From Bell Labs to Silicon Valley: A Saga of Semiconductor Technology Transfer, 1955-61

by Michael Rorison

Despite the fact that the Bell Telephone Laboratories had originated almost all the technology eventually used to invent the integrated circuit, or microchip, this revolutionary breakthrough occurred elsewhere—at Texas Instruments, Inc., in Dallas, and Fairchild Semiconductor Corporation in Mountain View, California. In the latter case, the transfer of this technology occurred largely through the offices of a pivotal but ultimately unsuccessful company, Shockley Semiconductor Laboratory, which had been formed by transistor pioneer William Shockley. After leaving Bell Labs in 1955, he brought together a stellar group of scientists and engineers who later departed (in September 1957) to found Fairchild, bringing a deep understanding of the diffused-silicon technologies they had learned while employed at Bell Labs.

One pivotal contribution to silicon technology, however, originated entirely at Fairchild—the planar manufacturing process itself, developed by the physicist Jean Hoerni. This crucial technique, in which an oxide layer on the silicon surface is used to protect the sensitive p-n junctions beneath it, has served ever since 1963 as the basis of microprocess chip fabrication. And Hoerni’s conception of the planar process, which occurred substantially earlier than most historical accounts have thus far reported.

In this article, I try to set the record straight by recounting the important steps and motivations behind the development of silicon technology to California—in the process laying the technological foundations of Silicon Valley.

Silicon Technology Heads West

By 1954 William Shockley was becoming dissatisfied with his lack of professional advancement at Bell Labs. Although head of transistor research, he had been passed over for higher positions and seemed mired at this middle-management level despite his many publications and patents, including the all-important invention of the transistor itself. In 1956, Shockley was about the age of 28, Noyce was about the same age and he, too, was restless. Both Shockley and his staff were already exploring ways to implement this new idea when Frosch and Derick’s paper was published in 1958 as the final volume in the classic series, *Transistor Technology*, which was becoming known throughout the semiconductor industry as “Ma Bell’s cookbook.” Shockley could also call upon his old colleagues Sparks, Tanenbaum, and Jack Morton, head of device development, to visit the new California company and consult with his charges in their converted Quonset hut at 391 San Antonio Road (Fig. 1). They spent most of that first year discussing or building the necessary equipment, such as silicon crystal growers and diffusion furnaces, and learning how to use it in making semiconductor devices.

On 1 November 1956, another news flash reached the Mountain View firm that Shockley had won the 1956 Nobel Prize in physics for the invention of the transistor, shared with John Bardeen and Walter Brattain. The next day they stopped working before noon for a celebratory luncheon at nearby Rickey’s Steakhouse, where Shockley was accompanied by one they turned him down that fall, claiming their families were too deeply rooted in New Jersey and they could not bear to leave Bell Labs. Thus he was still at the Pentagon, referring to micrometers-thin aluminum and lightning-fast impurity layers diffused into the silicon.

Over the next few months, Shockley began to lure away some of his most accomplished Bell Labs colleagues, including Tanenbaum and Morgan Sparks, who had fabricated the first junction transistor. But one by one they turned him down that fall, claiming their families were too deeply rooted in New Jersey and they could not bear to leave Bell Labs. Thus he was still at the Pentagon, referring to micrometers-thin aluminum and lightning-fast impurity layers diffused into the silicon.

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In March 1955 his sense of urgency in these efforts was stimulated by news from Bell Labs. Not only had chemist Henry Theurer finally produced silicon with impurity levels of less than 1 part per billion using float-zone refining. But Morris Tanenbaum and D. E. Thomas had also succeeded in forming the first diffused-based (emitter) silicon transistor using samples grown by Calvin Fuller (see article by Nick Holonyak on p. 30). "Morrie has AAS plus Al bonded," read a cryptic note in Shockley’s pocket notebook dated 23 March 1955, while he was still at the Pentagon, referring to micrometers-thin aluminum and lightning-fast impurity layers diffused into the silicon.

