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Carver Mead: "It's All About Thinking," A Personal Account Leading up to the First Microwave Transistor

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ABSTRACT This article is the second in a continuing series of biographical pieces on individuals who have made significant contributions to microwave science, technology and applications over the course of their careers. It is intended to bring to the reader, especially those new to the field, a portrait of an individual who serves as a role model for the community and a detailed description of their accomplishments. At the same time, it tries to bridge with commonality, the experiences of the subject with those of the scientists, engineers and technologists who are following in their footsteps or hope to establish a similar record of success. The articles are composed only after an extensive face-to-face interview with the subject and are helped immensely by additional input and editing by the subjects themselves. The focus of this article is Caltech Professor Carver A. Mead, perhaps best known for his ground breaking work on VLSI design techniques, but also for the first demonstration of the GaAs MESFET and the originator of Moore's Law. However, Professor Mead has contributed so much more, and to so many disciplines other than electrical engineering. From his own description of his interests and focus, he is a chameleon of knowledge, scrambling into, blending with, and then distinguishing himself in a new field every thirteen years or so, over a career spanning seven decades and still going. At age 86, his latest paper, on an intuitive approach to electromagnetically coupled single-electron quantum systems, was just published this summer. Although we cannot do justice to all his contributions, we hope the reader will see something of the polymath in Professor Mead as we focus just on his earliest work, where he single handedly conceived, constructed, and tested the world's first Schottky barrier gate transistor in his modest laboratory at Caltech.

INDEX TERMS Carver Mead, California Institute of Technology, MESFET, transistors, microwave history.

Carver Mead[1] grew up as an only child under what most people would classify as significant social isolation. He was born in 1934, at a hospital in Bakersfield, California, then thirty miles from his home along the north fork of the

[1] This article was compiled after a series of two interviews with Professor Mead on August 26th and 27th, 2020. Normally, the interviews would have been face-to-face, but Covid 19 restrictions forced their conversion into video conference sessions. Although the author has been associated with the California Institute of Technology since the late 1980's he did not know Professor Mead personally before this interview, although he occasionally passed him in the elevators and hallways of the Moore Electrical Engineering building on campus, where Professor Mead spent a large part of his time. After delving more deeply into Professor Mead's background, and especially after the series of interviews with him, the author's admiration has only grown stronger. I think anyone who reads this article will feel the same awe and inspiration, and perhaps feel that science is in good hands so long as people like Carver Mead are given free rein to act upon their curiosity.

Kern River, where his father Arnold Mead, and his mother, Grace, lived at the remote Kern River 3 Hydroelectric Power station. At age 2, he moved even further from "civilization", relocating to one of the Big Creek Power Plants in the Sierra Mountains, an approximately two and a half hour drive northeast of Fresno, California. Arnold Mead had heard about good long term job openings for power station operators in the late 1920's, the start of the great depression in the US. After some intensive self-studying, he was able to trade his position as a delivery driver for life in the beautiful, but isolated mountains of California. The Meads lived in a small community of some 14 families in Southern California Edison provided cottages for the staff who monitored and maintained the vast series of hydroelectric power stations strung across California's mountain rivers. Two of these power station "camps" shared a single room elementary school with one teacher and about 20 children for all of grades 1–8. The classwork was divided by age group with the lone teacher moving from group to group for the in-person instruction, while those not receiving a lecture worked on their own. Some of the cleverer of the younger age group (and you can already guess that Carver was one of these) could listen in on the lessons being given to the older children when they were bored with their own assignments. Carver's mother helped out as a part-time school bus driver and Carver himself (his unusual first name comes from his father's best friend, whose middle name was Carver), seemed perfectly adapted and satisfied with his situation. When he wasn't outdoors hiking, fishing or hunting, he passed his free time learning about power station technology, especially electronics, both via his father's annual tours of the facility and from "show and tell" components brought home for examination and use in various projects. Carver was also able to order books off a list that were mailed to him from the nearest library. He became very interested in radios and naturally, which I attribute at least partially to his isolation, was attracted to the ham (amateur radio) community[2]. With help from one of his neighbors and an uncle, who were both active hams, and with savings he had accumulated from odd jobs, including trapping and selling furs via mail to Sears Roebuck and Company, Mead was able to purchase and build up radio transmitter and receiver equipment by tapping the vast supply of cheap war surplus electronics available at the time. He set himself up in the 40 meter band, where he could reach Asia and Europe with Morse code, and by age 15 had acquired his license and call number: W6HJQ.

