

# THE BRIDGE

The Magazine of IEEE-Eta Kappa Nu

## Celebrating Engineering Accomplishments

Bridges I Have Crossed ♦

Bistatic Radar ♦

Designing the First Microprocessor ♦

An Early History of the Internet ♦

November 2013 Vol. 109 / No. 3





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As an honor society, IEEE-Eta Kappa Nu has plenty of opportunities designed to promote and encourage outstanding students, educators and members.

Visit [www.hkn.org/awards](http://www.hkn.org/awards) to view the awards programs, awards committees, list of past winners, nomination criteria and deadlines.

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ISSN-0006-0809 Vol. 109 / No. 3

# THE BRIDGE

The Magazine of IEEE-Eta Kappa Nu

## November 2013 Features

8

### Bridges I Have Crossed

By Thomas B. Greenslade, Jr.

*A look at the Wheatstone bridge and other devices...*

16

### Bistatic Radar

By Hugh Griffiths

*Looking Back...Looking Forward*

24

### Designing the First Microprocessor

By Marcian E. Hoff

*How rethinking a customer's specifications led to innovation...*

40

### An Early History of the Internet

By Leonard Kleinrock

*Observations from the origins and development of the ARPANET*

## Departments

### Members and Chapters

22 Chapter News

32 Member Profiles

### Feature Extensions

36 IEEE Milestones

37 Eminent Members

### IEEE-HKN Updates

15 History Spotlight

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## LETTER FROM THE PRESIDENT

### **JOHN A. ORR** *Alpha Chapter*

Dear IEEE-Eta Kappa Nu Members and Friends:

To those of you who are in the academic community, whether that is as students, faculty, or staff, I hope you are enjoying a productive and stimulating academic year. For me, the rhythm of the academic seasons has been a valuable aspect of being a faculty member. No matter what time of year, the start of a new term literally brings a new beginning. Each commencement season demonstrates the reason that I am in this profession, congratulating students, meeting parents, and helping to launch a new group of graduates into what I hope are productive and fulfilling lives. This brings me to IEEE-HKN! For students, our honor society helps them see the importance of their academic pursuits, and recognizes excellence in those pursuits. IEEE-HKN alums, particularly recent alums, can play a very valuable role in their chapters. IEEE-HKN headquarters, under Nancy Ostin's leadership, is working to make it easier for Chapters and individual IEEE-HKN alums to make those connections. In Nancy's letter, you will see the results to date of our strategic planning work. This plots a great future for IEEE-HKN.

Over the next few months, you will see new services and activities and you will have the opportunity to let us know how IEEE-HKN can serve you better. Please take advantage of these initiatives.

In closing, I want to encourage you to nominate deserving individuals for our awards for outstanding teaching, outstanding student performance, outstanding performance as a young engineer, and outstanding technical achievements. These awards form an important part of IEEE-HKN's fundamental mission of recognizing excellence, and we need you to identify exemplars across the profession. The process is simple, and begins here: <http://hkn.org/awards/index.asp>.

My very best wishes,

Phone + 1 508-831-5273

Email: [j.orr@ieee.org](mailto:j.orr@ieee.org)

#### **IEEE-HKN PLEDGE**

"I sincerely promise that I will live up to ... in word and in deed ... the principles for which IEEE-Eta Kappa Nu stands ... To the members now and to those to come after ... I bind myself to the faithful observance of these promises ... I give my solemn word of honor."



## LETTER FROM THE EDITOR-IN-CHIEF



**DR. STEVE E. WATKINS**

**Gamma Theta Chapter**

Dear IEEE-Eta Kappa Nu Members and Friends:

This last issue of THE BRIDGE magazine for 2013 has a theme of “Celebrating Engineering Accomplishments.” We have features that highlight the history of Wheatstone bridge instrumentation, radar, microprocessors, and the internet. An understanding of how these technologies were developed will give a better appreciation for these technological advances and engineering innovation in general.

Many other engineering accomplishments have equally interesting histories. The IEEE Global History Network (<http://www.ieeehkn.org/>) is an online resource of the IEEE History Center. The Center has a mission to provide a record of important engineering developments, distinguished engineers and scientists, and activities of the society itself. I encourage you to take advantage of the rich content that is provided here. I especially enjoy the Milestone program in which key events and locations are identified. For instance, the IEEE Milestone Birthplace of the Internet, i.e. the first internet transmission in 1969 at UCLA, is described later in the issue.



IEEE, IEEE-USA, and IEEE-HKN have many opportunities for student involvement and education in 2014. IEEE-USA will be the host for Engineers’ Week; IEEE Sections Congress will be held outside North America in Amsterdam, Netherlands; and IEEE-HKN has a Student Leadership Conference at Iowa State University in Ames, IA. THE BRIDGE magazine will have the following themes:

- March 2014 “Lasers, Optics, and Photonics,”
- June 2014 “Engineers’ Involvement in Society”
- November 2014 “Spotlight on Student Undergraduate Research”

As always, we invite your comments and submissions. In particular, send us a photograph of any displays and monuments that your chapter has for promoting IEEE-HKN at [info@hkn.org](mailto:info@hkn.org).

Best regards,

*Steve E. Watkins*

Phone + 1 573-341-6321

Email: [steve.e.watkins@ieee.org](mailto:steve.e.watkins@ieee.org)

### Did you Know?

The Greek letters HKN were chosen from the 1st, 4th, and last letter of the Greek word for amber or electron:



**ΗΛΕΚΤΡΟΝ**

## LETTER FROM THE DIRECTOR



**NANCY M. OSTIN, CAE**

Dear IEEE-Eta Kappa Nu Members and Friends,

As I celebrate my first year at IEEE-HKN, I would like to extend my gratitude to the many volunteers and members who have been instrumental in teaching me about IEEE-HKN by sharing their vision for the future of the organization and working with me to better understand the needs of IEEE-HKN and all we serve, including our members, Faculty Advisors, and universities.

My goals for the first year were: to improve the level of service to our membership; listen to students and Faculty Advisors in order to better understand what the needs are at the local level; design better methods within the headquarters office to provide assistance to the organization; strengthen existing programs and services; and bring you the member experience you deserve from IEEE-HKN. I am very positive about the work that has been done, the feedback we have received, and our potential for the future.

I would like to take this opportunity to share with you IEEE-HKN's Envisioned Future. The Strategic Planning Committee of the Board of Governors, under the direction of Past President Steve Goodnick, has been exploring the current state of IEEE-HKN. The Committee has considered the changing environment in education and the needs of members to put forth a plan and strategy to grow, strengthen, and assure the validity of IEEE-HKN for years to come. The IEEE-HKN Envisioned Future includes.

### **Core Purpose:**

To realize IEEE-HKN's potential as a recognized leader in encouraging excellence in scholarship, technical achievement, leadership, and service in the IEEE's technical fields of interest.

### **Our five-year strategic goals:**

- Realize continuous membership growth
- Establish financial security
- Expand signature activities, such as the annual Student Leadership Conference
- Grow alumni participation
- Integrate IEEE-HKN fully into IEEE
- Establish corporate partnerships

I invite each of you to share your thoughts on the future of IEEE-HKN, please email me at [n.ostin@ieee.org](mailto:n.ostin@ieee.org), or call +1.732.465.6611. Thank you for an incredible first year, and for all that is to come.

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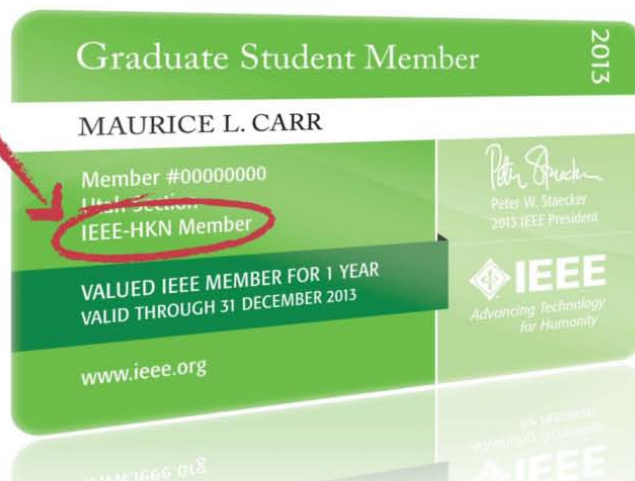
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## IEEE-HKN Global Network

The new IEEE-HKN Global Network is a platform for all HKN and IEEE-HKN to meet, share, learn and stay in touch. The platform (<http://bit.ly/15LTaIC>) includes:

- Chapter Officers Forum
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- Conferences (permanent and new content all the time)
- Resource Center (to share and find resources)
- Alumni Reconnection Center
- Chapter Websites
- Shared Google Calendar



The IEEE-HKN Global Network was created to make it easier for Chapters, members and Headquarters to share resources with each other. Under this Global Network exists a place to participate in workshops, share best practices and ask questions about IEEE-HKN. With the IEEE-HKN Global Network, we can all work better together.

# Bridges I Have Crossed



## A look at the Wheatstone bridge and other devices...

By Thomas B. Greenslade, Jr.

The Wheatstone bridge was still in use when I received my Ph.D. in physics in the early 1960s. I researched the thermal conductivity of superconducting thin films at Rutgers University in New Jersey using standard 1/10 W Allen-Bradley carbon resistors as thermometers, and measured their resistance with a Wheatstone bridge built from top-of-the line components. Since then, I have moved from experimental physics to the study of apparatus used in physics in the late 19th and early 20th centuries. During this time, the construction of high-precision electrical measurement equipment was raised to an art in the United States by companies such as Leeds & Northrup (L&N) of Philadelphia and General Radio Co. of Cambridge, Massachusetts. In this paper I will discuss some favorite pieces of apparatus in my own collection based on bridge circuits.

### Christie's Bridge

Most of us attribute the basic diamond-shaped arrangement of four passive elements with a detector across one diagonal and a source of EMF across the other to Charles Wheatstone (1802-75) (Figure 1). However, Wheatstone gave a footnote in the published version of his Bakerian Lecture in 1843



Figure 1. 1903 L&N Wheatstone Reversible Meter Bridge

in which he describes methods for measuring resistance. He noted that "Mr. (Samuel Hunter) Christie, in his 'Experimental determination of the laws of magneto-electric induction' printed in the Philosophical Transactions for 1833, has determined a differential arrangement of which the principle is the same as that on which the instruments described in this section have been devised. To Mr. Christie must, therefore, be attributed the first idea of this useful and accurate method of measuring resistances" [1].

Samuel Hunter Christie (1784-1865) was the father of William Christie, the Astronomer Royal from 1881 to 1922. When I read Samuel Christie's paper from his Bakerian Lecture in 1833, it was rather hard going as it had to be



translated into modern usage. Christie investigated what we today would call induced EMFs and showed that they had the same effect as thermal EMFs and voltaic EMFs. He showed that the “conducting power [i.e. the inverse of the resistance] of wires varies as the squares of the diameters directly and as their lengths inversely” [2].

In the section of his paper in which he endeavored to “ascertain the law of the intensity [current] as depending on the length of the connecting wire,” Christie set up a diamond shaped circuit driven at two opposite corners by an induced EMF. This was produced by a coil of wire falling past the poles of the huge permanent magnet at the Royal Institution. The detector, connected across the other diagonal of the diamond, was a galvanometer. This bridge was never balanced, but the current in the galvanometer was measured as a function of the lengths of wire on the sides of the diamond.

## The Wheatstone Bridge and Other Devices

Figure 2 shows the original design for the Wheatstone Bridge circuit. The wires forming the diamond occupied a space on a board only 14in by 4in (35.6cm x 10.2cm) and were 0.05 in (1.27mm) in diameter. The source of EMF was attached between points C and Z and the

galvanometer between points b and a. The gaps were closed with jumper wires and the sliding contact point b was moved until the galvanometer read zero. Then, the jumper wires were replaced by the unknown and the rheostat, point b, stayed fixed and it was adjusted until there was no galvanometer deflection. Then, the jumper wires were replaced by the unknown and the rheostat, and point b stayed fixed. The rheostat was

adjusted until there was no galvanometer deflection. The unknown then had the same resistance as the rheostat.

Wheatstone developed the rheostat during this time period and added it to his bridge circuit [3] (Figure 3). The rheostat design was based on the observation of Georg Simon Ohm (1789-1854) that, for a wire of uniform cross section, the resistance is proportional to the length. Wheatstone wound a brass resistance wire 0.01in. diameter from one cylinder to another with the crank and the length of the wire remaining was read from a scale between the cylinders and from the dial at the end of the cylinder. The modern version of this device is the ten turn Helipot™.

Wheatstone is properly remembered for many experimental techniques and devices [4]. In 1834, he measured the speed of the electric signal in a wire by using the rotating mirror technique later used for velocity of light measurements. Three years later he and Josiah Cooke patented a widely used telegraph system, and the next year Wheatstone wrote the seminal paper on stereoscopic effects.

Those who make precision electrical measurements should read Wheatstone’s 1843 Bakerian Lecture, “An account of several new Instruments and processes for determining the Constants of a Voltaic Circuit”, given to the Royal Society of London [1]. He discussed resistivity and methods for systematically measuring resistance using Ohm’s Law.

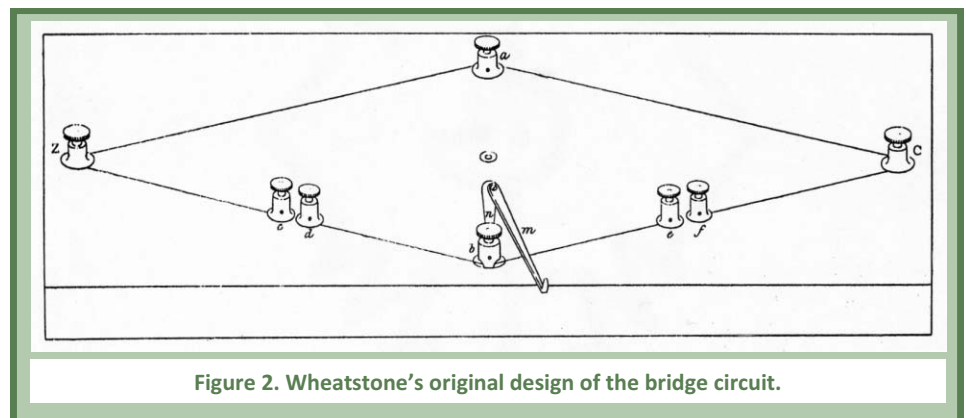


Figure 2. Wheatstone’s original design of the bridge circuit.



Figure 3. Wheatstone’s 1843 Rheostat by J. White of Glasgow in the

## Leeds & Northrup Wheatstone Bridges

Leeds & Northrup was formed in 1903 when Edwin Northrup joined forces with Morris E. Leeds to produce precision instruments used mostly for direct current measurements. The company's products can immediately be identified by their massive switches, thick Bakelite top plates and beautifully-crafted wooden bases. Opening an instrument reveals thick, smooth solder joints.

The L&N Wheatstone Reversible Meter Bridge in Figure 1 is the bridge design closest to Wheatstone's original circuit that I have. The scale is engine divided and has a slow-motion vernier scale to allow the meter-long slide wire to be read to the nearest 0.0001 m. (To produce a high-quality scale, companies use a machine called a dividing engine that scribes marks on a scale one after another; thus called an engine-divided scale.) The unknown and the two resistances making up the ratio arms can be attached to the gaps in the flat copper conductors with screw connections or mercury cups. There is a reversing switch in the center that is picked up and rotated by 90° to interchange the two resistors which make up the ratio arms, and it also has mercury contacts. At that time, it cost \$115 and was out of the catalogue by 1920. Many other bridges with additional features were available.



Figure 4 shows two small bridges that stayed in the catalogue. These instruments are still viable. On the right-hand side in Figure 4 is the L&N Decade Resistance Box and Wheatstone Bridge from 1907 that cost \$60. An unusual feature is the arrangement of the two plugs for the two resistors making up the ratio arms. By inserting them properly, ratios of 1 to 10,000 up to 10,000 to 1 may be obtained, going in steps of ten. Each resistance coil in the ratio arms is good to 0.05%. The instrument can also be used to

measure high-quality resistance; its coils were adjusted to 0.1% accuracy.

On the left-hand side of Figure 4 is the classic L&N Post-Office Pattern Wheatstone Bridge, later designated for student use. The design, by the British Post Office Department, was in the very first L&N catalogue from 1903 and the instrument in the catalogue still bears the name of Morris E. Leeds, the parent company. The goal was to produce a quality bridge at a low price (\$40) by using standard parts made in great quantities. The ratio arms are non-reversible and are adjusted to 0.1% while the resistors in the rheostat section are good to 0.2%. To aid the student, the circuit was engraved on the top plate and there are tap switches for the galvanometer and the power supply circuits. This design was copied or sold by other American apparatus makers (Ziegler, Knott, Welch, Chicago Apparatus and Cenco) into the second half of the 20th century.

In the latter years of the 19th century, self-contained, portable Wheatstone bridges were developed, and L&N offered ones with plug-type resistors as early as 1907. The Type S Portable Testing set from 1917 in Figure 5 had the new style, switch-selected resistance decades that L&N patented in 1914, and it cost about \$90, and this one is still usable. The galvanometer could be clamped down to prevent damage when the instrument was "transported over rough roads in small automobiles" [5]. Complete operating instructions are printed inside the top of the hinged lid of the oak case suggesting that the instrument may





have been largely used to locate faults in cables and lines in the field. As Wheatstone bridges, I found them sensitive enough to use for a number of years in a first year physics experiment on the temperature coefficient of resistance of #40 copper wire. The coils and ratio arms have the same specifications as the Post Office Bridge.

An aside: The logo of the Cambridge Instrument Company displays a wonderful scientific pun: a diamond (representing the bridge) with the representation of a cam inside it.

## The Kelvin Bridge

It is now time to look at an offshoot of Wheatstone's original design. One problem with the original form of Wheatstone's bridge was its inability to measure very low resistances. The resistance of the wires connecting the bridge to the sample could be comparable to the sample, leading to errors. Lord Kelvin (1824-1907) devised a modification that allowed measurement of the resistance of a few tens of centimeters of thick copper rod. Common to all Kelvin bridges is a large diameter, low resistance rod that serves as a resistance standard.

A Kelvin bridge found in most American electrical measurements laboratories is the L&N Student Kelvin Bridge introduced about 1920. The instrument in the foreground of Figure 6 is an example. This sold for \$70.00 in 1927. The bridge can measure resistances from  $0.00001 \Omega$  to  $0.1 \Omega$ . The sample is held between the massive clamps at the rear and the standard resistance is a brass rod of uniform cross section at the front of the instrument. A sliding contact to this rod allows the bridge to be balanced. The standard resistance bar has a uniformity of 1% and the ratio arms are good to 0.2%. This is a fine instrument and can still occasionally be found, unused, in storage rooms of American physics departments.

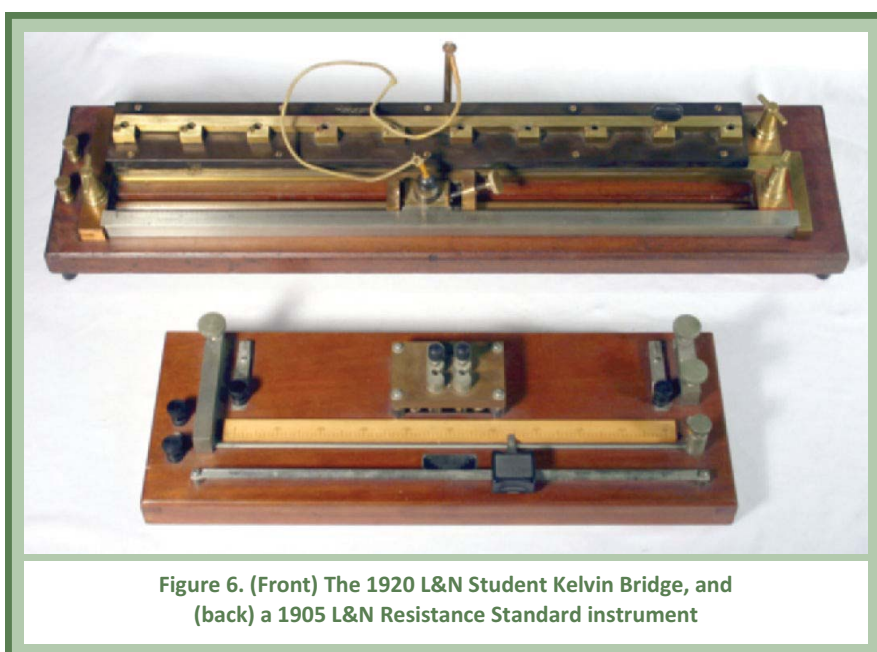


Figure 6. (Front) The 1920 L&N Student Kelvin Bridge, and (back) a 1905 L&N Resistance Standard instrument

For research purposes, L&N offered modular Kelvin bridges. The heart of the bridge was the free-standing, adjustable standard low resistance to which a box was added containing ten ratio coils and a set of stout copper current and potential clamps that were applied to the sample. A galvanometer completed the ensemble. The ratio coil box cost \$100 and had coils good to 0.01%. It looks like a typical plug-type resistance box. It was not usually preserved.