Over the next few months, Shockley began talking with executives at RCA, Raytheon, Texas Instruments and others about the possibility of starting a firm expressly devoted to producing diffused-silicon devices. For most of that summer, he met with only passing interest until he spoke to his friend and fellow Caltech alumus Arnold Beckman, founder and president of Beckman Industries, Inc. In early September they met in Newport Beach, California, and Shockley formed a new division led by Shockley whose early preprints of the papers that would be published in 1958 as the final volume in the classic series, *Transistor Technology*, which was becoming known throughout the semiconductor industry as “Ma Bell’s cookbook.” Shockley could also call upon his old colleagues Spaks, Tanenbaum, and Jack Morton, head of device development, to visit the new California company and consult with his charges in their converted Quonset hut at 391 San Antonio Road (Fig. 1). They spent most of that first year discussing or building the necessary equipment, such as silicon crystal growers and diffusion furnaces, and learning how to use it in making semiconductor devices.

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Upon returning from Stockholm in mid-December, Shockley found a package in his mail from the patent licensing department of the Bell Telephone Company, AT&T’s manufacturing arm. It contained a preprint of an article by Carl Frosch and Philip Derick titled “Surface Protection and Surface Masking during Diffusion in Silicon” (Shockley had delivered a paper on diffusion in the same vein at the conference, but it did not contain much information about use of a silicon-dioxide layer to passivate the silicon surface because Bell Labs was still applying for a patent on this important method. The preprint also contained crucial new information about how to etch tiny openings in that layer and to use the remaining oxide as a mask against the diffusion of trace impurities into the silicon. That technique would allow workers to establish intricate patterns of n-type and p-type material in the silicon. Shockley circulated this document among his technical staff (Fig. 3), giving them all a crucial early glimpse of what would become one of the core enabling technologies for silicon integrated circuits and ultimately lead to the emergence of Silicon Valley.

But all was not well at the Mountain View laboratory, for by 1957, members of the technical staff had begun to resent Shockley’s often heavy-handed management style and his quirky selection of R&D projects. After a couple of worrisome incidents, he started investigating the backgrounds of a few of his employees. When he gave one of them a vicious, public reprimand, several of his staff members were extremely dissatisfied and ready to quit.

For reasons about which we can only guess, Shockley had lost interest in the original goal set for the firm—manufacturing diffused-base transistors. He instead began to focus the company’s talents and energies on devices that were then at the forefront of semiconductor technology, such as field-effect transistors and the four-layer p-n-p-n diode, often called the Shockley diode because he held a patent on it. At a given potential called the breakdown voltage, current would suddenly begin to flow through the diode, this dual device, flowing from “off” to “on.” A remarkably simple circuit—two transistors in series, it was the ultimate realization of a goal that had been subtly implanted over the years at Bell Labs decades earlier.

The following September, a brilliant concept, however, the four-layer diode was extremely difficult to fabricate with adequate uniformity and reliability. Workers had to polish a silicon wafer to have exactly the same thickness on one or both sides and then carefully diffuse impurities into the wafer from both sides simultaneously. Lack of enough precision meant the diffused silicon was10 unpredictable, leading to variations in the breakdown voltage and other electrical characteristics.

Frosch, Moore, and others thought that this diode was much too difficult a project for the young company to undertake. But it was an early stage in a new evolutionary approach to electronics. We should concentrate on developing ways to implement this disruptive new technology.
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Despite the fact that the Bell Telephone Laboratories had originated almost all the technology eventually used to invent the integrated circuit, or microchip, this revolutionary breakthrough occurred elsewhere—at Texas Instruments, Inc., in Dallas, and Fairchild Semiconductor Corporation in Mountain View, California. In the latter case, the transfer of this technology occurred largely through the offices of a pivot but ultimately unsuccessful company, Shockley Semiconductor Laboratory, which had been formed by transistor pioneer William Shockley. After leaving Bell Labs in 1955, he brought together a stellar team of scientists and engineers who later departed (in September 1957) to found Fairchild, bringing a deep understanding of the diffused-silicon technologies they had learned while employed there. One pivotal contribution to silicon technology, however, originated entirely at Fairchild—the planar manufacturing process technique developed by the physicist Jean Hoerni. This crucial technique, in which an oxide layer on the silicon wafer is used to protect the sensitive p-n junctions beneath it, has served ever since 1963 as the basis of microchip fabrication. And Hoerni's conception of the planar process was published substantially earlier than most historical accounts have thus far reported.