When he graduated from 8th grade his parents decided to send him to high school in Fresno, rather than to the more local facility – a 60-plus minute bus ride down the mountain. Carver was able to move in with his grandmother who lived on the north side of the city, a short bicycle ride from Fresno High School. He was lucky to find that there was one elective class offered on electronics taught by Sherman Hewitt, which he signed up for all 4 years. Carver's self-taught background in amateur radio served him well in Fresno. He was able to add a commercial radio operator's license to his amateur ham credential, and thus get work after school as a transmission engineer in one of the five commercial AM radio stations in Fresno at the time. He also helped out at an electronics repair shop. Upon joining the ham radio club in Fresno, he began meeting college-aged adolescents and technically inclined adults, who recognized Carver's drive and ambition to learn about and understand electronics. They suggested he look beyond Fresno to a really good technical university upon graduating high school. His applications to both Stanford and Caltech were accepted, and fortunately for Caltech, he arrived in Pasadena to begin his freshman year there in 1952.

Although Carver claims he was way over his head as a freshman when compared to students who had come from much more rigorous academic backgrounds, he managed to hold his own, although he is not proud of his grades. Double Nobel Laureate Linus Pauling – Chemistry 1954 and Peace Prize 1962 – was his freshman chemistry professor and remains his most admired teacher ever. Pauling's intuitive approach to conveying quantum concepts stayed with Carver for his entire career and later helped spawn a ten year quest to change the way physics was taught at Caltech. Even at this time, he had a reputation for asking tough questions of his professors and approached his coursework by trying to gain an understanding that went beyond the mathematical formalisms. His parents' modest financial means meant that Carver had to work throughout his years at Caltech. He had a variety of in-school, after-school and full-time summer jobs, including working as a technician for the physics department. This proved to be a fortunate hardship, as it exposed Carver to graduate students who he could ask for advice, but also who he could compare himself with, and as a result realize that his understanding of physics and math was not as severely constrained as his grades might indicate. In his junior year, Carver was working at a nearby Pasadena company, Consolidated Engineering Corp.[3] That made sonic transducers for the oil and gas industry. He asked his boss if Consolidated would donate some of the transducers he was working on to Caltech to be used in an undergraduate EE lab course he was interested in setting up. They agreed, and the lab was so successful that Carver became the Teaching Assistant for the course while still in his senior year at Caltech. This was his first exposure to teaching, and he loved it.

After completing his senior year, Carver had intended to go out and search for a job in the electronics industry, but EE professor Hardy Martel (another of Carver's admired mentors whose "strength was in his basic, intuitive grasp of ideas and how things worked," [2]) argued in favor of continuing on to a Master's degree in anticipation of a much higher career salary scale. At this point, David Middlebrook (noted author of *An*

[2]The term "HAM" referring, since the 1920's, to amateur radio operators, is not an acronym but rather a slight applied to telegraphy operators with poor coding skills who were called – ham fisted, i.e. amateurs [1].

[3]Founded by Herbert Hoover Jr., a graduate of Caltech and son of US President Herbert H. Hoover, later Consolidated Electrodynamics and a subsidiary of Bell and Howell.

Introduction to Junction Transistor Theory [3] and a founder of modern power electronics) had just arrived at Caltech from Stanford and was teaching electronics, and specifically transistor theory and design. Mead took, and loved his class, and hooked up with Middlebrook, who became his advisor. At this point Carver also got a chance to lecture a bit as a teaching assistant for an undergraduate introductory electronics class, which earned him some money and which he really enjoyed.

When his Master's degree was complete Carver wanted to continue on for a PhD. However, the department was skeptical of his abilities to succeed based on his less than stellar academic grades. They devised a "mini" oral exam for him, which some on the committee hoped would allow them to deny him a slot. However, Mead did so well, he not only was accepted into the PhD program, but the mini oral became a fixture at Caltech that all future Master's students would have to pass before being admitted for a PhD. Carver stayed with David Middlebrook that year and together they began thinking about the physics of the transistor junctions, especially understanding the behavior of minority carriers.

