combined entropy of the two objects. And that new principle establishes the direction that natural processes proceed. All natural processes occur in such a way that the total entropy of the universe increases. The only heat transfer that could occur and leave the entropy of the universe unchanged is one that occurs between two objects which are at the same temperature - but that is not possible, since no heat would transfer. So a reversible isothermal heat transfer that would leave the entropy of the universe constant is just an idealization - and hence could not occur. All other processes - meaning, all *real* processes - have the effect of increasing the entropy of the universe. That is the second law of thermodynamics.

Entropy is a measure of the disorder of a system. That disorder can be represented in terms of energy that is not available to be used. Natural processes will always proceed in the direction that increases the disorder of a system. When two objects are at different temperatures, the combined systems represent a higher sense of order than when they are in equilibrium with each other. The sense of order is associated with the atoms of system A and the atoms of system B being separated by average energy per atom - those of A being the higher energy atoms if system A is at a higher temperature. When they are put in thermal contact, energy flows from the higher average energy system to the lower average energy system to make the energy of the combined system more uniformly distributed – *i.e.*, less ordered. So the disorder of the system has increased - and we say the entropy has increased. But the process of increasing the disorder has removed the possibility that the energy that was transferred from A to B can be used for any other purpose - for example, work cannot be extracted from the energy by operating a heat engine between the two reservoirs of different temperatures. So although energy was conserved in the transfer (the first law), the entropy of the universe has increased in becoming more disordered (the second law) and consequently the availability of energy for doing work has decreased.

The second law of thermodynamics can be summarized in many different statements - and has been by many thermodynamicists in the last century and a half. All of the statements are an attempt to put a reason to the things all of us have observed - that when two objects are in thermal contact, heat always goes from the warmer to the cooler and never the other way. This universal result can be stated in many different ways and probably has as many explanations as there are physicists trying to explain it - and is still the subject of serious consideration by some of the best theorists. The difficulty does not lie in what the second law says - or how it should be interpreted - but rather in what the fundamental, underlying reason is for why nature behaves in that way.

> *Every process in nature converts some energy to a form that is irretrievable. Hence there can be no such thing as a perpetual motion machine – a mechanical device that runs forever.*
>
> *Any process either increases the entropy of the universe - or leaves it unchanged. Entropy is constant only in reversible processes which occur in equilibrium. All natural processes are irreversible.*
>
> *All natural processes tend toward increasing disorder. And although energy is conserved, its availability is decreased.*
>
> *Nature proceeds from the simple to the complex, from the orderly to the disorderly, from low entropy to high entropy.*
>
> *The entropy of a system is proportional to the logarithm of the probability of that particular configuration of the system occuring. The more highly ordered the configuration of a system, the less likely it is to occur naturally - hence the lower its entropy.*

In the language of entropy, the Carnot cycle still represents the theoretical maximum efficiency in any cyclic process. That is, maximum efficiency would occur if the entropy of the universe did not increase as a result of the cyclic process, hence there would be no loss of availability of doing work. But entropy can only remain constant in a reversible isothermal process. So, again, any heat transfer would have to occur isothermally. Therefore the most efficient cyclic process possible involves only reversible isothermal steps and steps in which no heat is transferred – *i.e.*, adiabatic. And even in this idealized reversible process in which the entropy of the universe was left unchanged, the efficiency of conversion of heat to work is limited by the two temperatures involved in the isothermal steps.

Based on the ideas of Lord Kelvin, Joule, Boltzmann, Carnot, and Clausius, the first and second laws of thermodynamics can now be restated in two profound sentences. And these two fundamental principles of nature describe how the universe works – and put *limits* to what is possible.

The total energy of the universe is a constant.
The total entropy of the universe always increases.

Physics is to the intellect what music is to the soul.

Is the universe a great mechanism, a great computation, a great symmetry, a great accident or a great thought?

John Barrow, Mathematician

Our planet is a lonely speck in the great enveloping cosmic dark.... There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we've ever known.

Carl Sagan

Sometimes I think we are alone. Sometimes I think we are not. In either case, the thought is staggering.

Buckminster Fuller

To have arrived on this Earth as the product of a biological accident, only to depart through human arrogance, would be the ultimate irony.

Richard Leakey

Why is music such a pleasure?

Nicholas Humphrey, Psychologist