The standard resistance apparatus at the back of Figure 6 was listed in the 1906 L&N catalogue for \$200. The basic construction can easily be seen in this instrument. The electrical connections are made to massive blocks of copper and the standard resistance rod is made of manganin. This copper-manganese-nickel alloy has a low temperature coefficient of resistance, and the relatively high thermal conductance of the rod keeps both ends at the same temperature, almost completely eliminating thermal EMFs. The contact point can be moved manually to a point on the bar and then is driven by a slow motion screw connected to a vernier scale as the balance point is reached. The bar has a resistance of  $0.01 \Omega$  and can be read to one part in a thousand. Coarser adjustments are made with a series of ten precision resistances, each  $0.01 \Omega$ , contained in the body of the instrument and selected with the plug.

## ac Bridges

The alternating current bridge has long since been removed from the undergraduate physics curriculum but in the second half of the 1950s, it was a key element of the Electricity and Magnetism course. We became expert at complex impedances:  $Z = j\omega L$  for an inductance of value  $L$  with a sinusoidal signal of angular frequency  $\omega$ , and  $Z = -j/\omega C$  for a capacitor of value  $C$  under the same circumstances.

A typical alternating current bridge had combinations of resistances, capacitances and inductances in the four arms and the conditions for balance were obtained by putting the appropriate impedances in the equation for the direct current Wheatstone bridge, now written as  $Z_1 Z_4 = Z_2 Z_3$ . There were always two balance conditions: one for the real part of the equation and one for the imaginary part. The source of alternating EMF was a 1000 cycle [sic] "hummer" like the Type 213 General Radio fork-driven oscillator that sold for \$34 in 1935. The detector was a pair of earphones and users adjusted two components of the bridge until blessed silence was achieved in the phones clamped to their ears.

## General Radio ac Bridges

In the 1930s, the General Radio Company of Cambridge, Massachusetts started to produce a whole range of self-contained bridge instruments for the measurement of resistance, capacitance and inductance. The "Rolls-Royce" of the series was the Type 650A Impedance bridge patented in 1928-29 (on the right in Figure 7). I suspect that very few university and industrial physics labs were without this instrument, which, in my own undergraduate days and early years of teaching, was in constant use in the electricity and magnetism laboratory. It was a heavy, solid instrument that cost \$175 in 1935 and the code word when ordering it was BEAST!



Figure 7. (R) A 1930 General Radio Co. Type 650A Impedance Bridge, and (L) a 1935 General Radio Co. Type 635A Skeleton Bridge

The 650A was completely self-contained for resistance measurements with four tall No. 6, 1.5 V dry cells contained in the compartment at the upper end to serve as a dc power supply. The galvanometer on the front panel indicated when the bridge was in balance. Binding posts were available for an external power supply and an external detector for more sensitivity to measure the larger resistances. Even without these you could measure from 1 mΩ to 1 MΩ with an uncertainty of only 1%. A dial with graduations spanned 12in (30.5cm) around the rim helped spread out the readings.

For inductance measurement a self-contained 1000 cycle hummer driven by the internal batteries supplied the alternating signal (an external source could also be used), and the detector was a pair of earphones. The two dials used to balance the ac bridge gave the inductance of the coil and the direct-current resistance. For measurements of capacity, both the capacitance and the power factor (the ratio of the impedance to the resistance) were indicated.

The General Radio Type 635A Bridge (on the left in Figure 7) is a skeleton bridge, as is suggested by the circuit diagram on the lower left side of its top plate. Inside is a pair of 4.5 V batteries, a 1000 cycle hummer and a 10,000 ohm rheostat with a logarithmic scale. The open drawer contains a series of fixed resistors and capacitors to allow the user to construct a custom bridge. Without these, the skeleton bridge cost \$65 in 1935 and with them it had the same specifications as the 650A bridge.

The General Radio Bridge in Figure 8 is a Type 216 Capacity Bridge, costing \$175 in 1935. The catalogue for that year notes that the bridge was designed to measure small capacitances in the 1μF to 10μF range at frequencies of 200 to 10,000 cycles. This required shielding; the interior of the opened instrument is lined with thick sheets of copper. Ratio arms were provided, but the ac source, the detector and a standard of capacitance were external. The 1935 General



Radio Catalogue "H" noted that "with a power source of 100 volts at a frequency of 1 kilocycle and using a two stage amplifier and telephones as a null indicator, the capacitance balance can be adjusted to one part in a million."

## Summary

You perhaps now see why these instruments based on Wheatstone's bridge are among my favorite pieces of electrical measurement apparatus. These instruments range from the most basic to ones with many enhancements. All of the bridges described and illustrated in the figures are from my collection and were donated by various American college and university physics departments. These tools offer a history of the quickly developing field of electrical measurement in the late 19th and early 20th Centuries.

## References

- [1] C. Wheatstone, "An account of several new Instruments and Processes for determining the Constants of a Voltaic Circuit", Philos. Trans. Roy. Soc. London, vol. 133, pp 303-324, 1843.
- [2] S. H. Christie, "Experimental Determination of the Laws of Magneto-electric Induction in different masses of the same Metal, and of its Intensity in different Metals", Phil. Trans. Roy. Society, vol. 123, pp 95-142, 1833.
- [3] T. B. Greenslade, Jr., "Nineteenth Century Textbook Illustrations XXIII: The Rheostat, Phys. Teach., vol. 16, pp 301-302 (1978).
- [4] B. Bowers, Sir Charles Wheatstone, Her Majesty's Stationery Office, 1975.
- [5] Leeds and Northrup Catalogue, 1927, "Apparatus for Electrical Resistance Measurements, Catalogue 40", Leeds & Northrup, Philadelphia, 1927, p 19.



Figure 8. A 1935 General Radio Co. Type 216 Capacity Bridge

## About the Author

Thomas B. Greenslade, Jr. ([greenslade@kenyon.edu](mailto:greenslade@kenyon.edu)) is a Professor Emeritus of Physics at Kenyon College in Gambier, Ohio, U.S.A. He received his A.B. in physics from Amherst College in Massachusetts in 1959 and his doctorate in experimental low temperature physics from Rutgers University in New Jersey in 1965. Since the early 1970s, he has specialized in the study of the American physics course in the 1850 to 1950 era. One result of this work is an extensive web site on historical physics teaching apparatus, located at <http://physics.kenyon.edu/EarlyApparatus/index.html>.

His museum of early apparatus is a wing on his 1857 house fronting the Kenyon campus and holds over half of the 700 items in his collection. He writes and lectures frequently on early apparatus and the history of photography (including a series of over 375 pictures in American Journal of Physics), and he served for eight years as the chair of the Committee on the History and Philosophy of Physics of the American Association of Physics Teachers.



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## IEEE-HKN HISTORY SPOTLIGHT



### THE WHEATSTONE BRIDGE



The Wheatstone bridge symbol was selected as the emblem of HKN by the founding group, even though Founder Maurice Carr preferred the Caduceus. In later years, Carr acknowledged that he had not realized that the medical profession had already selected his preferred symbol.

A Wheatstone bridge is an electrical circuit used to measure an unknown electrical resistance by balancing two legs of a bridge circuit, one leg of which includes the unknown component. Its operation is similar to the original potentiometer. It was invented by Samuel Hunter Christie in 1833 and improved and popularized by Sir Charles Wheatstone in 1843. One of the Wheatstone bridge's initial uses was for the purpose of soils analysis and comparison.



## – Call for Articles –

### November 2014 Issue Theme: Undergraduate Student Research

- Have you written an article resulting from your undergraduate research?
- Would you like to publish an article in THE BRIDGE?

The theme of one of the 2014 issues of THE BRIDGE is "Spotlight on Student Undergraduate Research." IEEE-HKN seeks to honor excellence in engineering by recognizing the leaders of today and tomorrow. This issue of THE BRIDGE will spotlight articles written by IEEE-HKN student members, and is a great way for you to be recognized.

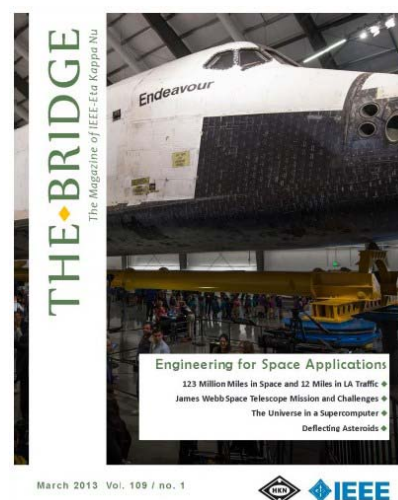
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# Bistatic Radar

## Looking Back...Looking Forward

By Hugh Griffiths

### Bistatic Radar

Radar is a technology that is over 100 years old – the first example of what we would now call a radar was actually

demonstrated and patented by a German inventor, Christian Hülsmeyer, in 1904, though it was not a commercial success. Nowadays radar is used for a wide range of purposes, including Air Traffic Control (ATC), marine navigation, geophysical monitoring of Earth resources from space, automotive safety, weather tracking, as well as numerous applications in defense and security.

Bistatic radar, in which the transmitter and receiver are at separate locations rather than being co-located, has a history almost as long as radar itself. Not surprisingly, the separation of transmitter and receiver introduces some complications, but there are some advantages as well. A quotation from the philosopher George Santayana reads: 'Those who cannot learn from history are doomed to repeat it'. And that is just as true in engineering, not only in understanding just how things were conceived and made to work, but also in understanding ideas from the past which maybe did not work, but only because the technology was not then available. So the purpose of this paper is to look at some historical developments of bistatic radar – some of which have only just come to light – and to show how they can help guide our thinking in present-day radar engineering.

### Klein Heidelberg

In the years leading up to the Second World War, developments took place in several countries to try to devise a reliable means to detect hostile aircraft. In the UK this led to the development of a radar system called Chain Home (Figure 1), which was installed all around the south and east coast (Figure 2). By many standards it was quite primitive: it used a relatively low frequency between 20 and 30 MHz, broad antenna beams and long transmit pulses [1]. But it was a crucial factor in winning the Battle of Britain. In fact the key to its success was the way in which it formed part of an air defense system, so that the information from its detections was brought to a central control room and used to guide the scarce fighter resources so that they were in the right place at the right time.

In Germany, radar was being developed too, in some ways more sophisticated and better-engineered than in the UK. Both sides were able gradually to find out about each other's radars, by intercepting and analysing the signals and in

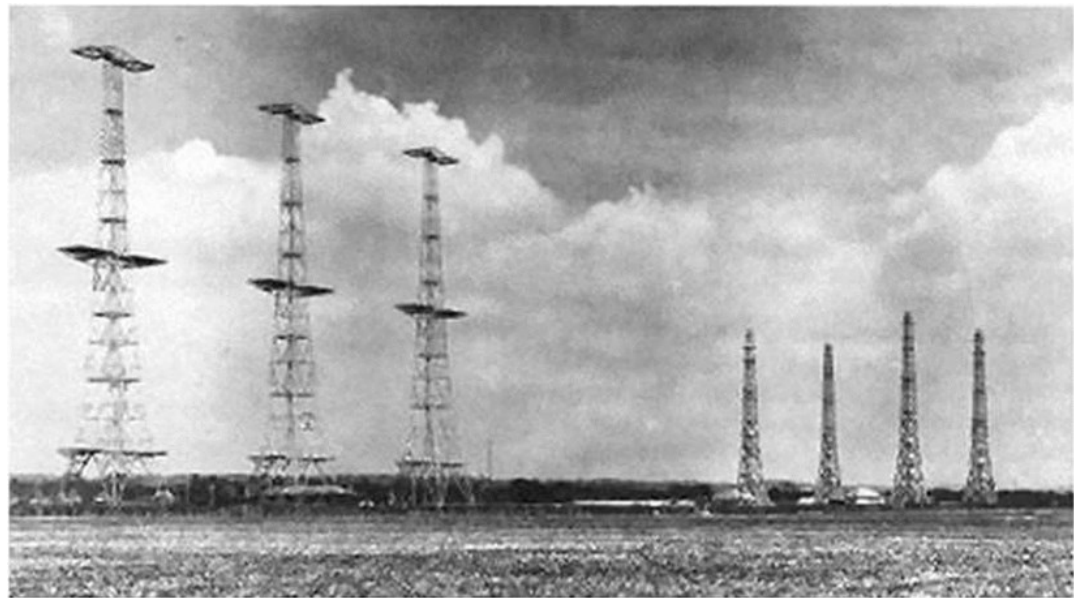




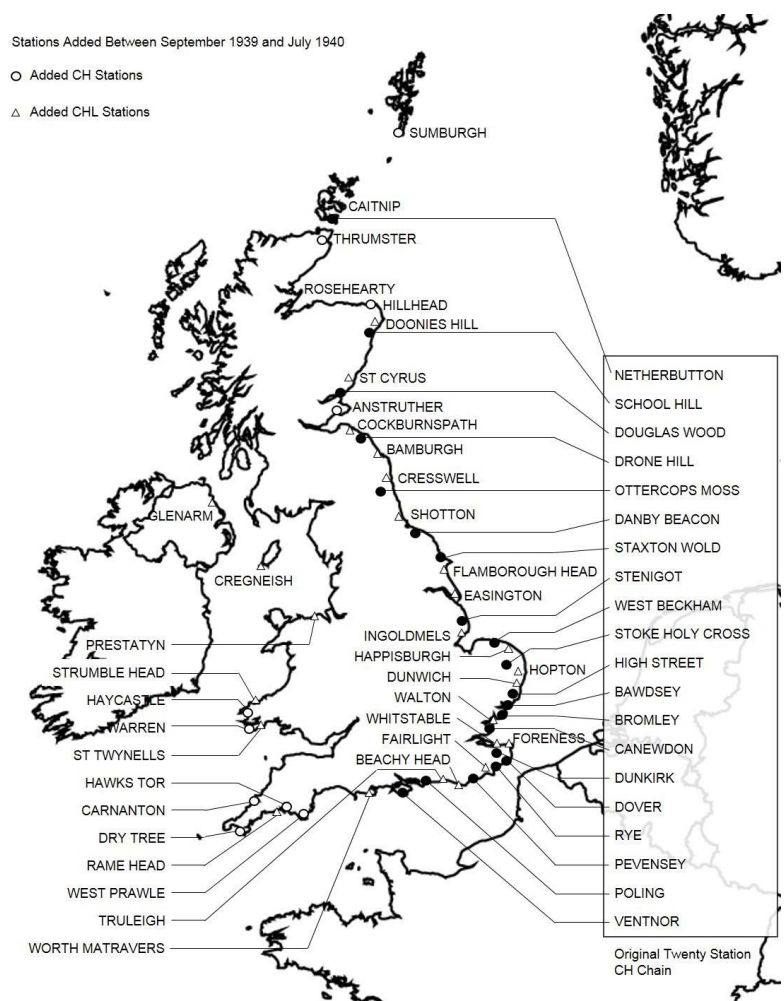
some cases from captured hardware, and quite naturally they each devised countermeasures to jam and otherwise upset the operation of their opponents' systems. This was the origin of what we now call Electronic Warfare.

German radar engineers realized that they could exploit the transmissions from the British radar, and devised a system called Klein Heidelberg which used the British Chain Home transmitters as their radar source [2]. The principle is very simple: the Klein Heidelberg receiver would receive the direct transmitted pulse from the Chain Home transmitter, then a fraction of a second later, the echo from an aircraft target. That time difference defines an ellipse, with the transmitter and receiver as the two focal points, on which the target must lie (Figure 3). A measurement of the direction of arrival of the echo, using a directional antenna (Figure 4), then provides the position of the target on the ellipse.

Of course, the big advantage of such a system was that it was undetectable, since it emitted no signal of its own. The antenna was disguised, by mounting it on the back on an existing radar. Not only that, but even if its existence was known it was impossible to jam, since to do so would also have jammed the British Chain Home radars. Six of the Klein Heidelberg radars were built (though only four reached full operational status), and in fact, the British did not find out about it till November of 1944, several months after the D-Day landings. Information from an intelligence document from the time reveals, from interrogation of a captured radar operator, that



**Figure 1. The British Chain Home radar. The transmit antennas are suspended between the towers on the left; the receive antennas are on the four wooden towers on the right, with each tower initially operating on a separate frequency.**



**Figure 2. Locations of the British Chain Home radars on the south and east coast of the United Kingdom (adapted from [1]).**

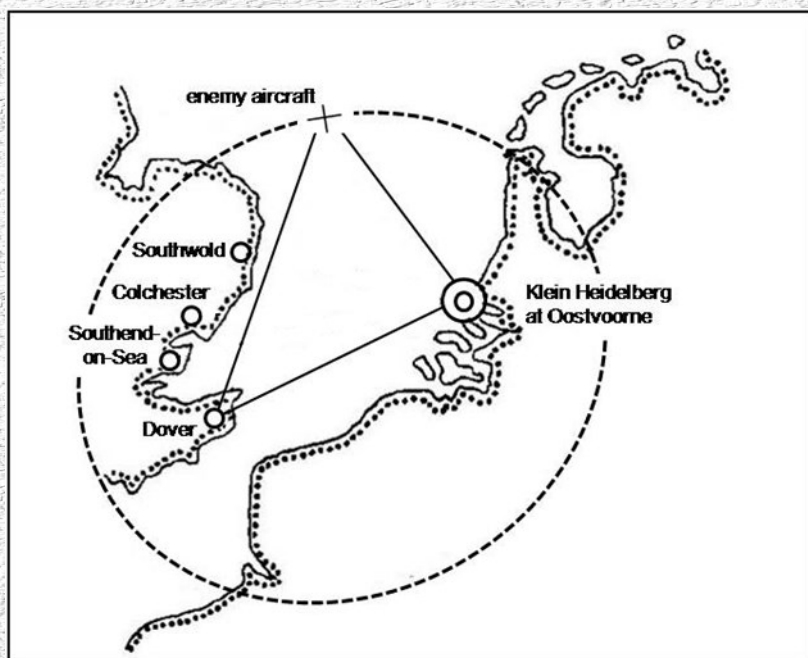


Figure 3. Geometry of the Klein Heidelberg system (adapted from [2]). The difference in delay between the direct pulse from the Chain Home transmitter and the target echo defines an ellipse with the transmitter and receiver at the two focal points. In this case the receiver is at Oostvoorne in The Netherlands and the transmitter is at Dover. Three other transmitters are shown as well.

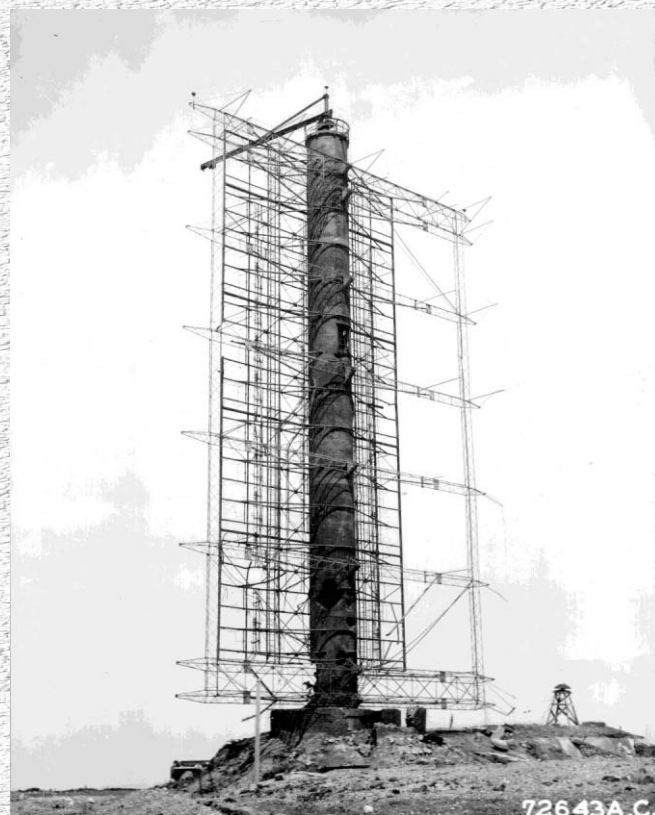


Figure 4. Klein Heidelberg antenna, mounted on the back of a Wassermann-S tower (Conseil Régional de Basse-Normandie / National Archives USA).

the maximum detection range achieved each day was of the order of 450 km – which would be regarded as impressive even today. It was an example of an idea that was decades ahead of its time.

## Radar Detection of V-2 Rocket Launches

Although not explicitly a bistatic radar, another example of innovative radar engineering from that time was the British use of radar to detect and track the launches of the German V-2 rockets towards London [3]. The V-2 was the world's first ballistic missile (Figure 5), and carried a warhead of 750 kg of explosive. Its range was about 200 km and the time of flight was only about 5 minutes. The threat was given the codename 'BIG BEN', and the document from which this information came had the rather delightful title: 'Visibility of BIG BEN to Radar' [4] and was highly classified at the time. It calculates the form of the radar signature of a V-2 rocket, using electromagnetic scattering theory. This was almost certainly the first-ever example of this kind of radar signature calculation. Of course, in those days the equations would have had to be evaluated by slide rule or mechanical calculator, and plotted by hand, which would have represented a substantial task.

It showed that the low radar frequency of the Chain Home radar was quite well suited to this task since the radar signature of the V-2 was quite broad in angular extent, which meant that it could be detected and tracked for a minute or more of its trajectory. This gave little or no time to provide a warning to Londoners, but it did allow the tracks to be traced back to find the launch points, which meant that they could subsequently be attacked. These same techniques form the basis of today's counter-battery radars.