In his second year of grad school, Middlebrook took off for a sabbatical and Mead was asked to teach the graduate level transistor course. When he began, he had a very hard time trying to teach the class the way Middlebrook had taught it. The students were more senior and there were even a group of professional engineers attending who did not appreciate his attempt to be a "little Middlebrook." After a long hike in the mountains he had an epiphany that would have a major impact on his teaching career – he decided to approach the course material through a more intuitive understanding of the concepts, following up with the rigorous mathematical models and the application of equations, only after a sound grasp of the underlying physics had been obtained. A good example of this method can be found in one of Mead's recent lectures on his unique approach to general relativity [4]. He also appreciated deeply, and tried to communicate that real world problems could almost never be solved exactly, in spite of what most physicists and engineers were taught, and that understanding the limits of the models and the approximations that would have to be employed was critical. By the end of the semester he had won over the students and realized that his own approach to learning hard material could also be a valuable tool for others. His later classes, many text books, and even his papers were all approached from this viewpoint.

Already married with children, Carver was very pleased when Middlebrook introduced him to some folks at Pacific Semiconductors (later TRW Semiconductors, and now Northrop Grumman Space Technologies) in nearby Culver City, California who were looking for some long term consultants for their transistor development program. Mead worked with James Buie (noted inventor of TTL logic) and others at Pacific Semiconductor for more than 5 years (throughout his graduate school days). It helped support his family and exposed him to state-of-the-art commercial design and fabrication people – a strategy he would continue throughout his long career.

In his third year of graduate school, Mead found his thesis topic – the physics of fast transistor switching and charge storage effects, and he began experimenting on his own. Middlebrook was busy with his second book focused on transistor amplifiers [5], and Carver was pretty much left to his own devices. Guided by John Linvill's approach to transistor modelling – which separated the small signal linear minority-carrier behavior from the highly non-linear junction equations [6], Mead derived a detailed model for charge distribution and junction behavior that could be used to design and characterize real world devices for logic circuits and switching power supplies [7], [8], [9].

Near the end of his thesis work in 1959, the EE department at Caltech was in transition, and Carver, with his now very extensive experience and industry connections in modern transistor technology was asked if he wanted to stay on as a faculty member. Supporting three children who were solidly at home in Pasadena, it was a natural choice, although even then, it was not typical for graduate students to take permanent positions at their graduating institutions. As it turned out, it was good for Mead and good for Caltech in the long run.

Carver had just experienced another epiphany around this time, when Leo Esaki (1973 Nobel Laureate, and inventor of the Esaki tunnel diode) came to Caltech to give a talk on his newly discovered tunneling device. This demonstration of quantum mechanical behavior in a solid-state device brought Mead back to his early classes with Linus Pauling, and he became very interested in understanding the phenomenon. He started experimenting with highly doped germanium and then switched to aluminum-aluminum oxide-aluminum [10]. By understanding in detail the barrier physics, Mead was able to create triodes and vacuum emitter diodes that worked with majority carrier tunneling. These later became known as the first hot electron devices [11].

In 1962, Carver hooked up with William Spitzer who had just come over to Pasadena (Bell and Howell) from Bell Laboratories and was setting up a lab to work on barrier devices. Carver asked Spitzer if, while he was waiting for his lab to be equipped, he would like to team up on some experiments at Caltech. Together they did some ground breaking studies of photoemission [12], band gaps [13] and barrier height measurements [14], which helped Carver get some much needed recognition in the burgeoning solid-state device community. He was also helped by mentor and friend Albert Rose of RCA (photoconductivity expert and TV tube pioneer, 1979 Edison Medal winner). The detailed study of thin metal-insulating-metal barriers, and metal-semiconductor "Schottky" junctions, occupied Mead for the next 15 years and he has more than 80 refereed papers on this subject [15].

During this early period of Mead's appointment at Caltech two other significant contacts appeared unannounced at his office door [16]. One was Arnold Shostak, who was a program manager at the Office of Naval Research. After hearing what Mead was working on, Shostak asked him if he wanted some research funding (this will be a shock to anyone working in science today!). Mead had a start-up grant from the

University that totaled something like \$3500. Shostak was offering \$10K-\$15K. All he asked for was a short proposal and a budget – neither of which Carver had generated before. With some help from Caltech contracts (grants office), he had his first government funded research program and it continued for the next 15 years.