In this article, I try to chart the record straight by recounting the important steps and milestones in the development of silicon technology to California—in the process laying the technological foundations of Silicon Valley.

Silicon Technology Heads West

By 1954 William Shockley was becoming increasingly dissatisfied with his lack of professional advancement at Bell Labs. Although head of transistor research, he had been passed over for higher positions and seemed mired at Bell Labs, in part because despite his many publications and patents, including the all-important Bell Labs. When he and the others left Bell Labs, they were able to bring Shockley's technical staff with them to Fairchild. The next day they stopped working before noon for a celebratory luncheon at nearby Rickey's Studio Inn in Palo Alto. Another photograph of that gathering (Fig. 2), with Shockley at the head of the table being toasted by his friend and fellow Caltech colleague, such as Tanenbaum and Walter Brattain. The next day they

automated means for producing diffusion-based transistors.

and right of him is Sheldon Roberts. Robert Noyce stands in the middle and Jay Last is at far right, both lifting glasses. (Courtesy of Intel Corporation)

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would be published in 1958 as the final volume in the classic series, Translator Technology, which was becoming known throughout the semiconductor industry as "Ma Bell's cookbook". Shockley could also call upon his old colleagues Sparks, Tanenbaum, and Jack Morton, head of device development, to visit the new California company and consult with his charges in their converted Quonset hut at 391 San Antonio Road (Fig. 1). They spent most of that first year purchasing or building the necessary equipment, such as silicon crystal growers and diffusion furnaces, and learning how to use it in making semiconductor devices.

On 1 November 1956, marvellous news reached the Mountain View firm that Shockley had won the 1956 Nobel Prize in physics for the invention of the transistor. Shockley circulated this document among his technical staff (Fig. 3), giving them all a crucial early glimpse of what would become one of the core enabling technologies for silicon integrated circuits and ultimately lead to the emergence of Silicon Valley by the time Frosch and Derek's paper was published in the Journal of The Electrochemical Society the following September, Shockley and his staff were already developing new ways to implement this disruptive new technology.

A Rebellion Erupts

But all was not well at the Mountain View laboratory. In 1957, members of the technical staff had begun to resent Shockley's often heavy-handed management style and his quirky selection of R&D projects. After a couple of worrisome incidents, he started investigating the backgrounds of a few of his employees. He feared he gave one of them a vicious, devastating "cold shoulder," and many others overheard. Several of the early employees were extremely dissatisfied and ready to quit. For reasons about which we can only guess, Shockley had lost interest in the original goal set for the firm—manufacturing diffused-base transistors. He instead began to focus the company's talents and energies on devices that were then at the frontiers of semiconductor technology such as field-effect transistors and the four-layer p-n-p-n diode, often called the Shockley diode because he held a patent on it. At a given potential called the breakdown voltage, current would suddenly begin to flow through the two-terminal device, spurring it from "off" to "on." A remarkably simple component—a transistor switch—it was the ultimate realization of a goal that had been subtly implanted over the decades earlier. A brilliant conception, however, the four-layer diode was extremely difficult to fabricate with acceptable yield and reliability. Workers had to polish a silicon wafer to have exactly the same edge parallel on both sides and then carefully diffuse impurities into the wafer from both sides simultaneously. Lack of enough precision meant the diffused layer would sometimes grow in unpredictable depths, leading to variations in the breakdown voltage and other electrical characteristics.
first on three-layer devices such as the diffused-base transistor, and get a product out the door. After that they could begin attempting the more difficult problem of fabricating the four-layer diode. But Shockley was not listening and began desiring more and more of the company's resources to this pet project. He eventually set up a separate Little group working mostly in secret on the four-layer diode, which further angered technical staff members left out of the loop.

The conflict reached the boiling point in mid-May 1957, when Beckman came up for a meeting to discuss the division’s problems and plans. Taking umbrage at his partner’s proposals and request to control expenses, however, Shockley stood up and stomped out of the room, shouting, “If you don’t want what we’re doing here, I can take this group and get support anywhere else!”