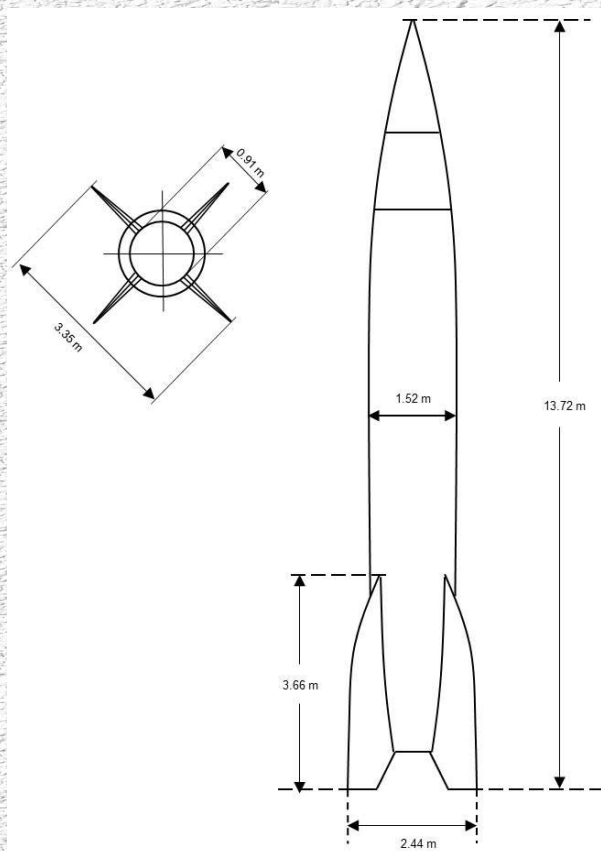


Figure 5. The V-2 rocket (adapted from [4]).

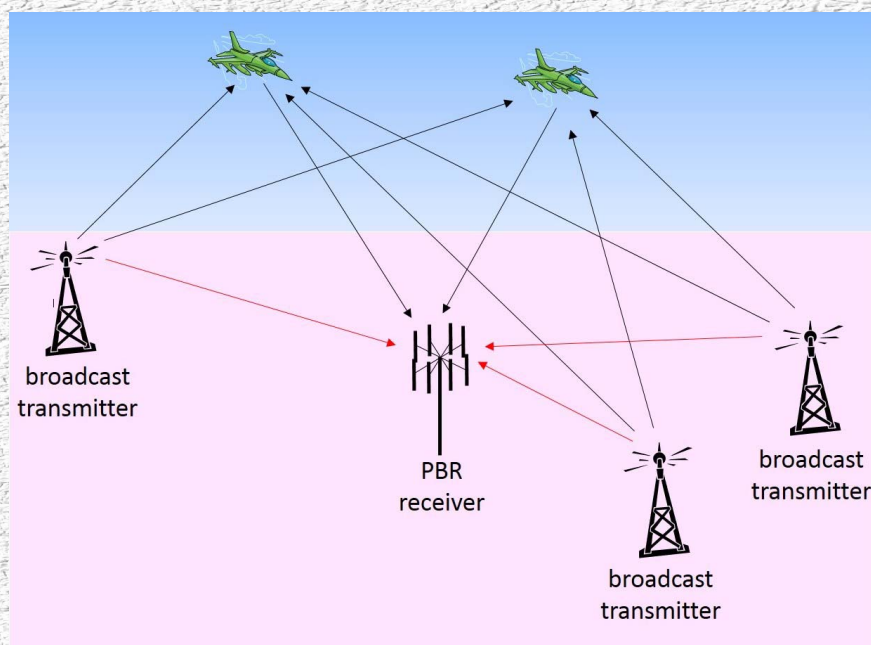


Figure 6. Principle of Passive Bistatic Radar. In this case a single PBR receiver receives direct signals from three transmitters, plus echoes of the signals from all three transmitters from two targets. From measurements of delay, angle of arrival and Doppler shift it is possible to detect and track multiple targets.

## Bistatic Radar Today

Bistatic radar is now a subject of great interest and research activity – as evidenced by the number of papers on the subject in journals and at conferences. There are several reasons for this. First of all, the same advantages that were identified with the Klein Heidelberg system: that the bistatic receiver is potentially undetectable and difficult to jam. There are also several applications to which bistatic operation is suited, especially ones where the heavy transmitter and its power supply can be on one platform and the smaller, lighter receiver on another. But as well as this, the enormous advances in digital signal processing power mean that processing that was previously very difficult can now readily be carried out in real time with standard hardware. Another factor is that geolocation and synchronisation between transmitter and receiver, which were also very difficult in the past, are now easily achieved using GPS.

## Passive Bistatic Radar

One of the most exciting current developments is Passive Bistatic Radar (PBR). Here, rather than using a dedicated radar transmitter, the system makes use of existing transmissions – such as broadcast, communications or radionavigation signals (Figure 6). Such sources tend to be high-power and sited to give wide coverage. The hardware required for an experimental system is usually simple and low-cost, and there are no licensing issues because the transmitter sources already exist. As well as this, PBR may also allow VHF and UHF frequencies to be used which are not normally available for radar purposes, and where in a defense context there may be an advantage against stealthy targets compared to conventional microwave radar frequencies. Finally, since such radars do not cause any additional spectral congestion, the technique has been described as ‘green radar’.

Early PBR experiments were based on analog TV or FM radio signals. It was soon realized that such signals are not quite ideal for radar, since their waveforms are time-varying and depend on the instantaneous modulation – so cacophonous rock music is better (for radar purposes, at least) than a person speaking! Digital modulation is much better in this respect, since the signals are more noise-like, without periodic features which would lead to ambiguities, and do not depend on the program content.

PBR systems based on TV or radio transmitters are easily capable of detecting and tracking aircraft targets at ranges of 100 km or more (Figure 7). There are several applications that are being considered. It is well known that the coverage of air traffic control and air defense radars is affected by wind farms. PBR may be used as a low-cost gap-filler to restore full coverage. Another application is as a possible substitute for air traffic control – though the need for complete coverage and reliability represents a significant challenge. At shorter range, WiFi or WiMAX transmissions can be used as the basis for detecting people within buildings, or for border or perimeter surveillance.

This potential had led several companies, including Lockheed Martin, Thales and Selex-SI, to build prototype PBR systems. The market for the next ten years is estimated to be worth \$10bn [5].

## The Intelligent, Adaptive Radar Network

Looking further into the future, there is therefore an

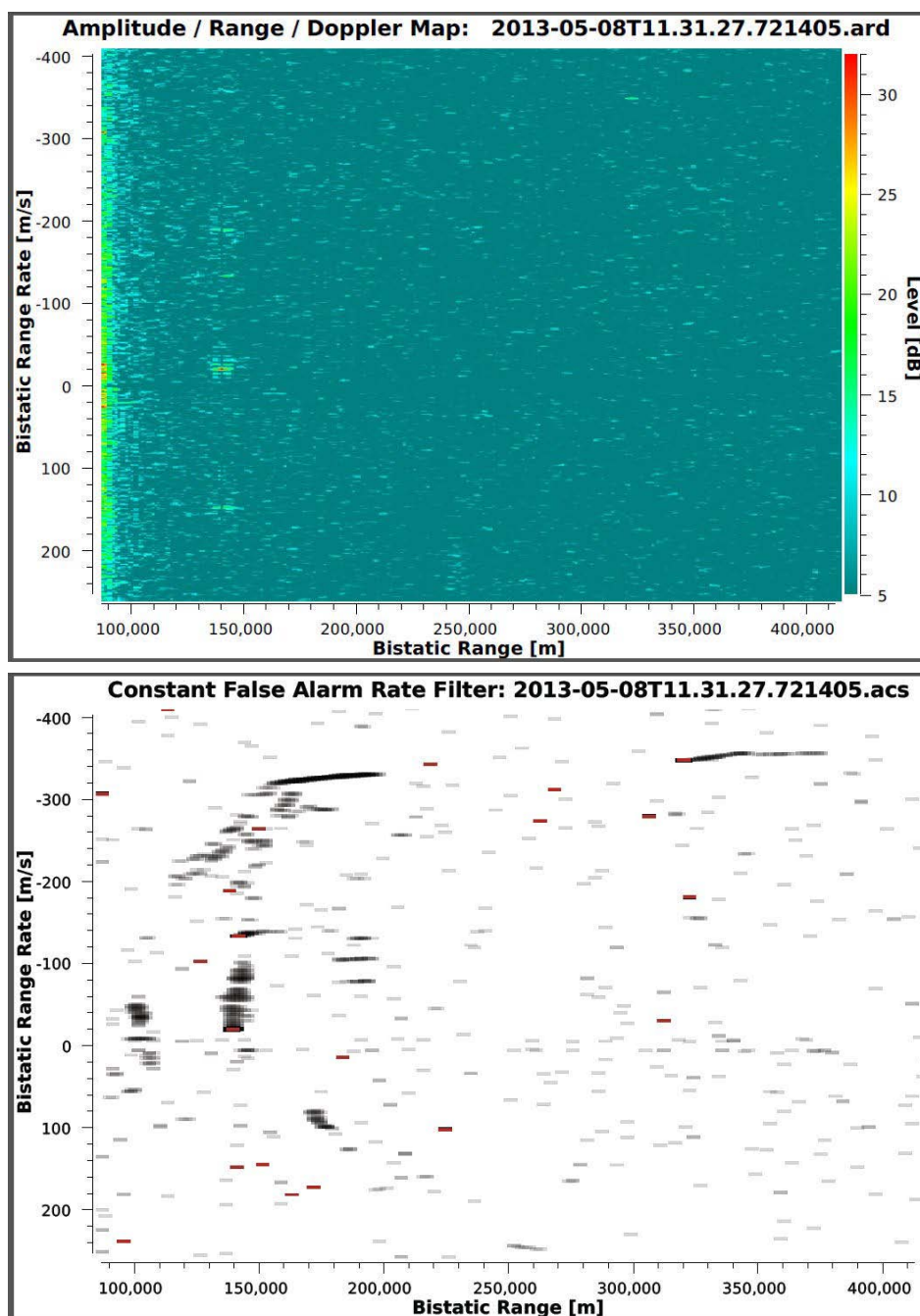


Figure 7. Passive Bistatic Radar tracking of aircraft using 98.0 MHz FM radio transmitter in Johannesburg, South Africa, presented as Range-Doppler plots (upper: raw data, lower: target tracks), and showing tracking of aircraft at bistatic ranges of well over 200 km. Image courtesy of Craig Tong and Mike Inggs, University of Cape Town.

imperative to think in new ways about sensor systems, and to devise concepts that are more flexible, of higher performance, and yet more affordable. We realize that the conventional single-platform radars that have been the norm for so many years may not actually be the best approach, and ideas have begun to emerge that point towards the 'adaptive intelligent radar network' [6]. Here,



the 'radar' consists of a set of nodes, on fixed or (preferably) moving platforms, working in an adaptive, intelligent manner. Such a scheme has a number of attractions:

- It is inherently flexible. The number and the locations of the individual platforms can be optimized to the particular tasks, and varied dynamically.
- The network has the same advantage of 'graceful degradation' of a phased array radar, in which the failure of one element of the array does not cause catastrophic failure but only degrades the overall performance slightly. In the case of the sensor network not only may the loss of one node of the network be tolerated, but also the network may be reconfigured accordingly in response.
- The platforms and the sensors carried by them need not be homogeneous. Different types of platform and sensors can be used according to the requirement.
- The locations of the platforms can give multiple perspective views of targets ('spatial diversity') to aid in target classification and identification.
- Radar sensors can be used multistatically, giving potential advantages in detecting stealthy targets, including the enhancement of target signatures that occurs in forward scatter (whilst recognising that this gives poor range and Doppler resolution). Some platforms might be receive-only and hence potentially covert, and may operate closer to the target scene.

Seen in this way the network has some similarities to a phased array radar – except that here the target is actually inside the network. In an analogous way to a multifunction phased array radar, the waveforms, beam pointing directions and hence dwell times and update rates for a particular target can be varied dynamically according to the behaviour of the targets within the scene.

All of this represents a bold vision, but there are many issues to be resolved before such a system could genuinely be realized. Three particular challenges are (i) synchronization and geolocation, particularly in a situation where GPS may be denied; (ii) communication between nodes, and (iii) control and management of the network.

In this respect there is much to be learned from natural, cognitive systems such as bats, so the network may operate in an adaptive, intelligent manner.

## The Future ...

So radar systems of the future may be rather different to the ones we are used to today, and may certainly take advantage of bistatic and multistatic radar techniques and intelligent, cognitive control schemes. That inspires us to think in new ways – but at the same time we ignore the lessons from the past at our peril. Today's engineers should not only understand and embrace all new technologies and techniques, but also devote adequate time to understanding the successes – and failures – from the past.

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## About the Author:

**Hugh Griffiths ([h.griffiths@ieee.org](mailto:h.griffiths@ieee.org)) is President of the IEEE Aerospace and Electronic Systems Society and holds the THALES/Royal Academy of Engineering Chair of RF Sensors at University College London. He has published over 400 technical articles and books in the fields of radar, sonar and antennas. He recently received the IET A F Harvey Research Prize for his work on bistatic radar.**

## CHAPTER NEWS



### WISE 2013: An Experience in Internet Policy for an Electrical Engineering Student

By Lucas Wadman, IEEE-HKN Delta Pi Chapter

From June to August 2013, I lived and worked in Washington, DC, as a Public Policy Analysis Intern for IEEE-USA, under a program called Washington Internships for Students of Engineering (WISE). The WISE program dates back to the early 1980's, when IEEE and other professional engineering societies recognized a need to introduce more engineering students to the realm of public policy.

I saw the WISE program as an opportunity to expand the interdisciplinary nature of my engineering experience and to augment my technical background with an understanding of policy issues. The program was an intense, nine-week experience that placed 15 interns in the middle of downtown DC to work on a policy issue of their choosing. My selected topic was Internet governance - the blend of technical and political rulemaking that dictate the low and high-level operation of the global Internet. I explored the history of the issue and the current state of affairs and I developed policy recommendations for the future. The research was unlike anything I've encountered in my more traditional engineering experiences, as it involved a combination of first-person interviews, seeking out and attending panel presentations, and hours of writing and rewriting. The end product was a similar to a concise thesis with a presentation to the sponsoring societies.



Lucas Wadman

I would highly recommend the WISE experience to any IEEE-HKN member looking to put themselves outside the box of a more traditional engineering education and career. I would also challenge employers, graduate programs, and undergraduate academic advisors to recognize the value of such non-traditional engineering experiences. The engineer of tomorrow needs to be well-rounded, dynamic, flexible, people-oriented, and much more. The issues in Washington, and throughout the world, require an interdisciplinary view of the world rather than strict compartmentalized and discipline-specific skills that have dominated the engineering landscape. It is plain that the field of engineering has been moving this direction for many years, but from the view of a current student, it has not been moving quickly enough. We need more engineers that understand the core of these highly technical issues – whether they be Internet governance, the future of the smartgrid, or infrastructure development for fuel cell vehicles. This requires not only more interest from current engineering students, but encouragement and investment in these more world-view engineers.

I encourage all eligible IEEE-HKN members to check out the WISE program ([www.wise-intern.org](http://www.wise-intern.org)). We need technical, skilled individuals to help address policy issues in the US and the rest of the world.

*Lucas Wadman is a 5th year undergraduate student studying electrical engineering with minors in biomedical engineering and mathematics at Colorado State University in Fort Collins, CO. He was a 2013 WISE Intern and wrote "Splinternet versus Open Internet," as part of the program.*





*Luke Wadman and the other 13 WISE interns posing on the steps of the Library of Congress on 31 July 2013.  
Image Credit: Erica R. Wissolik, IEEE-USA*

## Engineering Internships in Public Policy

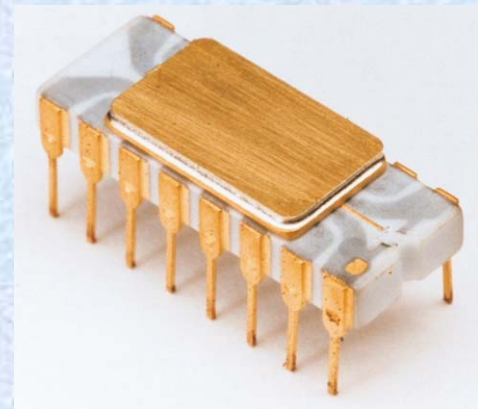
The Washington Internships for Students of Engineering (WISE) Program is an educational opportunity for engineering undergraduates in science and technology (S&T) public policy. Third-year or fourth-year students are selected through a national competitive process for a paid summer in Washington, D.C. The program includes mentoring activities on issues of engineering and public policy, interactive meetings with leaders in government and policy organizations, and student research on an engineering-related policy issue. This collaborative effort among several sponsoring engineering societies has been operating since 1980. Students participate each year with sponsorships from IEEE and other science and engineering professional associations.

The objectives of the WISE program are to teach students how S&T public policy decisions are made, to show students how engineers can contribute to legislative and regulatory decisions, and to guide students on an independent research project related to their sponsoring society. The schedule has private visits with staff from congressional committees, administrators in executive agencies, reporters of the Washington press, members of lobbying organizations (including engineering groups), and other policy leaders. The student research results in an analysis paper published in the online *Journal of Engineering and Public Policy* and presented to the sponsoring societies. Information on the program and student papers in the online journal are available at [www.wise-intern.org](http://www.wise-intern.org). Student applications are due December 31, 2013 for the 2014 program.



# Designing the First Microprocessor

How rethinking a customer's specifications led to simplifications that made the first microprocessor possible.



By Marcian E. Hoff,  
IEEE-HKN Eminent Member

Intel® 4004 - 740KHz / 10-micron, 1971. Image Credit: Intel

We now routinely buy personal computers in which microprocessors with millions of transistors perform at gigahertz speeds, so it is easy to forget that the first microprocessor was not a simple or obvious choice to produce. At the time it was being contemplated, metal oxide semiconductor (MOS) technology was still quite new, and integrated circuits themselves had existed less than a decade. While MOS circuits with a thousand transistors were being manufactured, the economics of integrated circuits of that day limited how far the technology could be pushed. A 2-inch diameter silicon wafer, costing perhaps US\$50 to process, might have a 10% yield for a 0.02-in.<sup>2</sup> die. If we pushed the die size higher, there would be fewer potential die per wafer, and yield would fall precipitously. Table 1 shows how the die cost might vary with die size.

## IC ECONOMICS IN 1968

A die costing US\$82 would have to sell for a price close to US\$200 for the vendor to show a profit. Since a minicomputer with much higher performance than MOS might be made using 100 small- and medium-scale integrated circuits, each costing about US\$1 installed, overly ambitious MOS designs would probably fail to develop a market.

Integrated circuits needed to be sold in large volumes to recover their relatively large design cost, typically in the order of US\$50,000 per design. A concern of the day was that large-scale integration (LSI) would have limited use as computer logic because of the "parts proliferation problem"; i.e., when logic-chip complexity reached 100 gates or more, any one chip design would find application in only one computer, and a 10,000 gate computer might need 100 different chip designs. The design cost of all those different LSI chips would render the LSI-based computer uncompetitive with other technology.