The second knock on the door came in early 1960, from Gordon Moore (Caltech PhD and founder of Fairchild Semiconductor and Intel). Carver had not met Moore before, but he did know about Fairchild. Moore wanted to know what Mead was working on, and then he offered him two large manila envelopes full of discrete transistors which he thought could be useful for lab classes (2N697s and 2N706s, two of Moore’s early successes – the 2N697 was Fairchild’s first marketed transistor and came out in 1958). The two men immediately hit it off, and Gordon invited Carver up to Fairchild for a tour and a talk a few weeks later. This began a weekly consulting gig that would last until Moore and co-founder Robert Noyce left to form Intel in 1968. On his trips to Fairchild, Carver would meet with Moore before and after his day at the Fairchild lab and he got to know the technical staff well, collaborating with Andrew Grove (who was teaching a similar transistors class to Mead’s at UC Berkeley and finishing his very well-known textbook [17], which Carver helped review), Bruce Deal and Edward Snow [18]. This strong relationship and interaction with the Fairchild engineers, and with Moore in particular, would extend through to this day.

As mentioned earlier, one of the topics that Mead and Spitzer were working on involved measuring the barrier heights of various metal-semiconductor interfaces. For III-V materials the barrier height was nearly independent of the applied metal contact even though the work function of the different metals was changing significantly. This was attributed to semiconductor surface states that could absorb significant charge from the metal without much change in the surface energy (Fermi level pinning). However, for most II-VI materials, Cadmium Sulfide in particular, the barrier energy varied directly with the metal work function. Mead and Spitzer worked with a mixed crystal of Cadmium, Sulfide-Selenide with varying concentration of sulfide, and found a transition where the Fermi level pinning disappeared. They attributed the change to a quantum state transition from distributed to localized wavefunctions (ionic to covalent transition) and wrote it up for *Physics Review Letters* [19]. The paper caused a ruckus, with half the reviewers not believing the measurements could be correct, and the other half not realizing there was anything new in the revelation. It took a chance meeting with John Bardeen (BCS theory, transistor inventor, two time winner of the Nobel Prize in Physics – 1956 and 1972) who was visiting Caltech for a talk, to settle the issue in favor of Mead and Spitzer. Their second paper on the subject, evaluating additional semiconductors, was less controversial [20] and confirmed their explanation that blended quantum theory with traditional crystallography. This very careful measurement, plus a first principles understanding of the observed phenomena, is steadfast in all of Mead’s work. The focus on metal-contacts [21], especially Schottky barriers and tunnel junctions [22], which blend the quantum and electronic worlds, led to the demonstration which is the principle subject of this bio-review: the first microwave transistor.

The week of November 22nd, 1965 had Carver in Dallas Texas where he was regularly consulting at Texas Instruments (at the same time he was also consulting for rival Fairchild, *all above board*, in case you were wondering). He was talking with materials chemist, Louis Bailey at TI who was working on epitaxially grown GaAs, and he asked Bailey if he had ever grown any doped GaAs on insulating substrate material. Most of the time the epitaxial layers were grown on heavily doped substrates for eventual use as bipolar devices. As it turned out, Bailey had a small sample of epitaxially formed n-type GaAs on a semi-insulating wafer. Carver was hoping to try out an idea he had been thinking about for a while: to make a field effect transistor with a Schottky barrier gate rather than a p-n junction. The goal was to try to avoid introducing minority carriers to the depletion channel when the gate junction is forward biased because it is a very slow process to remove them, and this has a dramatic impact on the switching speed of the transistor. Even in forward bias, as would occur in the “on” period of a “class C” amplifier, a Schottky gate would not introduce any majority carriers and the recovery time would be vastly improved. The Schottky gate also has an ideal reverse bias characteristic with very low saturation current.