But nobody left the room except Shockley. His outburst triggered a four-month sequence of events that led in September to the departure of eight of his top lieutenants—including Hoerni, Last, Moore, and Noyce. A pivotal moment in the history of the semiconductor industry, it is briefly recorded in Shockley notebook: “Walid 18 Sep—Group resigns.”

A Successful Semiconductor Company

Within days the group of eight rebels—which also included the metallurgist Sheldon Roberts and engineers Julius Blank, Victor Grinich, and Eugene Kleiner—signed a $1.38 million agreement brokered by the community banking firm Hayden Stone with Fairchild Camera and Instrument Corporation of New York, on New York Island 4. Using these start-up funds, the eight began setting up a new firm known as the Fairchild Semiconductor Corporation just over a mile away on Charlestown Street in Falo Alto.4

At almost exactly the same moment, Fisch and Derek’s revolutionary paper was published in the September 1957 issue of the Journal of The Electrochemical Society. But because they had read the preprint of this paper while working at Shockley Lab, the Fairchild group had a head start on most of the competition. According to Roberts, some of them—including Hoerni, Moore, and Noyce—had already begun experimenting with double diffusion and oxide masking while they were there.

The first commercial product attempted by Fairchild was a high-frequency, diffused-base silicon transistor to drive electromechanical control computer that IBM was making for the guidance-and-control system of the B-70 bomber. The engineers applying the silicon technology they had learned and developed at Shockley Semiconductor. Robert Moore turned to focus their efforts while Moore tackled issues of doping impurities into them. Last and Noyce took on the intrusive tasks involved in photolithography and photomasking, developing a “step-and-repeat” camera to make their own masks in defining tiny, precise p- and n-type areas in the silicon wafer.5

In May 1957, the group had successfully fabricated prototype n-p-n silicon transistors, based on the “mesa” structure pioneered by Van Benschoten and Thomas at Bell Labs.6 In such a structure, a p-type base layer and an n-type emitter layer were diffused into an n-type silicon wafer that formed the collector of this bipolar junction transistor. Oxide masking and photolithography were used to define these regions. But after attaching the electrical leads, workers etched away any remaining portions of the silicon dioxide sheath, exposing the underlying sensitive junctions. Moore thought this was standard practice in the semiconductor industry at the time, for the oxide layer was widely viewed as “dirty”—especially at Bell Labs. Fairchild’s transistors were the first commercially successful mesa transistors, beating out Texas Instruments, which was also working on similar devices. Not only did they meet IBM’s stringent specifications, but they also began to be used in other avionics applications. Fairchild Semiconductor recorded sales of $300,000—almost all of it coming from this product—in 1958, its first full year of operations, and ended the year in the black. Meanwhile, the loyal staff members remaining at Shockley Semiconductor Laboratory were still struggling to make four-layer diodes. But a serious problem emerged with these mesa transistors that threatened the continued success of the fledgling company. Some of these devices experienced catastrophic failures that were traced to bits of foreign material being dislodged and becoming attached to the mesa transistors, attracted by strong electric fields there. Slightly tapping on the metal cans housing this bipolar junction transistor. Oxide masking and photolithography were used to define these regions. But after attaching the electrical leads, workers etched away any remaining portions of the silicon dioxide sheath, exposing the underlying sensitive junctions. Moore thought this was standard practice in the semiconductor industry at the time, for the oxide layer was widely viewed as “dirty”—especially at Bell Labs. Fairchild’s transistors were the first commercially successful mesa transistors, beating out Texas Instruments, which was also working on similar devices. Not only did they meet IBM’s stringent specifications, but they also began to be used in other avionics applications. Fairchild Semiconductor recorded sales of $300,000—almost all of it coming from this product—in 1958, its first full year of operations, and ended the year in the black. Meanwhile, the loyal staff members remaining at Shockley Semiconductor Laboratory were still struggling to make four-layer diodes.