## INTEL IS FOUNDED - 1968

I was born in Rochester, New York, and did my undergraduate study at Rensselaer Polytechnic Institute in Troy, New York. After receiving a bachelor of electrical engineering degree in 1958, I moved to California to do graduate work at Stanford University. I received a Ph.D. degree in 1962 and stayed on at Stanford doing government-sponsored research on what would today be called neural networks. One day in the summer of 1968, I received a phone call --



**Table 1. Effect of Die Size on Cost**

Die area (in <sup>2</sup> )	0.01	0.02	0.04
Percent yield	31	10	1
Die cost	US\$0.60	US\$3.80	US\$82.00

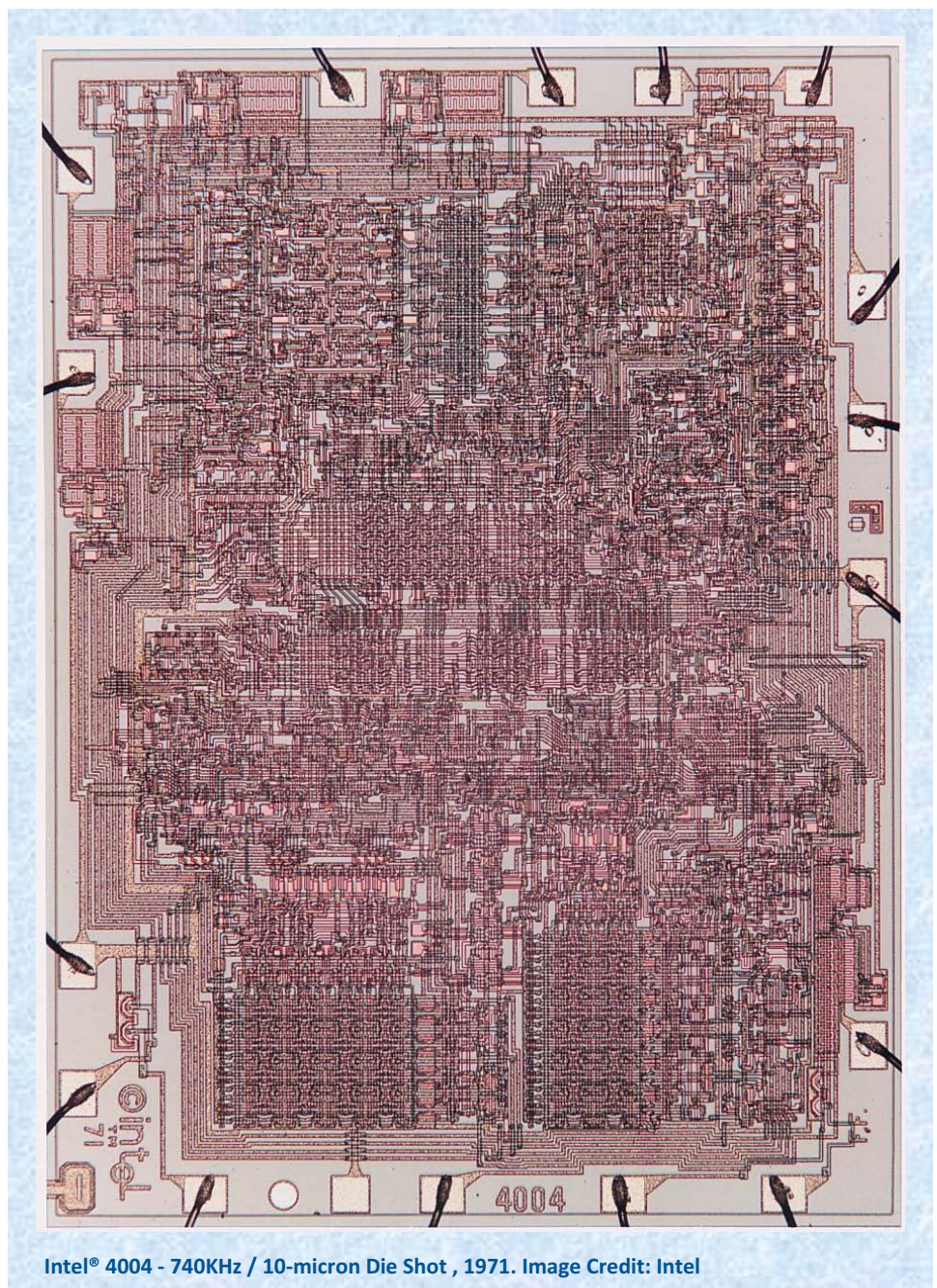
the caller, Bob Noyce, introduced himself and asked if I might be interested in joining a new company he was starting.

The new company, Intel Corporation, was being founded by Noyce and Gordon Moore, who had both just left Fairchild Semiconductor. I interviewed at Bob Noyce's home and was fortunate to receive an employment offer, becoming employee number 12 at Intel.

The purpose of the new company was to develop semiconductor memory that could compete with the magnetic core memory of the day and could be expected to reach high-volume production. Two new semiconductor processes were to be developed: a Schottky bipolar process and a self-aligned p-channel silicon gate MOS process. The company began operation in September of 1968.

I was given the title "manager of applications research." My responsibilities were to help define the memory products Intel would develop, with the expectation that I would help to produce application aids for those products when they were ready for sale. Having been in the rather biased world of academia for some years, I was surprised to find how much could be learned from Intel's marketing people and by talking to potential customers about what they might require from semiconductor memory products.

Magnetic core memory was well established as the standard computer memory by that time, and it was understood that it might take some time for a sizable customer base to materialize. As the new processes became production worthy, Intel management decided that some needed revenue might be derived by performing custom development for a few selected customers.





## THE BUSICOM PROJECT

In April 1969, Intel met with the management of a Japanese calculator manufacturer, Nippon Calculating Machine Corporation (NCM), whose calculators were sold under the name Busicom. Intel agreed at that time to do custom LSI for them. Figure 1 shows the first page of the agreement between the two companies. Intel was confident that its new silicon-gate MOS technology was ahead of its competitors and felt comfortable that random-logic chips up to 2000 transistors would be quite manufacturable.

The specifications for the chips would be developed in Japan by an organization known as Electro-Technical Industries (ETI), and eventually those specifications would be transferred to Intel for completion of the chip designs. In June of 1969 a team of three engineers, Masatoshi Shima, Hiroyuki Masuda, and Shogo

Takayama, came from Japan to transfer the specifications

to Intel. I was assigned to act as liaison for the engineering team. My responsibilities were primarily to help connect the Japanese engineers with the appropriate Intel employees. I should emphasize that I was not given design responsibility, primarily because I did not have experience in MOS chip design. I did have some MOS circuit experience, primarily from writing and testing computer simulations of MOS circuits. These computer simulations were used to aid the design of MOS integrated circuits because, unlike bipolar integrated circuit concepts, which could usually be tested by building breadboards with discrete components, MOS devices were too sensitive to parasitic capacitance to be breadboarded.

## EXPLORING WAYS TO SIMPLIFY

Having designed interfaces to various computers, including an IBM 1620, an IBM 1130, and a Digital Equipment Corporation PDP-8, I was curious about the calculator design and studied the specifications perhaps more than was necessary to merely transfer the design. At the April meetings with Busicom, I had learned the cost targets for the chips, and I soon became concerned that the specifications were more ambitious than we had originally expected,

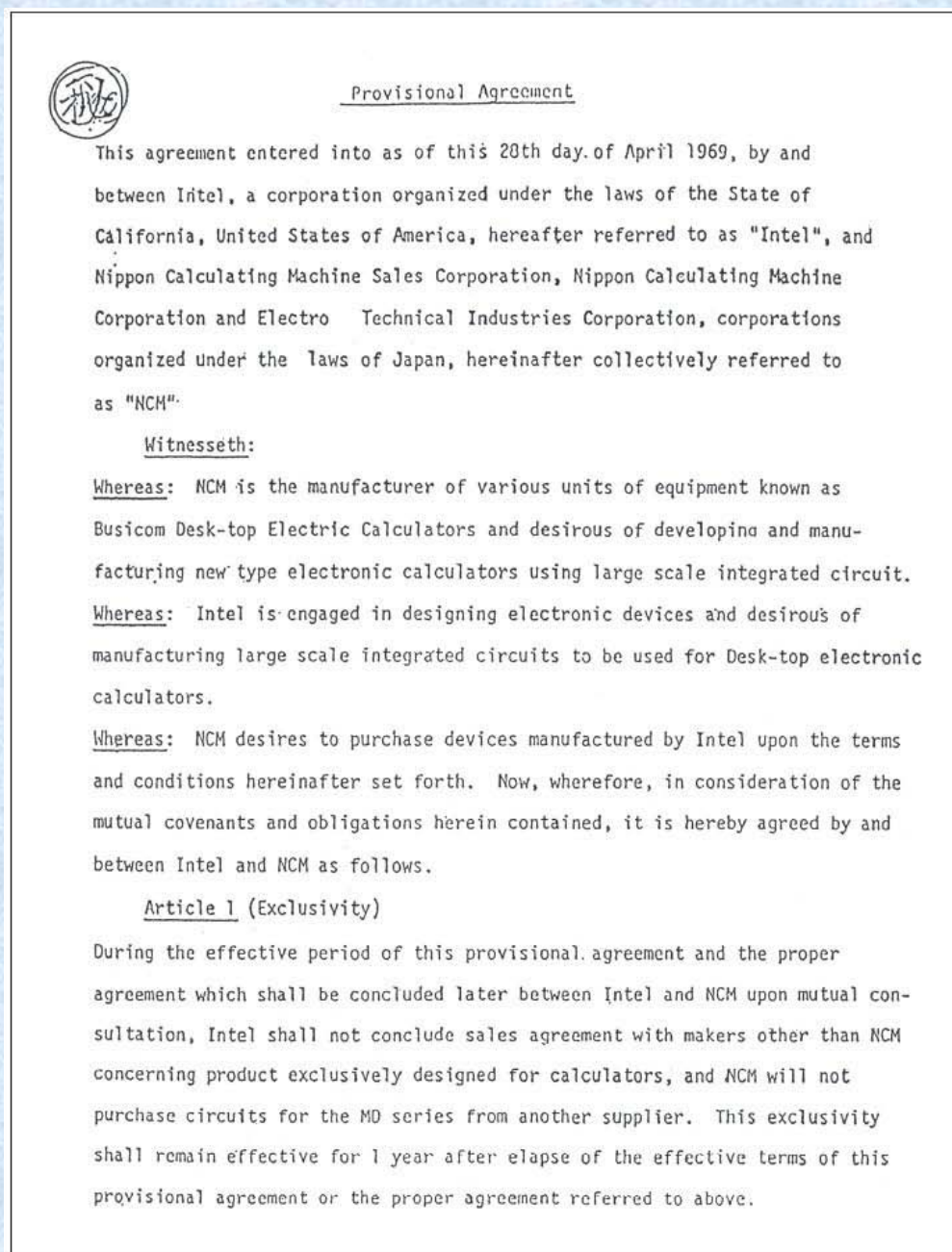


Figure 1: The first page of the 28 April 1969 agreement between Intel and NCM to make LSI chips for the Busicom calculator—an agreement that led to the first microprocessor.



both in terms of logic complexity and package pin count. I expressed some of my concerns to Bob Noyce, and he encouraged me to explore ways by which the design might be simplified.

The design specifications had several features that I thought might be exploited to achieve simplification. The specifications included a read-only memory (ROM) that was used to adapt the proposed chip set to different calculator models, but it seemed to me that the instruction set executed from that ROM could be made simpler. In addition, adding a multilevel subroutine capability should allow ROM-based routines to substitute for complex instructions. The memory to be used in the original design called for 64-b shift registers that required six transistors per bit and rather complex logic to track data location. It seemed that the DRAM being developed at Intel might be a better choice, because it required but three transistors per bit, and could access data much more simply and rapidly than the shift register.

Other features of the original specifications were separate chips for such functions as scanning and debouncing a keyboard, maintaining a multiplexed display, and controlling a small drum printer. If an instruction set could be made more rudimentary and made to operate quickly enough, then perhaps it could be used to perform some of those functions by programming, instead of by separate and unique chips. Eliminating some or all of those chips would help ease the load on Intel's limited MOS-chip design staff.

## A MORE PRIMITIVE ARCHITECTURE

With continued encouragement from Noyce, I started looking at a more primitive architecture that would process 4 b per operation. It seemed that by providing an instruction for converting a 5-b binary value in the range from 0 to 19 into a valid binary coded decimal (BCD) digit and a carry, the processor could be capable of both binary and BCD operations. Eliminating the serial logic needed for a shift-register interface reduced the processor complexity, while very little extra logic was needed to allow parallel 4-b operations. Another promising innovation was to use three-state logic for buses. MOS technology made it quite easy to multiplex signals onto a bus, and the use of multiplexing would permit us to reduce the package pin count. At the time there were some concerns about silicon-gate devices in plastic packages. Being able to eliminate the need for 40-pin packages was additional cost insurance. With a multiplexed 4-b-wide bus, all of the chips of the set could be in 16-lead packages, and even with that limited pin count, each package made available a few pins for input/output connections.

An instruction cycle of eight steps seemed reasonable, with three steps for sending a 12-b address to program ROM, two steps to fetch an 8-b instruction, and three steps for execution. Because the DRAM was used only during it would occur for the first five steps of each instruction cycle. During that time, the DRAM could be refreshed. Because each chip needed to know what step of the cycle was being performed, some timing information needed to be sent from the CPU to other chips in the system. It seemed reasonable to count down the clock on each chip and synchronize the chips via a single signal from the CPU rather than to use more pins. Even with the eight-step instruction cycle, the use of DRAM allowed instruction execution times to be about one-tenth of what would have been needed had 64-b shift registers been used. The transmission of the 12-bit program address to program ROM was done low-order bits first, which had two advantages:

1. The program counter could be advanced by using only a 4-b incrementer with end-around carry.
2. The relatively slow access to ROM content could take place while the central processor transmitted the high-order program address bits (which determined which ROM would respond).

Most of these concepts were developed in July and August of 1969. I tested the proposed instruction set by writing routines for arithmetic, keyboard scanning, and display maintenance. With reasonable estimates for processor clock speeds, it appeared that most of the calculator interface functions could be done by programming.

## THE PROJECT IS LAUNCHED

In September of 1969, Stanley Mazor joined my group and helped put the finishing touches on the specifications for the simplified Intel chip set proposal. In mid-September, Intel's Marketing department sent a letter to Busicom, suggesting they consider the simplified design. Ultimately, Busicom management came to California, and we presented them with two options: a somewhat modified version of the original Busicom chip-set specifications, and

the Intel approach. Even then, Mazor and I emphasized the more versatile nature of the Intel approach. At the end of the session, Busicom's management team chose the Intel design.

The main goal of the effort thus far was not to make a single-chip computer; rather it was to simplify the design and to reduce the number of complex chips to be developed. At the time we made the presentations to Busicom's management, the central processing unit would have consisted of two chips, with the second chip being primarily devoted to generating timing signals. Later, as the design specifications were being finalized, it became evident that the timing functions could be integrated onto the central processing chip. With that change, the target specification called for a central processing unit implemented on a single chip.

The chips of the Busicom set were ultimately given the numbers 4001, 4002, 4003, and 4004; the 400 was the central processing unit. Early in 1970, a contract that gave the rights to the set to Busicom was signed, although contract clauses did indicate that other sales might be contemplated.

With the specifications finalized, the design was transferred to Intel's MOS group, headed by Leslie Vadasz. Figure 2 shows Intel's staff about this time. Vadasz brought Federico Faggin on board in April of 1970 to perform the actual chip circuit design and layout, which were completed early in 1971.

The 4004 central processor chip had an area of just about 0.02 in<sup>2</sup>, which allowed the chip to be very competitive. Within a year, the 4004 was priced at US\$60 each in single quantities, at US\$30 each for a quantity of 100, and at even lower prices when purchased in much higher volumes. At those prices, the 4004 was a much less expensive processor than could have been built using standard logic families.

## THE 8008 MICROPROCESSOR

The 4004 was not the only microprocessor in development at Intel during 1970. In December of 1969, Computer Terminals Corporation (CTC) had contacted Intel about a custom memory chip for an intelligent terminal CTC was developing. The memory chip was to be used to implement various registers for a fairly simple general-purpose processor within the terminal. By this time Intel was committed to build the Busicom microprocessor, and when we realized that the CTC processor was not that much more complex than the Busicom processor, we proposed that CTC's processor also be implemented as a single chip. That proposal ultimately led to the Intel's second microprocessor, the 8008. The 8008 was intended to operate with standard semiconductor memory devices, so unlike the four-chip Busicom set, only one chip, the CPU itself, was defined.



**Figure 2: Once the specifications for chip numbers 4001, 4002, 4003, and 4004 were finalized, the design was transferred to Intel's MOS group, headed by Leslie Vadasz. Les brought Federico Faggin on board in April 1970 to perform the actual chip circuit design and layout, which were completed early in 1971. This photo shows Intel's staff about this time.**



After the Busicom set and the 8008 were transferred to Intel's MOS group, my activity primarily consisted in developing design tools for the microprocessors, as well as other applications development. One product needing support was the newly developed Intel erasable programmable read-only memory (EPROM). This device was ideal for developing applications that would ultimately be cast into ordinary mask-programmed ROM, so my group developed circuit boards that allowed 4004 microprocessor applications to be developed on EPROMs, with the expectation that they would eventually be converted to the mask-programmed 4001. We also developed tools that allowed "burning" data into the EPROM's.

## MAKING THE MICROPROCESSOR AN INTEL PRODUCT

When the Busicom chips became available early in 1971, we found that they could be very useful for many applications in our own lab where we had been using medium and small-scale integrated circuits. I then learned that Busicom was requesting price reductions. Mazor and I begged our Marketing department to get the rights to sell the chips to other customers, feeling that since we found microprocessors to be useful for our applications, other engineers would find them useful as well. In May of 1971, Intel negotiated the right to sell the chips to others, but Intel Marketing and upper management were reluctant to offer them.

A major concern was that the large computer companies -- that is, our memory-product customer base -- would see us as competitors and reject us as suppliers. We tried to emphasize that the applications for the relatively low-performance Intel microprocessors were very likely to be different from those for more expensive minicomputers with far higher performance. In fact, one of our concerns was that customers, used to minicomputer capabilities, would try our microprocessors and be so disappointed by their limited performance that a market for them would not develop. Throughout the summer of 1971, there were many discussions about how the products might be supported. When a new marketing director, Ed Gelbach, joined Intel, the attitude changed in favor of the microprocessor as a product, and in November 1971 the MCS-4 family (consisting of the 4001, 4002, 4003, and 4004) was advertised with the proclamation "Announcing a new era of integrated electronics." To help launch the new products, my group produced a user's manual and assisted in the preparation of the data sheet. The first page of that data sheet is shown in Figure 3.

**intel MCS-4 MICRO COMPUTER SET** NOVEMBER 1971

- Microprogrammable General Purpose Computer Set
- 4-Bit Parallel CPU With 45 Instructions
- Instruction Set Includes Conditional Branching, Jump to Subroutine and Indirect Fetching
- Binary and Decimal Arithmetic Modes
- Addition of Two 8-Digit Numbers in 850 Microseconds
- 2-Phase Dynamic Operation
- 10.8 Microsecond Instruction Cycle
- Easy Expansion—One CPU can Directly Drive up to 32,768 Bits of ROM and up to 5120 Bits of RAM
- Unlimited Number of Output Lines
- Single Power Supply Operation ( $V_{DD} = -15$  Volts)
- Packaged in 16-Pin Dual In-Line Configuration

The MCS-4 is a microprogrammable computer set designed for applications such as test systems, peripherals, terminals, billing machines, measuring systems, numeric and process control. The 4004 CPU, 4003 SR, and 4002 RAM are standard building blocks. The 4001 ROM contains the custom microprogram and is implemented using a metal mask according to customer specifications.

MCS-4 systems interface easily with switches, keyboards, displays, teletypewriters, printers, readers, A-D converters and other popular peripherals.

A system built with the MCS-4 micro computer set can have up to 4K x 8 bit ROM words, 1280 x 4 bit RAM characters and 128 I/O lines without requiring any interface logic. By adding a few simple gates the MCS-4 can have up to 48 RAM and ROM packages in any combination, and 192 I/O lines. The minimum system configuration consists of one CPU and one 256 x 8 bit ROM.

The MCS-4 has a very powerful instruction set that allows both binary and decimal arithmetic. It includes conditional branching, jump to subroutine, and provides for the efficient use of ROM look-up tables by indirect fetching.

The Intel MCS-4 micro computer set (4001/2/3/4) is fabricated with Silicon Gate Technology. This low threshold technology allows the design and production of higher performance MOS circuits and provides a higher functional density on a monolithic chip than conventional MOS technologies.

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**Figure 3: The first page of Intel's first microprocessor data sheet.**



The 8008 followed in early 1972. Interest in the products was high, sales followed, and feedback from customers, primarily users of the 8008, suggested improvements that ultimately led to the 8080 in early 1974. The 8080 also took advantage of a new n-channel MOS process that allowed it to achieve minicomputer-class performance.

## IN RETROSPECT

People have often asked me if we foresaw the applications for microprocessors, usually referring to personal computers. The market we anticipated for microprocessors is what today would be called embedded control. While we might have liked to see personal computers developed, memory and peripheral devices, such as printers and disk drives, were then so costly that it is unlikely that many could have afforded them.

Advances in the underlying semiconductor technology have made enormous improvements in performance and almost unimaginable reductions in cost. An article I coauthored in Intel's early days predicted that semiconductor memory would cost less than a penny a bit by 1972 -- a prediction that proved true. However, at that price, the memory to store one typewritten page would have cost over US\$200. Today's semiconductor memory is some seven orders of magnitude less expensive. Peripherals manufacturers have also made enormous strides in performance and cost reductions, so that today's personal computer owner can buy a color laser printer or a 500-GB disk drive for a tiny fraction of what the cheapest printer or disk drive would have cost in the early 1970s. For example, at that time US\$10,000 might have purchased a 2-MB disk drive.

Today it sometimes appears that the media are aware only of microprocessors used for personal computers and don't realize that embedded control applications utilize much larger numbers microprocessors. Embedded controllers help reduce automobile pollution, and they are found in cellular telephones, digital cameras, and countless other devices we do not think of as computers. Indeed, an embedded controller, in the form of a cardiac pacemaker, has helped me remain alive for the last 17 years.

## WHAT NEXT?

Around 1975, at Bob Noyce's request, I started a group that developed products for the telephone industry. I believe we developed the first commercially available monolithic telephone coder-decoder (CODEC), a device that converts between analog and digitally-encoded voice signals. Our group also produced the first commercially available monolithic switched-capacitor filter, which provided needed antialiasing for the CODEC.

I left Intel in 1983 to join Atari Inc. Atari had some very advanced research programs in the area of computer graphics and home computer applications. However, the company lacked the kind of discipline that I took for granted at Intel, and when its main source of profit, video games, took a downturn, Atari stumbled and was sold by its parent company, Warner Communications, in mid-1984. I left at that time and became an independent consultant. From 1986 on, I did my consulting through Teklicon Inc., a small company specializing in providing expertise to attorneys in patent litigation. At first Teklicon acted as my agent, but in 1990 I officially became Teklicon's "chief technologist." I retired from Teklicon in 2007.

