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The Impact of Solid State Science in Our Society

Juana Acrivos
San José State University

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by Juana Vivó Acrivos
Department of Chemistry

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Esteemed madame president, colleagues and friends,* thank you very much indeed for bestowing on me the privilege of this address. The purpose of my remarks is simply dedicated to give an insight into the life of scientists in our society. It is possible that some of you will disagree with our philosophy. We only ask you to understand that tolerance is very necessary for our work.

The 125th Anniversary of San Jose State University as an institution of higher learning (the oldest in the State) occurs when the advances of our society depend like no other time before on the education provided at all levels for our people. The task for an educator today is substantial. First, we must transmit a given body of knowledge to our students, but that is not all. We must recognize and encourage their creative skills and together with them advance this body of knowledge. Above all, we must teach our students their responsibilities to this society which has made their education possible. The job is formidable and no one can do it to perfection. But, we all try and are fortunate to be able to learn from examples set by predecessors in our chosen field. My remarks, then, are dedicated to showing how the founders of the movement known as solid state science dispensed their obligations to society. The stage for this movement is set first in central Europe at the beginning of the 20th century, and we shall follow it as it moves westward after the second world war, reaching an industrial explosion in the Santa Clara Valley during the decade of the seventies.

The decade of the eighties appears uncertain at this time, and the solution to our woes will depend very much upon the ability of our society to respond to the economic reversals we are experiencing. Today, I shall try to draw your attention to how opportunities were seized and sometimes missed in the process of developing an abstract concept, then testing it to verify its premises and finally using it for the benefit of our society. Thus my reflections on the solid state sciences are divided into three parts:

1. Early scientific development and the human involvement,
2. The excitement of discovery at the University, and finally
3. How this development has changed our valley.

I. Early Scientific Development

Historians have taught us that human behavior throughout the ages has been influenced by the ability of its people to handle their environment for both artistic and useful purposes. Our times are not essentially different from those that preceded us, except in one respect. Both the industrial and artistic innovations of the 20th century depend to an exceptional extent on abstract ideas conceived in academic halls. These are scientific concepts.

The story begins with a professor at the University of Giessen, P. Drude. In the year 1900 he proposed the following abstract concept:

> "The electrons discovered by the Cavendish Professor J. J. Thompson in rarefied gas experiments three years earlier are responsible for the conduction of electricity in metals."

His mathematical premises were improved by another professor, H. A. Lorentz, at Leyden four years later. Drude and Lorentz are considered to be the founders of solid state sciences.

As soon as the new concepts were stated and properly understood by others, they were tested for truth and consistency. There were many cases in which the theory triumphed, but the experiments which showed inconsistencies in the theory were much more interesting. Among these were the discovery of the total loss of electrical resistance in some metals like mercury and lead at liquid helium temperatures by another professor at Leyden, H. K. Onnes, in 1911. This phenomenon is called superconductivity, and it was understood completely only in 1956. Even today my students and I continue to investigate the phenomena which give rise to superconductivity in order to find new materials which can be used to lower the cost of living at the level (especially of power consumption) to which our society has become accustomed.

We will come back to this subject in the second part of my reflections, but let us go back to 1911. The conflicts of experimental results with the Drude—Lorentz theory persisted until another abstract concept was proposed in 1925 by Professor W. Pauli. This is the Exclusion Principle which slightly simplifed states that:

> "Two electrons in the same atom cannot be described at the same time by the same set of quantum numbers."

Thus, mathematically stating the fact that two material corpuscles cannot occupy the same point in space at the same time. The application of the Exclusion Principle to understand the motion of electrons in condensed matter was attempted by many notable professors (W. Pauli in Germany, E. Fermi in Italy, and R. H. Fowler and P. A. M. Dirac in England), but success was achieved by a professor at Munich, A. Sommerfeld, in 1927. He used the Drude-Lorentz Theory in its entirety, but the electrons in their motion were made to obey the new quantum statistics developed earlier by Fermi and Dirac. Then, in 1928, a grauate student in Leipzig, F. Bloch, enters the stage to complete the theory of electrons moving in periodic structures. His main contribution was to visualize the effect that periodic structures have on the motion of electrons in metals and state it mathematically. By 1928, the foundations of the theory were completely developed. The Bloch theory which describes the motion of electrons in metals is consistent with another abstract concept postulated in 1925 by Prince L. V. de Broglie:

> "A moving material corpuscle of atomic dimensions is associated with a wave and can therefore cause interference in the same manner as light."