The Planar Manufacturing Process

When Hoerni conceived this approach in December 1957, Shockley lacked the technical abilities needed to implement it. And the new firm’s talents and energies had to be devoted almost entirely to getting its first mesa transistors out the door. But once the techniques of diffusion, oxide masking and photolithography had been mastered in March 1958, he recognized his conception as a way to address their reliability problems. With the help of Hoerni, Last, who made the extra mask he needed, Hoerni out this idea in March 1959, fabricating prototype planar transistors that avoided the problems of the failure-prone mesa. (Fig. 5. What’s more, he soon showed they had far superior electrical characteristics, higher gains, and leakage currents often less than a nanoampere. As Hoerni confessed in a letter presented at an October 1960 meeting on electronic devices in Washington, DC, “the planar design offers considerable improvement and stabilization of the parameters likely to suffer from surface contamination.”)

The Monolithic Idea Becomes Reality

Only nine days after Hoerni’s formal patent disclosure, Noyce, stimulated in part by the urgings of his partner, began writing a lab notebook under the heading, “Semiconductor Lab at Fairchild—The Monolithic Idea.”7 He thought it a terrible waste to create all these transistors on a single wafer had to be cut apart, have leads attached to them individually, and then be placed back together with other components to assemble, “14 January 1958, decided to reorient Fairchild’s transistor production toward a promising new planar approach.8
first on three-layer devices such as the diffusion-base transistor, and get a product out the door. After that they could begin attempting the more difficult problem of fabricating the four-layer diode. But Shockley was not listening and began desiring more and more of the company's resources to this pet project. He eventually set up a separate little group working mostly in secret on the four-layer diode, which further angered technical staff members left out of this loop.

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But nobody said the room except Shockley. His outburst triggered a four-month sequence of events that led in September to the departure of eight of his top lieutenants—including Hoerni, Last, Moore, and Noyce. A pivotal moment in the history of the semiconductor industry, it is briefly recorded in another Shockley notebook: “Wid 18 Sep—Group resigns.”

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Within days the group of eight rebels—which also included the metallurgist Sheldon Roberts and engineers Julius Blank, Victor Grinich, and Eugene Kleiner—signed a $1.38 million agreement brokered by the investment-banking firm Hayden Stone with Fairchild Camera and Instrument Corporation of New York, on the island of Manhattan. Using these start-up funds, the eight formed a separate R&D Corp. and Magnum Photos)

By May 1958 the group had already begun to consider a new and different way to fabricate transistors. An admitted contrarian, he suggested that instead of etching away the oxide layer at the end of processing, it instead be left in place to protect the sensitive junctions. He entered this revolutionary new idea on page 247, and 4 of his crisp new lab notebook on 1 December 1957, hardly more than two months after the firm had been founded.

Titled “Method of protecting exposed p-n junctions at the surface of silicon transistors by oxide masking techniques,” it was witnessed that same day by Noyce. The very first paragraph is revealing:

The general idea underlying this invention is the setting up of an oxide layer prior to diffusion of dopant impurities, so that the places on the surface of the transistor at which p-n junctions are expected to emerge from the body of the semiconductor, the oxide layer so obtained is an integral (coaxial) part of the device and will protect the otherwise exposed junctions from contamination and possible electrical leakage due to subsequent handling, cleaning, [and] cannery of the device. 22

This approach had the further advantages that all electrical leads could be attached and all processing steps performed from the same side of the silicon wafer—features that would be of utmost importance when this planar process was later applied to fabricating integrated circuits. With only slight exaggeration, the history of technology Christophe Lécuyer has called this planar process “the most important innovation in the history of the semiconductor industry.”

While Hoerni conceived this approach in December 1957, Fairchild lacked the technical abilities needed to implement it. And the new firm’s talents and energies had to be devoted almost entirely to getting its first mesas transistors out the door. But once the techniques of diffusion, oxide masking and photolithography had been mastered in 1958, he refused to rest on his conception as a way to address their reliability problems. With the help of Last, who made the extra mask he needed, Hoerni proved out this idea in March 1959, fabricating prototype planar transistors that avoided the problems of the failure-prone mesas (Fig. 5). What’s more, he soon showed they had far superior electron mobility, higher gains, and leakage currents often less than a nanoampere. As Hoerni concisely put it, the planar presented at an October 1960 meeting on electron devices in Washington, DC, “the planar design offers considerable improvement and stabilization of the performance likely to suffer from surface contamination.”