Two years ago, I was invited to judge a collegiate inventors competition sponsored by the National Inventor's Hall of Fame. One project that intrigued me involved water desalination. It seemed to me that the energy budget of most modern desalination systems is much higher than would be predicted by the relatively small differences in the properties of seawater and freshwater. I have been recently investigating this area and believe that it should be possible to significantly reduce the cost of desalinating seawater.

## ABOUT THE AUTHOR

Marcian E. "Ted" Hoff ([MHoffJr@aol.com](mailto:MHoffJr@aol.com)) received a bachelor of electrical engineering degree from Rensselaer Polytechnic Institute, Troy, New York, in 1958 and M.S. and Ph.D. degrees, both in electrical engineering, from Stanford University, California, in 1959 and 1962, respectively. During the summers of 1954–1959 he worked for General Railway Signal Co., Rochester, where his work resulted in two patents. After receiving his Ph.D. degree, he remained at Stanford University as a research associate from 1962 to 1968. In September 1968 he became manager of Applications Research at the newly founded Intel Corporation. In 1975 he headed a group developing products for the telephone industry. He later headed a group that developed products for speech recognition.

He left Intel in early 1983 to become vice-president for Corporate Technology of Atari Corp. When Atari was sold in mid-1984, he left to become an independent consultant. From 1986 on, most of his consulting was done through Teklicon Inc. in Mountain View, California. He became an official employee of Teklicon in 1990, as chief technologist. He retired from Teklicon in October 2007.

He is named as inventor or co-inventor on 17 U.S. patents. He has published numerous articles on topics such as adaptive systems, memory components and their application, microprocessors and their applications, and telephony-related products.

He has been recognized many times for his contribution to the first microprocessor with awards such as the Stuart Ballantine Medal of the Franklin Institute, the Clelio Brunetti Award and the Centennial Medal of the IEEE, the National Inventors Hall of Fame, the Kyoto Prize, and the Davies Medal for Engineering Achievement given by Rennselaer Polytechnic Institute. His contribution has also been recognized in many books about Silicon Valley.

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## FURTHER PERSPECTIVE: CURIOSITY AND CAREER

by Marcian E. "Ted" Hoff

In looking back over my career, I sometimes wonder why I was lucky enough to have my work recognized when so much good engineering is taken for granted. I recognize that there were many influences that helped determine the directions I would take. Those influences led me to make decisions that played major roles in my education, location, and job choices. My hope is that my story will help the reader in making their own best choices.



Several guidelines seem to cover my experience. One is to get an early start. I am concerned that we seem to wait until students are in high school or college before teaching them much about technology. Another guideline is to be curious. Even there I feel that sometimes children who are curious about technology are discouraged because the adults they might ask are not comfortable with technology. Curiosity helped me greatly. Even as I worked in electronics as a job, I also played with electronics as a hobby, and tried to make my hobby work different from my work. I would often find a few years later that what I had learned from the hobby activity would end up being useful for my job. Another guideline is to be persistent and consistent in satisfying curiosity. Make sure that an explanation makes sense to you, and that you can prove to yourself it is accurate. My last guideline is that you must sell your ideas. That selling process is often more difficult than the engineering development itself. Emerson may have stated that "If you build a better mousetrap....the world will beat a path to your door" but that statement is false unless you are as good a salesman as you are a mousetrap designer. No one is likely to adopt your ideas unless you yourself are passionate about them and can convince others to join you in your passion.



## MEMBER PROFILE



### *Catherine Slater* *Beta Chapter*



Catherine Slater received B.S., M.S., and Ph.D. degrees in Electrical Engineering from Purdue University in 2003, 2005, and 2009, respectively. Her dissertation was supported through the Graduate Assistantships in Areas of National Need Teaching Fellowship and National Science Foundation Graduate Research Fellowship. Her work focused on mathematical algorithms and segmentation techniques for biomedical image processing. During her tenure in graduate school, Catherine balanced her research with various teaching activities. She also remained an active member of Eta Kappa Nu, including serving as Vice-President, Awards and Scholarships Chair, and Historian for the Beta Chapter. Since graduation, Catherine has served as the IEEE-USA IEEE-USA Graduates of the Last Decade (GOLD) Representative and is presently serving her second of three years as a Governor-at-Large for IEEE-HKN Board of Governors. Catherine is employed as a Systems Engineer in the aerospace industry and enjoys running along the beach near her residence in Southern California.

#### ***Why did you choose to study the engineering field?***

I was not sure which major to choose when I was applying to colleges. I spoke with a few trusted mentors about my apprehension of making the wrong choice at such a young age. They seemed to provide responses with a common theme: While the topics were constantly evolving, I enjoyed finding solutions to challenging problems. They all recommended that I consider studying engineering. One or two of the mentors also pointed out that an engineering degree could serve as a stepping stone to essentially any field during graduate school. In essence, they told me that I could make my career choice after I had more information. I was also strong in math and science and thus declared engineering as my major.

#### ***What do you love about engineering?***

One of my favorite things about engineering is that engineers are always working on new and exciting projects. You are also surrounded by intelligent people who have a passion to change the world to make life better for everyone. Engineering is also applicable to every industry and many people do not realize the impact engineers have on the world. It is exciting to hear comments about new technologies being adopted that we worked on a few years earlier. It is sometimes hard to believe that they pay us to have so much fun!

#### ***What don't you like about engineering?***

Even engineers with multiple patents can feel overwhelmed with the sheer amount of knowledge required to constantly push the envelope. There are often so many details right in front of you that you have to actively remind yourself to look at the big picture and not forget the basics. In addition, there are stereotypes of engineers. It takes time to prove that you're outgoing and capable of communication as well as knowledgeable on the technical information.

#### ***Whom do you admire, and why?***

While my dad could have fully immersed himself in his work, he made sure to maintain a solid work-life balance so he could be very involved in my sister and my lives while we were young. He taught us to apply common sense as well as complex principles when we were undertaking a new challenge. He showed us the benefit of clearly identifying a problem and then breaking it down systematically to save time in developing solutions. He also taught us the importance of continuously looking to improve upon one's knowledge followed by teaching and mentoring those who have not yet learned a given topic. I did not realize how valuable these skills would be to my



career until after finishing school but I admire him for realizing it and making sure to pass the skills to us.

### ***How has the engineering field changed since you started?***

I have only been out of school for a few years, but during this short time, we have seen many changes. We have witnessed the transition from the occasional cell phone to handheld computers capable of browsing Internet and social media. We have also observed the transition of medical records from paper-based filing to electronic data storage. These changes have drastically affected information handling, dissemination, and privacy regulations. Even with significant changes happening before our eyes, however, engineers have maintained an important standard of ethics and, especially within IEEE and IEEE-HKN, a strong desire to have a positive impact on humanity through use of our skills.



### ***What direction do you think that the engineering field is headed in the next 10 years?***

I honestly have no idea where technology is headed, but I know engineering will lead it there. I know for sure that the world will continue to change. I expect social media will continue to expand in importance for things like finding new employees or employers, areas to study, or dissemination of information. I also envision the stereotypes of engineers will be broken as we see more people who grew up with social media graduate and become the engineering leaders.

### ***What is the most important thing you have learned in the field?***

Never become complacent. The knowledge you possess upon graduation is a collection of tools and a subset of the skills you will need during the course of your career. Things are constantly changing so you need to always be looking for a new opportunity to learn and evolve both technically and personally. You need to look for ways to learn and develop new technical expertise, maintain prior knowledge, expand your communication skills, and eventually learn how to organize, motivate, and lead others.

### ***What advice would you give to recent graduates entering the field?***

Find someone who you can trust to help you navigate your career. An ideal person will answer every question, regardless of magnitude, and will maintain an open-door policy that you feel comfortable using. Mentors will help you identify opportunities for continual improvement through challenges, both professional and personal. The best mentors will work very hard to accomplish their goals but ensure that all stakeholders are involved and all team members are progressing. A strong mentor and will champion for you when new opportunities become available. Finally, look for a mentor who will understand the importance of a life outside of work but will always make sure you have just a little more than you currently feel comfortable with so you are always improving your current skill set.

### ***If you were not in the engineering field, what would you be doing?***

One of the fields I was considering prior to choosing engineering as a stepping stone was medicine. If I was not a practicing engineer, I would have gone to medical school and become a doctor. Instead of becoming a doctor, though, I have been able to make an impact on medicine in a different way. My graduate dissertation focused on how to improve medical technologies so doctors could perform surgical interventions more effectively while providing better patient recovery and a faster return to normal life.



### ***Finish this sentence: "If I had more time, I would..."***

...be excited to spend more time with friends and family. As professionals, you often follow your job so you end up with a network of people all over the place, but you are not always located right next to your family or friends. I would love to have the opportunity to visit them more often."



## MEMBER PROFILE



### *Bhaskar Krishnamachari* Delta Chi Chapter



Bhaskar Krishnamachari is an Associate Professor and Associate Chair at the Ming Hsieh Department of Electrical Engineering at University of Southern California's Viterbi School of Engineering. He received his B.E. in 1998 from The Cooper Union for the Advancement of Science and Art, and his Ph.D. in 2002 from Cornell University. His research and teaching are centered on his interest in the design and analysis of algorithms, protocols and applications for next-generation wireless networks. He has co-authored close to 200 technical articles on these topics, including four conference articles that have received best paper awards. He is also the author of a book titled "Networking Wireless Sensors", published by Cambridge University Press. He is a recipient of the National Science Foundation CAREER Award, the American Society for Engineering Education Terman Award, and the IEEE-HKN Outstanding Young Electrical and Computer Engineering Award. In 2011, he was included in TR-35, MIT Technology Review's annual listing of the top 35 young innovators under the age of 35. He has served as an Associate

Editor for the IEEE Transactions on Mobile Computing, the IEEE Transactions on Wireless Communications, and the Association for Computing Machinery Transactions on Sensor Networks.

#### ***Why did you choose to study the engineering field?***

I fell into engineering somewhat accidentally. In high school, when applying to colleges, I was primarily interested in being a biology major. I was thrilled to be offered admission at the prestigious Cooper Union in New York City, a unique institution that offered a completely free education to all its students in the form of a full-tuition scholarship. Cooper Union didn't have biology as a major, but it had a first-rate engineering school. I didn't really understand what engineering was at that stage, but I knew I couldn't give up this fantastic opportunity. I started out studying chemical engineering. But a year and a half later, I switched to electrical engineering, because of an inspiring teacher who spent an hour talking to a class about what this major was all about. Something about its sheer breadth -- spanning everything from the design of hardware to information theory -- really appealed to me. This was my first conscious choice to study a field of engineering, and I haven't ever regretted it.



#### ***What do you love about engineering?***

What I love most about engineering is the creative challenge. How do you develop something that provides a new functionality? How do you make something that is better, faster, cheaper, more efficient, and more sustainable, than anything like it before?

#### ***What don't you like about engineering?***

My complaints are not about engineering itself, but about the ways in which it fails to meet its full potential. As an academic, it's sometimes frustrating that, for economic and socio-political reasons, it's not always the best technology that makes its way from the drawing board to reality. I also think that it is at least partly due to economic and socio-political reasons that the vast talents of our engineers have not been harnessed sufficiently to focus on environmental issues.



## ***Whom do you admire, and why?***

Peter Cooper -- he was a nineteenth century inventor, industrialist, and philanthropist. He was, by turns, a tinkerer, a cabinet-maker, a grocer, the owner of a glue factory and then an iron works, and president of two telegraph companies. He built America's first steam locomotive, called Tom Thumb. Peter Cooper also invented gelatin and was involved with the laying of the first transatlantic telegraph cable. I admire him for his brilliant mind, his entrepreneurial spirit, and most of all, his golden heart. He was a tireless do-gooder, someone who thought of wealth not as an end but as a means to help mankind. He founded The Cooper Union for the Advancement of Science and Art in New York City, because he believed that education should be open and free to all. Since 1859, this institute has been one of the few completely free private colleges in the United States.



## ***How has the engineering field changed since you started?***

Engineering has been revolutionized by improvements in information technology. The engineering workforce is now much more geographically distributed. Computing, networked communication, and sensing have become increasingly pervasive in many applications. Data-driven machine learning and statistical signal processing techniques are rapidly making our engineered systems more intelligent than before. On the negative side, I fear that there is less investment in basic engineering research from industry than in the past, which could affect long-term innovation and create big gaps between academic research and industry practice.

## ***What direction do you think that the engineering field is headed in the next 10 years?***

I think the biggest revolution in our lifetimes will be the design and deployment of the Internet of Things, which will drastically increase the reach of information technology into the physical world, from smart buildings to vehicles that talk to each other on the road. They have the potential to dramatically improve the quality of our lives. This revolution, in its early stages now, will continue to gather steam over the next 10 years. I also think more attention will be paid to the environment and green engineering.

## ***What is the most important thing you have learned in the field?***

Success in engineering, in academia and in industry, has a lot to do with how people relate to each other. It is important to seek out, associate, and collaborate with passionate and intellectually-stimulating people.

## ***What advice would you give to recent graduates entering the field?***

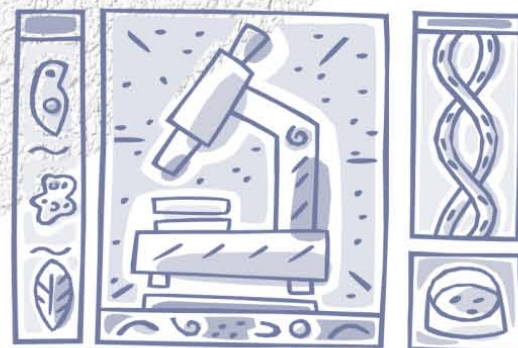
Identify, observe, and learn from as many mentors and role models as you can. There are many experienced engineers out there who can offer advice and help, and the more people you observe doing things well, the more you can learn about different approaches to creativity, problem-solving, working with people, learning, maintaining work-life balance, etc., and synthesize them to figure out effective approaches that would work for you. And, in turn, offer others as much of your help, assistance, and encouragement as you can --- it will make for a very satisfying career.

## ***If you were not in the engineering field, what would you be doing?***

I think I'd probably be a biologist of some sort.

## ***Finish this sentence: "If I had more time, I would..."***

...spend more time in nature, watching, photographing, and learning about birds, plants, and insects."





## ARPANET to the Internet

### IEEE Milestones: Birthplace of the Internet, 1969

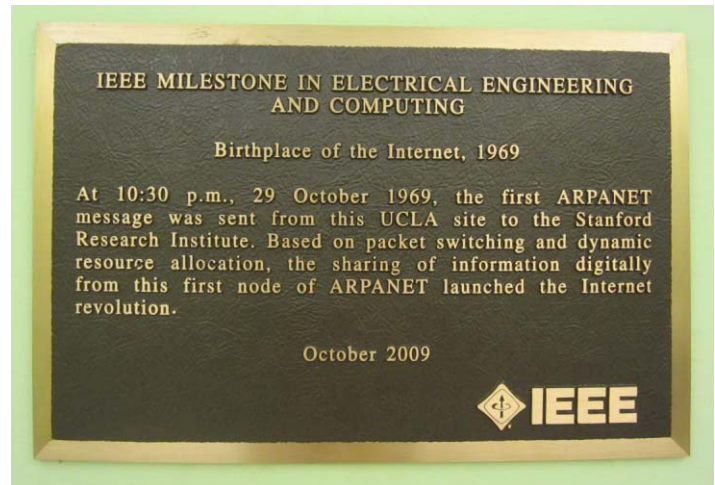
At 10:30 p.m., 29 October 1969, the first ARPANET message was sent from this UCLA site to the Stanford Research Institute. Based on packet switching and dynamic resource allocation, the sharing of information digitally from this first node of ARPANET launched the Internet revolution.

The plaque can be seen at the UCLA Henry Samueli School of Engineering and Applied Sciences, 405 Hilgard Ave., Los Angeles, California, U.S.A.

The deployment of the ARPANET set in motion a train of developments that led to the Internet as we know it today. The ARPANET was the first global packet-switching based network, and allowed remote network access to varied applications from multiple users among different computer platforms. It also applied the concept of protocol layering to communications. This development was the key to allowing a diverse set of users to operate over the telephone network of the time, which was optimized for voice and not suited to data traffic. With the introduction of a highly-adaptive and robust technology for network access, the ARPANET formed the foundation of today's Internet.

The application of packet switching and demand access are fundamental differences between the Internet and previous circuit switching based networks. It uses network resources by dynamically sharing them among many streams. This leads to significantly improved efficiency and robustness of the network. The layering scheme it introduces has allowed the development of flexible protocols, as well as the efficient communication between different computing platforms.

ARPANET differed from previous computer networks (e.g. SAGE) in that those networks were specialized constructions, designed to link specific machines of a similar type, whereas ARPANET was designed to allow machines to communicate efficiently irrespective of type.



**IEEE Milestone Plaque at UCLA**  
**Image Credit: Courtesy of the Iota Gamma HKN Chapter and the Computer Science Department, the University of California, Los Angeles, October 2013**

UCLA was selected as the site of the very first IMP (Interface Message Processor). The major reason for this choice was due to the fundamental work and involvement of UCLA's Professor Kleinrock with many early developments of the ARPANET/Internet. His work in extending and applying queuing theory to data network design and his development of the network measurement technology were keys in the decision to make UCLA the first Internet node, and to serve as the Network Measurement Center. Many further research contributions crucial to the Internet's development and growth were generated by the UCLA team.

The reigning switching technology of the 1960s was circuit switching, which was suited to the long holding times of voice traffic. Voice traffic was so dominant, and computer-generated and related traffic was so sparse, that it was difficult to see the merit of packet switching. When packet switching technology was first suggested, the large networking companies considered the technology to be unworkable and unimportant. It was necessary to overcome their dismissal of packet switching and develop it without their support.

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### What are Milestones?

The IEEE Milestones in Electrical Engineering and Computing program honors significant technical achievements in all areas associated with IEEE. It is a program of the IEEE History Committee, administered through the IEEE History Center. Milestones recognize the technological innovation and excellence for the benefit of humanity found in unique products, services, seminal papers and patents. Milestones are proposed by any IEEE member, and are sponsored by an IEEE Organizational Unit (OU) such as an IEEE section, society, chapter or student branch. Learn more about the IEEE Milestones program. See "IEEE Milestones" link at the IEEE Global History Network ([www.ieeehkn.org](http://www.ieeehkn.org)).

## First Message on the Internet – “Lo[gin]” on 10:30 p.m., 29 October 1969

“The procedure was for us to type “log” with the system at SRI set up to be clever enough to complete the rest of the command, namely, to add “in” and thus create the word “login.” Charlie and Bill Duvall, the programmer at the SRI end, each had a telephone headset so they could communicate by voice as the message was transmitted. At the UCLA end, we typed in the “l” and asked SRI if they received it; “Got the l,” came the voice reply. We typed in the “o” and asked if they got it and received “Got the o.” UCLA then typed in the “g” and asked if they got it, and the system crashed! This was quite a beginning. However, on the second attempt, it worked fine! So, the first message on the Internet was a crash, but more accurately, was the prescient word “lo” (as in “lo and behold!”).”

Leonard Kleinrock, “History of the Internet and Its Flexible Future,” *IEEE Wireless Communications*, Feb. 2008, pp. 8–18.

### Dr. Leonard Kleinrock

#### Eminent Member of IEEE-HKN, Elected 2011

Professor Leonard Kleinrock is Distinguished Professor of Computer Science at UCLA. Known as a “Father of the Internet”, he developed the mathematical theory of packet networks, the technology underpinning the Internet as an MIT graduate student in 1961. His host computer at UCLA became the first node of the Internet in September 1969. He wrote the first paper and published the first book on the subject; he also directed the transmission of the first message ever to pass over the Internet. Kleinrock's work was recently recognized when he received the 2007 National Medal of Science, the highest honor for achievement in science bestowed by the President of the United States. His other honors include membership in the National Academy of Engineering and a membership in the American Academy of Arts and Sciences; he is an [IEEE](#) fellow and an [ACM](#) fellow.

Leonard Kleinrock received his Ph.D. from [MIT](#) in 1963. He has served as a Professor of Computer Science at the [University of California, Los Angeles](#) since then, serving as Chairman of the department from 1991-1995. He received his BEE degree from [CCNY](#) in 1957 and his MS degree from MIT in 1959. He has published over 250 papers and authored six books on a wide array of subjects, including packet switching networks, packet radio networks, local area networks, broadband networks, gigabit networks, nomadic computing, performance evaluation, intelligent agents and peer-to-peer networks. During his tenure at UCLA, Dr. Kleinrock has supervised the research for 47 Ph.D. students and numerous M.S. students.

#### Interactive Extras and More Information:

- [Audio interview with Dr. L. Kleinrock](#)
- [IEEE Global History Network Resources](#)
- [The Kleinrock Internet History Center at UCLA](#)
- [DARPA Internet Resource Page](#)
- [Computer History Museum](#)



**Dr. Leonard Kleinrock with Internet Message Processor**  
Image Credit: Courtesy of Computer Science Department, the University of California, Los Angeles, September 2013



**Four-Node ARPANET in 1969**



## A Technical History of the ARPANET

A timeline of major events in the history of the ARPANET, providing an overview of the ARPANET's conception, growth, and development.