Thus, the development of the theory of metals, from Drude's classical picture to Bloch's quantum mechanical treatment, reflects the advances in physical science during the first three decades of this century.

The semiconductor theory, so necessary for the developments in our valley, was more complicated, and, therefore, success came much more slowly than for the theory of metals. In the beginning there were many human and fate reversals that had to be overcome. The story starts with Professor R. W. Pohl who was awarded a chair in Gottingen in 1916 but could only take it up in 1919. He had finished his graduate education in 1906 and had worked towards understanding the spectra of transparent crystals such as the common table salt. The reversals came about because of an intervening war and because his work could not be explained by the popular atomic theory of N. Bohr which occupied the attention of theoreticians during the first part of this century. As a result, his German colleagues did not want to hear about Pohl's work. The first theoreticians to recognize the relevance of Pohl's work during the 1930s was one of my mentors, Professor N. F. Mott (from England), one of his associates, J. W. Mitchel (from New Zealand) whose work on the formation of latent images on silver salts by light later advanced photography, and one of the first fully trained U. S. scientists, F. Seitz. They were real pioneers in the sense that they recognized the impact of Pohl's work on society.

Early in 1933, Pohl used the same premises as Drude to propose a very similar idea, but this time it was not an abstract concept. He said in a public lecture that:

> "Semiconductor crystals can be used to replace the vacuum tubes in radios."

Five years later Bardeen, Shockley, and Brattain at Bell Labs demonstrated that this was possible and later received a Nobel Prize for their efforts. Thus, the Americans and big industry in the U. S. enter into the picture. However, at the same time of his discoveries, neither government nor industry were interested in Pohl's work. He discovered and named species responsible for color in transparent crystals called the F-centers.

After the second world war, the stage and some of the protagonists were different, but the ideas conceived first in central Europe moved westward to involve others in the excitement of discovery. But before proceding with historical facts, I wish to try to present my reflections on the excitement of discovery at the University, at the undergraduate level.

II. Excitement of Discovery

The task of an educator is not limited to transmitting a body of knowledge to a generation of students. One must find ways to recognize their creative skills and build upon them. In order to excite their imagination and help them visualize difficult concepts, we use all sorts of analogies. My attempt to attract high school students to study the solid state sciences (a birthday present to the University this anniversary year) is called: "Ode to Football Fans Who Want to Learn About Metals." In this slide-sound presentation made by our Audio Visual Department,* we draw an analogy between the motion of an electron in a metal and how it is intercepted by the massive ions leading to power losses with the motion of a football intercepted by the heavy players in a field. Here with a play of words I define the parameters which control the transport of power from a source to the home to sustain our society. The presentation is light entertainment where I bring the students to a 1956 level of knowledge about metals using their joy and associations with a football game.

Ode to Football Fans Who Want to Learn About Metals by a Solid Prof

A metal is a solid with electrons that form a shield.
The electron, like the football, is first kicked in a field.
It is passed and intercepted only by opposite ions wearing a shield.

The football is passed a distance on a macho path called . .L. .
It is intercepted by a moving host.
A cheerleader named . .Kay. . cries to a boy . .el. .
Eventually the football reaches the post.

The goal of metallic conductivity is to send electrons in a line
To provide us with light.
We must increase the frequency of electron home touchdowns —
Yours and Mine.

At San Jose State, we study the solid state.
We measure the electronic specific conductivity as
The goals per unit time, area and field, called . .K. .
And . .K. . depends on the electron free path . .L. .

The electron free path like that for a football, depends on the host's mobility
Today we lose one out of three electrons on transmission causes,

[redacted]

There has to be a way to reduce our power losses.
We can freeze the lines and improve the conductivity.