When Carver returned to Pasadena, he spent Thanksgiving day in the lab etching down the epitaxial layer on his very tiny one wafer sample, step-by-step, until he could see punch through from a metallic contact at 10V. The process he was using was a rough timed chemical etch employing methanol and bromine, and although 10V was a bit high, he had already gone through several etch, metalize, and measure steps (using C vs V to get the doping and depletion layer thickness) to reach to this point. He decided to stop, and using a heated Rapidograph (old style liquid ink drafting pen) filled with black wax, he drew a stripe across the wafer to define the active area of what would be the source-drain region, and then carefully etched through the epitaxial region and down to the semi-insulating GaAs everywhere else – remember he had only one tiny wafer! Next, and incredibly, he spot-welded two straight edged razor blades to small cross pieces to make a mask for a very narrow gate. The blade edges were so closely spaced that they formed a diffraction pattern along their almost touching edges. Using this makeshift mask, he then evaporated a very thin (a few microns wide) aluminum gate electrode through the gap in the blades and along the midpoint of the mesa. He then soldered Indium-Mercury ohmic contacts to the mesa on opposite sides of the gate, to form the source and drain. Remarkably the device functioned and Carver was able to record beautiful FET I-V curves, given that the transistor operated at 10V. He wrote up the short paper and submitted it to *Proceedings of the IEEE* in December [23], calling the new device a Schottky Barrier Gate Field Effect Transistor, which later became the MESFET (metal-semiconductor FET). Photos of the MESFET and original

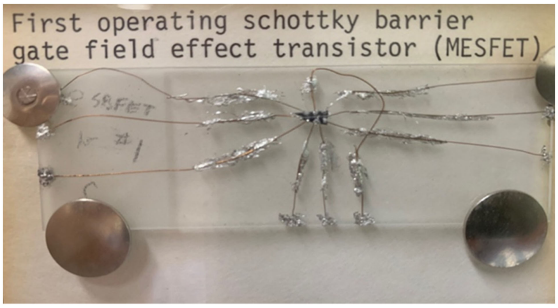


FIGURE 1. **Photo of the first GaAs MESFET chip, as wired up on a microscope slide.**

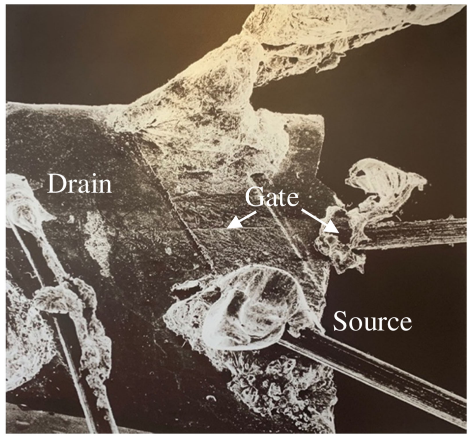
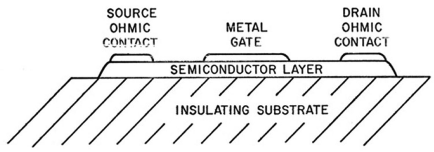
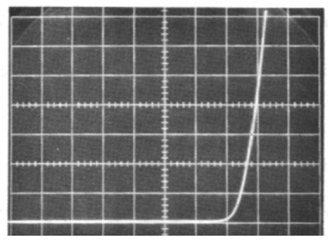


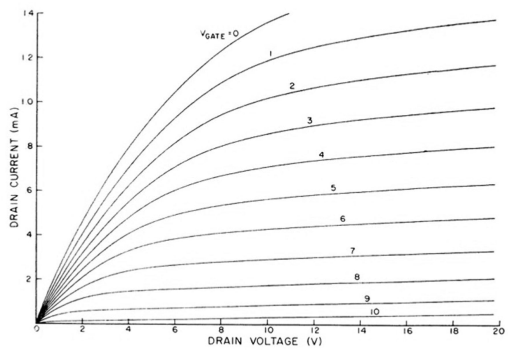
FIGURE 2. **Photomicrograph of the first MESFET.**



(a) Cross section of Schottky barrier gate FET.



(b) I-V characteristic of gate-channel barrier. Horizontal: 0.2 volt/maj. div. Vertical: 10μA/maj. div.



(c) Drain family for surface barrier gate device. Gate voltages are negative with respect to source.

FIGURE 3. **Reproduced figures from Mead's MESFET paper [23]. Top: Transistor configuration on GaAs wafer. Middle: Schottky gate IV curve. Bottom: Transistor IV curves.**

figures of the performance that were part of the paper [23] are shown in Figures 1–3.