- 1958** Eisenhower forms the Advance Research Projects Agency (ARPA) in response to the USSR's launch of Sputnik.
- 1966** December: The ARPA Computer Network (ARPANET) project begins.
- 1967** April: It is suggested that the ARPANET utilize a separate computer between the host and the network. This computer would perform the packet switching and routing. This separate computer dubbed the Interface Message Processor or IMP.
- 1968** December: Contract to build the IMPs is won by Bolt Beranek and Newman Inc. (BBN). BBN designs the IMP (cf. BBN reports 1763, 1783, 1837, and 1890) and releases the first specification for Host to IMP communication (BBN report 1822).
- 1969** April: The discussion of the Host to Host Protocol begins with RFC 1. The Network Working Group (NWG) forms to deal with the task of Host-Host layer communication protocols.  
  
September: The first IMP is delivered and connected to a SDS Sigma 7 computer at UCLA. This IMP constitutes the first node of the ARPANET. The IMP is located in the Network Measurement Center, which will keep statistics, stress the network, and evaluate network performance.  
  
October: The second node of the ARPANET is installed at Stanford Research Institute (SRI). The IMP is connected to an SDS 940 Computer. The first host-to-host message is sent across the network and received.  
  
November: The third node of the ARPANET is installed at UCSB.  
  
December: The fourth node of the ARPANET is installed at The University of Utah.
- 1970** The network is stressed by inducing congestion. Several problems are revealed.  
  
March: The ARPANET now spans the United States, with the installation of an IMP at BBN, in Cambridge, MA.  
  
March: The Network Control Center (NCC) at BBN begins operation. All IMPs have to report to the NCC every minute to confirm they are alive.  
  
November: The IMP's software is upgraded to allow the IMPs to be able to download any new software from each other. This allows IMP software to be installed on one IMP, and the software will propagate throughout the IMP-subnet. Likewise, if a problem occurs, and an IMP needs to restore its software, it can download it from a neighboring IMP.
- 1971** The first host-to-host protocol is implemented, NCP (Network Control Program).  
  
September: The Terminal IMP (TIP) is installed in the ARPANET, allowing direct terminal access to the network.
- 1972** March: SNGMSG and READMAIL allow the first e-mail basic system on the ARPANET.  
  
July: The first File Transfer Protocol (FTP) specification is released (RFC 354).  
  
October: First public demonstration of the ARPANET occurs at the International Conference on Computer Communication (ICCC), Washington.
- 1973** The first attempt at internetworking two networks (ARPANET and Packet Radio Network) begins.  
  
May: The first Ethernet operation at Xerox Palo Alto Research Center.
- 1974** May: Transmission Control Protocol (TCP), is specified. This protocol allowed for internetworking and eventually replaced NCP.
- 1977** October: TCP operations begins over the ARPANET, Packet Radio Net, and the Satellite Network (SATNET).
- 1978** March: TCP is split into TCP and IP, where TCP is the end-to-end process, and IP is the network routing process.
- 1983** MILNET (Military Network) is split off of ARPANET, leaving the ARPANET with 68 nodes. The two networks are connected by a gateway.  
  
January: The ARPANET officially transitions to TCP/IP.  
  
November: Domain Name System (DNS) is designed. (.com, .gov, .mil, .org, .net, .int)
- 1990** After 20 years, ARPANET is shutdown.

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<http://www.cs.utexas.edu/users/chris/nph/ARPANET/ScottR/arpnet/timeline.htm>



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# An Early History of the Internet

By Leonard Kleinrock  
IEEE-HKN Eminent Member

## Observations from the origins and development of the ARPANET

### INTRODUCTION

It is impossible to place the origins of the Internet in a single moment of time. One could argue that its roots lie in the earliest communications technologies of centuries and millennia past, or the beginnings of mathematics and logic, or even with the emergence of language itself. For each component of the massive infrastructure we call the Internet, there are technical (and social) precursors that run through our present and our histories. We may seek to explain, or assume away, whatever range of component technologies we like. It is equally possible to narrow Internet history down to specific technologies with which we are the most familiar.

There are also many individuals that may be said to have “predicted” the Internet. In 1908, Nikola Tesla foresaw [1] a technology that would allow “a business man in New York to dictate instructions, and have them instantly appear in type at his office in London or elsewhere” and would allow global access to “any picture, character,

drawing, or print.” Thirty years later, H. G. Wells articulated [2] his idea of a “World Brain” as “a depot where knowledge and ideas are received, sorted, summarized, digested, clarified and compared.” These ideas were followed by a 1945 essay [3] by Vannevar Bush, predicting a machine with collective memory that he called the memex, with which “Wholly new forms of encyclopedias will appear, ready-made with a mesh of associative trails running through them, ready to be dropped into the memex and there amplified.”

These predictions, however, do not help us understand why the specific events, innovations, people, and circumstances that formed our Internet emerged when they did. Doing so is not possible from the scale of centuries or single individuals. This column’s focus is on the defining inventions and decisions that separate early technologies that were clearly not the Internet, from a wide range of recent inventions that may help characterize our Internet, but were also built within it. Thus, in this column we trace both the early history of the

science and infrastructure that emerged as the ARPANET, and the trajectory of development it set for the even broader construct that we now call the Internet.

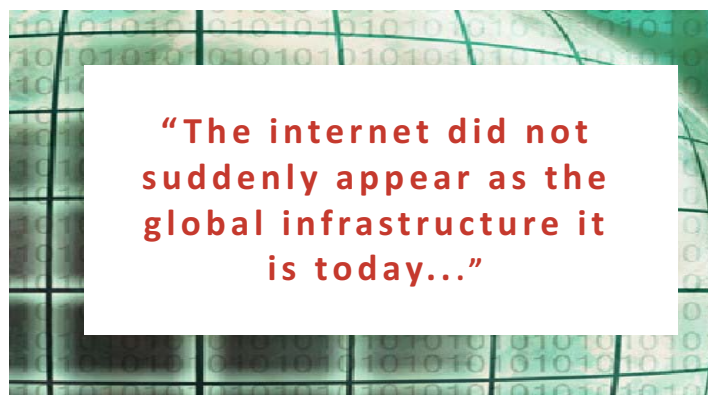
As one of many individuals who participated in the Internet's early history, I also offer a personal account of the same events, as an autobiographical element in this story. In doing so, I aim to further contextualize publications from the period — my primary source materials — with details from firsthand experience. This perspective may add to our depth of historical understanding, in which the extent of personal detail does not imply a greater importance to the events presented. In focusing on the work of individual researchers and developers, I rely on the various publications that followed the work of these individuals to link this story to the factual historical record we will follow. There are, of course, many important personal and institutional stories that have yet to be told. The University of California at Los Angeles (UCLA) is heavily mentioned in this column, as it was the site of so much foundational work. I view this period as a synergistic surge of technology, engineered by a magnificent group of researchers and developers amidst a defining period of challenge, creativity, invention, and impact.

## BEFORE THE BEGINNING: TWO THREADS THAT MEET

The Internet did not suddenly appear as the global infrastructure it is today, and neither did it form automatically out of earlier telecommunications. During the late 1950s and early 1960s, two independent threads were being woven. One was the research thread that eventually led to the packet switching networks of today's Internet. This thread followed three possible paths to the technologies that eventually emerged; the researchers involved were, in chronological order, myself, Paul Baran, and Donald Davies. Below we explore these three paths, which were independently pursued in the quest to provide data networking theory, architecture, and implementation. The second thread was the creation and growth of the Advanced Research Projects Agency (ARPA), the institution that funded and deployed these technologies — a process that, as we will see, was by no means automatic. These two threads merged in the mid-1960s, creating the historical “break” that led to the ARPANET. Once these threads merged, the implementation and deployment phase began, bringing in other key contributors and successive stages of development in Internet history. I present these threads and phases chronologically so we can revisit the history as it unfolded. One may find elaborations on this history in two earlier papers [4, 5].

## THE RESEARCH THREAD

In January 1957<sup>1</sup> I began as a graduate student in electrical engineering at Massachusetts Institute of Technology (MIT). It was there that I worked with Claude Shannon, who inspired me to examine behavior as large numbers of elements (nodes, users, data) interacted; this led me to introduce the concept of distributed systems control and to include the study of “large” networks in my subsequent thesis proposal. In that MIT environment I was surrounded by many computers and realized that it would soon be necessary for them to communicate with each other. However, the existing circuit switching technology of telephony was woefully inadequate for supporting communication among these data sources. This was a fascinating and important challenge, and one that was relatively unexplored. So I decided to devote my Ph.D. research to solving this problem, and to develop the science and understanding of networks that could properly support data communications.



Circuit switching is problematic because data communications is bursty, that is, it is typically dominated by short bursts of activity with long periods of inactivity. I realized that any static assignment of network resources, as is the case with circuit switching, would be extremely wasteful of those resources, whereas dynamic assignment (I refer to this as “dynamic resource sharing” or “demand access”) would be highly efficient. This was an essential observation, and in 1959 it launched my research thread as I sought to design a new kind of network. Its architecture would use dynamic resource allocation to support the bursty nature of data communications, and eventually provide a structure for today's packet-switched networks.

This concept of resource sharing was emerging at that time in a totally different context: that of timesharing of computer power. Timesharing was based on the same fundamental recognition that users generate bursty demands, and thus expensive computer resources were wasted when a computer was dedicated to a single user.



**"I sought to develop a model with dynamic resource sharing, incorporating the fact that data traffic was unpredictable as well as bursty."**

To overcome this inefficiency, timesharing allocated the computer to multiple users simultaneously, recognizing that while one user was idle, others would likely be busy. This was an exquisite use of resource sharing. These ideas had roots in systems like SAGE [6] and in the MIT Compatible Time-Sharing System (CTSS [7]), developed in 1961 by Fernando Corbato (among the first timesharing systems to be implemented). The principles and advantages of timesharing were key to my realization that resource sharing of communication links in networks could provide for efficient data communications, much like the resource sharing of processors in timeshared systems was accomplishing.

In addition, there was already an example of a special-purpose data network that used resource sharing: the store-and-forward telegraph network. The challenge I faced was to create an appropriate model of general-purpose data communications networks, to solve for their behavior, and to develop an effective design methodology for such networks.

To do this, I sought to develop a model with dynamic resource sharing, incorporating the fact that data traffic was unpredictable as well as bursty. In order to clear up some misconceptions regarding what I and other investigators were doing in the field in the early days, I will devote some space in the following paragraphs to discuss the relationship between dynamic resource sharing and packet switching, where the latter is but one of many ways to realize the former. The basic structure I chose was that of a queue since it is a perfect resource sharing mechanism. A queue is dynamic, adaptive, and efficient, and does not wait for a message that is not there, but rather transmits a message already waiting in the queue. Moreover, the performance measures one considers in queueing theory are response time, throughput, efficiency, buffering, priorities, and so on, and these are just the quantities of interest in data networks. In the late

1950s, the published literature contained almost no work on networks of queues. However, a singular exception to this was the work by James Jackson, who published a classic paper [8] on open networks of queues. As we see below, I was able to apply Jackson's result to represent the data networks of interest by making serious modifications to his model.

So the stage was set: There was a need to understand and design general purpose data communication networks that could handle bursty data traffic, there was an emerging approach based on resource sharing in timeshared systems, there was an existing special-purpose network that suggested it could be done, and there was a body of queueing theory that looked promising.

As a result, I prepared and submitted my MIT Ph.D. thesis proposal [9] in May 1961, entitled "Information Flow in Large Communication Nets" in which I developed the first analysis of data networks. I chose a queueing theoretic model based on Jackson's model to characterize a data network as a network of communication channels whose purpose was to move data messages from their origin to their destination in a hop-by-hop fashion. Each channel was modeled as a resource serving a queue of data messages awaiting transmission; I discussed how "The nets under consideration consist of nodes, connected to each other by links. The nodes receive, sort, store, and transmit messages that enter and leave via the links...." My underlying model assumed that the stream of messages had randomly chosen lengths and, when applied to data networks, yielded a problem whose exact solution turned out to be hopelessly intractable. I altered the model and also introduced a critical mathematical assumption, the Independence Assumption,<sup>2</sup> which tamed the problem and allowed for an elegant solution. With this solution, I was able to solve for the many performance measures of these networks. For example, I showed that by scaling up the network traffic and bandwidth properly, one could reduce the system response time, increase the network efficiency, and increase the network throughput, all simultaneously [10].

In the course of examining data network performance, it became clear to me that it was important to explore the manner in which mean response time was affected when one introduced a priority queueing discipline on the traffic. I chose to understand this influence in the case of a single node first and then to apply the results to the general network case. This led to a publication in April 1962, which turned out to be the first paper [11] to introduce the concept of breaking messages into smaller fixed-length pieces (subsequently named "packets," as explained below). In it I provided a mathematically exact

analysis of the mean response time, and showed the advantages to be gained by utilizing packet switching for this new network.<sup>3</sup> Note that the fixed length packets I introduced did not match the randomly chosen lengths of the model, but fortunately, the key performance measure I solved for, the overall mean system response time, did not require that assumption, so the mathematical model properly reflected the behavior of fixed length packets as well.

I also developed optimal design procedures for determining the network capacity assignment, the topology, and the routing procedure. I introduced and evaluated distributed adaptive routing control procedures, noting that network/ routing control is best handled by sharing control among all the nodes rather than relegating control to one or a small number of nodes. This distributes the control load (thereby not unduly loading any one node), introduces the ability to change routes on the fly dynamically (based on current load, connectivity, and destination address), enables the network to scale to a very large number of nodes, and dramatically improves the robustness of the network.

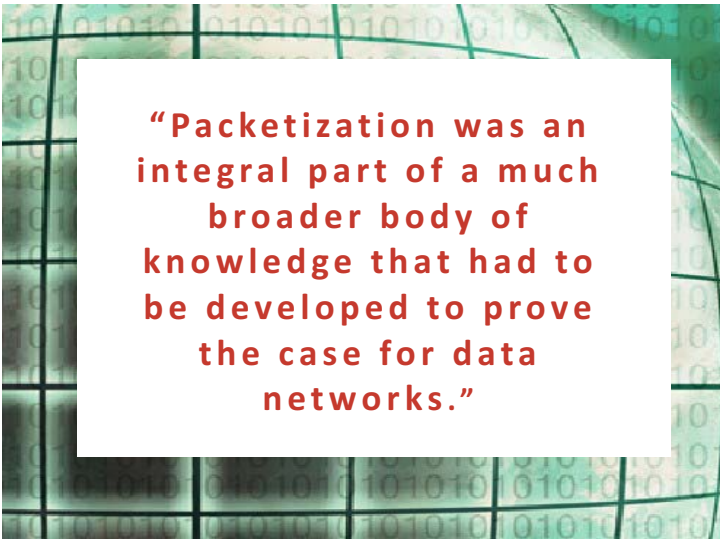
Whereas my focus was not principally on the engineering details of packet networks, I did address engineering details when I built a complete network simulation model and conducted extensive simulation experiments confirming the correctness of the theory. These experiments included detailed message blocks (with headers, origin and destination addresses, priority indicators, routing labels, etc), dynamic adaptive routing tables, priority queueing structures, traffic specifications, and more.<sup>4</sup>

Packetization was an integral part of a much broader body of knowledge that had to be developed to prove the case for data networks. Indeed, packetization alone was not the underlying technology that led to ARPANET design fundamentals. To be sure, packetization was and remains a core element of today's networking technology, but it is not identical to network efficiency. Rather, the fundamental gain lies in dynamic resource sharing. It is important to point out that there are many ways in which dynamic resource sharing can be accomplished, with packet switching being only one such method; other methods include polling [12], message switching [13], asynchronous time-division multiple access (ATDMA) [14], carrier sense multiple access with collision detection (CSMA/CD) [15], and others.

I completed and filed my Ph.D. dissertation [16] in December 1962, having created a mathematical theory of packet switching for dynamic resource sharing, thus providing the fundamental underpinnings for ARPANET

technology. I showed that these networks were efficient, stable, scalable, robust, adaptive, and, most of all, feasible. Decades of important research on these topics have since taken place around the world.

By the time my dissertation was published as the first book [17] on computer networks in 1964, the idea of packetization itself was appearing more broadly. The next contributor to packet switching was Paul Baran of the RAND Corporation, who was busy working on military command and control systems during the early 1960s with the goal of using redundancy and digital technology to design a robust multilateral military communications network. He recognized the vulnerability of the telephone



**“Packetization was an integral part of a much broader body of knowledge that had to be developed to prove the case for data networks.”**

network due to its centralized architecture. In September 1962 he published a paper [18] on how “hot potato” adaptive alternate routing procedures and distributed principles could utilize a “standard message block,” also to fall under the “packet” umbrella, which will be addressed below. His purpose was to create a network capable of functioning after a Soviet nuclear attack [19]. In August 1964 he produced a set of 11 important reports [20] reinforcing his prior description with simulations and elaborating on many details of the design. He, too, discovered the importance of going to digital networks and of the robustness provided by distributed routing. He attempted to get AT&T to implement the design, but failed to convince them (presumably due to their analog mindset). In 1965 RAND approached the Air Force to implement it, but they deferred to the DCA<sup>5</sup>; at this point, Baran decided not to pursue the implementation any further. Baran's work was done independently of the work that I had done earlier at MIT and, in many ways, the results we achieved in addressing the problem of packet networks were complementary.

The third early contributor to packet switching was Donald Davies, of the National Physical Laboratory (NPL) in the



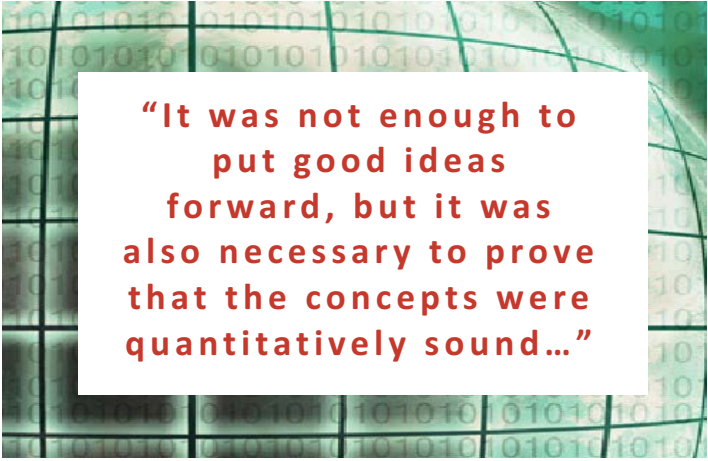
United Kingdom. He began thinking about packet networks in 1965 and coined the term “packet” that year. In a privately circulated paper [21] dated June 1966, he described his design for a data network and used my earlier theory to calculate its performance. Davies lectured to a public audience in March 1967, recommending the use of his technology for the design of a public switched data network, and published an October 1967 paper [22] with his NPL group in which details of the design were first described in an open publication. This plan was for an NPL Data Communications Network, but the U.K. Department of Trade and Industry only authorized the implementation of one node. That node became operational in 1970. Further details of a full network design were described by the NPL team in 1968 [23, 24] and 1969 [25]; it is not clear where a multiplenode deployment by this team might have led, but it obviously had potential. This reluctance to support an NPL packet-switched network was reminiscent of the view taken by AT&T and DCA in not supporting an implementation of the RAND work.

The work of Baran and Davies focused on the engineering and architectural issues of the network design. My work emphasized and provided the mathematical underpinnings and supporting simulation experiments of the network analysis and design, including optimization as well as formulating the basic principles of packet networks that include dynamic resource sharing; this quantitatively showed that these networks were feasible. My trajectory was more fortunate as the ARPA thread rolled out and adopted my principles for their design of the ARPANET, and provided me the opportunity to participate in its implementation and deployment. Different trajectories were taken by Baran and then later by Davies, with Baran’s unsuccessful attempts to get his ideas implemented and with Davies’ frustration by the foot-dragging of the U.K. government. It was not enough to put good ideas forward, but it was also necessary to prove that the concepts were quantitatively sound, and then to implement and deploy an operational network that would bring these ideas and designs to use.

## THE ARPA THREAD

Let us step back chronologically and now pursue the second thread: the role of ARPA in defining the need for a data network, putting the management structure in place to enable its development, and providing the funding necessary for its implementation and deployment.

J. C. R. Licklider (“Lick”) entered the story when he published his landmark 1960 paper [26] “Man-Computer Symbiosis.” He defined the title as “an expected



**“It was not enough to put good ideas forward, but it was also necessary to prove that the concepts were quantitatively sound...”**

development in cooperative interaction between men and electronic computers.” This work envisaged a system “to enable men and computers to cooperate in making decisions and controlling complex situations without inflexible dependence on predetermined programs”; he had seen such a flexible system in the aforementioned SAGE system. Once again, we find a forecast of what future telecommunications might provide — and Lick was perhaps the first to write at a time when viable ways to create that future were emerging. Although a visionary, Lick was not a networking technologist, so the challenge was to finally implement such ideas.

In May 1962 Lick and Welden Clark outlined their views on how networking computers could support social interaction, and provide networked access to programs and data [27]. This extended his earlier ideas of what he now referred to as a Galactic Network (in fact, he nicknamed his group of computer experts “The Intergalactic Network”).

Lick was appointed as the first director of ARPA’s newly formed Information Processing Techniques Office (IPTO) in October 1962. He quickly funded new research into advanced computer and networking technologies as well as areas that involved man-computer interaction and distributed systems.