Experiments show that our light is poor when the lines are hot,
But if we freeze the lines with liquid nitrogen,
The home light is bright.
This means that if the ions don't move the free path . .L. .
increases, and so does . .K. .

For copper lines at room temperature . .K. . measures
One electron arrival every millionth of a millionth of a
millionth of a second,
But it increases tenfold at liquid nitrogen temperatures.

We can take pictures with electrons.
The electrons behave as light, produce diffraction.
We see bright spots when there is constructive interference.
The spots tell us how the heavy ions are situated.
If the spots are bright, they move very little.
If the spots are blurred, the ions can be anywhere.

We produce these changes with chemicals sandwiched between layers of metals.
Among these we look for metals with no interceptors.
They care called superconductors.
Yet, they have electrons and ions in the field.
But the game is played by two electrons coupled within the shield.

The first electron of the pair attracts the opposite ions.
The second electron is free to go for the post.
. .L. . has no bounds,
An electron reaches the home goal at no cost.
It is the football liberty pass.

But we do not use superconductors for transmission lines NOW
We need to find more of them.
For a happy ending to our energy woes,
Won't you come join us at SJSU to find out HOW!

The exitement of discovery at the university is contagious and great fun! In testing premises and theories, scientists have to be tolerant and persistent, but the joy of discovery sustains us throughout all the setbacks which we necessarily encounter and which is seldom written about in history books. An example of opportunities missed during the 1930's in Cambridge is the students' refusal to study semiconductor cause properties because after all everything was known and written in the *Handbuch der Physik*. The *Handbuch der Physik* classified solids into three classes: metals, semimetals, and insulators according to their ability to conduct electricity. For metals, the specific conductivity measures one electron arrival per attosecond in the Drude electrostatic units and this increases as the temperature decreases. For semiconductors, the conductivity is several orders of magnitude smaller than that for metals (one per picosecond), and their conductivity changes with temperature in the opposite direction as that for metals, increasing as the temperature increases. Insulators are transparent to visible light and have very low conductivities. Even in 1935 the *Handbuch der Physik* stated that semiconductors were only impure metals. This myth was dispelled only after methods for zone refining were developed after the second world war. But in 1935 the students at the Cavendish quoted the *Handbuch* as if it were the Bible and refused to investigate both silicon and germanium. The differences between conductors and insulators were explained by Mott and Gurney in 1940 but were put to practice in photography and in electronics only after the second world war, mostly in our valley by people who understood the theory very well.

III. Our Santa Clara Valley

The last part of my reflections is dedicated to the professionals of our valley, both at the University and in industry. Here one feels the excitement of discovery at every level and my affinity for explorers goes back to the time when I fell in love with Christopher Columbus at six years of age in the old cathedral in Habana.

The understanding of solid state phenomena has made possible industrial innovations which also favor the arts such as photography and sound reception as we have shown in Part II of our talk. It also makes our scientific work a visual pleasure! The figures reproduce beautiful electron diffraction photographs during the intercalation reaction of some solids we are investigating at present. They were taken in England with my colleague, G. Tatlock, using the technique called transmission electron diffraction which is based on the de Broglie Principle. The information contained in these photographs is formidable, and the way we investigate them reveals the entire educational process. The data was collected during 1977, after my students and I had worked for seven years on developing the principles of the reactivity of layer solids such as graphite and molybdenum disulfide. These, like flintstone, are natural materials which were known to the primitive man by their slippery texture. They have been used for drawing, writing, and as lubricants. We found that we could change their ability to transport electricity by introducing certain gas molecules between the layers, thereby changing metals to semiconductors and vice versa. This was exciting! However, the first period, 1970-1977, was spent gaining and transmitting knowledge on this new field of chemistry called intercalation. During this time, I was blessed with very creative students, and for this I am very grateful. The next period, 1978 to date, has been dedicated to finding and characterizing new materials. We proceed to learn the effects of the size and symmetry of the intercalated molecules on the spectra and transport property of layer solids. It all started in Cambridge and in a small laboratory at San Jose State. But, when it became necessary, the U. S. National Science Foundation and the North Atlantic Treaty Organization (NATO) came to our aid.* The objective of our work is to obtain unequivocal answers to the consequences of the electronic changes produced by the intercalation of gas molecules into layer solids. Eventually, we wish to make some of our work useful.