Carver tried to patent the device and also to interest both Fairchild and TI in the new invention. The patent search returned prior art by Julius Lilienthal from 1925 [24] and 1926 [25] which had a concept for a FET device, but could not possibly have worked for material reasons, and another later patent from Bell Labs that also was not functional. The patent attorney suggested trying to reduce the scope of the invention to III-V materials only, but Carver did not think it was worth the effort at the time (note: Carver has more than 80 patents now). As to getting the silicon gurus of the day interested in the new high speed transistor idea – that too fell flat, and except for one more demonstration using GaSe [26], Carver went back to his junction work. A year or two later, a Japanese representative from Fujitsu he recollected, visited Mead's office bearing a gift for his published MESFET invention, which was now apparently the basis for a whole new line of high speed commercial devices in Japan! Even though Fairchild and TI ultimately decided to stick with silicon based devices, Fairchild did try out the MESFET concept, and within a year after Carver's paper, Hooper and Lehrer reported operating a GaAs MESFET above 3 GHz [27]. The MESFET has been going strong ever since, both in silicon and III-V materials, and has been a workhorse for GHz communications. Its later derivative, the HEMT (high electron mobility transistor) has now reached frequencies above 1 THz [28]!

Although Mead did not gain financially from this particular creative and heroic single-handed effort over a Thanksgiving holiday, it is only a very small part of what he has contributed to both engineering science and to the semiconductor industry, and I have no doubt he is satisfied with the rewards he, his students, his many professional colleagues, and the world have reaped from his insights and his accomplishments.

After the invention of the MESFET, Professor Mead started on a career path that is almost certainly better known to most engineers, covering modern VLSI design, programmable logic, high power silicon carbide devices, limits on large scale integration (Moore's Law), helping set up the first publicly available MOS wafer foundry (MOSIS), developing the first silicon retina devices, early CMOS imagers, neuromorphic circuits, an approach to teaching fundamental physical processes through electrodynamic principles, and most recently an intuitive formulation of electromagnetically coupled single-electron quantum systems [29]. Papers, talks and descriptions of all of these contributions from Mead's long and very fruitful career in science and engineering can be found on his website [30] and you can learn more through his many interviews and YouTube video talks [31]. One of Carver's many mantras, and perhaps the most visible secret of his success is: "It's all about thinking." However, for this series, and for this journal in particular, in which our intent is to reach out to both engineers and scientists, it seemed appropriate to close with a quote from Professor Mead that I hope all of our colleagues take to heart:

> "I've never made a distinction between science and engineering. To me it was all figuring the thing out and being able to do things with it. And if you're doing what you think of as science, you have to figure the thing out and make the experiment work, which is all engineering work. And if you're doing what you call engineering, you have to figure out the fundamentals so you know what to build, and that's science. So to me they could never be pulled apart …" [16 page 14].

SUBJECT BIO

CARVER MEAD (Life Fellow, IEEE) received the B.S., M.S., and Ph.D. degrees in electrical engineering from Caltech, Pasadena, CA, USA, in 1956, 1957, and 1960, respectively, and the honorary doctorates from the University of Lund, Lund, Sweden and USC, Los Angeles, CA, USA, in 1987 and 1991, respectively. He taught at Caltech for more than 40 years before retiring in 1999 as Caltech's Gordon and Betty Moore Professor of Engineering and Applied Science, Emeritus. Some of his pioneering contributions include electron tunneling, semiconductor interface energies, invention of the MESFET, scaling of technology, structured very-large-scale-integrated (VLSI) circuit design, the first VLSI circuit design course, physics of computation, neuromorphic VLSI circuit systems, and collective electrodynamics. He also pioneered the Silicon Foundry concept and the Fabless Semiconductor business model. Among his many honors and awards are the National Medal of Technology, BBVA Frontiers of Knowledge Award, NAE Founder's Award, IEEE John von Neumann Medal, Walter Wriston Public Policy Award, ACM Allen Newell Award, IEEE Centennial Medal, and the Lemelson-MIT Prize. He is a member of the National Academy of Sciences and the National Academy of Engineering. He is a Fellow of the American Physical Society, American Academy of Arts and Sciences, and the National Academy of Inventors (NAI). He is a member of the Computer History Museum, a Foreign Member of the Royal Swedish Academy of Engineering Sciences, and among others. He now lives in the Seattle area with his wife, Barbara, while also continuing to work in his Caltech lab regularly where he is engaged in a collaborative research project on high-temperature superconductivity. Website: carvermead.caltech.edu

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