By the end of 1962, Lick had articulated his grand vision for the Galactic Network, of which I was unaware, and I had laid out the mathematical theory of packet networks, of which Lick was also unaware. These ideas would soon intersect and reinforce each other in a series of key events between 1962 and 1969. I joined the UCLA faculty in 1963. Lick passed the directorship of IPTO to Ivan Sutherland, an MIT colleague of mine, in September 1964. In that role Sutherland wished to connect UCLA’s three IBM mainframes in a three-node on-campus computer network, which would have been easy to accomplish with the means I had laid out in my Ph.D. dissertation.

However, the UCLA network was never realized due to administrative discord. Nevertheless, the seeds for an ARPA-funded network had now been sown.

Early the next year (1965), Sutherland awarded Larry Roberts (another MIT colleague of mine who was quite familiar with my networking research) a contract to create a dialup 1200 b/s data connection across the United States. Later that year, Roberts accomplished this in collaboration with Thomas Marill, demonstrating that such a connection required a different, more sophisticated network than the telephone network offered [28].

Meanwhile, at ARPA, Sutherland recruited Robert Taylor to become associate director of IPTO in 1965. While there, Taylor also recognized the need for a network, this time specifically to connect ARPA research investigators to the few large expensive research computers across the country. This would allow them to share each other's hardware, software, and applications in a cost-effective fashion.<sup>6</sup> Taylor then dropped into the office of the ARPA director, Charlie Herzfeld, to request funding for this nascent networking project. Herzfeld was a man of action who knew how to make a fast decision, and within 20 minutes he allocated \$1 million to Taylor as initial funding for the project. Taylor, who had since succeeded Sutherland as IPTO director in August 1966, brought in Roberts as the IPTO chief scientist that December. Bringing Roberts in to manage the networking project turned out to be a critical hire as Roberts was to contribute at all levels to the coming success of data networking.

The research and ARPA threads had now merged, and the project would soon become the ARPANET.

These were critical steps in Internet history, for not even in the post-war United States did technological progress flow directly from ideas. In contrast to refusals from the private sector to fund the beginnings of the project, ARPA made available the will and funding of the U.S. government.<sup>7</sup> ARPA's management and support fostered the early culture of shared, open research that was crucial to the success of the ARPANET program.

## THE BEGINNING: THE ARPANET LAUNCH

The commitment to create the ARPANET was now in play. Roberts was empowered to develop the network concept based on Lick's vision, my theory, and Taylor's application.

There were basically two matters to be considered in this project. One was the issue of creating the switches and links underlying the network infrastructure, with the proper performance characteristics, including throughput,

response time, buffering, loss, efficiency, scalability, topology, channel capacity, routing procedure, queueing discipline, reliability, robustness, and cost. The other was to create the appropriate protocols to be used by the attached (host) computers<sup>8</sup> so that they could properly communicate with each other.

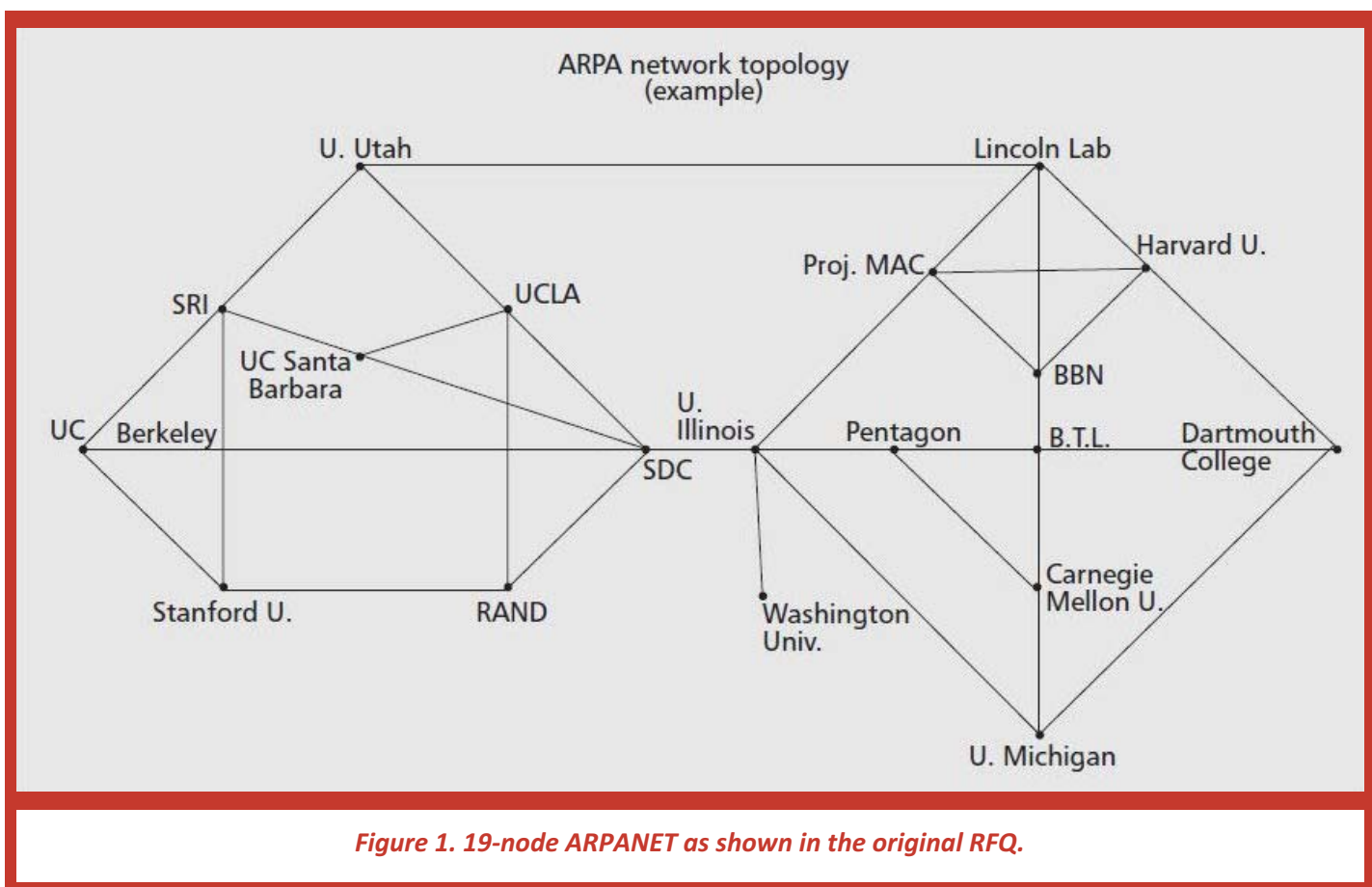
Shortly after his arrival, Roberts called a meeting of the ARPA Principal Investigators (PIs) in April 1967 at the University of Michigan, where ARPANET planning was discussed in detail. It was there that the basic specifications for the underlying network were debated among us PIs. For example, Wesley Clark put forward the



concept of using an unmanned minicomputer at each location to handle all of the switching and communications functions; it was to be called an Interface Message Processor (IMP). This would offload the networking functions from the host, greatly simplify the design by requiring only one interface to be written for each host to the standard IMP, and at the same time would decouple the network design from any specific host hardware and software. Another specification had to do with the measure of reliability of the planned network; this we specified by requiring that the topological design<sup>9</sup> produce a "two-connected net," thus guaranteeing that no single failure would cause any non-failed portion of the network to lose connectivity.

Yet another requirement we introduced was for the network to provide an experience as if one were connected to a local timeshared computer even if that computer was sitting thousands of miles across the network; for this we specified that short messages should have response times no greater than 500 ms (the network design provided 200 ms at its inception). Moreover, since this was to start out as an experimental network, I insisted that appropriate measurement tools be included in the





**Figure 1. 19-node ARPANET as shown in the original RFQ.**

IMP software to allow for tracing of packets as they passed across the network, taking of snapshots of the IMP and host status at any time, artificial traffic generation, gathering and forwarding of statistics about the network, and a mechanism for controlling these measurements.

Following this April meeting, Roberts put together his outstanding plan for the ARPANET design and presented it as a paper [29] at a conference in Gatlinburg, Tennessee in October 1967. At this conference, Roger Scantlebury of the NPL also presented their aforementioned jointly published paper [22] describing a local network they were developing. It was during a conversation with Scantlebury at this meeting that Roberts first learned of the NPL work as well as some details of the work by Baran at RAND. The research by myself at MIT, by Baran at RAND, and by Davies, Scantlebury, et al. at NPL had all proceeded independently, mostly without the researchers knowing about the others' work. There was, though, some cross-fertilization: Davies had used my analytical model for data networks in his work; as a result of discussions at this conference, Roberts adopted Davies' word "packet" for the small fixed length pieces I had suggested we break messages into, and which Baran referred to as "message blocks"; its fixed length was chosen to be 1024 bits for the ARPANET design (both Baran and Davies had suggested this same length); as a result of the discussion with

Scantlebury, Roberts decided [30] to upgrade the backbone line speed from 9.6 kb/s to 50 kb/s for the ARPANET design.

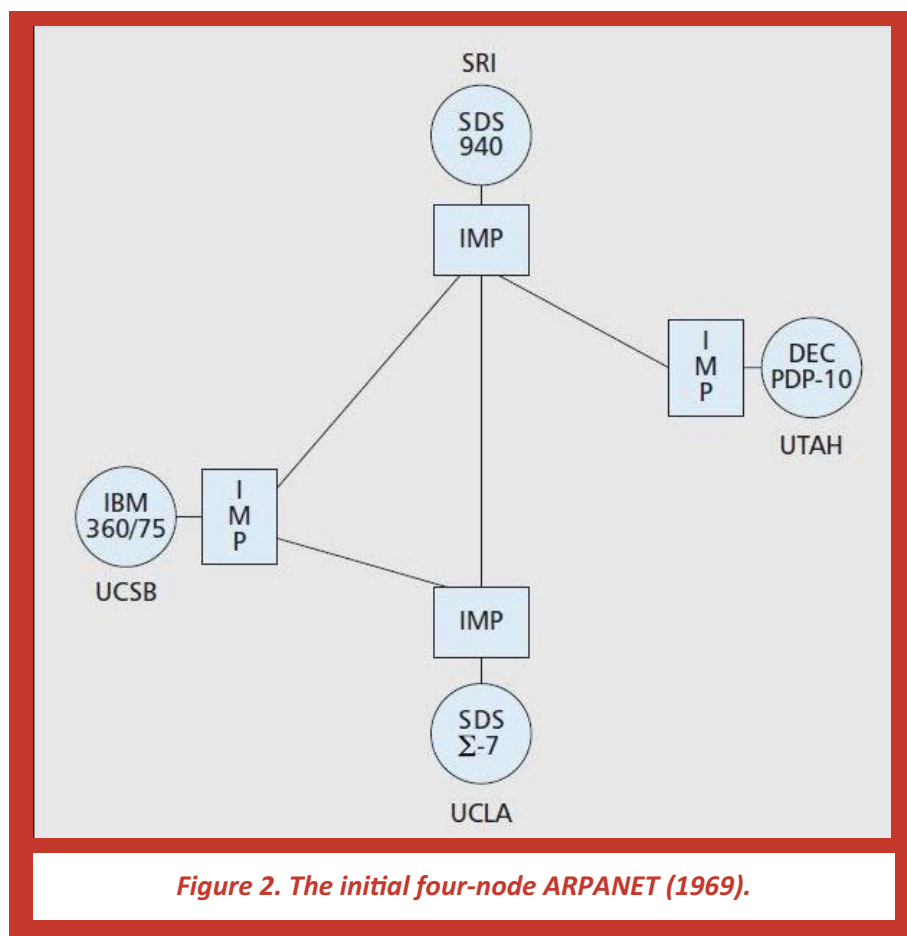
Following these 1967 meetings, a sequence of drafts for the IMP specification was prepared.<sup>10</sup> This culminated in March 1968 when Roberts and Barry Wessler produced the final version of the IMP specification, which they then discussed at an ARPA PI meeting later that month. On June 3, 1968, the ARPANET Program Plan [31] was formally submitted to ARPA by Roberts, and it was approved on June 21, 1968. The ARPANET procurement process was now officially underway.

By the end of July 1968, a Request for Quotation (RFQ) [32] for the network IMPs was mailed to 140 potential bidders. The 19-node example to be delivered by the contractor is shown in Figure 1.

The handling of data streams specified that the hosts would communicate with other hosts by sending messages (of maximum length 8192 bits) to their attached IMPs, that these messages would be broken into packets (of maximum length 1024 bits each — thus, at most 8 packets per message) by the IMP, and that IMPs would communicate with each other using these packets. The movement of packets through the subnetwork of IMPs was to be controlled by a distributed dynamically updated

routing algorithm based on network connectivity and loading as well as packet destination and priority. Errors in packet transmission between IMPs were managed by error detection and retransmission. Packets were to be reassembled into their original messages at the destination IMP before delivery to the destination host. The basic structure of this IMP specification contained contributions from a number of individuals, including my own research. Roberts had been well aware of my work since my time at MIT, where we were officemates, later stating,<sup>11</sup> "In order to plan to spend millions of dollars and stake my reputation, I needed to understand that it would work. Without Kleinrock's work of Networks and Queueing Theory, I could never have taken such a radical step." [33]

The RFQ resulted in 12 proposals being submitted in August 1968 (notably missing were IBM and AT&T). As these proposals were being evaluated at ARPA, Roberts awarded a research contract to me at UCLA in October to create the Network Measurement Center (NMC). The task of the NMC was to measure the behavior of the ARPANET by conducting experiments to determine its faults, performance, and outer limits (through the use of stress tests). I was fortunate to have a star team<sup>12</sup> of graduate student researchers, developers, and staff for this project; a number of these appear in continued roles later in this story. A week before Christmas 1968, Bolt, Beranek and Newman (BBN) won the competitive bid and was awarded the contract to develop the IMP-to-IMP subnetwork. The BBN team,<sup>13</sup> supervised by Frank Heart, produced some remarkable accomplishments. This team had selected the Honeywell DDP-516 minicomputer with 12 kb of memory for the program to be the machine on which the IMP would be based; they were contracted to implement the IMP functions by modifying the hardware and software of the DDP-516, to connect these IMPs to long-haul 50 kb/s lines leased by Roberts from AT&T under the DoD Telpak tariff, and to deploy the subnetwork. The BBN team developed an elegant host-IMP design that met the ARPA specifications; this specification was written as BBN Report 1822 [34] by Robert Kahn, who was in charge of the system design at BBN (Kahn appears later in this story in some very significant roles, as we shall see below). One of the BBN team, Dave Walden, points out that he



**Figure 2. The initial four-node ARPANET (1969).**

was most likely the first programmer on the Internet by virtue of having done code design for the IMP in their 1968 response to the RFQ. Whereas members of the BBN team were busy testing the IMP's ability to provide IMP-to-IMP data exchanges, testing the behavior of a network of IMPs was difficult to do in a laboratory environment; the true behavior was more properly tested in the deployed network with real traffic and with many nodes, which is exactly what the NMC was designed to do. Basically, BBN was given less than nine months to deliver the first IMP to UCLA by early September 1969. Their performance was outstanding. The first IMP at UCLA was to be followed by the second IMP in October to SRI, the third IMP in November to the University of California at Santa Barbara (UCSB), and the fourth IMP in December to the University of Utah. The initial network was to be that shown in Fig. 2.

These four sites were selected due to their ability to provide specialized network services and/or support. Specifically, UCLA (connecting an SDS Sigma-7 Host computer) would provide the NMC (under my supervision), SRI (connecting an SDS 940 host computer) would provide Doug Englebart's Human Intellect Augmentation System (with an early version of hypertext in his NLS system) as well as serve as the Network Information Center (under Elizabeth [Jake] Feinler's



supervision), UCSB (connecting an IBM 360/75 host computer) would provide interactive graphics (under Glen Culler's and Burton Fried's supervision), and the University of Utah (connecting a DEC PDP-10 host computer) would provide advanced 3D graphics (under the supervision of Ivan Sutherland). The fact that Heart and his team at BBN succeeded in delivering this new technology with new applications and new users in an ontime, on-budget fashion was incredible.

But this contract to develop the underlying network was only the first of the two key tasks that were needed to deploy a working packet-switched network. Recall that the other task was to create the appropriate protocols to be used by the attached (host) computers so that they could properly communicate with each other.

This second task was assigned to the four chosen ARPANET research sites to figure out on their own. Thus began another thread of innovative development that characterized the ARPANET culture. This thread actually begins in the summer of 1968 when Elmer Shapiro of SRI, in response to a request by ARPA, called a meeting of programmers from among those first sites that were to be connected into the ARPANET. Their main charge was to study and resolve the issues of host-tohost communication. Present at this meeting was one programmer from each of the first four sites to receive IMPs as follows: Steve Crocker (UCLA), Jeff Rulifson (SRI), Ron Stoughton (UCSB), and Steve Carr (University of Utah). This group, plus the many others who joined later, were soon to be named the Network Working Group (NWG) with Shapiro its first chairman.<sup>14</sup> UCLA's Jon Postel served as the Request for Comments (RFC) editor (a role he held until his untimely death in 1998). They had no official charter against which to work, and so were afforded the unique opportunity to invent and create as needed. There was no sense of qualifying membership; all one had to do was to contribute and participate. Their focus moved to the creation of high level interactions and, eventually, to the notion of a layered set of protocols (transport services below a set of application-specific protocols). Basically, this was a highly resourceful, self-formed, collegial, loosely configured group of maverick graduate students who we (the ARPA PIs) had empowered to design and implement the protocols and software for the emerging network. They took on the challenge we ceded to them and created an enduring NWG structure that later led to today's Internet Engineering Task Force (IETF).<sup>15</sup>

Once the IMP-host specification was released by BBN in the spring of 1969, the NWG began to focus on the lower level issues such as message formats. They decided to

exchange ideas through a very informal set of notes they referred to as "Requests for Comments" (RFC). The first RFC [35], entitled "Host Protocol," was written by Crocker in April 1969. Crocker became the second Chairman of the NWG early on.

We now had the two main ARPANET development efforts underway:

- ♦ A formal contract with BBN to create the IMP-IMP subnetwork
- ♦ An informal group of programmers (mostly graduate students) who were charged with developing the Host-to-Host Protocol

Things began to move rapidly at this point. The date of the first IMP delivery, scheduled to arrive to us at UCLA in early September 1969, was fast approaching. Meanwhile, at the NMC, we were busy collecting data so that we could predict performance of the network based on my earlier theory. For this, it was necessary to estimate the traffic loads that the host sites would present to the network. Roberts and I contacted a number of the early sites and asked them how much traffic they expected to generate and to which other sites. We also asked them how much traffic they would allow into their sites; to my surprise, many refused to allow any traffic from the network to use their hosts. Their argument was that their hosts were already fully utilized serving their local customer base. Eventually they relented and provided their expected traffic loads. That traffic matrix was used in the July 1968 RFQ [32] and in a paper I published [36], thereby sealing their commitment.

On July 3, 1969, two months before the IMP was due to arrive, UCLA put out a press release [37] announcing the imminent deployment of the ARPANET. In that release I described what the network would look like, and what would be a typical application. I am quoted in the final paragraph as saying, "As of now, computer networks are still in their infancy, but as they grow up and become more sophisticated, we will probably see the spread of 'computer utilities,' which, like present electric and telephone utilities, will service individual homes and offices across the country." It is gratifying to see that the "computer utilities" comment anticipated the emergence of web-based IP services, that the "electric and telephone utilities" comment anticipated the ability to plug in anywhere to an always on and "invisible" network, and that the "individual homes and offices" comment anticipated ubiquitous access. However, I did not foresee the powerful social networking side of the Internet and its rapidly growing impact on our society.

29 OCT 69 100 LOADED OP. PROGRAM CSK  
FOR BEN BARKER  
BBN

22:30 Talked to SRI Host to Host CSK

Left op imp program CSK  
running after sending  
a host dead message  
to imp.

**Figure 3. The entry in the original IMP log, which is the only record of the first message transmission on the Internet.**

On Saturday, August 30, 1969, the first IMP arrived at UCLA. On September 2, the day after Labor Day, it was connected via a 15-foot cable to the UCLA host computer, our SDS Sigma-7 machine. This established the first node of the fledgling network, as bits moved between the IMP and the Sigma-7. This is often regarded as a very significant moment in the Internet's history.

In early October the second IMP was delivered by BBN to SRI in Menlo Park, California. The first high-speed link of what was to become the Internet was connected between those two IMPs at the "blazing" speed of 50 kb/s. Later in October, SRI connected their SDS 940 host computer to their IMP.

The ARPANET's first host-to-host message was sent at 10:30 p.m. on October 29, 1969 when one of my programmers, Charley Kline, and I proceeded to "login" to the SRI host from the UCLA host. The procedure was for us to type in "log," and the system at SRI was set up to be clever enough to fill out the rest of the command, adding "in," thus creating the word "login." Charley at our end and Bill Duvall at the SRI end each had a telephone headset so they could communicate by voice as the message was being transmitted. At the UCLA end, we typed in the "l" and asked SRI "did you get the l?"; "got the l" came the voice reply. We typed in the "o," "did you get

the o?," and received "got the o." UCLA then typed in the "g," asked "did you get the g?," at which point the system crashed! This was quite a beginning. So the very first message on the Internet was the prescient word "lo" (as in, "lo and behold!"). This, too, is regarded as a very significant moment in the Internet's history.