So gratifying was this early success that in the 1 December 1957 entry in his lab notebook—indicating the great accuracy of his original theoretical insight—just a few months later Moore and Noyce, who had by then emerged as the natural leaders of the group, decided to reorient Fairchild’s transistor production away from the promising new planar approach.

The Monolithic Idea Becomes Reality

Only nine days after Hoerni’s formal patent disclosure, Noyce, stimulated in part by the urgings of the patent attorney, began writing his lab notebook under the heading, “The idea of isolating multiple devices.” He thought it a terrible waste to place all these transistors on a single wafer had to be cut apart, have leads attached to them individually, and then be reordered back together with other components to assemble. On 14 January 1958, Hoerni had written that all the interconnections could be instead placed directly on the wafer surface during the last step of the etching process. Here again, the silicon-dioxide interface
layer played the key role as an enabling technology. In many applications now it would no longer be desirable to make multiple devices on a single piece of silicon in order to be able to make interconnections between devices as part of the manufacturing process and thus reduce size, weight, etc., as well as cost per active element. 

Noey began to hoard his planar process, he added the provision that aluminum be used to connect the individual devices to be placed on top of the oxide layer, which would insulate them from the back of the wafer all the way to the backside of the wafer. This “flip-flop” logic circuit employed four transistors. (Courtesy of Fairchild Semiconductor). …

**About the Author**

MICHAEL RIORAN

 earned his PhD in physics from MIT. He is an adjunct professor of physics at the University of California, Santa Cruz, and a Lecturer in the Electrical and Computer Engineering Department. His research interests include nanoscale electronics, nanomaterials, and quantum information processing.

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**References**

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In 1958, Fairchild began to plan its plant in Palo Alto, and to recruit employees including Robert Noyce and Gordon Moore. Noyce and Moore replaced him as Fairchild’s General Manager and Moore replaced him as Fairchild’s plant manager as Jay Last, who formed a development team. The group then developed a planar processing technology. Since the junction transistor’s invention, it was recognized that a Bell Labs group under M. M. Kieff that a Bell Labs group under M. M. Kieff had conceived similar ideas earlier. It was also recognized that a Bell Labs group under M. M. Kieff had conceived similar ideas earlier.

Throughout this technological evolution, from bipolar to field-effect transistors to planar integrated circuits, the silicon-dioxide layer discovered in 1955 by Fosch and Derick remained essential in the connection between this super, flexible interface between silicon and its environment, the junction, and the circuitry it hosted. It could not be unthinkable. It is the sine qua non of planar integrated circuits. It was the most distinguishable silicon from all other material alternatives.

Although ultimately unsuccessful financially, the Shockley Semiconductor Corporation did play an important role in introducing technology-transfer roles in this saga. It was a great moment in the history of the world where men came together with ideas on the West Coast, and began working together on the research, on the implementations of the new silicon technologies pioneered in the mid-1950s by Bell Labs. There were so revolutionary, in fact, that it took a small rebellion, much celebrated in Silicon Valley lore, to realize them. The development and implementation of planar processing Fairchild Semiconductor Corporation was what really threw the floodgates open to extremely reliable silicon transistors and microchips of endlessly growing complexity.

The junction transistor’s inventor, William Shockley, dimly perceived this bright future, but he lacked the management skills to bring it off under his direction. In the early 1950s, he began teaching at Stanford University, first as a research associate and then as a professor of engineering and applied physics. Shockley’s company eventually failed and was eventually dissolved. Yet without Shockley’s contributions in bringing together this stellar group of researchers and introducing them to the concept of planar processing, there would be no Silicon Valley—still less in Northern California.

About the Author

MICHAEL RIORDAN earned his PhD in physics from MIT. He is an adjunct professor of physics at the University of California, Santa Cruz, and a Lecturer delegates at Stanford University. He is author of The Hunting of the Quark (Simon & Schuster, 1987) and The Origin of Quantum: Fire: The Birth of the Information Age (NY: Basic Books/Perseus, 2002). He is the 1999 Sally Hacker Prize of the Society for the History of Technology. A fellow of the American Physical Society, the IEEE and the American Academy of Arts and Sciences. He is the recipient of the American Institute of Physics.

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