Our former students are all working in the valley. This spring one of our June 1982 Chemistry graduates has had five job offers at salaries equal to that of a midstep associate professor at SJSU. I wish the best for this generation and know that one of them will grow to be like that graduate student in Leipzig during 1928, F. Block, who came to our valley to gain a nobel laureate for Stanford. But I am also concerned that with the present economic setbacks, society will not have sufficient educators to prepare the next generation. The unanswerable dilemma is: Why must academics pay such heavy taxes to Caesar while at the same time they must produce society's most valuable product, their educated people? I do not know the answer to this question. I only hope our esteemed President does.

To end with a happy note, my remarks will focus on the social impact of one of the most successful solid state innovators of our valley, Intel. They were among the five companies trying to hire my student, but this is not the reason I chose them. I am aware that other companies are similar, but the president of Intel (Dr. A. Grove) is a former student of my husband, which allows me to close the circle concerning the obligations of an educator. Not unlike other companies in the valley, Intel was founded by three outstanding Ph.D. scientists who were willing to dedicate both their financial and intellectual resources to provide jobs for the people in our valley to produce an excellent product. I want to believe that they chose our valley because of the high density of academic institutions in the area and that they are interested in our product, students. The founders of Intel decided on the mass production of complex devices as a matter of challenge, such as the silicon gate MOS technology. Whatever reversals they encountered, the three founders appear to have had both their hands and their intellect on the job, advancing with their co-workers as if the best production and management procedures must be learned at a given time. The last quotation of my reflections then is a statement of fact by Intel founder, Dr. R. N. Noyce:

> "The semiconductor industry has always been intensively competitive. And it has always been a brain-intensive one rather than a capital-intensive one."

Thus, I have described solid state scientists at all stages. First they proposed abstract concepts, then came the applied ones, and finally came Noyce's statement of fact. In ten years, Intel scientists successfully extended their production outside our valley into the rest of the world and remain active, hard at work and at play. "The high devotion to perfection" is an obsession to these industrialists as it is to us in academia. Their mass produced technology is their pride. As our students are our pride.

Thanks to the industry in our valley, we have had advances in microprocessors which touch our everyday life in more than 100,000 ways. These are used for communications and for scientific work but are also used to transcribe and synthesize music. The full impact of the solid state technology on society therefore is not limited to the sciences. Here the industrial giants are also fulfilling their obligations to the society that made it possible for them by making education available for the people they hire.

Thus, the valley named by the missionaries after Saint Francis' most precious saint has gone industrial from the early mercury mines or Almaden to a semiconductor-brain-intensive industry. May their source of educated people never run out.

Juana Vivó Acrivos
San Jose State University
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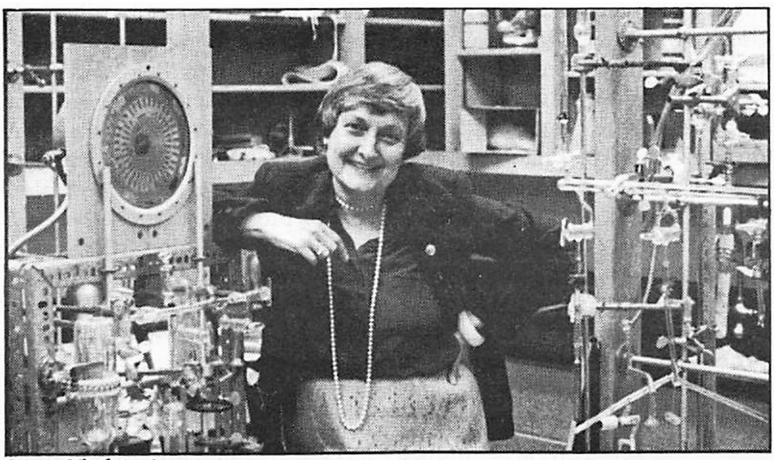

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