The only record of this event is an entry in our IMP log recording it as shown in Figure 3. Here we see that on October 29, 1969, at 10:30 pm, we at UCLA "Talked to SRI Host to Host."

In November and December the IMPs and hosts at UCSB and the University of Utah were connected, respectively, thus completing the initial four-node network. Further IMP deliveries were halted until we had an opportunity to test this four-node network, and test it we did. Among other things, we were able to confirm with measurements some of our theoretical models of network delay and throughput as presented by Gerry Cole [38].

The ARPANET had now been launched. We now turn to the story of its rollout through its first decade.

## THE FIRST DECADE: FOUR NODES AND THEN THE WORLD

By the time the first four nodes were deployed in



December 1969, Roberts (who had succeeded Taylor in September to become the IPTO director) once again met with the NWG and urged them to extend their reach beyond what they had articulated in their first RFC [35], "Host Protocol." This led them to develop a symmetric Host-to-Host Protocol, the first implementation of which was called the Network Control Program (NCP) and was described by Crocker in RFC 36 in March 1970 [39]. This protocol stack was to reside in the host machines themselves and included a hierarchy of layered protocols to implement more complex protocols. As NCP began deployment, the network users could begin to develop applications. The NCP was the first protocol stack to run on the ARPANET, later to be succeeded by TCP/IP. The trajectory of protocol stack development touched on below is another example of multiple possible paths that led the way from the ARPANET as it evolved into the Internet.

After the short evaluation period following the initial four-node deployment, a continual succession of IMPs and networks were then added to the ARPANET. In May 1970, at the AFIPS Spring Joint Computer Conference, a

**The reaction of the computer manufacturers to this ARPANET phenomenon was to create proprietary network architectures based on their own brand of computers.**

landmark session was devoted to the presentation of five papers [40] regarding the newly emerging ARPANET technology; these papers were packaged into a special ARPA pamphlet that was widely circulated in the community and spread information of the then-current technology that had been deployed. (Two years later, in May 1972, another key session at the same conference was devoted to the presentation of five papers [41] that updated the ARPANET state of the art; this, too, was packaged into a second special ARPA pamphlet.) In mid-1970 the first cross-country link was added with a connection from UCLA to BBN, and by July the network contained 10 IMPs. The net grew to 15 IMPs by March 1971. In September 1971 BBN introduced a terminal interface processor (TIP) that conveniently would allow a terminal to connect directly to the ARPANET without the

need to connect through an attached host. Later in the year, BBN slipped in a "minor" feature called electronic mail. Electronic mail had existed since the mid-1960s for standalone timeshared computer systems, but in late 1971 at BBN, Ray Tomlinson added a small patch to it that allowed the mail to pass between different computers attached to the ARPANET using an experimental filesharing network program called CPYNET. Once he saw that it worked, he sent an email message to his group at BBN announcing this new capability, and so "The first use of network email announced its own existence." [42]. This capability went out as a general TENEX release in early 1972. By July 1972, Roberts added a management utility to network email that allowed listing, selective reading, filing, forwarding, and replying to email messages. In less than a year email accounted for the majority of the network traffic. The network's ability to extend communication between people was becoming evident, a nascent image of Lick's vision.

Later that year, in October 1972, the first public demonstration of the ARPANET technology took place at the International Conference on Computer Communications (ICCC) in Washington, DC. Kahn, who by now had been hired into ARPA by Roberts, organized this large and very successful demonstration in which dozens of terminals in Washington accessed dozens of host computers throughout the United States in a continuously reliable fashion for the three-day duration of the conference.

The reaction of the computer manufacturers to this ARPANET phenomenon was to create proprietary network architectures based on their own brand of computers.<sup>16</sup> The telephone company continued to ignore it, but the open network that was the ARPANET thrived.

Soon, additional networks were added to the ARPANET, the earliest of which were those whose origins came out of work on wireless networking. Connecting the ARPANET with these different networks proved to be a feasible but not seamless interoperability issue, and it received a great deal of attention. The interconnection of networks was referred to as "internetworking" during the 1970s, a neologism from which the expanded ARPANET was eventually renamed as the Internet.

Let us briefly trace the work on wireless networking that led to these additional networks, which themselves forced attention on improving interoperability solutions. As pointed out above, these networks were based on wireless multi-access communications in which a shared channel is accessed by many users. By late 1970, Norm Abramson had developed AlohaNet [43] in Hawaii, a 9600

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b/s packet radio net based on the novel “unslotted (pure) ALOHA” multi-access technique of random access. In this scheme (unsynchronized) terminals transmit their fixed length packets at any time over a shared channel at random times; if more than one transmission overlaps (i.e., collides), then destructive interference prevents any of the involved packets from succeeding. This tolerance of collisions was a departure from the more standard methods of wireline communications to control multi-access systems that used demand access methods (queueing, polling, etc., as mentioned earlier) and allowed only one transmission at a time (thus precluding such collisions). In 1973 Abramson calculated the capacity of the unslotted ALOHA system [44], which had a maximum efficiency of 18 percent, and in 1972 Roberts calculated the capacity of a synchronized version (i.e., slotted ALOHA) [45] whose capacity was doubled to 37 percent. However, these analyses ignored an essential issue with random access to shared channels: that they are fundamentally unstable, and some form of dynamic control was needed to stabilize them, for example, a backoff algorithm to control the way in which collided transmissions are retransmitted. This stability issue was first identified and addressed by Lam and myself [46, 47].

It is interesting to note that the ALOHA systems studies eventually led to an investigation of carrier sense multiple access (CSMA) as another wireless access method. CSMA itself led Robert Metcalfe to consider a variation called CSMA with collision detection (CSMA/CD), which was the basis for the original Ethernet development. Based on these concepts, Metcalfe and David Boggs implemented CSMA/CD on a coaxial cable network, which was up and running by November 1973. In sum, they created the Ethernet, which is today perhaps the world's most pervasive networking technology [48]. Ethernet is crucial to the story of NCP and TCP/IP, for researchers at Xerox

PARC built on this technology in efforts to address the challenges of internetworking. Implemented in 1974 and published in 1975, the PARC Universal Packet (PUP) remained an internetwork architecture as late as 1979 [49]. PUP was one potential means through which to improve on NCP, although as we see below, that role was later taken on by TCP/IP. This is one of many stories that call out for more research into the histories and the individuals involved.

Let us now return to the story of the above-mentioned wireless technologies to help explain the motivation that led to TCP/IP (as different from that which motivated PUP). These technologies led to wireless networks that attached to the ARPANET, thereby exposing the nature of the problems of supporting connectivity among heterogeneous networks.

The first step was taken in December 1972, when an IMP in California used a satellite channel to connect to AlohaNet through an ALOHA host in Hawaii. Thus, the ARPANET, running the existing host-to-host Network Control Protocol, NCP, was now connected to a ground radio packet network, the AlohaNet. This was the first new network to connect to the ARPANET. AlohaNet had its own protocol and was working independent of ARPANET, yet a gateway provided internetwork connectivity between the two. In 1972 Roberts extended the ARPANET to Norway over a leased line that ARPA had already installed to receive seismic data and then extended it to London in the United Kingdom. This was the ARPANET's first international connection. In London Peter Kirstein then built a gateway to connect the ARPANET to a network built with another protocol between the U.K. universities. This was another case of different networks “internetworking,” and as this function became an increasingly important focal point of ARPANET development, the network came to be known as the Internet to reflect this growth. NCP was now handling the network- to-network interconnection of AlohaNet and the U.K. university network, both of which were attached to the ARPANET. The problems resulting from interconnected heterogeneous networks were becoming clear, and included the network-to-network protocol conversion needed between any (and every) pair of networks that were interconnected. It was clear that the combinatorial complexity of this pairwise protocol conversion would present considerable problems as the number of attached networks scaled up. TCP/IP was soon to emerge as the response chosen to address these problems.

At DARPA<sup>17</sup> in early 1973, Kahn was the program manager responsible for, among other things, the ground packet radio network and the satellite packet radio network. He



recognized the differences between the ARPANET running NCP, and these two radio networks. As a result, he set out to design a scalable end-to-end protocol that would allow dissimilar networks to communicate more easily. In the summer of 1973 Kahn discussed his approach for dealing with this internetwork complexity with Vint Cerf of Stanford who had considerable knowledge of NCP, since he had been a key member of the UCLA software group involved in the NCP design. Together, they drafted a detailed design of a new protocol, the Transmission Control Program (TCP). TCP was to take over the NCP's functions, but handle them in a more uniform manner: it would allow applications to run over an internetwork while hiding the differences between network protocols by using a uniform internetwork protocol. They distributed this design at a computer communications conference held at Sussex University in September 1973. (In October 1973 Roberts left IPTO to become CEO of TELENET, the first commercial packet switching network carrier.) By 1974, Cerf and Kahn fleshed out their design and published a definitive paper [50] on TCP. Underlying TCP was the key idea of an open network architecture that allowed packet networks of different types to interconnect with each other and for computers to exchange information end-to-end across these interconnected networks.

This contribution by Cerf and Kahn was a critical step in the development of the Internet. In 1973–1974 DARPA commissioned three independent implementations of TCP: Cerf at Stanford University, Tomlinson at BBN, and Kirstein at University College London. In addition, David Clark of MIT worked on a compact version of TCP for the Xerox Alto personal workstation in the mid-1970s and later for the IBM PC desktop computer; David Reed, also of MIT, was working on internetworking among high-performance computers on LANs for the Laboratory for Computer Science Network (whose work was merged with the general TCP project in 1976). In August 1976 these implementations led to the first experimentation using TCP to connect two different networks: the packet radio network using Stanford's TCP implementation, and the ARPANET using BBN's TCP implementation. Following that, in 1977, Kahn implemented the satellite reservation protocol Roberts had designed, creating a second path from the ARPANET to the United Kingdom, sharing the capacity of a 64 kb/s Intelsat IV satellite broadcast channel among a number of ground stations in Europe and the East Coast of the United States. This Atlantic Packet Satellite Net (later to be called SATNET) was the ARPANET's second international connection. This was the second two-network TCP demonstration. Then a three-network demonstration of TCP was conducted on

**“Underlying TCP was the key idea of an open network architecture that allowed packet networks of different types to interconnect with each other and for computers to exchange information end-to-end across these interconnected networks.”**

November 22, 1977, when the packet radio network, SATNET, and ARPANET were interconnected to allow an Internet transmission to take place between a mobile packet radio van at SRI and a USC/ISI host computer (both in California) via an intercontinental connection through University College London. This impressive feat was the first three-network TCP-based interconnection.

This first version of TCP only supported virtual circuits at the transport level (which is fine for applications that require reliable transmission). But it failed to support, among other things, real-time traffic such as packet voice where many aspects of the session flow were more properly handled by the application as opposed to the network. That is, real-time traffic called for support of an “unreliable” transport mechanism that would cope with missed packets, packets with errors, out-of-order packets, delayed packets, and so on. The use of unreliable transport support was already in use with NCP, prior to TCP; specifically, the early ARPANET IMP protocol allowed for unreliable transport by use of what was called type 3 packets (also known as “raw” messages), which were introduced by Kahn in the BBN 1822 report. However, BBN was concerned that the uncontrolled use of these packets would degrade the network performance, so they regulated the use of type 3 packets to be on a limited, scheduled basis. In 1973–1974 Danny Cohen of USC/ISI implemented a Network Voice Protocol (NVP) [51] under ARPA support and requested BBN to allow him to use type 3 packets; with Kahn's influence, BBN allowed this. Cohen's real-time network voice experiments required the ability to cope with unreliable data transport. The early Version 1 design of TCP in 1974 did not support it, nor did Version 2 when it was implemented around 1977.

It was around this time that pressure for supporting unreliable transport in TCP came from Cohen, now joined by John Shoch and Reed, and with involvement from Crocker and Bob Braden. That is, they advocated modifying TCP such that type 3 packet functionality would be supported alongside reliable data transport. Cohen convinced Jon Postel of this, and Postel added a further concern, addressing layer violations, stating “We are screwing up in our design of internet protocols by violating the principle of layering. Specifically we are trying to use TCP to do two things: serve as a host level end-to-end protocol, and to serve as an Internet packaging and routing protocol. These two things should be provided in a layered and modular way. I suggest that a new distinct internetwork protocol is needed, and that TCP be used strictly as a host level end-to-end-protocol.” [52] Postel then went on to describe how to break TCP into “two components: the hop-by-hop relaying of a message, and the end-to-end control of the conversation.” A robust internetworking solution was no easy task, and today’s TCP/IP was built with much experimentation on the ground laid by NCP.

Thus, there was a clear call to cleave TCP, splitting the function of network layer connectivity, which involved addressing and forwarding, from its transport-layer end-to-end connection establishment, which also involved flow control, quality of service, retransmission, and more. TCP Version 3 (1978) introduced the split into two components, but it was only in TCP Version 4 (1980, with an update in 1981) that we see a stable protocol running that separated out the Internet Protocol (IP) from TCP (which now stood for Transport Control Protocol) and was referred to as TCP/IP. This version has come to be known as IPv4. Along with the split into TCP and IP, the capability to support unreliable transport (i.e., type 3 packet functionality) was included. The formal name for this unreliable transport support was the User Datagram Protocol (UDP) [53].

In 1980 the U.S. Department of Defense (DoD) declared [54] the TCP/IP suite to be the standard for DoD. In January 1983, TCP/IP became the official standard [55] for the ARPANET; after a short grace period of a few months, no network was allowed to participate in the Internet if it did not comply with IPv4. Of course, Internet protocols never stop developing, and the 1998 upgrade to Version 6 dramatically extends the address space and introduces some significant security enhancements. It is still in the process of being deployed worldwide.

Meanwhile, as the 1970s rolled out, in addition to the ARPANET and TELENET, other packet networks were being designed across the globe in this period. Peter Kirstein, in

his earlier paper [56] in this IEEE Communications Magazine History of Communications series, addresses much of the international work, especially the U.K. story (to which we refer the reader for more details). As a result of these national and international activities, an effort, spearheaded by Roberts, was put forth that resulted in the International Consultative Committee on Telephone and Telegraph (CCITT) Recommendation X.25. This agreed-upon protocol was based on virtual circuits — which was to be the CCITT’s own equivalent of TCP — and was adopted in 1976 [57]. During this period, the Network Measurement Center (NMC) at UCLA was deeply involved in measuring, testing, stressing, and studying the ARPANET. Bill Naylor and I published a summary of the tools used by the NMC as well as details of a weeklong measurement and evaluation of the results in 1974 [58]. In 1976 I published the first book that described the ARPANET technology, including its analytical modeling,

**“Of course, Internet protocols never stop developing, and the 1998 upgrade to Version 6 dramatically extends the address space and introduces some significant security enhancements.”**

design, architecture, deployment, and detailed measurements. A summary of the ARPANET principles and lessons learned appeared in a 1978 paper [59] after almost a full decade of experience with the use, experimentation, and measurement of packet networks; this paper was part of a special issue on packet communications which contains a number of key papers of that era [60]. One of the first measurements we made was to determine the throughput from UCLA to UCSB in the initial four-node network shown in Figure 2; note that there are two paths between these two nodes. Whereas only one path was tagged as active in the routing tables at any one time, we found that both paths were carrying traffic at the same time since queued traffic continued to feed one of the paths when the other path was tagged. Among the more spectacular phenomena we uncovered were a series of lockups, degradations, and traps in the early ARPANET



technology, most of which were unintentional and produced unpredicted side effects. These measurements and experiments were invaluable in identifying and correcting design issues for the early ARPANET, and in developing a philosophy about flow control that continues to inform us today. Moreover, it provided us, as researchers, a wealth of information for improving our theoretical models and analysis for more general networks. In July 1975 responsibility for the ARPANET was given to DCA. This terminated the systematic measurement, modeling, and stress testing that the UCLA NMC had performed for almost six years, and was never again restored for the Internet.<sup>18</sup>

It is outside the scope of this column to address Internet histories beyond those of its early period as the ARPANET. Likewise, I have not done justice to the untold stories that abound, but I hope to have convinced the reader that many people contributed to its success. This early history of the Internet, the first decade of design and deployment of the ARPANET, laid foundations on which today's networks depend and continue to develop.

## ACKNOWLEDGMENT

I want to thank Bradley Fidler, Mischa Schwartz, and the reviewers of this column and reprint for their helpful comments and suggestions.

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## ENDNOTES

*1 Later that year on October 4, I experienced a widely shared feeling of surprise and embarrassment when the Soviet Union launched Sputnik, the first artificial Earth satellite. In response, President Eisenhower created ARPA on February 7, 1958 to regain and maintain U.S. technological leadership.*

*2 Chapter 3 of my dissertation [16] elucidates this problem and the role of the Independence Assumption.*



**3** One of the important advantages of using packets turned out to be that short messages would not get “trapped” behind long messages; I was able to show this gain in response time exactly.

**4** Access to my simulation notes can be found at [http://ucla.worldcat.org/title/leonard-kleinrocks-correspondence-course-and-research-notes-1961-1972/oclc/263164964?referer=brief\\_results](http://ucla.worldcat.org/title/leonard-kleinrocks-correspondence-course-and-research-notes-1961-1972/oclc/263164964?referer=brief_results)

**5** Defense Communications Agency, which was renamed in 1991 to be today’s (2010) Defense Information Systems Agency — DISA.

**6** This sharing of resources was the primary motivation for creating the ARPANET. Paul Baran developed a network design (described above) that would maintain communications — and specifically, Second Strike Capability — in the event of a nuclear attack by the USSR. His and my work served different aims. When ARPA began work on the ARPANET, my work was used for the reasons described herein. His application to military communications gave rise to the myth that the ARPANET was created to protect the United States in case of a nuclear attack. This is not to take away from Baran’s accomplishments; indeed, by the time the ARPANET began in 1969, he had moved on to different projects, including the Institute for the Future (he stepped back into the ARPA foray in 1974–1975 to recommend that an early commercial version of the ARPANET be instituted beside the original research-driven network).

**7** In sharp contrast to ARPA’s enthusiasm for networking, in the early 1960s, when I introduced the ideas of packet-switched networks to what was then the world’s largest networking company, AT&T, I met with narrow-minded and failed thinking, and was summarily dismissed by them. They commented that packet switching would not work, and even if it did, they wanted nothing to do with it. Baran had a similar reaction from AT&T.

**8** A major challenge for such a network was that it would connect computers with incompatible hardware and software.

**9** To assist with the topological design, Network Analysis Corporation (NAC), whose CEO was Howard Frank, was brought in as a contractor.

**10** Among those involved in these first drafts were Frank Westervelt, Elmer Shapiro, Glen Culler, and myself.

**11** Roberts also goes on to say that my dissertation was “critical to my standing up to them and betting it would work.”

**12** Key members of my UCLA team included a research team (Jerry Cole, Al Dobieski, Gary Fultz, Mario Gerla, Carl Hsu, Jack Zeigler), a software team (Vint Cerf, Steve Crocker, Gerard DeLoche, Charley Kline, Bill Naylor, Jon Postel), a hardware engineer (Mike Wingfield), and others.

**13** Key members of Heart’s team included Ben Barker, Bernie Cosell, Will Crowther, Robert Kahn, Severo Ornstein, Truett Thach, Dave Walden, and others.

**14** The names of some of the other key individuals who participated early on in the NWG include Bob Braden, Vint Cerf, Danny Cohen, Bill Duvall, Michel Elie, Jack Feinler, Jon Postel, and Joyce Reynolds.

**15** It is remarkable how effective the RFCs, the NWG and the IETF have served the network community. In spite of the fact that they are loosely structured and involve large numbers of outspoken professionals, they have been able to move forward on a number of critical Internet issues.

**16** Among the proprietary networks were IBM’s SNA and DEC’s DECnet.

**17** ARPA was renamed DARPA in March 1972 when the word “Defense” was prepended.

**18** The work of the NMC required a strong degree of cooperation from BBN since it was they who controlled any changes to the network code and architecture. At the NMC, each time we discovered a lockup, hardware problem, or other measured network problem, we alerted BBN so that they would take corrective action. Over time we developed an efficient working relationship with them, and errors were dealt with more expeditiously. It is worthwhile noting that the history of packet networks has met with institutional impediments to its progress, as have so many other technical advances over the course of history. In this case I have called out three with which I was personally involved: AT&T’s lack of interest in packet switching, the researchers’ reluctance to connect to the early network, and the above-mentioned negotiation with BBN.

## About the author

Leonard Kleinrock’s contributions to the internet are well-documented. Over the span of his 50-year career at UCLA, he has graduated 48 PhD students and taught thousands more. He judges these interactions and the research they have produced with him as his most gratifying and enriching activities. Outside of the University, Kleinrock has co-founded a number of successful companies and enjoys biking, skiing, marathoning, karate and world travel. His webpage can be found at [www.lk.cs.ucla.edu](http://www.lk.cs.ucla.edu).

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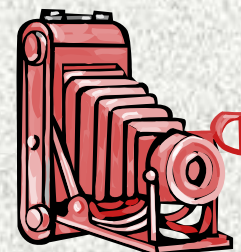
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